BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

COLORADO DEPARTMENT OF TRANSPORTATION

CLIMATE STUDY

CHANGING CLIMATE AND EXTREME WEATHER IMPACTS ON GEOHAZARDS IN COLORADO

FINAL

PROJECT NO.: 1836003 DATE: May 14, 2021

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY
701 12th Street – Suite 211
Golden, CO USA 80401
Telephone (720) 598-5982

May 14, 2021
Project No.: 1836003

Ty Ortiz
Colorado Department of Transportation
4670 Holly Street, Unit A
Denver, CO 80216

Dear Mr. Ortiz,

Re: Changing Climate and Extreme Weather Impacts on Geohazards in Colorado

This report presents the findings BGC Engineering USA Inc.'s assessment of how extreme weather and climate change may affect geohazard impacts through changes to their frequency and magnitude. We have enjoyed working on this unique and interesting project and look forward to continuing to support the Colorado Department of Transportation's geohazard management program.

Yours sincerely,

BGC ENGINEERING INC.
per:

Joseph Gartner, Ph.D., PE
Geotechnical Engineer

EXECUTIVE SUMMARY

In partnership with the Federal Highway Administration (FHWA), the Colorado Department of Transportation (CDOT), AEM Corporation (AEM) and BGC Engineering USA Inc. (BGC) have evaluated the impact of climate change induced weather patterns and extreme weather events on geologic hazards (geohazards).

For this study, AEM Corporation provided a climate change assessment to identify expected weather patterns and extreme weather events that are a result of climate change. With the information provided by the climate change assessment, BGC evaluated how geohazard Frequency and Magnitude (FM) could be affected. CDOT has overseen this work and has provided input with help from FHWA and the National Center for Atmospheric Research (NCAR).

The approach taken in this study was to build event trees to evaluate semi-quantitative estimates for the likelihood that a geohazard would increase, decrease, or stay the same given a change in a single climate variable. A single event tree consisted of mutually exclusive and collectively exhaustive combinations for how a single climate variable could affect what is termed a geophysical process, which would in turn affect a geohazard. The term ‘geophysical process’ was used to describe a change to the earth, rather than within the atmosphere.

Each event tree consisted of three categories: a climate variable, a geophysical process and a geohazard FM outcome. Mutually exclusive and collectively exhaustive combinations of these categories were mapped out to characterize unique scenarios which could result in one of three possible outcomes: the geohazard FM increased, stayed the same or decreased as a result of the climate variable, and geophysical process scenarios. The scenarios were each illustrated by a single branch in the tree. Along each branch were a set of values that were multiplied together to estimate the conditional probability of occurrence associated with that scenario outcome. The sum of the branches with the same outcomes provided an overall likelihood for that outcome.

For this study, three categories were considered for each event tree. Judgment was used to select all geophysical processes that (a) might be meaningfully impacted by a climate variable and (b) have a meaningful impact on a geohazard. This number of decisions could be different than three, and the process would remain the same. This process was repeatable and simplistic, and it could be expanded.

One key simplification was that the magnitude of change was not assessed, only the anticipated trend: increase, decrease or stay the same. Another simplification was that the changes were considered independent at each node, meaning the climate variables were independent, the geophysical processes were independent and the geohazard FM trend was independent. For example, scenarios of a climate being cold and wet versus cold and dry were not considered. The rationale for simplification was that the added analytical complexity and present uncertainty in the input parameters would prove unlikely to enhance the results of this work at a sufficient level of confidence. Such refinement is best undertaken with respect to specific geotechnical needs.

Linkages between inputs from modeled climate projections and many geophysical processes can be tenuous, in part because most climate models are tuned to optimize coarser climate metrics (e.g., monthly, or annual timesteps and larger areas), and may contain considerable uncertainty regarding low probability events (e.g., extreme temperature or precipitation). Other uncertainties were represented by the challenges of downscaling regional models, and by using ensembles of climate models.

A series of workshops (including BGC, CDOT, FHWA and AEM) were held to assign trends to characterize how climate variables affect various geophysical process and how geophysical processes affect geohazard FM. The workshops were summary sessions of expert elicitations of geohazard professionals with total geohazard backgrounds ranging from five to 25 years. The educational background for the group consisted of two individuals with B.S. degrees, two individuals with M.S. degrees, and three individuals with Ph.D. degrees. The geohazard professionals were asked to consider each of the linkages between climate variables, geophysical processes and geohazards and, based on their experiences, to select among a list of answers to describe the direction and strength of a trend that describes the linkage. Again, it was considered that a simplification was in order at this stage, and each expert was given five choices, from likely increasing to likely decreasing. Based on the answers provided, probability values were assigned that reflect the confidence and direction of the trend.

Based on discussions between BGC, CDOT and AEM, 24 event trees were developed that consisted of various combinations of climate variables, geophysical processes and geohazard types. This number of independent scenarios was judged to be appropriate to demonstrate the process and give CDOT some valuable information, and to be respectful of the uncertainty that currently lies in the inputs.

The results of each event tree analyses provided semi-quantitative estimates that characterize the likelihood that geohazard FM would increase, stay the same or decrease. These semi-quantitative estimates provided insight into the general trend of a geohazard FM to be affected by a changing climate variable.

There was general agreement among the answers provided by the different geohazard professionals with the majority of differences being disagreement in the strength of the trend (e.g., “likely increasing” vs. “possibly increasing”) which would, in turn, affect the geohazard FM. Table E-1 identifies scenarios where there was general agreement that there would be a change in geohazard FM.

Table E-1. Summary of scenarios that could affect geohazard Frequency and Magnitude (FM). Bold text identifies increases to geohazard FM.

Climate Variable Trend	Geophysical Process Trend	Geohazard FM
Number of Extreme Freeze thaw days increases	Discontinuity Aperture increases	**Rockfall increase**
	Material strength decreases	**Debris flow increase**
Winter precipitation increases	Increasing water in discontinuities	**Rockfall increase**
	Increasing overland flow	**Debris flow increase**
	Increasing infiltration	**Shallow landslide increase**
	Increasing river runoff	
	Increasing groundwater level	**Deep landslide increase**
Number of extreme heat days increases	Increasing wildfire frequency	**Debris flow increase**
Summer precipitation decreases		
Summer precipitation decreases	Decreasing overland flow	Debris flow decrease
	Decreasing infiltration	Shallow landslide decrease

The event tree approach is flexible and can accommodate improvements to climate modeling and characterization of the links between climate variables, geophysical processes and geohazards. Improved information for climate change variables may be a result of more accurately downscaled models that are specific to a location rather than broad representations of the entire state. With improvements to climate change modeling, improvements to how geohazards are affected may also be expected.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIMITATIONS

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1.0 INTRODUCTION

In partnership with the Federal Highway Administration (FHWA), the Colorado Department of Transportation (CDOT), AEM Corporation (AEM) and BGC Engineering USA Inc. (BGC) have evaluated the impact of climate change induced weather patterns and extreme weather events on geologic hazards (geohazards). For the purpose of this study, an extreme weather event is defined as an event that is notable in terms of weather records or typically has a low return period based on past records.

For this study, AEM provided a climate change assessment to identify expected weather patterns and extreme weather events that are a result of climate change (described in Sections 2.4, 3.1, 4.1 and Appendix A). With the information provided by the climate change assessment, BGC evaluated how geohazard frequency and magnitude (FM) is expected to be affected. CDOT has overseen this work and has provided input with guidance from FHWA and the National Center for Atmospheric Research (NCAR).

This report presents BGC's study of the effect of changing weather patterns and extreme weather events on geohazard FM. This work was performed for CDOT under the following work authorization from Yeh and Associates, Inc.: Agreement No. 218-034-A, Task Order 2, effective February 1, 2019.

For this study, specific estimates for geohazard FM that include event return periods, velocity, volume and/or intensity were not provided for the geohazard evaluated. Rather the geohazard FM was defined in this study to reflect general trends that could be expected due to changing weather patterns or extreme weather events.

The geohazards evaluated are rockfall, debris flow, shallow landslides and deep-seated landslides. These geohazards are defined in Section 2.1. Variables describing changing weather patterns and extreme weather events are April 1 Snow Water Equivalent, Snow Residency Time, Extreme Freeze Thaw Days, Extreme Heat Days, Summer Precipitation, Winter Precipitation, Maximum Daily Summer Temperature and Maximum Daily Temperature, as described in Section 3.1.1. The development of maps describing the changes to the variables averaged over the 1975 to 2005 and 2071 to 2090 time periods is provided in described in Section 3.1 and the maps are presented in Appendix A.

Managing geohazards for transportation infrastructure annually costs millions of dollars (Vessely et al., 2017). Budgeting for such expenses needs to be done years in advance. Therefore, to better understand the potential future costs of managing geohazards in the future, the potential impacts of climate change on geohazard FM needs to be considered. The goal of this study is to provide CDOT with a better understanding of how changing climate and extreme weather could affect geohazards and to provide tools to help characterize if the geohazard FM is expected to increase, decreases or stay the same. The information and methods developed by this study are intended to inform management of geohazard impacts on transportation infrastructure.

2.0 BACKGROUND

Climate change is a broadly accepted occurrence in the scientific community and populations are currently documenting the effects of rising temperatures, changing precipitation regimes and extreme weather events. The International Panel on Climate Change (IPCC) predicts a warming between 2.7 °F to 10.4 °F (1.5 °C to 5.8 °C) by 2050 for North America (IPCC, 2014). Observational evidence does not support a natural explanation for the amount of warming that has globally occurred since 1900, but instead points to greenhouse gas emissions by humans to be the dominant cause of warming temperatures (USGCRP, 2018). Consequences of climate change can manifest as increased extreme weather events (e.g., heat waves, hurricanes, and atmospheric rivers) that are destructive in and of themselves as well as by affecting geomorphic processes that trigger geohazards. Changing patterns and trends in extreme weather events have been attributed to climate change (National Academies of Sciences, Engineering and Medicine 2016).

General Circulation Models (GCMs) have been developed to predict changes in temperature and precipitation at a global scale that are a result of low and high emissions scenarios. At the low end of the spectrum, the Climate Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway (RCP) 2.6 scenario assumes that emissions peak between 2010-2020 and then decline substantially. At the high end of the spectrum the CMIP5 RCP 8.5 scenario assumes that greenhouse gases continue to rise through the entire 21st century. GCMs provide future climate projections on coarse spatial scales (e.g., 1 - 3° latitude or longitude), but output from the GCMs can be downscaled to provide higher resolution estimates for future temperature and precipitation characteristics that are specific to smaller regions. The downscaled estimates of temperature and precipitation characteristics can account for broad topographic changes such as the change in elevation from the eastern plains of Colorado to the Continental Divide. However, the downscaled estimates are unable to resolve local topographic influences that may be caused by a sub-range within the Rocky Mountains, or a certain valley that may contain a highway (NCAR, personal communication on November 18, 2019).

Despite the challenges associated with downscaling GCMs to model climate change at finer resolutions, modeling studies and trend analyses are in general agreement that temperatures are increasing (e.g., Easterling et al., 2009; Lopez et al., 2018; Mudelsee, 2018; National Academies of Science, Engineering, and Medicine, 2019). More specifically, modeling results have found that potential increases in extreme high temperatures and decreased extreme low temperatures (Easterling et al., 2009) are expected between the 2020s and the 2030s in the western United States (Lopez et al., 2018).

The effect of climate change on precipitation is less well understood due to complex interactions between precipitation extremes, atmospheric circulation, warming and moisture (Pendergrass, 2018). Since the beginning of the last century, annual precipitation has decreased across much of the western United States, however, over the next century precipitation is projected to increase for the northern United States (USGCRP, 2018). Increased annual rainfall amounts are anticipated to be a result of more frequent extreme rainfall events (Easterling et al., 2009;

Pendegrass and Knutti, 2018). Colorado is at the southern edge of the portion of the United States anticipated to have increased rainfall and the increases in rainfall are projected to occur during the winter months (USGCRP, 2018). At higher elevations, the increased precipitation may fall as snow, however, at lower elevations the rain will more frequently fall as freezing rain or rain.

Annual and seasonal changes to temperature and precipitation are expected to decrease snowpack depth, shift spring snowmelt and runoff to be earlier, decrease soil moisture and increase the frequency and severity of wildfire (USGCRP, 2018). Table 2-1 summarizes how temperature and precipitation in Colorado are affected by climate change.

Table 2-1. A summary of how temperature and precipitation are changing in Colorado.

Variable	Projections	Source
Temperature	Temperature will increase by 2˚ F to 6.5˚ F by year 2050	Garfin et al., 2013 Gordon and Ojima, 2015
	Daily minimum temperature is increasing more than daily maximum temperature.	
	Summer has experienced the greatest increase in temperature over all seasons.	
	The strongest warming trend will be in southwest Colorado, the San Luis Valley and the Front Range	
	Heatwaves, drought and wildfire are expected to increase.	
Precipitation	Under RCP 8.5 precipitation changes from -3% to + 8% by 2050, depending on the GCM applied.	Garfin et al., 2013 Gordon and Ojima, 2015 U.S. Bureau of Reclamation, 2012 Muller Engineering Company, 2018
	Precipitation depths increase 8% to 16% on western slopes of Rangely, Grand Junction, Montrose and Durango, and from 5% to 13% for high mountain locations of Steamboat Springs, Vail, Salida, Alamosa, depending on the emission scenario.	
	Precipitation will increase in Winter but more of it will fall as rain rather than snow	

These changes to climate described above are expected to affect the size and frequency of various geohazard types. The occurrence of landslides has direct economic consequences to roads and infrastructure (Winter et al., 2018). Adapting to the potential geohazard implications of climate change involves identifying the specific geohazard characteristics that may change, preparing for potential impacts to infrastructure, implementing solutions to improve resiliency and adopting guidelines for future development to consider changing climatic conditions in the design. Geohazard risk assessments that consider climate change are also beneficial (e.g., Kaspersen and Halsnaes, 2017; Peduzzi, 2019). General guidelines and methods for integrating climate adaptation and resiliency into engineering practice have been developed in the U.S. (e.g., FHWA, 2015; Olsen, 2015; Filosa et al., 2017) and Canada (Engineers Canada, 2018; Palko and Lemmen, 2017).

2.1. Geohazard Definitions and Triggering Mechanisms

In Colorado, the CDOT geohazards program recognizes and manages debris flows, drainage/seepage features, embankment distress, landslides, rockfall sites, rockslides, sinkholes, subgrade distress including swelling and collapsing soils. Where they occur, the magnitude and frequency are a function of geology, topography and climate. As such, when climate changes, especially through more frequent extreme weather events, an impact to geohazards is expected.

After initial discussion on a wide range of geohazards, a focus on landslides was chosen. The term “landslide” describes a variety of gravity driven movement of soil, rock and/or artificial fill that travel downslope as falls, topples, slides, spreads and/or flows (Hungr et al., 2014; Highland and Bobrowsky, 2008; Varnes, 1978). For this study, the following landslide geohazards were considered:

- Deep landslide: a landslide with a typical maximum depth greater than approximately 50 feet (approximately 15 m) and typically extending beyond the right of way (ROW). Volume consists of more than about 100 yd^3 (approximately 75 m^3) of soil and/or rock with a planar or rotational sliding surface located more than about 15 ft (approximately 5 m) below the soil surface. Movement of deep landslides may be slow to rapid and internal deformation may range from little to extensive.
- Shallow landslide: a landslide with a typical maximum depth of approximately 15 feet (approximately 5 m) in embankments or natural slips within the ROW. Volumes are typically less than about 100 yd^3 (approximately 75 m^3) of soil and/or rock with a planar or rotational sliding surface. Movement of shallow landslides may be slow to rapid and internal deformation may range from little to extensive.
- Rockfall: the sliding, toppling or rolling of rocks or rock blocks of all sizes within or above ROW. Falling fragments travel at very rapid to extremely rapid velocities and typically strike the underlying slopes at an angle which then causes bouncing and rolling of the material. Rockfall, as defined here, includes rockslides, which consist of one or more blocks that collectively exceed 30 yd^3 (approximately 25 m^3) so a full range of event size is considered.
- Debris flow: the mobilization and travel into the ROW or onto the road of soil, rock and water initiated through shear failure of soil and rock or entrainment of soil and rock by flowing water. Debris flows can erode and entrain large volumes of channel bed sediment as they flow down steep channels (Jakob et al., 1997; Hungr et al., 2005) and deposit large volumes of sediment on depositional fans.

Figure 2-1 provides examples of each of the landslide geohazard types evaluated for this study. Other geohazards, such as swelling and collapsing soils, are also important to CDOT, and could be evaluated in a similar way, but they were not included at this time.

Figure 2-1. Examples of the landslide geohazard types considered for this study: deep landslide (top left, photo by CDOT), shallow landslide in an embankment (top right, photo by CDOT), rockfall (bottom left, photo by CDOT), debris flow (bottom right, photo by USGS)

The occurrence and size of the various landslide geohazards are closely tied to soil moisture and the water table elevation, material properties and slope angle, among other factors. Climate change in the form of increase temperatures and changed precipitation regimes will affect soil and water characteristics below the soil surface (e.g., soil moisture, water table elevation, material strength, freeze-thaw cycles, etc.). These changes to the climate and the subsequent impact to soil and water characteristics will, in turn, affect landslide geohazard FM.

Examples reported from elsewhere, and not specific to Colorado, are that fewer landslides are expected during dryer summer months in the future whereas there will be an increase in landslide activity in the spring and fall seasons due to an increase in precipitation amount and intensity (L’Heureax et al., 2018). Warming temperatures will affect the frequency of freeze-thaw cycles which are closely tied to rockfall occurrences (Pratt et al., 2018).

Earlier snowmelt and higher spring and summer temperatures are expected to increase the frequency, severity and duration of wildfire seasons (Westerling et al., 2006). Wildfire substantially increases the probability of debris flow within a watershed due to development of water repellant soils (Debano, 1981; Doerr et al., 2000), exposing bare ground to rainfall impact through the removal of the canopy, litter and duff (Cannon and Gartner, 2005; Meyer, 2002; Moody and Martin, 2001). As a result of these changes to the soil caused by wildfire, typical rainfall conditions (e.g., a storm with a 2-year return period) can trigger post-wildfire debris flows (Cannon et al., 2008).

2.2. Economic impacts of geohazards

Managing landslide geohazards for transportation infrastructure annually cost millions of dollars. The costs are generally due to building resilience into infrastructure, maintaining existing mitigation structures and responding to recent geohazard events. Increases to the frequency and magnitude (FM) of landslide geohazards can have significant broad economic impacts.

CDOT has inventoried several hundred locations where landslide geohazards have or are impacting CDOT roadways. Estimated annual direct department costs from geohazard events averages about $17 million to $20 million, which includes maintenance activities included in approximately 8,500 work orders each year. Of this estimate, over one-half of the direct cost is the result of landslide geohazards. In 2014, the total economic impact from geohazards on Colorado DOT roadways was estimated to be nearly $30 million when including both direct and indirect costs (Vessely et al., 2017). The data also suggest annual impacts will exceed $30 million when lower probability or extreme events occur in a single year.

Regarding rockfall, CDOT has an inventory of over 700 rockfall sites and responds to both frequent and infrequent events. For instance, CDOT maintenance work orders suggest routine maintenance response for rockfall creates an annual direct cost of over $5 million (Vessely et al., 2017). In terms of larger rockfall events, the economic impact for two rockfall events that closed I-70 for several days in 2004 and 2010 was estimated to be more than $40 million each. A change in FM for these will have a significant economic impact.

Geohazard management programs that focus on proactive mitigation can have greater benefit than those that reactively mitigate hazards. Benefits of proactive management of geohazards include:

- Decreasing road closure times
- Maximizing limited budgets to mitigate highest priority sites
- Strategic use of mitigation funds for mitigation during periods of decreased geohazard activity
- Systematic response to avoid or mitigate geohazard sites.

2.3. Examples Extreme Weather Impacts on Geohazards

Extreme weather events have triggered landslide geohazards across broad areas with extensive damage to highways and roads in mountainous areas of Colorado. A recent example occurred during September 2013, when a long duration storm with periods of intense rainfall in the Colorado Front Range triggered over 1000 shallow landslides and debris flows (Coe et al., 2014). This storm also caused widespread flooding and associated damage to roads traveling along the many canyons west of Boulder, CO. Most of the landslides and debris flows were triggered during two intense rainfall periods on September 11 and September 12, 2019 where peak 10-minute rainfall rates were 2.6 and 1.5 in/hr (67 and 39 mm/hr), respectively.

Another example is when about 480 debris flows were triggered in alpine areas along the Continental Divide in Clear Creek and Summit counties and the central Front Range of Colorado during an intense rainstorm during July 1999 (Godt and Coe, 2007). The debris flows were triggered by 1.4 inches (35 mm) of rainfall which fell within the first two hours of a thunderstorm (a 100-year return period rainstorm). Several of these debris flows impacted Interstate 70 near Loveland Pass, U.S. Highway 6 and the Arapahoe Basin ski area.

These two examples were both triggered by extreme rainfall events. In general, changes to precipitation regimes are expected to take the form of more frequent extreme rainfall events with high rainfall intensities (Easterling et al., 2009; Pendergrass and Knutti, 2018). Therefore, an increase in the frequency and magnitude of widespread geohazard events might be expected on this basis.

2.4. Climate Variables

Geologic hazards such as landslides, rockfall and debris flow are earth surface processes which are influenced by weather events. Weather impacts on geologic hazards may be a result of changes experienced on shorter time scales such as diurnal temperature changes, thunderstorms, and rapid accumulation of winter snow. Other geologic hazards (e.g., deep landslides) are affected by changes occurring deeper beneath the ground surface (e.g., the water table) which require longer duration changes to weather (e.g., longer wet season or a shift to higher annual precipitation).

Key extreme weather climate variables include absolute values, rates of change and numbers of cycles, as all three can be linked to geohazards. From perspective of impact to geohazards, the following are judged to be important measures of temperature extremes:

- Average change in each season and annually
- Minimum, maximum, median and mean daily temperature during each season
- Number of freeze-thaw days and number of extreme freeze days
- Number of extreme heat days (during the summer) or cold days (during the winter)
- Rate of temperature change in spring (how fast would snow melt, start date of springs, false springs and winter melt periods).

From perspective of impact to geohazards, the following are judged to be important measures of precipitation extremes:

- Total annual rainfall amount
- Rainfall amount per season

- Percentage of precipitation falling as snow
- Number, severity and geographic probability of thunderstorms
- Number of extreme winter storms
- Time, duration and rate of annual snowpack melt
- Number of prolonged rainfall events.

Many of these measures of temperature and precipitation must be extracted from current observation systems throughout the state, and a review of the literature suggests that this is not being done routinely. Similarly, climate model output must be further processed to derive the identified measures. As this is beyond the scope of this work, the closest available measures have been selected herein. In other words, while the variables listed above would be of greatest value for predicting impacts to the frequency and magnitude of the landslide geohazards considered here, most are not output from climate models. Consequently, the model outputs that are closest to the desired variables are what was used.

3.0 APPROACH AND METHODOLOGY

The approach taken in this study involved the following steps:

- Perform a climate change assessment to evaluate how various climate variables are expected to have changed in Colorado between the periods between 1970 to 2000 and 2070 to 2100.
- Develop event trees to provide semi-quantitative estimates for the likelihood (probability) that a geohazard would increase, decrease or stay the same given a change in a climate variable. Each event tree consisted of mutually exclusive and collectively exhaustive combinations for how a single climate variable could affect a "geophysical process" which would in turn affect a geohazard frequency or magnitude.

Expert elicitation was used to capture judgment of the geohazard professionals within BGC, AEM, FHWA and CDOT. The results of each event tree analysis provided semi-quantitative estimates that characterize the likelihood that geohazard FM would increase, stay the same or decrease.

These semi-quantitative estimates provided insight into the expected general trend of a geohazard FM to be affected by a changing climate variable. The expected direction of the trend is the outcome. Estimates were not suitable for quantifying the magnitude of change. In addition, "Geohazard FM" was used by this study to generally characterize that a geohazard may become more impactful by becoming more frequent and/or larger, less impactful by becoming less frequent and/or smaller or stay the same. Estimates on the nature of the FM relationships for how geohazard event return periods, volumes, velocities and/or intensities change were not made.

3.1. Climate change assessment

The climate change assessment task was led by AEM with inputs provided by BGC, CDOT and NCAR. BGC provided AEM with desired climate variables that BGC expected to have an influence on geophysical processes and, in turn, geohazard outcomes. NCAR provided technical guidance for how to analyze and interpret the climate data. AEM provided a set of climate variable maps that show the changes to each climate variable averaged over a historical period to the projected averaged value for a future period.

Climate data was downloaded from the U.S. Department of Agriculture (USDA) and the U.S. Bureau of Land Reclamation (USBLR) websites. Table 3-1 provides the data sources for the downloaded data and Table 3-2 lists the 20 GCMs represented in the USDA and USBLR data. The climate variable maps generated from data provided by the USDA represent values averaged across 20 GCMs, using CMIP5, *MACAv2,* RCP 8.5 data, downscaled to 4 km grid squares. USDA data covered the time periods 1975 to 2005 and 2071 to 2090 (USDA, 2019). The climate variable maps generated from USBLR data were derived from values averaged across 20 GCMs using CMIP5, *LOCA,* RCP 8.5 data, downscaled to 4 km grid squares. The USBLR data covered the time periods 1970 – 2000 and 2070 to 2099 and does next extend beyond year 2099 (USBLR, 2019).

The RCP 8.5 data were used to generate the climate variable maps because these data were identified to provide more definitive results for the trend changes in the climate variables than the RCP 4.5 or RCP 6 data. Trends in how climate variables are projected to change may be muted for the RCP 4.6 and RCP 6 scenarios due to variability among the various GCMs.

Table 3-1. Source data for the climate modeling analyses.

Agency	URL
USBR	https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html
USDA	https://www.fs.fed.us/rm/boise/AWAE/projects /NFS-regional-climate-change-maps/categories/us-raster-layers.html

Table 3-2. List of 20 GCMs used by the USDA and USBLR for the climate variables.

Model Name	Country
bcc-csm-1	China
bcc-csm1-1-m	China
BNU-ESM	China
CanESM2	Canada
CCSM4	USA
CNRM-CM5	France
CSIRO-Mk3-6-0	Australia
GFDL-ESM2M	USA
GFDL-ESM2G	USA
HadGEM2-EX	UK
HadGEM2-CC	UK
inmcm4	Russia
IPSL-CM5A-LR	France
IPSL-CM5A-MR	France
IPSL-CM5B-LR	France
MIROC5	Japan
MIROC-ESM	Japan
MIROC-ESM-CHEM	Japan
MRI-CGCM3	Japan
NorESM1-M	Norway

The downscaled climate data from the USDA and USBLR were analyzed using a Geographic Information System (GIS) to produce a set of maps to illustrate how different climate variables are anticipated to change in the future. Numerous climate variables influence geohazard FM.

However, due to limitations with existing climate models, only a select group of climate variables that could potentially influence geohazards were available as output from climate models. The variables were selected based on guidance from AEM and NCAR on uncertainties in the models and how closely they represent the more ideal climate measures presented in Section 2.4.

Table 3-3 provides a list of the climate variables that were assessed by AEM and their respective data sources. The climate variable maps were generated by comparing averaged climate variable data for a historical time period to projected climate variable data for a future time period. This was done by downloading downscaled climate variable maps for each future year within the in the time periods shown in Table 3-3 and using GIS to calculate the averages for the time period. Similarly historic climate variable maps were downloaded for the time periods shown in Table 3-3 and averaged using a GIS. NCAR recommended using the averaged values for the historical and future time periods to reduce uncertainty that could be caused by comparing specific years which may have anomalous rainfall or temperature records/projections.

Table 3-3. Climate variables evaluated by AEM.

Variable	Historical time period	Future time period	Unit	Climate Data source
Winter Precipitation	1975 - 2005	2071 - 2090	mm	USFS Rocky Mountain Research Center
Summer Precipitation	1975 - 2005	2071 - 2090	mm	
Snow Residency Time	1975 - 2005	2071 - 2090	day	
April 1st Snow Water Equivalent	1975 - 2005	2071 - 2090	mm	
Extreme Heat Days	1970 - 2000	2070 - 2099	day	USBLR
Extreme Freeze-Thaw Days	1970 - 2000	2070 - 2099	day	

Definitions for the climate variables and the methods for generating maps illustrating expected changes in the climate variables are described below.

- Winter Precipitation is defined as the total precipitation for the period from November through March. The change in winter precipitation was calculated as the difference between historical (1975 – 2005) and projected (2071 – 2090) winter precipitation.
- Summer Precipitation is defined as the total precipitation for the period from November through March. The change in summer precipitation was calculated as the difference between historical (1975 – 2005) and projected (2071 – 2090) summer precipitation.
- Snow Residency Time is defined as the number of days between the median date of the period when snow is accumulating and the median date of the period when snow is melting. The snow residency time map was derived from a model that utilizes mean average winter (November through March) temperature and precipitation (Luce, 2014). The change in snow residency time was calculated as the difference between historical (1975 to 2005) and projected (2071 to 2090) snow residency time.
- April 1st Snow Water Equivalent (SWE) is defined as the depth of water on April 1st of each year that would result if all the snowpack melted instantaneously. The April 1st SWE map is derived from a model that utilizes mean average winter (November through March)

temperature and precipitation (Luce, 2014). The change in April 1st SWE was calculated as the difference between historical (1975 to 2005) and future (2071 to 2090) April 1st SWE.

- Extreme Heat Days are defined as days when the maximum temperature equals or exceeds 95° F (35° C)35 degrees Celsius. The average number of extreme heat days per year was calculated for the periods from 1970 to 2000 (historical) and 2070 to 2099 (future). The change in the annual number of extreme heat days is the difference between historical and projected future annual number of extreme heat days.
- Extreme Freeze Thaw Days are defined as days when the daily maximum temperature is equal to, or greater than 9° F (5° C) and the daily minimum temperature is equal to, or less than 25° F (-5° C) (Haley, 2011). The average number of extreme freeze-thaw days per year was calculated for the periods 1970 – 2000 (historical) and 2070 to 2099 (future). The change in the annual number of extreme freeze-thaw days was calculated as the difference between historical and projected future annual number of extreme freeze-thaw days.

The climate variable maps were interpreted by AEM to estimate the likelihood that each climate variable increases, decreases or stays the same. The interpretation of the climate variable maps was assisted by categorizing the values shown in the maps into discrete bins so that differences could be visually identified. The interpretation of the trend in the climate variables to change was limited to the portion of Colorado west of Interstate 25 (approximately the western 2/3 of the state) where the vast majority of the geohazards considered by this study are focused. Although the climate variable maps represent downscaled data at a 4 km grid resolution, discussions with NCAR identified that the results portrayed at the downscaled resolution still reflect broader resolution of the GCMs. Therefore, the likelihood of a climate variable to increase, decrease or stay the same were assessed for the entirety of Colorado west of Interstate 25 rather than for individual road corridors.

3.2. Event tree – General Form

Each event tree consists of three categories of input: a single climate variable, a single geophysical process and a single geohazard. Mutually exclusive and collectively exhaustive combinations of these categories mapped out unique scenarios which result in one of three possible outcomes: the geohazard FM increases, stays the same or decreases as a result of the climate variable and geophysical process scenarios.

Figure 3-1 shows the general form of an event tree, with representative input likelihoods. A climate variable is at the far left of the figure which is the initiating event. The climate variable can increase, stay the same or decrease and values are assigned to describe the likelihoods for each of these scenarios. In Figure 3-1, the likelihood that the climate variable: increases = 0.9, stays the same = 0.1 and decreases = 0. This example represents the strong belief that the climate variable will increase.

In Figure 3-1, the next variable is a geophysical process. The geophysical processes are described in Section 3.2.1 and the activity of the geophysical process may increase, stay the same or decrease depending on if the preceding climate variable increases, stays the same or decreases. The likelihood that the activity level of the geophysical process increases, or decreases is characterized by the probabilities shown in the black boxes to the right of the orange boxes.

In Figure 3-1, the next variable to the right represents a geohazard FM. Depending on whether the preceding geophysical process increases, stays the same or decreases, the geohazard FM may increase, stay the same or decrease. The likelihood that the geophysical process increases, stays the same or decreases is shown to the right of the geohazard FM variable.

At the far right of Figure 3-1 are three possible geohazard outcomes: the geohazard FM increases, stays the same or decreases. There are 19 scenarios that can result in one of these three outcomes which are each illustrated by a single branch in the tree. Along each branch are a set of values that are multiplied together to estimate the conditional probability of occurrence associated with that scenario outcome.

The sum of the branches with the same outcomes provide an overall likelihood for that outcome. For example, in Figure 3-1, there are four scenarios where the geohazard FM increases and the sum of these values is 0.73. Therefore, the semi-quantitative estimate for the likelihood that the geohazard FM increases is 0.73 on a scale of zero to one (with zero being no possibility and one being absolute likelihood of occurrence).

Similarly, there are seven scenarios where the geohazard FM stays the same and the sum of these values is 0.27 and the semi-quantitative estimate for the likelihood that the geohazard FM stays the same is 0.27. Last, there are four scenarios where the geohazard FM decreases and the sum of these values is 0 (likelihood that the geohazard FM decreases = 0). The sum of all possible outcomes is 1.0.

In this example, there are exactly three categories that are being considered. Judgment is used to select all geophysical processes that (a) might be meaningfully impacted by a climate variable and (b) have a meaningful impact on a geohazard. The number of categories could be different than three, and the process would remain the same. This process is repeatable, simplistic, and can be expanded.

One key simplification is that the magnitude of change is not being assessed, only the anticipated trend: increase, decrease or stay the same. The use of consistent likelihood input values in the geohazard scenarios is intended to reduce bias among a group of individuals completing separate evaluations. Rather than estimating a precise likelihood of a process change (e.g., 60 or 90 percent likelihood of increasing), individuals completing the process need to only select from three options and the same probability values are applied. The probabilities assigned to the list of options are presented in Table 3-4.

Table 3-4. Values assigned to trends for each category in the event tree.

Climate Variable, Geophysical Process, or Geohazard FM	Confidence and Direction of Trend				
	Likely Increasing	Possibly Increasing	Likely not Influenced	Possibly Decreasing	Likely Decreasing
Increase	0.9	0.5	0	0.2	0
Stay the Same	0.1	0.3	1	0.3	0.1
Decrease	0	0.2	0	0.5	0.9

Another simplification is that the changes are considered independent at each node, meaning the climate variables are independent, the geophysical processes are independent and the geohazard FM trend is independent. For example, scenarios of a climate being cold and wet versus cold and dry are not considered in this work. Linkages between inputs from modeled climate projections and many geophysical processes can be tenuous, in part because most climate models are tuned to optimize coarser climate metrics (e.g., monthly or annual timesteps and larger areas), and may contain considerable uncertainty regarding low probability events (e.g., extreme temperature or precipitation). Furthermore, there is asymmetry in the estimates of how one category affects the subsequent category. For example, even though a climate variable increases and causes a likely increase in the geophysical process, there is not necessarily a corresponding decrease in the geophysical process if the climate variable decreases.

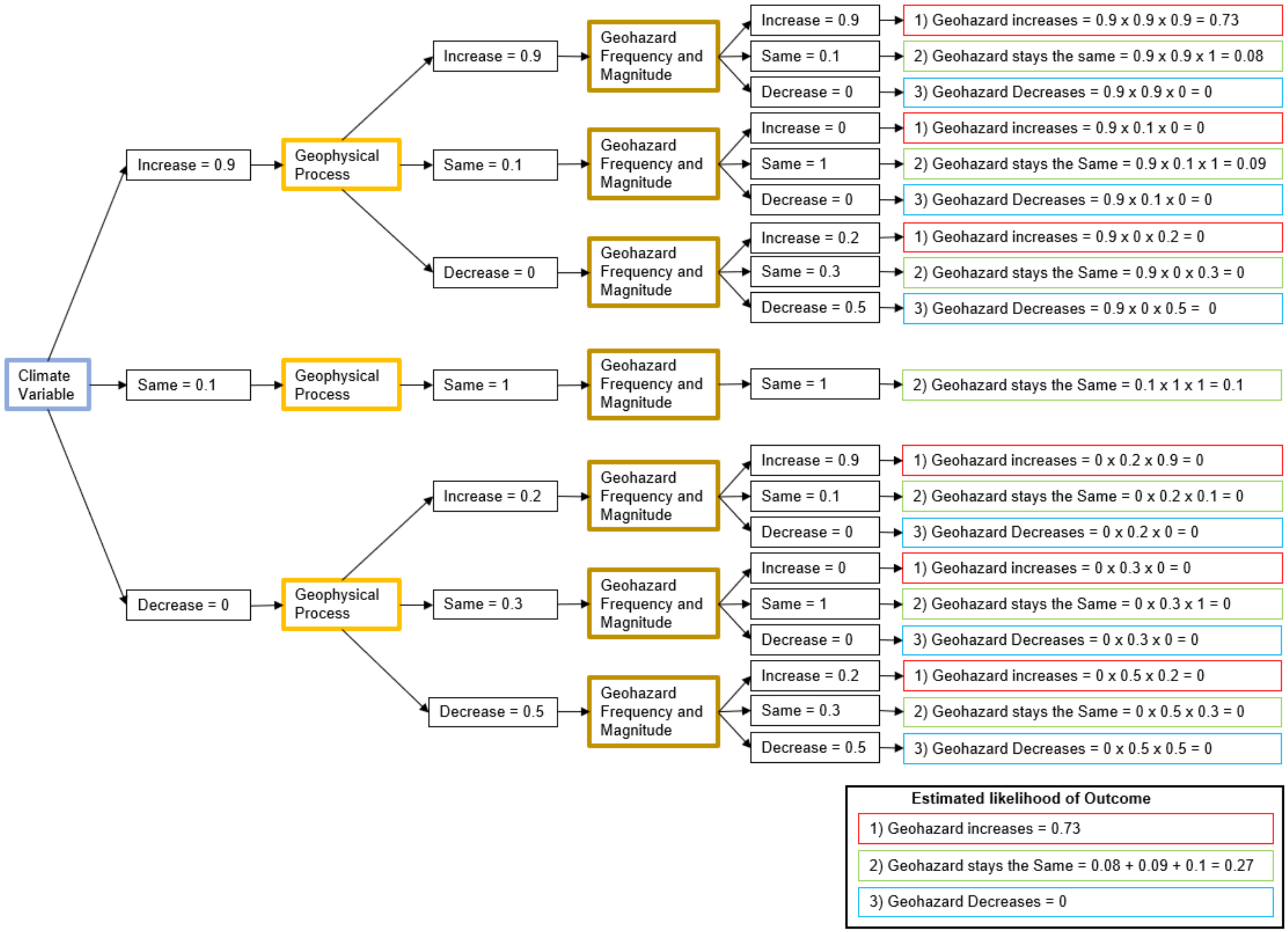

Figure 3-1. Idealized example of an event tree showing calculations for each mutually exclusive scenario and the cumulative probability of occurrence that geohazard FM increases, stays the same or decreases.

3.2.1. Geophysical Process

There are direct and indirect impacts from climate and extreme weather on geohazards. Geohazards are driven by geophysical processes, which are defined by this study as changes to the mechanical properties of water, soil and rock that might affect one of the four geohazards (deep-seated landslides, shallow landslides, rockfall and debris flow).

Direct impacts are characterized by weather events that directly influence a change in a geophysical process that drives the occurrence of a geohazard. An example of a direct weather impact on a geohazards is abundant rainfall increases groundwater levels and soil moisture which decreases soil and rock discontinuity strength and causes an increase in or expansion in areas with slope instability. In this example, the weather influences the occurrence of the geohazard.

An indirect impact of climate and extreme weather on geohazard is characterized by the occurrence of a geohazard being conditional on the occurrence of another event. For example, a warmer climate may create conditions that are susceptible to wildfire and wildfire-induced changes to the vegetation and soil affect runoff and erosion characteristics that result in a higher likelihood of debris flow. In this example, the warmer climate has created conditions (i.e., the wildfire) that influence susceptibility to debris flow, however, rainfall is still needed to trigger the debris flows.

Geophysical processes that were identified to be affected by the climate change variables and to directly and indirectly influence rockfall, debris flow, shallow landslides and deep landslides are defined as follows:

- Discontinuity Aperture applies to the changing width of opening in any type of fracture in rock, weathered rock or soil at or near the ground surface within or near the ROW.
- Material Strength refers generally to changing shear strength, but also to tensile and compressive strength if relevant, of near surface soil and rock within or near the ROW.
- Groundwater Level refers to the variable presence and distribution of positive water pressure (i.e., below water table) in areas within and near the ROW.
- Wildfire Frequency is a relative measure of the expected annual acreage of wildfire of such severity to kill vegetation and influence surface soil characteristics in watersheds that drain towards ROW.
- Soil Moisture refers to the percent of saturation and, inversely, the suction in near surface soil and rock within or near the ROW.
- Overland Flow creates shear stress imparted on the ground from precipitation and snow melt that does not infiltrate, and flows as dispersed sheet flow or channelized gully and rill flow within or near the ROW.
- River Runoff creates shear stress imparted on the ground from river and ditch channel area and water velocity within or adjacent to ROW.
- Infiltration creates an interstitial seepage force from precipitation and snow melt within or near the ROW that does not runoff on the ground surface.

- Water in Discontinuities is an estimate of water pressure and the extent to which discontinuities in soil or rock within or near the ROW are wet, or the depth to which they are filled with water.

3.2.2. Development of Event Trees

Based on group discussions during the workshops including BGC, AEM, FHWA and CDOT, 24 event trees were developed. This number of independent scenarios was judged to be appropriate to demonstrate the process and to be respectful of the uncertainty that currently lies in the inputs. The combinations of climate variables, geophysical processes and geohazard outcomes are presented in Table 3-5.

Table 3-5. Combinations of climate variables, geophysical processes and geohazard frequency and magnitudes.

Event Tree Number	Climate Variable	Geophysical Process	Geohazard
1	Number of Extreme Freeze Thaw Days	Discontinuity Aperture	Rockfall
2		Material Strength	Debris Flow
3		Material Strength	Shallow Landslide
4	Number of Extreme Heat Days	Groundwater Level	Rockfall
5		Wildfire Frequency	Debris Flow
6		Soil Moisture	Shallow Landslide
7		Groundwater Level	Deep Landslide
8	Snow Residency Time	Overland Flow	Rockfall
9		Overland Flow	Debris Flow
10		River Runoff	Shallow Landslide
11		Infiltration	Shallow Landslide
12		Infiltration	Deep Landslide
13	Winter Precipitation	Water in Discontinuities	Rockfall
14		Overland Flow	Debris Flow
15		Wildfire Frequency	Debris Flow
16		Infiltration	Shallow Landslide
17		River Runoff	Shallow Landslide
18		Groundwater Level	Deep Landslide
19	Summer Precipitation	Water in Discontinuities	Rockfall
20		Overland Flow	Debris Flow
21		Wildfire Frequency	Debris Flow
22		Infiltration	Shallow Landslide
23		Groundwater Level	Deep Landslide
24	April 1st SWE	Groundwater Level	Deep Landslide

The next step was to identify trends to describe the linkages between climate variables, geophysical processes and geohazards. This was done by asking the group of geohazard professionals to consider each of the linkages between climate variables, geophysical processes and geohazards and, based on their experiences, to select among a list of answers to describe the direction and strength of a trend that describes the linkage. Each expert was given five choices, from likely increasing to likely decreasing. Based on the answers provided, probability values were assigned that reflect the confidence and direction of the trend.

The questions asking how geophysical processes would be affected by a change in a climate variable and how geohazard FM may be affected by a change in a geophysical process are provided in Appendix B. The probability values associated with each answer are described in Table 3-4. For simplicity and efficiency in the process, these numerical values were fixed and the same for all, though that need not be the case.

The individual outcomes from these assessments were averaged, and outlying values were discussed. During the assessments, the same climate change input variables were used across all geohazard scenarios and the process was not influenced by different conclusions about climate model outcomes among the geohazard professionals performing the assessment.

All assessments made were conditional probabilities of a geophysical process change or a geohazard change. In other words, each assessment was based on the prior event having happened, even if the prior event had a low probability of doing so. This is a requirement of the event tree, but it also means that any assessment can be changed without impacting prior or posterior assessments in the steps of the tree, which makes future updates easy to accommodate.

3.3. Synthesis of Results

The answers provided by geohazard professionals during the workshops were used to develop multiple individual sets of 24 event trees. Each event tree, identified by the “event tree number” in Table 3-5, had multiple estimates for the geohazard outcomes. Estimates were carried forward into this analysis from the six people that were able to attend all of the workshops wherein the process, meanings of terms and outliers were discussed. These estimates were compiled into summary plots to illustrate a collective result provided by the various geohazard professionals. Trends were identified based on a second-order polynomial fit to the compiled response data.

Figure 3-2 shows conceptual examples of the summary plots. The x-axis of each plot describes the scenario outcome (e.g., the geohazard increases, the geohazard stays the same, or the geohazard decreases). The y-axis of the plot describes the likelihood of the outcome. In the example shown, collective results of the geohazard FM staying the same, having a slight increase, having a strong increase and having a slight decrease are all shown. These trends are shown by the second order polynomial lines fit to the data.

If the fit is symmetric about the center “stay the same” column of the plot, the expected outcome is that the geohazard FM will stay the same. If the trend slopes up toward “increase”, that is the consensus finding, and if the values are greater in the decrease column, that is the consensus finding. The fitted lines average all data and the plots also show the variability in the opinions of the geohazard professionals: where there is spread in the points in any column, there is greater difference in opinion.

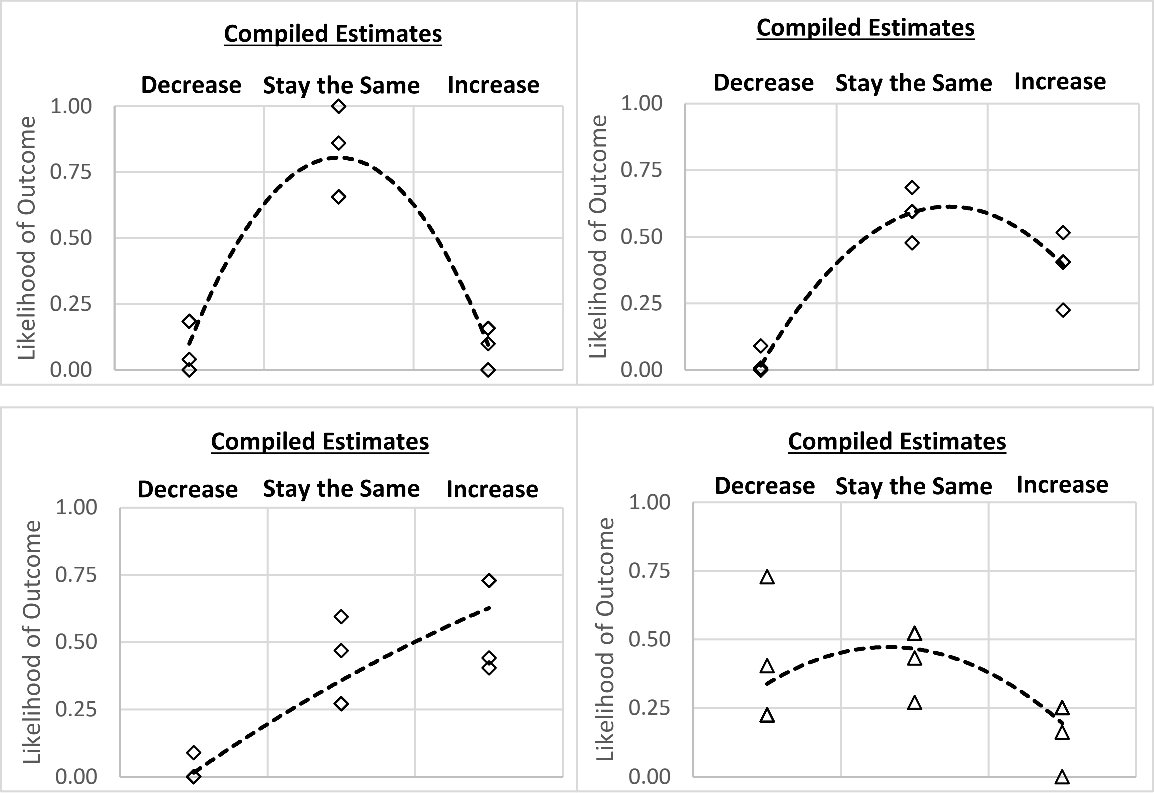

Figure 3-2. Examples of event tree summary plot showing no expected change in the geohazard FM (top left), slight (top right) to strong (bottom left) increase in geohazard FM and a slight decrease in geohazard FM (bottom right).

4.0 RESULTS

The following sections summarize the results of the workshops with geohazard and climate specialists to develop the event trees and the results of the event tree analyses.

4.1. Climate Variable Trend Assessments

The maps generated by AEM to model how climate variables are expected to change were reviewed by AEM to estimate expected trends for each of the variables. The trends and corresponding likelihoods of the variable to increase, decrease or stay the same are provided in Table 4-1. As described in Section 2.4, the climate variables listed in the table are those that are available as climate model output that most closely match the most desired variables. There is a considerable difference.

Table 4-1. Summary of climate variable trends estimated by AEM and associated likelihoods of the variable increasing, decreasing or staying the same.

Climate Variable	Trend of Climate Variable	Likelihood of Climate Variable Decreasing	Likelihood of Climate Variable Staying the Same	Likelihood of Climate Variable Increasing
Number of Extreme Freeze Thaw Days	Possibly Increase	0.2	0.3	0.5
Number of Extreme Heat days	Possibly Increase	0.2	0.3	0.5
Snow Residency Time	Possibly Decrease	0.5	0.3	0.2
Winter Precipitation	Likely Increase	0	0.1	0.9
Summer Precipitation	Likely Decrease	0.9	0.1	0
April 1st SWE	Likely not be Influenced	0	1	0

The trends described in Table 4-1 are judgement based and were informed by statewide maps generated by AEM. The maps generated by AEM are provided in Appendix A. As presented by AEM (2019), these maps are based on an average of an ensemble of climate models. The climate variable input to an event tree could be understood as the average output from an ensemble of climate models, downscaled to the state of Colorado, with emphasis on the western two thirds of the state where landslide geohazards occur.

An example of one of the climate variable maps (change in winter precipitation) is shown in Figure 4-1. This map shows that most of the mountainous areas are predicted to have an increase in precipitation. Since the majority of the western portion of the state shows an increase in winter precipitation, the general trend for this climate variable was assessed to “likely increase.” Given this anticipated trend, the values of 0, 0.1 and 0.9 were entered into the left-hand “column” of the event tree, as illustrated in Figure 3-1.

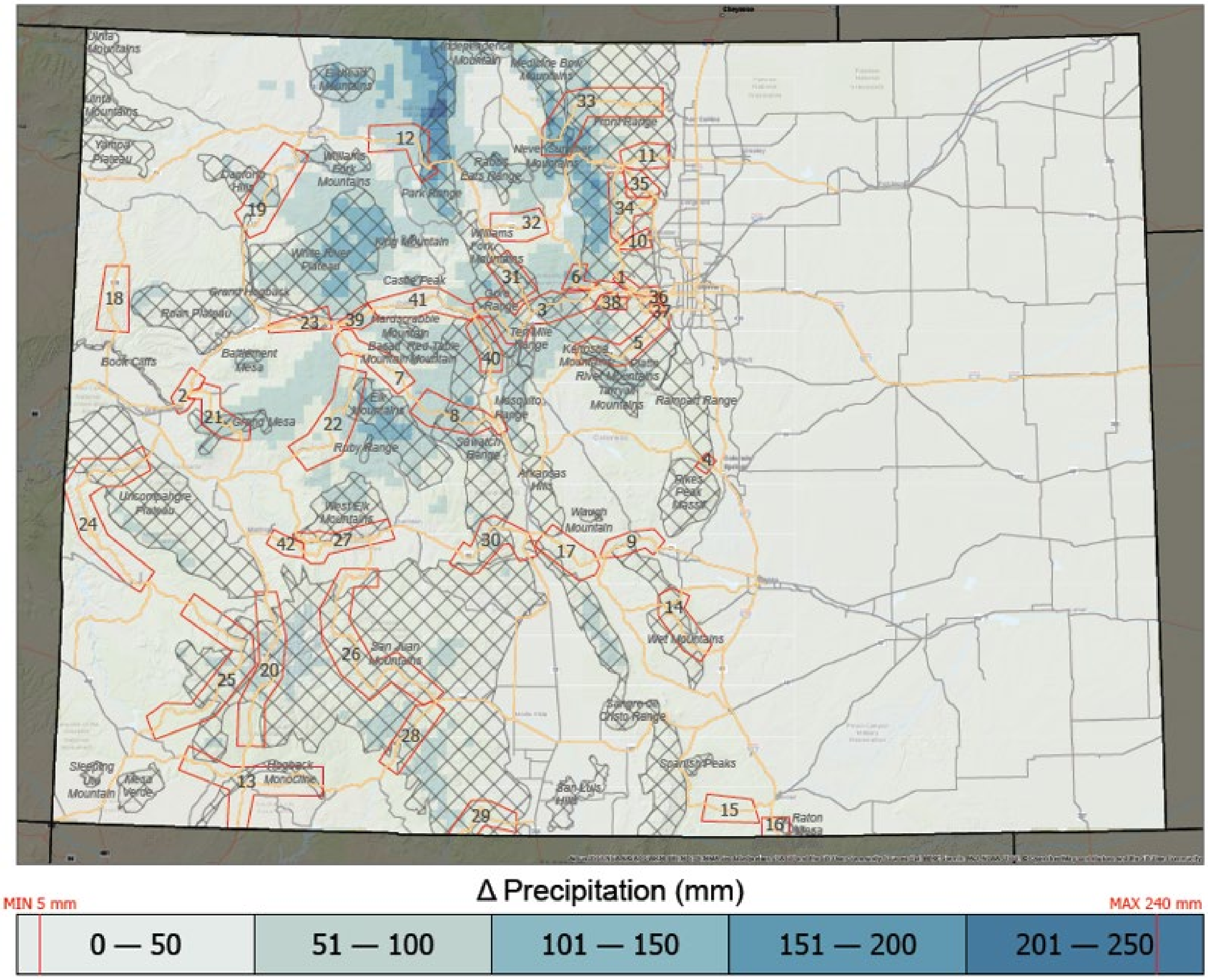

Figure 4-1. An example of one of the climate variable maps. This example demonstrates the change in winter precipitation which was assessed to likely increase.

Although some portions of the state in Figure 4-1 show higher increases in winter precipitation (e.g., the northern Front Range versus the Sangre de Cristo mountains), specific observations of how a climate variable might change in a specific road corridor (show in red polygons in Figure 4-1) or mountain range (hatched areas in Figure 4-1) should not be interpreted from the maps. The reason for this is because the downscaling has not been tailored to specific corridors or mountain ranges but rather to the entire state. As such, the climate variable maps are intended to demonstrate general trends in the climate variables across the western portion of the state. Road corridor or mountain range specific estimates the change in a climate variable could be achieved by a more detailed modeling approach that is optimized for a specific area.

4.2. Geophysical Process, and Geohazard Trend Assessments

There was general agreement among the answers provided by the different geohazard professionals with the majority of differences being differences in opinion regarding the strength of the trend (e.g., “likely increase” vs. “possibly increase”).

In general, each of the geohazard professionals agreed on the following climate impacts on geophysical processes:

- If the number of extreme freeze thaw days increases, then discontinuity aperture will increase, and material strength will decrease.
- If the number of extreme heat days increases, then groundwater level and soil moisture will decrease, and the wildfire frequency will increase.
- If winter precipitation increases, then water in discontinuities, overland flow, infiltration, river runoff and groundwater level will increase.
- If summer precipitation decreases then water in discontinuities, overland flow and infiltration will decrease, and wildfire frequency will increase.

If summer precipitation decreases, water in discontinuities, overland flow and infiltration will decrease and wildfire frequency will increase. Each of the geohazard professionals agreed on the following geophysical impacts on geohazard FM:

- If discontinuity aperture increases, then rockfall will increase.
- If material strength decreases, then debris flows and shallow landslides will increase.
- If groundwater level increases, then rockfall and deep landslides will increase.
- If wildfire frequency increases, then debris flows will increase.
- If soil moisture increases, then shallow landslides will increase.
- If overland flow increases, then rockfall and debris flows will increase.
- If river runoff increases, then shallow landslides will increase.
- If infiltration increases, then shallow and deep landslides will increase.
- If water in discontinuities increase, then rockfall will increase.

Of these assessments, the key takeaways for Colorado are:

- Increasing number of freeze thaw days and winter precipitation will increase rockfall.
- Increasing number of extreme heat days and decreasing summer precipitation will increase post-wildfire debris flows.

4.3. Event Tree Summary Plots

The event tree summary plots are provided in Appendix C and provided summary results for the multiple sets of 24 geohazard trees that were developed based on input from each of the geohazard professionals. The numbers on the y-axis of the plots are semi-quantitative estimates that are intended to identify general trends of how geohazard FM are expected to increase, decrease or stay the same. These results are not intended to support statements that identify a specific probability value for a geohazard to increase, decrease or stay the same.

Five rockfall scenarios were evaluated (event tree numbers 1, 4, 8, 13 and 19). Two of the scenarios are expected to increase rockfall FM due to:

- Increasing number of extreme freeze thaw days increasing discontinuity aperture.
- Increasing winter precipitation increasing water in discontinuities.

The other scenarios identified an expectation for rockfall FM to stay the same. Thus, in summary of all considered scenarios, rockfall is expected to increase.

Seven debris flow scenarios were evaluated (event tree numbers 2, 5, 9, 14, 15, 20 and 21). Four of the scenarios are expected to increase debris flow FM and one scenario identified a decrease in geohazard FM. Increases in debris flow FM are expected to be due to:

- Increasing number of extreme freeze thaw days decreasing material strength.
- Increasing winter precipitation increasing overland flow.
- Increasing number of extreme heat days increasing wildfire frequency.
- Decreasing summer precipitation increasing wildfire frequency.

Debris flow FM is expected to decrease due to decreasing summer precipitation causing a decrease in overland flow, and two scenarios show an expectation that debris flow FM will stay the same. Thus, in summary, only one scenario is expected to decrease debris flow FM, two are expected not to cause a change, and four scenarios result in an expected increase. Debris flow FM is therefore expected to increase.

Seven shallow landslide scenarios were evaluated. Two of the scenarios are expected to increase shallow landslide FM:

- Increasing winter precipitation increasing infiltration.
- Increasing winter precipitation increasing river runoff.

One scenario was found to decrease shallow landslide FM due to decreasing summer precipitation decreasing infiltration and four scenarios result in no expected change. Thus, there is some expectation of increasing shallow landslide FM from two of the seven scenarios. Of the two scenarios where shallow landslides would increase, there was more confidence in the process of increasing winter precipitation increasing infiltration and increasing shallow landslide FM.

Five deep landslide scenarios were evaluated. One of the scenarios is expected to increase in deep landslide FM due to increasing winter precipitation increasing groundwater level. One of the scenarios is expected to decrease deep landslide FM due to decreasing summer precipitation decreasing groundwater level. Both of these scenarios have considerable spread in the compiled results and therefore, there is little confidence in these geohazard FM trends. The expectation from the three other scenarios is that there is no change in deep landslide FM. Thus, in summary, the scenarios suggest no expected change in deep landslide FM.

A review of the plots in Appendix C reveals that for some of the scenarios all experts agreed (the symbols are stacked upon one another) and for other scenarios, there is considerable difference in the magnitude of the trend, though the trend would be generally the same if scatter were reduced. The results presented should be considered to reflect regional trends which may not reflect conditions at a specific site. For example, although debris flows were identified to decrease due to decreasing summer precipitation and overland flow, localized increases in precipitation intensity may result in an increase in debris flow activity. In addition, increasing winter precipitation on shallow soils overlying granite slopes that melts into steep canyon creeks may have little impact on infiltration or landslide risk.

5.0 OBSERVATIONS

Beyond the results that show expectation that rockfall, debris flow and shallow landslide FM will increase, several other observations are outcomes from this work. These observations are regarding estimates that the experts made on linkages between climate variable, geophysical process and geohazard FM, opportunities for improvement as climate modeling evolves, and the usefulness of the event tree as a way of capturing new inputs easily and regenerating improved estimates of the trend of geohazard FM.

5.1. Linkages

There were numerous scenarios where there was general agreement on how changes to a climate variable would change a geophysical process to affect geohazard FM (Table 5-1). The observations in Table 5-1 show that increases to geohazard FMs due to changing climate and extreme weather are possible for all geohazard types. They also show that climate variables that could drive increases in geohazard FM are increases in:

- The number of extreme freeze thaw days
- Winter precipitation
- The number of extreme heat days.

Decreasing summer precipitation was expected to both increase debris flows due to increasing wildfire frequency and to decrease debris flows due to decreasing overland flow. Decreasing summer precipitation was also linked to decreasing shallow and deep landslide FM due to decreasing infiltration and decreasing groundwater level.

Missing from Table 5-1 are the climate variables of April 1st Snow Water Equivalent, and the Snow Residency Time. Apparently, while these are relevant to climate science and for other reasons, the experts did not see a clear impact to geophysical process and, thereby, geohazard FM. Interestingly, while experts agreed that the geophysical process of increasing soil moisture would influence geohazard FM, it did not factor into any of the scenarios where geohazard FM change was predicted.

Table 5-1. Summary of scenarios that could affect geohazard FM. Bold text identifies increases to geohazard FM.

Climate Variable Trend	Geophysical Process Trend	Geohazard FM
Number of Extreme Freeze Thaw Days Increases	Discontinuity Aperture Increases	**Rockfall Increase**
	Material Strength Decreases	**Debris Flow Increase**
Winter Precipitation Increases	Increasing Water in Discontinuities	**Rockfall Increase**
	Increasing Overland Flow	**Debris Flow Increase**
	Increasing Infiltration	**Shallow Landslide Increase**
	Increasing River Runoff	
	Increasing Groundwater Level	**Deep Landslide Increase**
Number of Extreme Heat Days Increases	Increasing Wildfire Frequency	**Debris Flow Increase**
Summer Precipitation Decreases		
Summer Precipitation Decreases	Decreasing Overland Flow	Debris Flow Decrease
	Decreasing Infiltration	Shallow Landslide Decrease
	Decreasing Groundwater Level	Deep Landslide Decrease

5.2. Opportunities for Improvement

Opportunities for improvement come in two primary areas: (1) the ability to predict changing climate and report output meaningful to the geophysical process and geohazard FM linkage, and (2) the number and complexity of scenarios considered, and how they are compiled.

The downscaled climate model results for the various climate variables were generalized to estimate a trend representative of the area west of Interstate 25 (i.e. a single assessment was made on likelihood and direction of change for the majority of the state). This was done because further downscaling of the climate models was identified to potentially provide misleading results. Although the maps in Appendix A show the climate variables to have different projected outcomes for specific areas within the state, the topography that most influences the results is the broad change in elevation across the Rocky Mountains rather than the finer scale elevation changes within the smaller subranges within the state. Therefore, the most meaningful result of the downscaled climate model was identified to be the interpreted statewide trend for each climate variable. Improvements to provide more accurate results of finer-scale downscaling might remove some of the uncertainty in the climate variable. Improvements to downscaling could also be done if historical runs of the climate models were also downscaled and validated against weather observations from CDOT’s road weather network and other available weather data sources.

The maps in Appendix A represent the average of an ensemble of models. This average of all the climate models may not necessarily be the best indicator of a changing trend, but was done here for simplicity. This is especially true when considering that the distribution of ensemble output may not be normally distributed and may have one or two significant outliers that skew the average. If some climate models predict an increase, and others predict a decrease in a climate variable, the average may be that no change is expected. What will be valuable for any future revision to the approach is to compare the scatter of model predictions. Where there is little scatter about the mean, the confidence is high, and where there is large scatter about the mean, the confidence is low, and these observations could be input into the likelihood of change of the initiating event.

Both the uncertainty with downscaling and the fact that the average of an ensemble might not be correct in its trend resulted in the climate variables being assessed as possibly increasing or decreasing (rather than likely increasing or decreasing). As a result, the strength in the trends was muted and this propagated through to result in lower likelihoods of geohazard FM change, whether positive or negative.

Geophysical processes that drive geohazards are most influenced by extremes and rate changes, often at local and sub-annual scales. GCMs, to minimize stochastic bias over large areas and long lead times, are limited in their skill to accurately portray finer spatial and temporal distribution of extreme events throughout a future season or year. However, GCMs are continually advancing, suggesting that such output will eventually become available.

A projected effect of climate change is that there will be a shift towards more severe rainfall events. Storms with rainfall intensities and durations that are currently described as having a 100-year return period (i.e., a 1 in 100 chance of occurrence) are anticipated to become more common in the future and shift to having a 50-year return period (i.e., a 1 in 50 chance of occurrence). A shift to more frequent storms with higher rainfall intensities and durations is anticipated to affect the occurrence and magnitude of geologic hazards. Such a shift is anticipated to also shift the occurrence and magnitude and corresponding economic impact of geologic hazards (Figure 5-1). Steps towards identifying the changes to rainfall intensity-duration-frequency (IDF) curves has been done in Canada with the development of the climate change rainfall IDF tool developed by Western University, Canada (www.idf-cc-uwo.ca/home). This tool aims to specifically identify the shift in rainfall intensities for future time periods to provide detailed information for detailed assessments of geohazards affected by climate change.

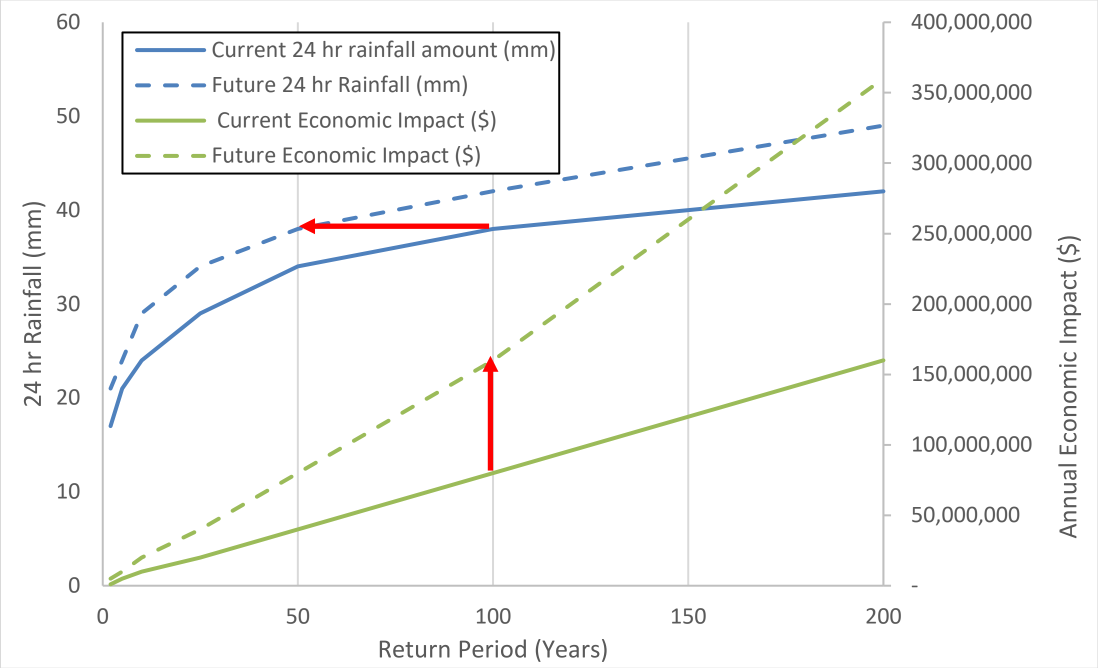

Figure 5-1. A conceptual figure showing how a 100-year return period storm may shift to be characterized as a 50-year return period in the future (horizontal arrow) which would affect the economic consequence of associated geohazards (vertical arrow).

5.3. Value of Event tree Methodology

The approach used by this study to evaluate changes to geohazard FM as a function of climate change using event trees is a flexible approach that can be expanded with improved climate modeling and identification of more links between climate variables, geophysical processes and geohazard FM. The climate variable inputs to event trees could be changed in future assessments based on results of more accurately downscaled models that are specific to a location rather than broad representations of the entire state, and more scenarios can also be considered and compiled.

Additional work to more completely identify geophysical processes that drive geohazards and are affected by climate change would also provide benefit and is possible with the framework developed here. In this study, 24 scenarios were defined, however, with improvements to climate modeling and the confidence in the modeled climate variables, new links between climate variables, geophysical processes and geohazard FM may be valuable to pursue. With the current uncertainty in climate model outputs useful for this work, the scenarios were kept simple.

The event tree approach developed here is a multi-disciplinary approach that combines knowledge and opinions from climate, earth science, and geotechnical experts. The method is flexible to accommodate improvements at all levels and could be further refined. CDOT could use this framework to provide ongoing characterization of how climate variables, geophysical processes and geohazard FM interact. As projected changes to climate variables become more refined, and more specific links between climate variables, geophysical processes and geohazards are characterized, the results of the analyses will improve and provide more specific expectations for how geohazards are affected by climate change.

One way to improve upon the understanding of the linkages between climate, geophysical processes and geohazard outcomes would be to develop a comprehensive database of geohazard events and the weather (e.g., temperature, rainfall intensity) and geophysical data (e.g., soil moisture, river runoff) associated with the geohazard event.

The geohazard trees could also be distributed to a broader set of participants (e.g. the transportation research board) to provide inputs to the trends between the climate variables, geophysical processes and geohazard outcomes. This activity would provide a broader consensus opinion for the links between the variables and also facilitate discussion and decision for the direction of future research on climate change influences on geohazards in Colorado.

The results of the event trees are most meaningful when there is high confidence in the trends of and linkages between the climate variable, geophysical process and geohazard outcome. Therefore, there is no minimum number of people required to provide a meaningful result using the event tree as long as there is confidence in the inputs.

6.0 CLOSURE

We appreciate the opportunity to assist on this project and trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

BGC ENGINEERING INC.
per:

Joseph Gartner, Ph.D., PE
Senior Geotechnical Engineer

Scott Anderson, Ph.D., PE
Principal Geotechnical Engineer

Reviewed by:

Mark Vessely, M.Sc., PE
Principal Geotechnical Engineer

JG/SA/MV/mp/sjk

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APPENDIX A
CLIMATE VARIABLE MAPS DEVELOPED BY AEM (DATED NOVEMBER 2019)

A.1. DESCRIPTION OF MAPS

In this appendix, Maps developed by AEM are provided that display the projected change in climate variables between the past time period between 1975 to 2005 and the future time period between 2071 to 2090.

The climate variables in the maps consist of the April 1st snow water equivalent, snow residency time, the average number of extreme freeze thaw days, the average number of extreme heat days.

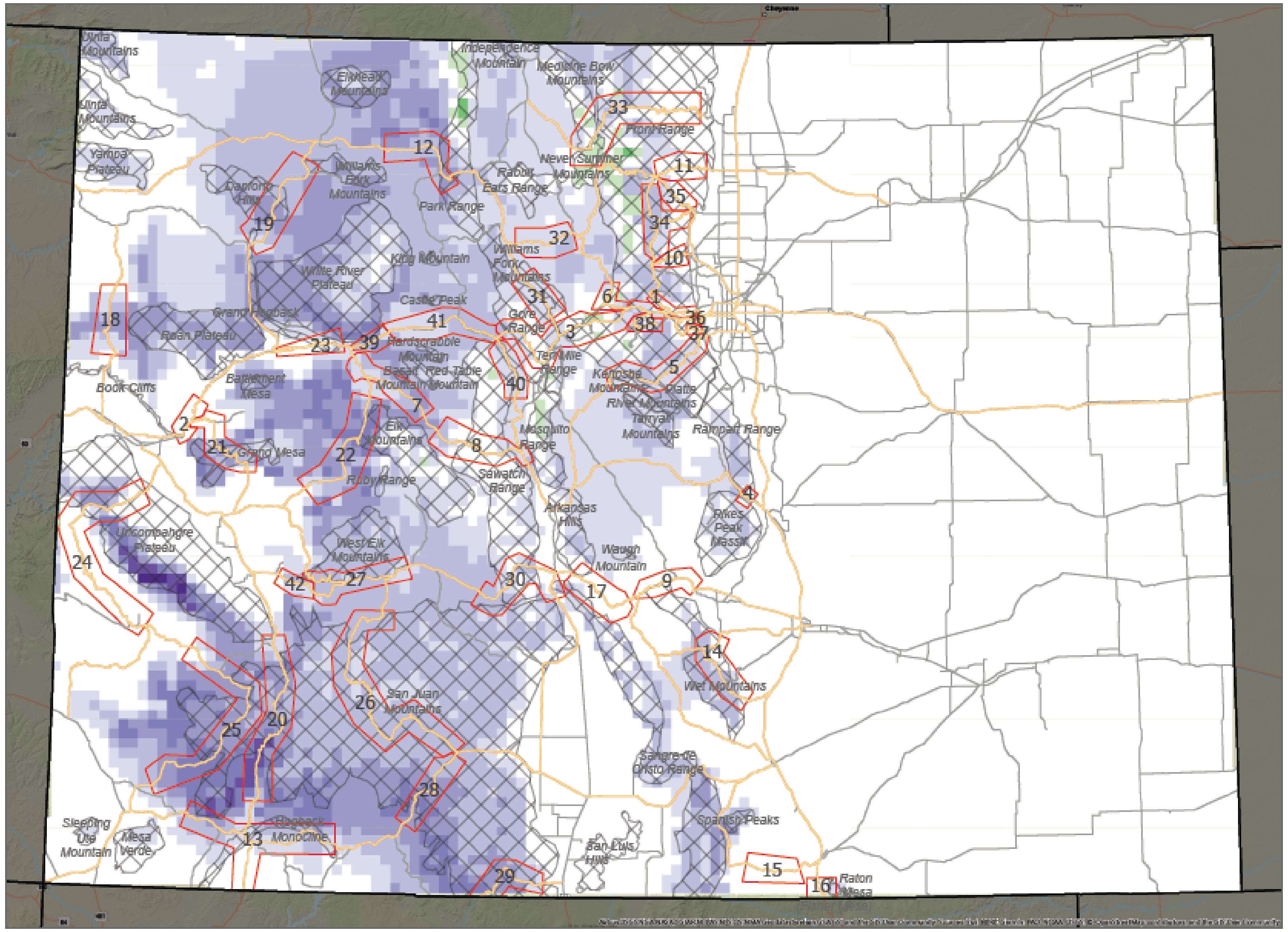
The data for the April 1st snow water equivalent and snow residency time maps was provided by the U.S. Forestry Service's Rocky Mountain Research Station. The data used to generate the other maps was calculated using more than 19 climate models that assume the RCP 8.5 conditions.

These maps are preliminary and are subject to change with advancements to climate models and downscaling model data to finer resolutions.

April 1st Snow/Water Equivalency (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS
GEOHAZARDS AND RESILIENCE



Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
0 — 1240	0 — 1310

Δ April 1st SWE (mm)

MIN -320 mm

MAX 70 mm

-350 — -300	-299 — -250	-249 — -200	-199 — -150	-149 — -100	-99 — -50	-49 — 0	1 — 50	51 — 100

This map displays the average change in the value of snow/water equivalency by April 1st of a given year. This number was calculated by combining the mean winter average temperature and precipitation around the zenith of April 1st, determining the amount of water contained within the snowpack. It is somewhat analagous to snow residency time, and its units are in milimeters of depth. This data is provided for the epochs of 1975-2005 and 2071-2090 by the US Forestry Service's Rocky Mountain Research Station.

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route

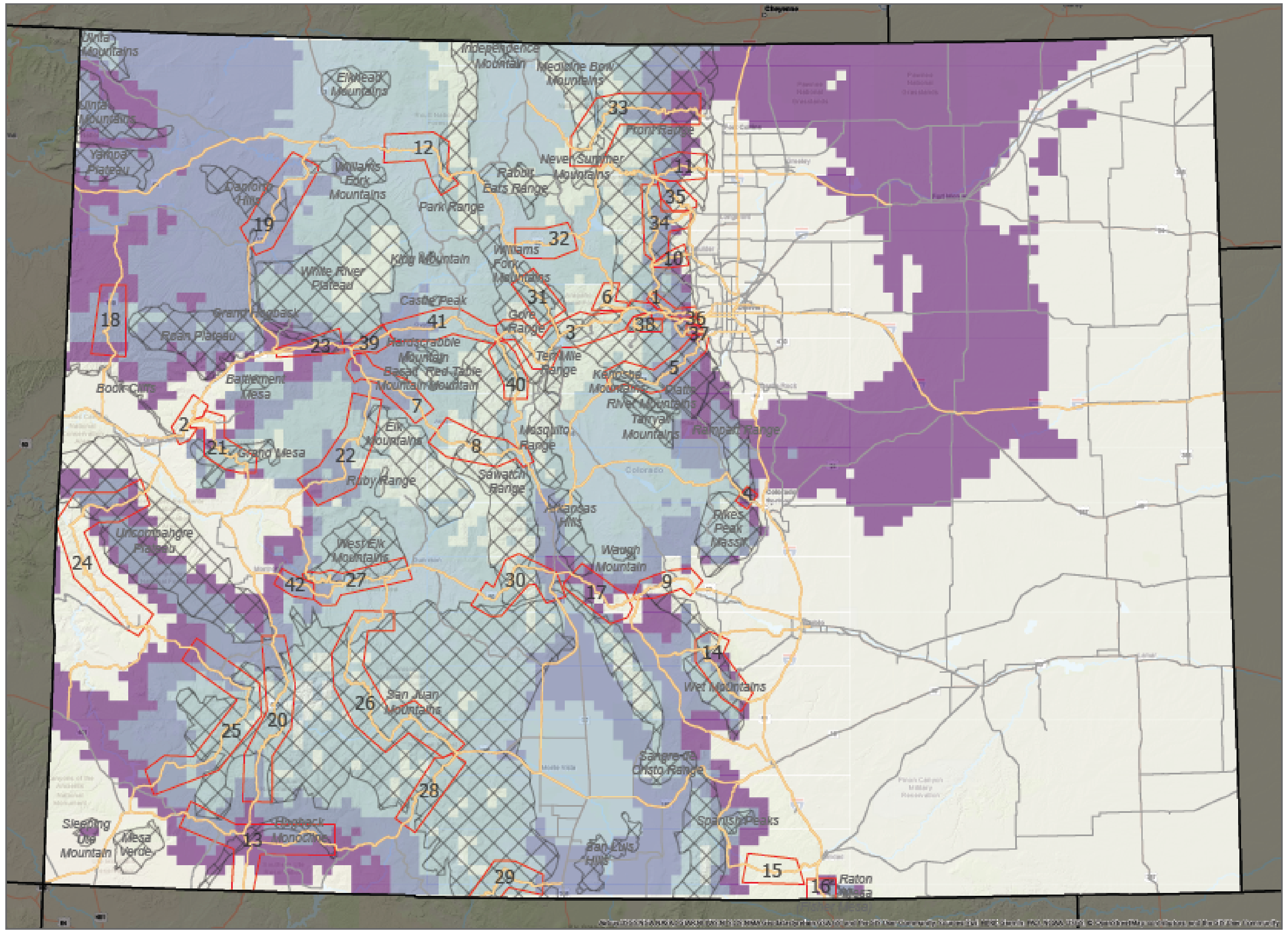
Geohazard Corridors
Mountain Ranges

Scale: 1:1,306,130

Snow Residency Time (Δ 1980s-2080s)

COLORADO Department of Transportation

FHWA EXTREME WEATHER EVENTS GEOHAZARDS AND RESILIENCE



Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
8 — 146 days	0 — 134 days

Δ % Snow Residency Time

MIN = -100 % MAX -7%

-99% — -74%	-75% — -49%	-50% — -24%	-25% — -1%

This map displays the percent change in the number of snow residency days for snow precipitation. This number was calculated as a combination of mean winter average temperature and precipitation, both based off of 20 RCP 8.5 climate models from the CMIP5 experiment. A value of -100% implies that the area already had a very low snow residency time wherein the unit for snow residency time is no longer expected to be a day. This data is provided for the epochs of 1975-2005 and 2071-2090 by the US Forestry Service's Rocky Mountain Research Station.

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

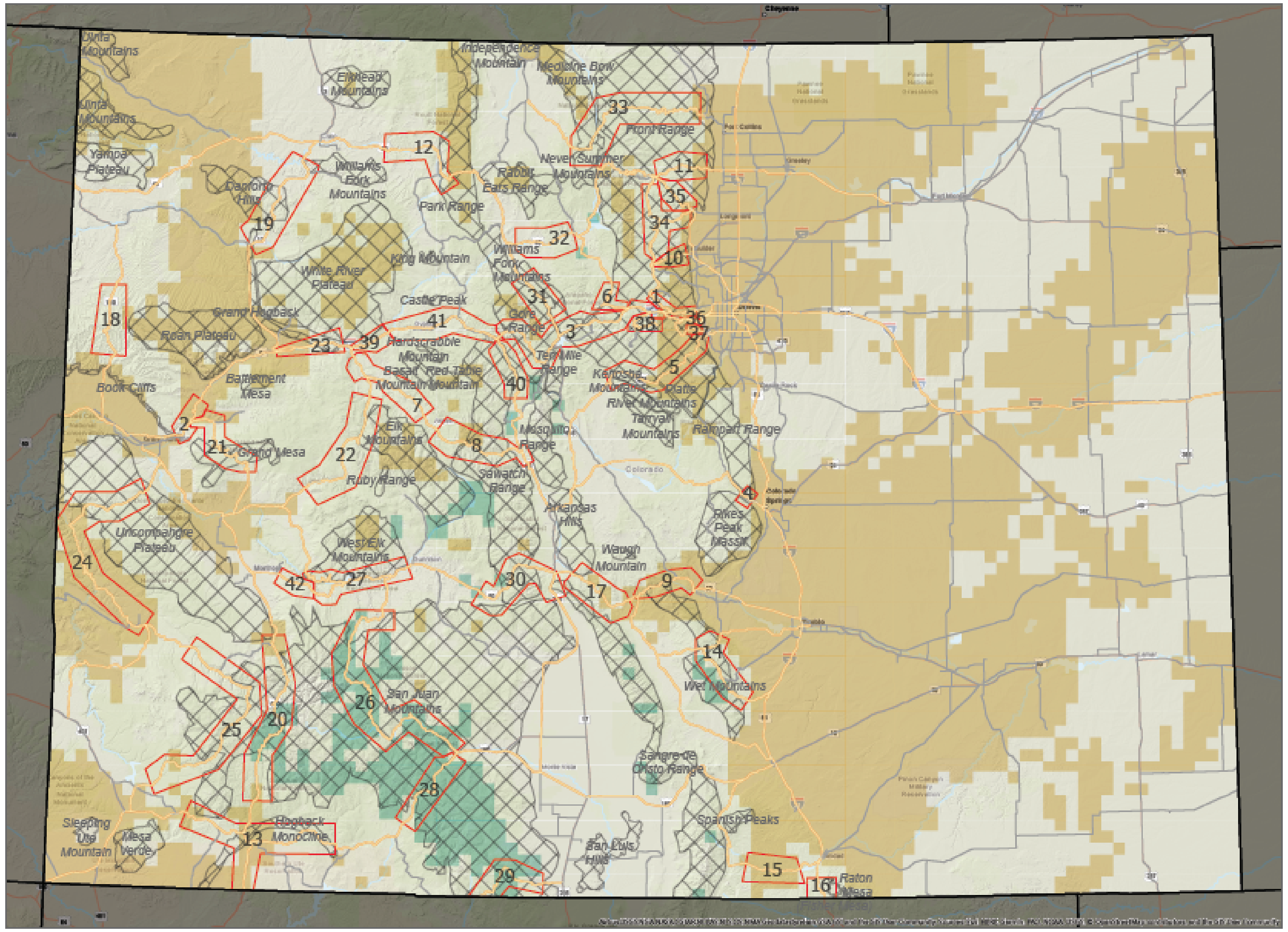
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Extreme Freeze Thaw Days (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS
GEOHAZARDS AND RESILIENCE



Δ Average # of Days

MIN -28 days | MAX 13 days

-30 — -15	-16 — 0	1 — 15

This map displays the change of the average number of extreme freeze/thaw days in a given year between the epochs of 1970-2000 and 2070-2100. An extreme freeze thaw day is defined as a day where the maximum temperature is above 5 C° and the minimum temperature is below -5 C°. This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
20 — 111	7 — 99

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

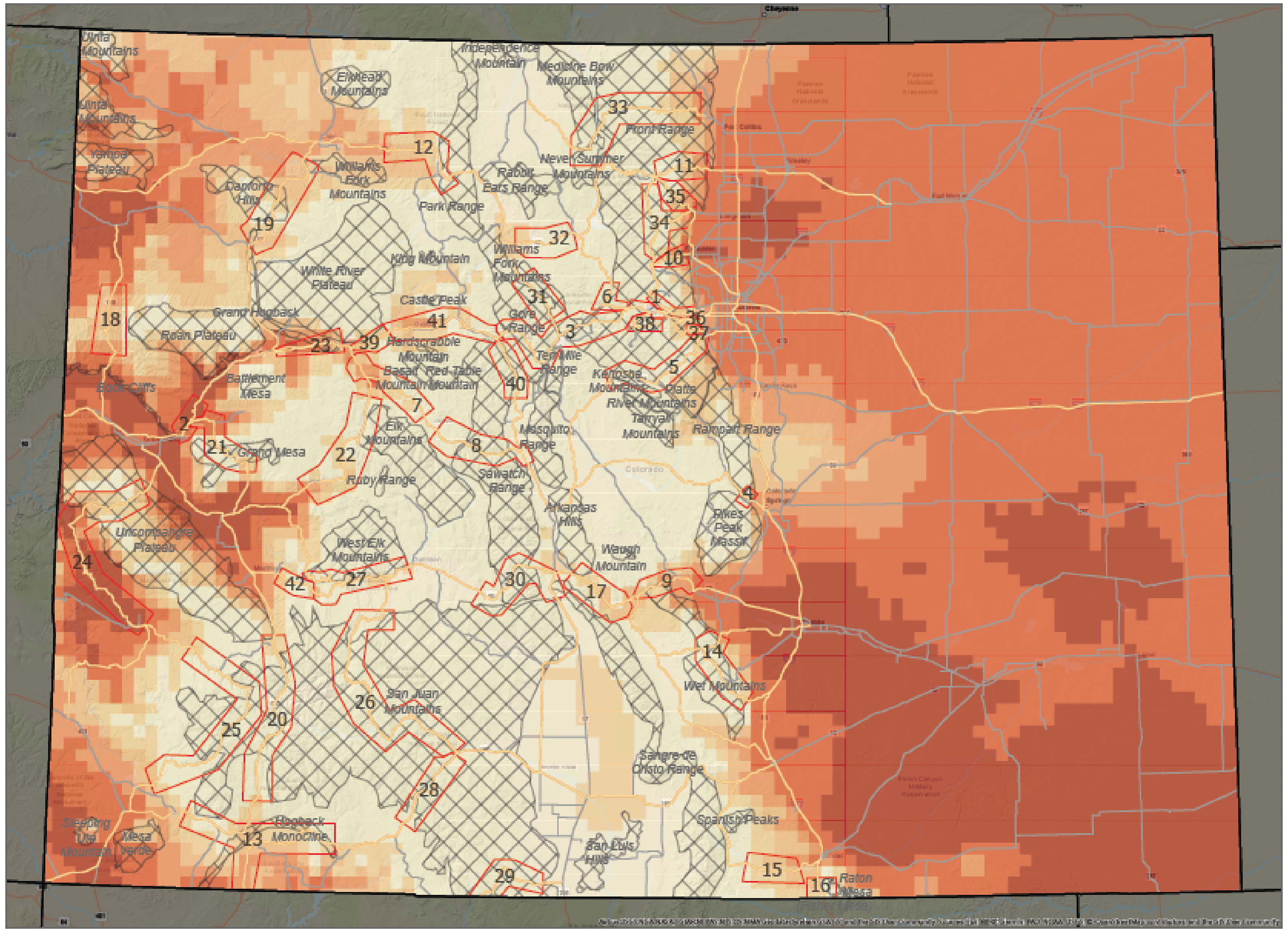
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Extreme Heat Days (Δ 1980s-2080s)

COLORADO Department of Transportation

FHWA EXTREME WEATHER EVENTS GEOHAZARDS AND RESILIENCE



Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
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6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

Δ Average # of Days

MIN 0 days — MAX 87 days

1 — 15	16 — 30	31 — 45	46 — 60	61 — 75	76 — 90

HISTORIC RANGE	FUTURE RANGE
0 — 49	0 — 121

This map displays the change of the average number of extreme heat days in a given year between the epochs of 1970-2000 and 2070-2100. An extreme heat day is defined as a day where the maximum temperature is above 35 C°. This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

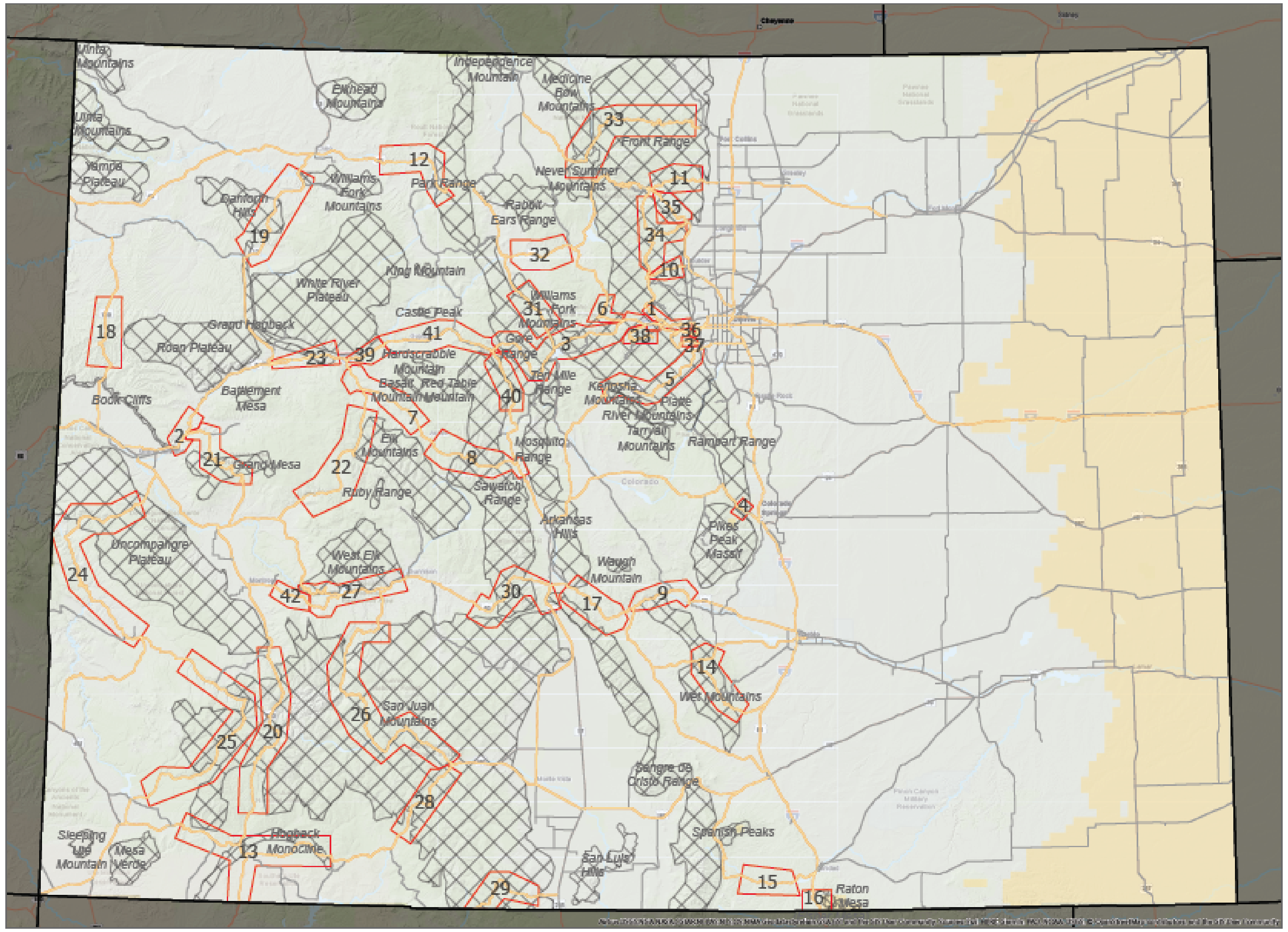
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Summer Precipitation (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS
GEOHAZARDS AND RESILIENCE



Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
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18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
45 — 320	50 — 300

Δ Precipitation (mm)

MIN -27 mm
MAX 18 mm

-40 — -20	-19 — 20	21 — 40	41 — 80	81 — 120	121 — 160	161 — 200	201 — 240

This map displays the change of the average total precipitation in summer in a given year between the epochs of 1970-2000 and 2070-2100.
This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

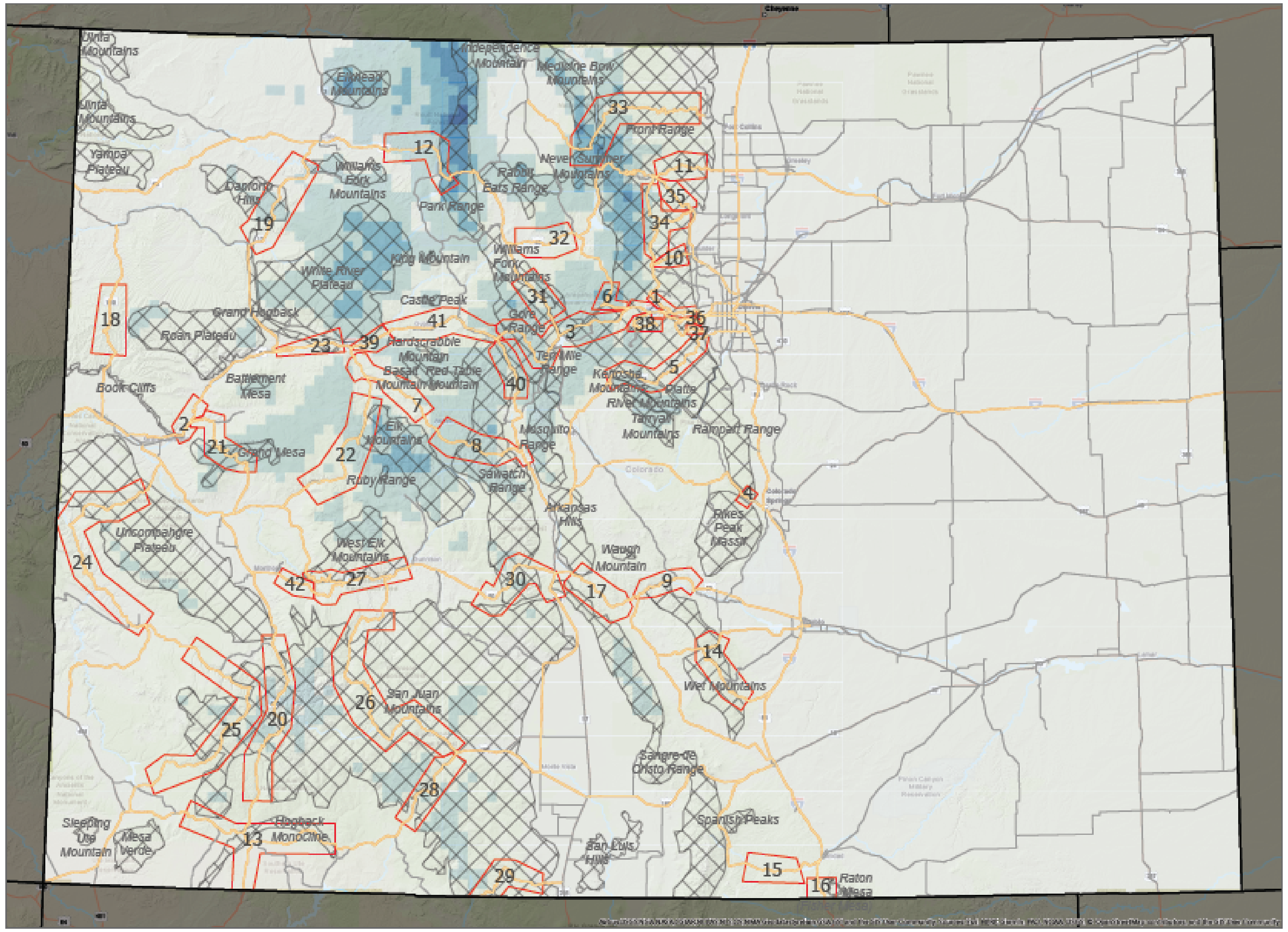
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Winter Precipitation (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS GEOHAZARDS AND RESILIENCE



Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
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13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
36 — 1,000	2 — 1,240

Δ Precipitation (mm)

MIN 5 mm

MAX 240 mm

0 — 50	51 — 100	101 — 150	151 — 200	201 — 250

This map displays the change of the average total precipitation in winter in a given year between the epochs of 1970-2000 and 2070-2100. This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

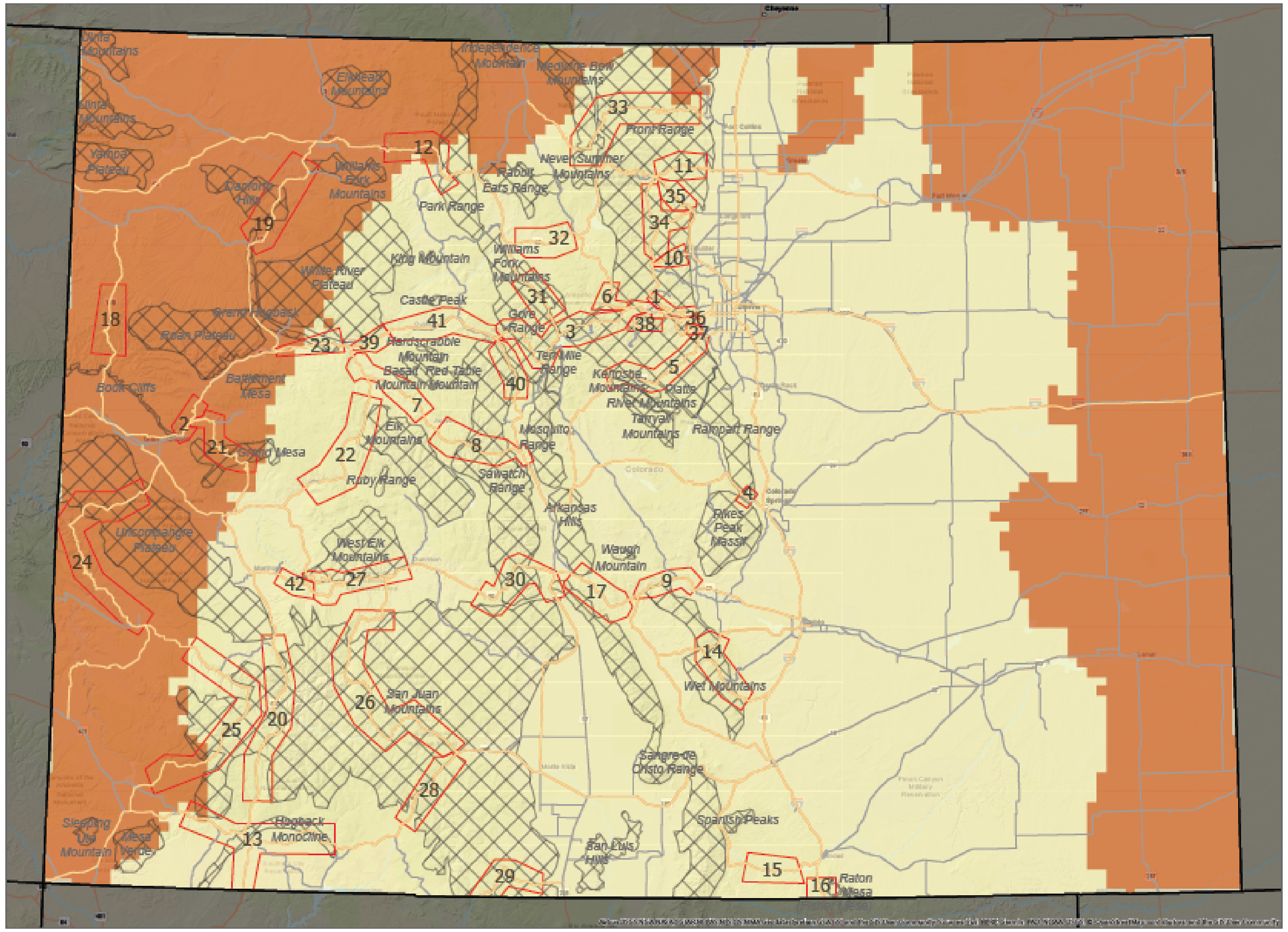
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Maximum Daily Summer Temperature (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS
GEOHAZARDS AND RESILIENCE



Δ of average daily maximum temperature (C°)

4 — 5	5.1 — 6

This map displays the change of the average maximum daily summer temperature in a given year between the epochs of 1970-2000 and 2070-2100. This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Id	Name	Route (2)	
1	Clear Creek	006G	119A
2	Debeque	070A	
3	Floyd Dowd	070A	
4	W. Colo. Springs	024A	
5	Denver Kenosha	285D	
6	Berthoud Pass	040A	
7	Glenwood Aspen	082A	
8	Indy Pass	082A	024A
9	Canon City	050A	069A
10	Boulder	119A	
11	Big Thompson	034A	
12	Steamboat	040A	
13	Durango Hub	160A	550A
14	Rye	165A	096A
15	Weston	012A	
16	Raton Pass	025A	
17	Salida	050A	
18	Douglas Pass	139A	
19	Craig Meeker	013A	
20	Red Mtn. Pass	550B	
21	Grand Mesa	065A	
22	Paonia	133A	
23	Rifle	070A	006D
24	Naturita	141A	
25	Rico	145A	
26	Lake City	149A	
27	Blue Mesa	050A	092A
28	Wolf Creek Pass	160A	
29	Antonito	017A	
30	Monarch Pass	050A	285B
31	Kremmling 1	009D	
32	Kremmling 2	040A	
33	Hwy 14	014B	
34	Peak 2 Peak Sys.	007A	072B
35	Lyons	036B	
36	Mt. Vernon	040C	
37	Morrison	074A	
38	Mt. Evans	103A	
39	Glenwood	070A	
40	Tennessee Pass	024A	
41	Eagle Vail	070A	
42	Cerro Summit	050A	

HISTORIC RANGE	FUTURE RANGE
6 — 26	11 — 30

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

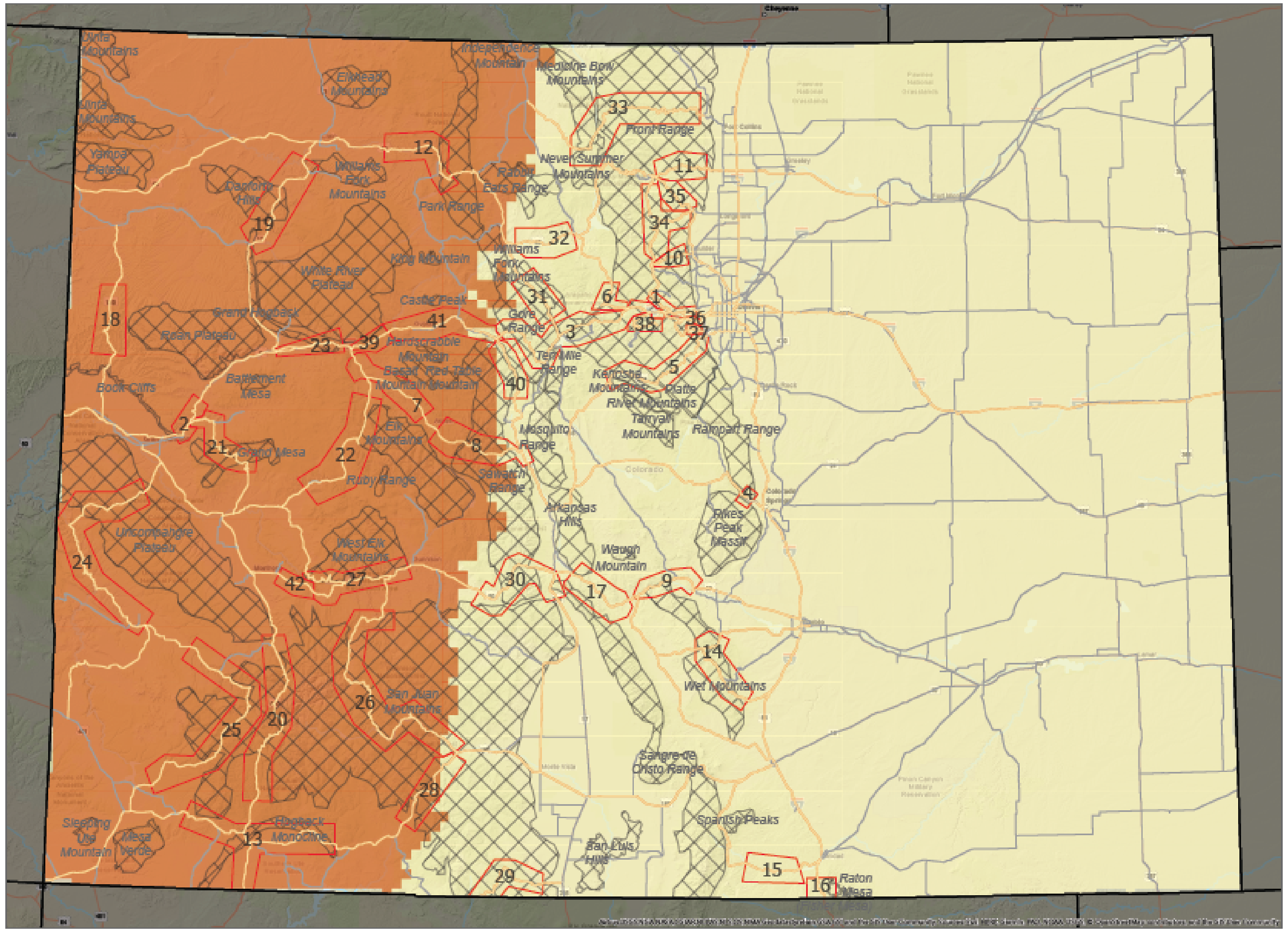
Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route
Geohazard Corridors
Mountain Ranges
Scale: 1:1,306,130

Maximum Daily Winter Temperature (Δ 1980s-2080s)

COLORADO
Department of Transportation

FHWA EXTREME WEATHER EVENTS GEOHAZARDS AND RESILIENCE



Δ of average daily maximum temperature (C°)

MIN 4.2 C°
MAX 5.3 C°

4 — 5	5.1 — 6

This map displays the change of the average maximum daily winter temperature in a given year between the epochs of 1970-2000 and 2070-2100. This data was calculated through the use of RCP 8.5 climate data, combining 19+ models for an increased sample size.

Id	Name	Route (2)		Id	Name	Route (2)	
1	Clear Creek	006G	119A	22	Paonia	133A	
2	Debeque	070A		23	Rifle	070A	006D
3	Floyd Dowd	070A		24	Naturita	141A	
4	W. Colo. Springs	024A		25	Rico	145A	
5	Denver Kenosha	285D		26	Lake City	149A	
6	Berthoud Pass	040A		27	Blue Mesa	050A	092A
7	Glenwood Aspen	082A		28	Wolf Creek Pass	160A	
8	Indy Pass	082A	024A	29	Antonito	017A	
9	Canon City	050A	069A	30	Monarch Pass	050A	285B
10	Boulder	119A		31	Kremmling 1	009D	
11	Big Thompson	034A		32	Kremmling 2	040A	
12	Steamboat	040A		33	Hwy 14	014B	
13	Durango Hub	160A	550A	34	Peak 2 Peak Sys.	007A	072B
14	Rye	165A	096A	35	Lyons	036B	
15	Weston	012A		36	Mt. Vernon	040C	
16	Raton Pass	025A		37	Morrison	074A	
17	Salida	050A		38	Mt. Evans	103A	
18	Douglas Pass	139A		39	Glenwood	070A	
19	Craig Meeker	013A		40	Tennessee Pass	024A	
20	Red Mtn. Pass	550B		41	Eagle Vail	070A	
21	Grand Mesa	065A		42	Cerro Summit	050A	

HISTORIC RANGE
-9 — 17

FUTURE RANGE
-5 — 21

Spatial Reference
Name: NAD 1983 UTM Zone 13N
GCS: GCS North American 1983
Projection: Transverse Mercator

Kilometers 0 25 50 75 100
Miles 0 25 50 75 100

Roads
Major Route
Geohazard Route

Geohazard Corridors
Mountain Ranges

Scale: 1:1,306,130

APPENDIX B
QUESTIONS ABOUT RELATIONSHIPS BETWEEN CLIMATE VARIABLES, GEOPHYSICAL PROCESSES AND GEOHAZARDS

B.1 - Influence of Climate Variables Geophysical Processes

IF		Then (select one)					
Number of Extreme Freeze Thaw Days	increases	Then Discontinuity Aperture Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Number of Extreme Freeze Thaw Days	increases	Then Material Strength Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
# Extreme Heat Days	increases	Then Groundwater Level Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
# Extreme Heat Days	increases	Then Wildfire Frequency Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
# Extreme Heat Days	increases	Then Soil Moisture Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Snow Residency Time	increases	Then Overland Flow Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Snow Residency Time	increases	Then River Runoff Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Snow Residency Time	increases	Then Infiltration Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then Water in Discontinuities Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then Overland Flow Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then Wildfire Frequency Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then Infiltration Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then River Runoff Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Winter Precipitation	increases	Then Groundwater Level Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Summer Precipitation	increases	Then Water in Discontinuities Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Summer Precipitation	increases	Then Overland Flow Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Summer Precipitation	increases	Then Wildfire Frequency Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Summer Precipitation	increases	Then Infiltration Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Summer Precipitation	increases	Then Groundwater Level Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
April 1st SWE	increases	Then Groundwater Level Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase

B.2 - Influence of Geophysical Processes on Geohazard Frequency and Magnitude

If		Then (select one)					
Discontinuity Aperture	increases	Rockfall Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Material Strength	increases	Debris-Flow Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Material Strength	increases	Shallow Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Groundwater Level	increases	Rockfall Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Wildfire Frequency	increases	Debris-Flow Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Soil Moisture	increases	Shallow Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Groundwater Level	increases	Deep Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Overland Flow	increases	Rockfall Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Overland Flow	increases	Debris-Flow Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
River Runoff	increases	Shallow Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Infiltration	increases	Shallow Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Infiltration	increases	Deep Landslide Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
Water in Discontinuities	increases	Rockfall Frequency and Magnitude Will?	Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase
	decreases		Likely Decrease	Possibly Decrease	Likely not be influenced	Possibly Increase	Likely Increase

APPENDIX C
EVENT TREE SUMMARY PLOTS

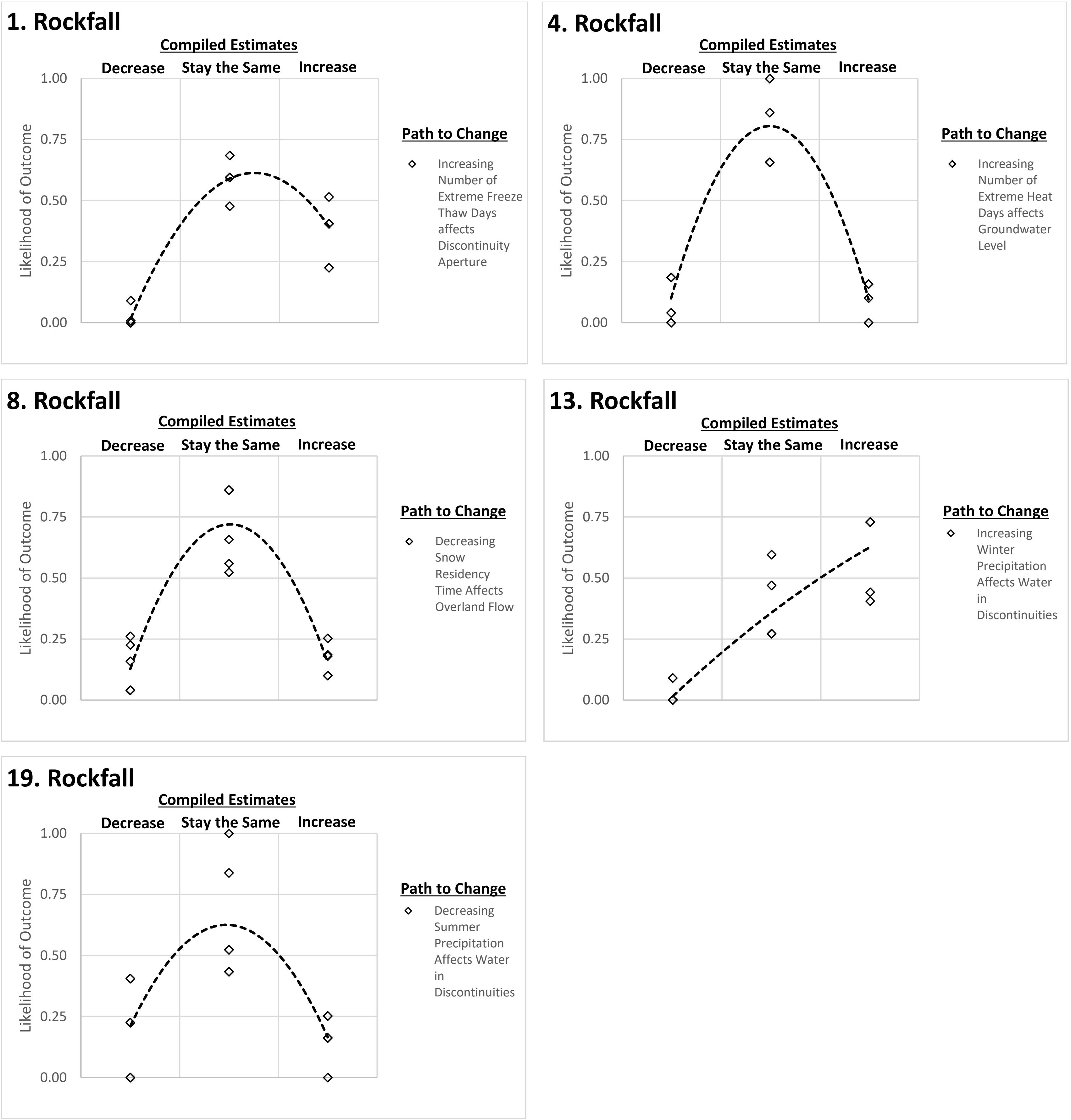


Figure C-1. Climate variables and geophysical processes that are most likely to increase rockfall FM are the increased number of extreme freeze thaw days affecting discontinuity aperture (Plot 1) and increased winter precipitation affecting water in discontinuities (Plot 13). The numbers in the top left of the plots correspond to the scenarios described in Table 4-1 in the main report.

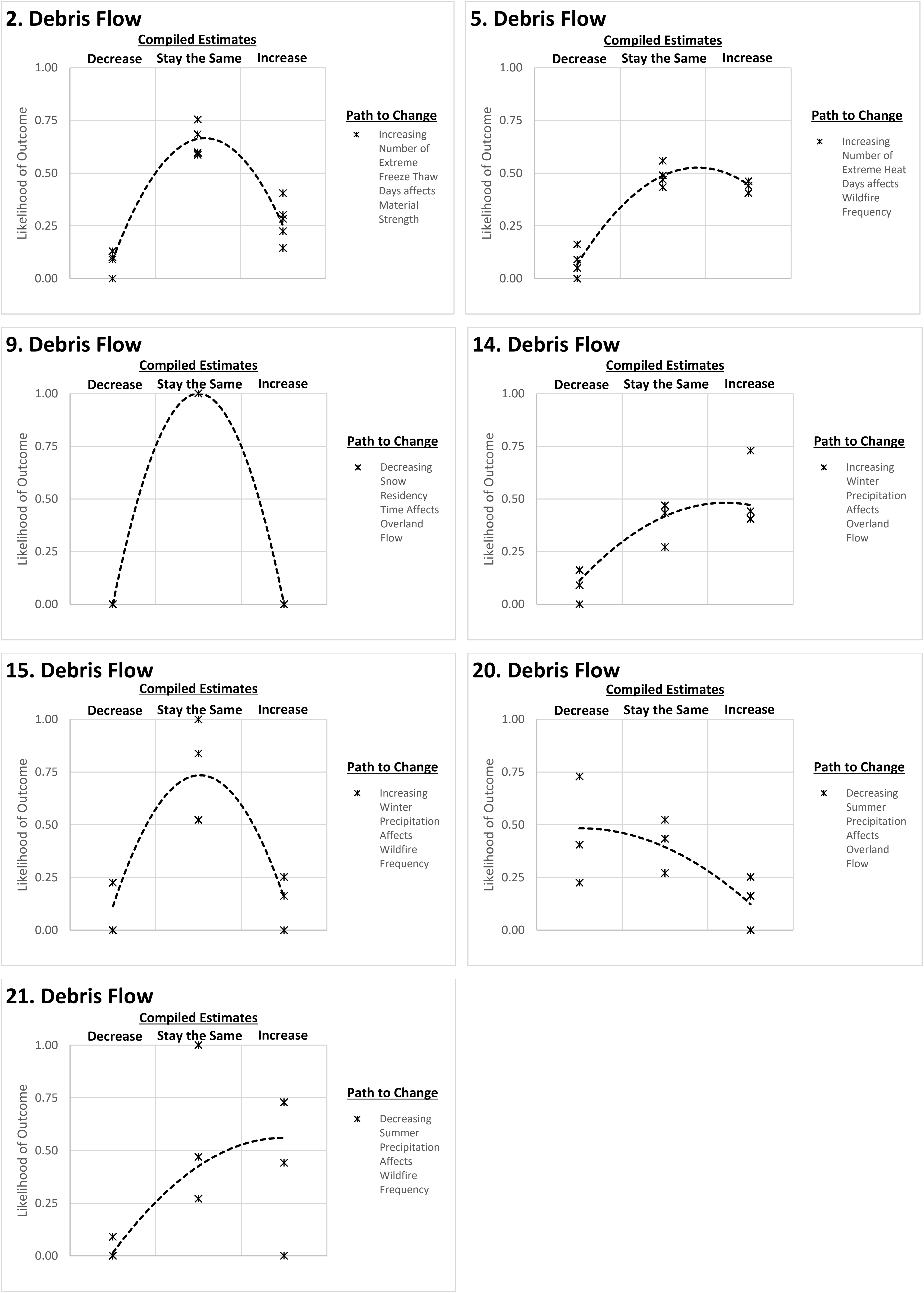


Figure C-2. Climate variables and geophysical processes that are most likely to increase debris flow FM include an increase in the number of extreme freeze thaw days decreasing material strength (Plot 2), an increase in the number of extreme heat days affecting wildfire frequency (Plot 5,) an increase in winter precipitation affecting overland flow (Plot 14) and a decrease in summer precipitation increasing wildfire frequency (Plot 21). A decrease in summer precipitation may also decrease overland flow and cause a decrease in debris flow FM (Plot 20). The numbers in the top left of the plots correspond to the scenarios described in Table 4-1 in the main report.

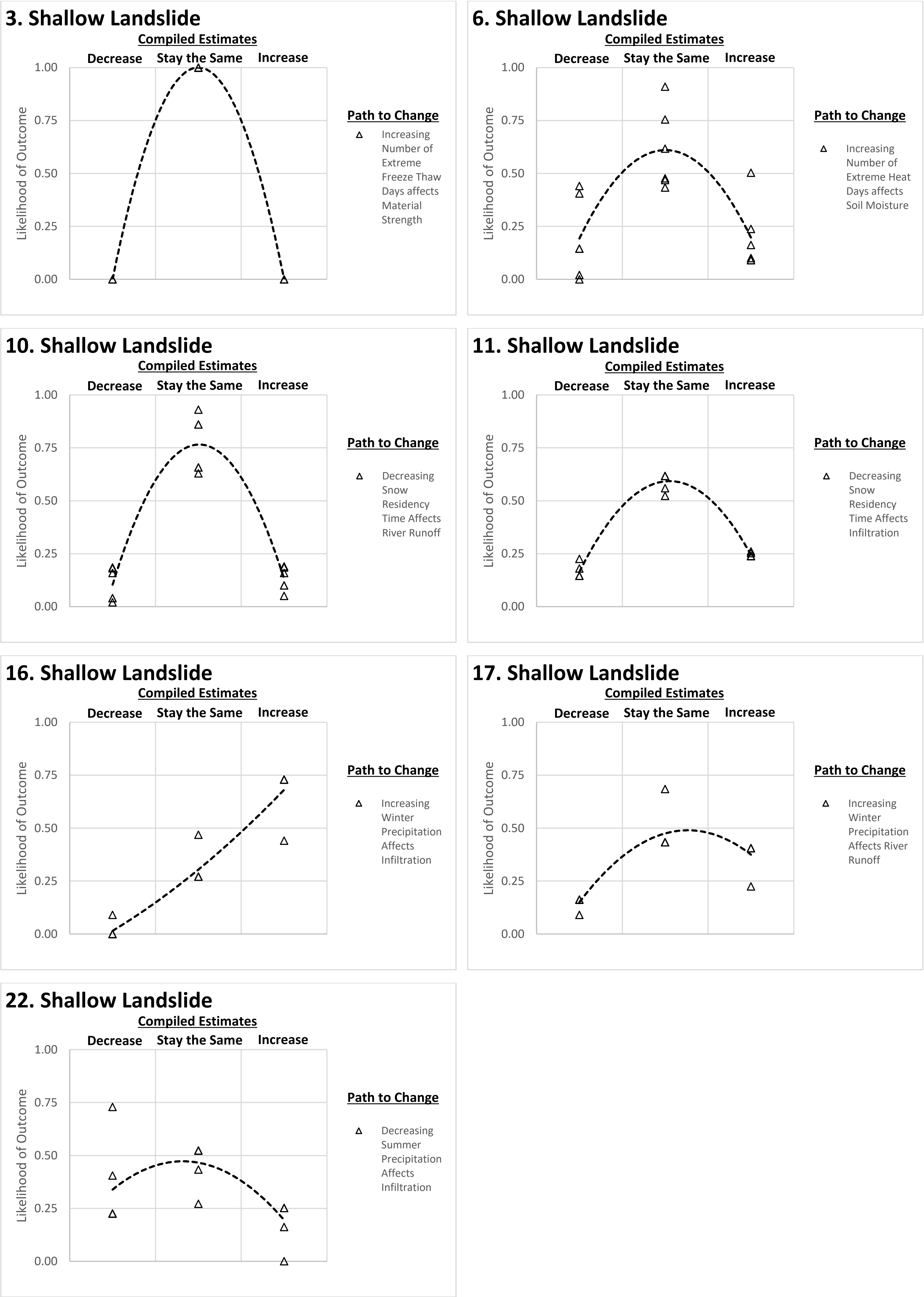


Figure C-3. Climate variables and geophysical processes that are most likely to increase shallow landslide FM include an increase in winter precipitation affecting infiltration (plot 16) and affecting river runoff (Plor 17). Shallow landslide FM could decrease as a result of decreased summer precipitation affecting infiltration (Plot 22). The numbers in the top left of the plots correspond to the scenarios described in Table 4-1 in the main report.

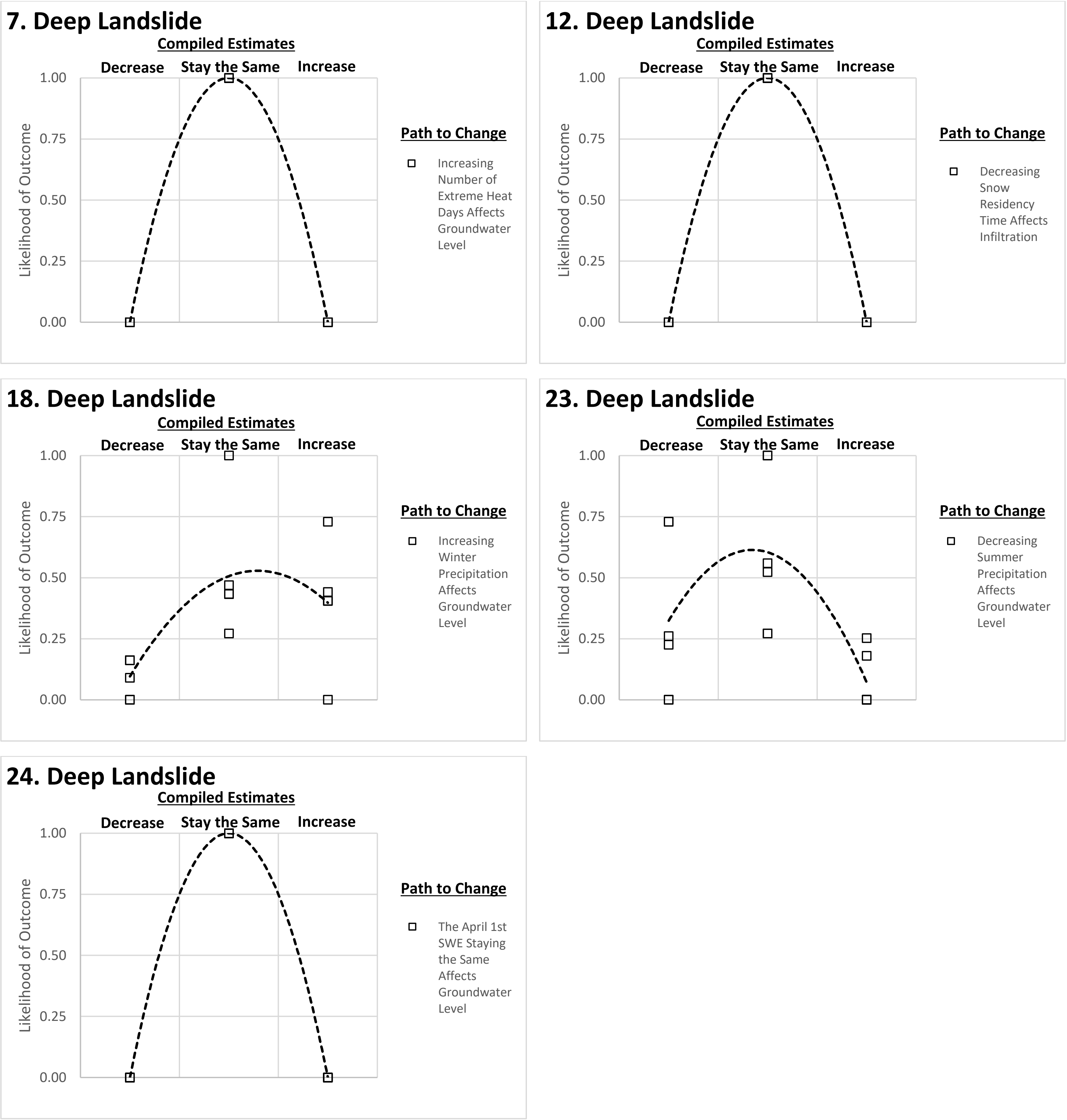


Figure C-4. Climate variables and geophysical processes that are most likely to increase deep landslide FM include an increase in winter precipitation affecting groundwater level (Plot 18). A decrease in summer precipitation could decrease deep landslide FM (Plot 23). The numbers in the top left of the plots correspond to the scenarios described in Table 4-1 in the main report.