Geo-Resilience 2023 Conference, Cardiff, Wales
D.G. Toll & M.G. Winter (Eds)
British Geotechnical Association, London. 2024
https://doi.org/10.53243/Geo-Resilience-2023-5-2

A Framework for Estimating Impacts on Transportation Infrastructure in a Changing Climate

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Abstract

For infrastructure exposed to geohazards, the challenge for owners and investors is how changes in climate will in turn affect frequency and magnitude of geohazards as well as deterioration of geotechnical assets. To assess the potential change to geohazard frequency and magnitude from changing climate variables, it is helpful to assess change to intermediate geophysical processes that involve a change to the earth, rather than within the atmosphere. Examples of such geophysical processes include groundwater levels, surface water flow, material strength loss, and wildfire. In the prediction of future conditions, uncertainty exists in the linkage between inputs from modelled climate projections and many geophysical processes, in part because most climate models are tuned to optimize coarser climate timesteps and large geographic regions. Other uncertainties are introduced from ensembles of climate models.

To inform planning decisions for an agency risk and resiliency program, a framework was developed for the Colorado Department of Transportation, with participation from the U.S. Federal Highway Administration. The framework uses conditional probability judgment estimates to evaluate the probability that a geohazard type would increase, decrease, or stay the same given a change in a single climate variable. Each event tree representing these estimates has three dependent categories: a climate variable, a geophysical process and geohazard outcome. Multiple scenarios were assessed to produce one of three possible outcomes: increase, decrease or remain stable. In the future, the framework will be used to inform resiliency plans and the potential changes to geohazard frequency from current climate model predictions.

Keywords: Risk, Geohazards, Climate Change

1. Introduction

The non-stationarity of climate is an accepted occurrence in the scientific community and is supported by including rising temperatures, changing precipitation regimes, and rapidly thawing permafrost. The International Panel on Climate Change (IPCC) predicts a warming between 1.5ºC to 5.8ºC by 2050 for North America (IPCC, 2014). The consequences of these changes in climate can manifest as increased extreme weather events (e.g., heat waves, hurricanes, and atmospheric rivers) as well as by affecting geomorphic processes that trigger geohazards.

In Colorado, the Colorado Department of Transportation (CDOT) recognizes and manages threats from rockfall originating from deteriorating cut slope assets and natural rock outcrops; debris flow hazards that intersect highway routes; swelling and unstable subgrades; slopes associated with deteriorating embankments; and natural terrain with known landslides. Where these geohazards exist along the highway network, the magnitude and frequency at each location are a function of geology, topography and climate. As such, when climate changes, a change to the frequency and magnitude of geohazards is expected. These types of geohazards and future changes to frequency and magnitude are ubiquitous to many transportation owners worldwide.

To understand how a changing climate can impact the frequency and magnitude of geohazards, CDOT commissioned a study to develop a framework that can be used in assessing changes in future risk in a changing climate. The following landslide geohazards were considered in this study:

- Deep landslide: a landslide with a typical maximum depth greater than approximately 15 m and typically extending beyond the boundary. Slide volume consists of more than 75 m^3 of soil and/or rock with a planar or rotational sliding surface located more than 5 m below the surface.
- Shallow landslide: a landslide with a typical maximum depth of approximately 5 m within an embankment asset or natural slips within the boundary. Volumes are typically less than about 75 m^3 of soil and/or rock with a planar or rotational sliding surface.

- Rockfall: the sliding, toppling or rolling of rocks or rock blocks of all sizes within or beyond the boundary. Falling fragments travel at very rapid velocities and typically bounce and roll well beyond the source area. Rockfall, as defined here, includes rockslides, which consist of one or more blocks that collectively exceed 25 m^3 so a full range of event size is considered.
- Debris flow: the mobilization and travel onto or near 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 crossed by highways.

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.

The outcome of approach taken in this study was to estimate the likelihood that a landslide geohazard would increase, decrease, or stay the same given a change in a climate variable. To accomplish this, a probabilistic framework using event trees to model 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.

2. Climate

2.1 Predicted Changes

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 estimate ranges for future temperature and precipitation characteristics that are specific to smaller regions.

Despite the challenges associated with downscaling GCMs to model climate change at finer resolutions, modelling 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, 2016). 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). A synthesis of how temperature and precipitation in Colorado are predicted to change is provided in Table 1.

Table 1: Synthesis of temperature and precipitation are changes predicted in Colorado.

Variable	Projections	Source
Temperature	Temperature will increase by 1.1˚ C to 3.5˚ 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
	Precipitation depths increase 5% to 16% on depending on the location and emission scenario.	
	Precipitation will increase in Winter but more of it will fall as rain rather than snow	

2.2 Climate Variables

The landslide, rockfall and debris flow hazards modelled in this study 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, and a review of the literature suggests that this is not being done routinely. Similarly, further processing of climate model output is required to derive the identified measures and such processing may not improve certainty in the outcome. 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.

The 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 climate science experts on uncertainties in the models and how closely they represent the more ideal climate measures presented previously.

Table 2 provides a list of the climate variables that were assessed and the 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 2 and calculating the averages for the time period. Similarly historic climate variable maps were downloaded for the time periods shown in Table 2 and averaged. The averaged values were used 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 2: Climate variables evaluated in study.

Variable	Historical time period	Future time period	Unit	Climate Data source
Winter Precipitation	1975 - 2005	2071 - 2090	mm	USDA (2019)
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	USBR (2019)
Extreme Freeze-Thaw Days	1970 - 2000	2070 - 2099	day	

3. Geohazard and Climate Change Assessment

3.1 Methodology

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. Each event tree consisted of three categories: a climate variable, a geophysical process and a geohazard frequency outcome and an example event tree is shown in Figure 1. 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.

The combinations of these categories were mapped out to characterize unique scenarios which could result in one of three possible outcomes: the geohazard frequency 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 frequency 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 site specific geotechnical needs.

Linkages between inputs from modelled 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 were held to assign trends to characterize how climate variables affect various geophysical process and how geophysical processes affect geohazard frequency and magnitude (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.

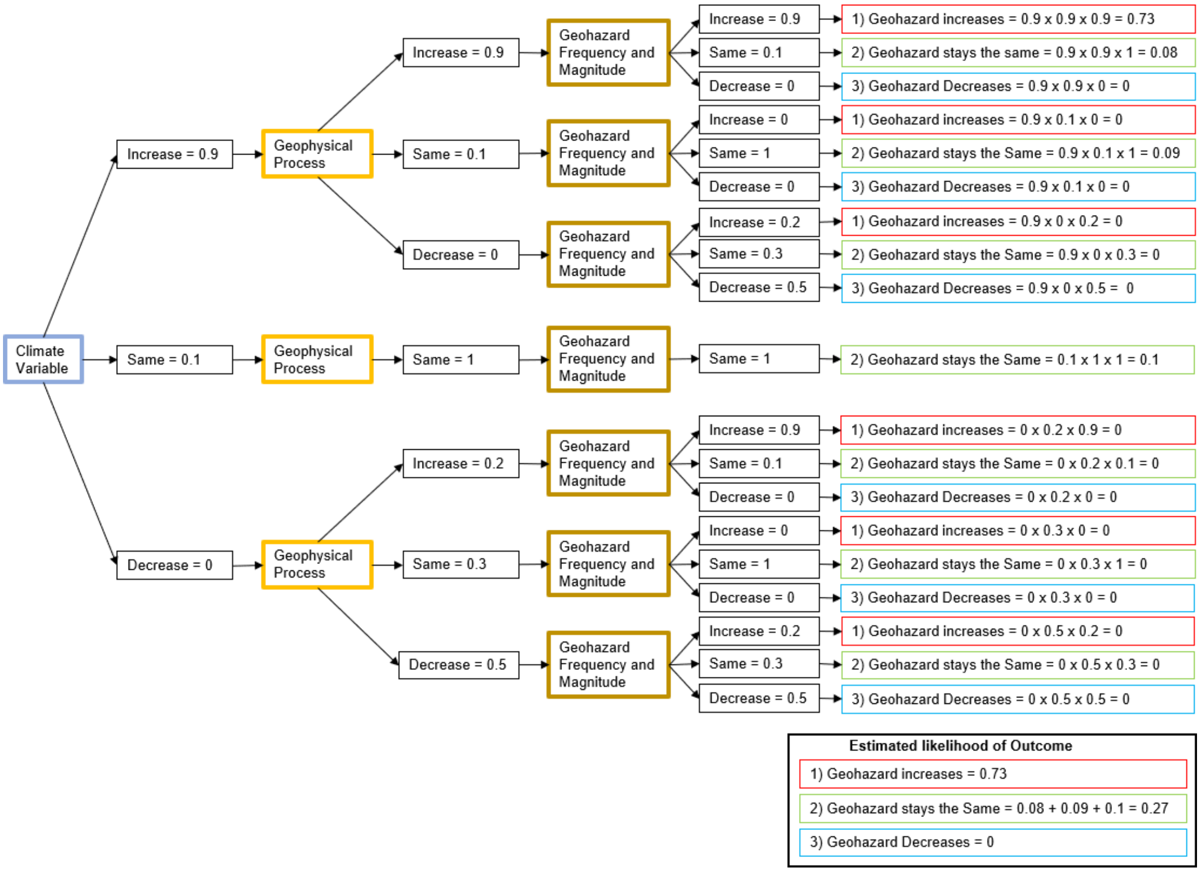

Figure 1: Example event tree showing calculations for a scenario and the modelled outcome to geohazard frequency.

3.1 Results

Using the workshop process, a total of 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 frequency 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 frequency. Table 3 provides a summary of the scenarios where there was a general consensus in the results on the change to a geohazard frequency based on a change to a climate variable and the connected geophysical processes.

Table 3: Summary of scenarios that could affect geohazard frequency with bold text identifying where frequency is predicted to increase.

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

4. Conclusions

The probabilistic event tree approach is flexible method for developing predictions in the trends of geohazard frequency that may occur through climate change. The approach can be applied for all forms of geohazards and at scales ranging from project to regional scale, similar to the application of climate change forecasts. The resulting estimates can be used to inform asset and risk management plans for infrastructure owners with exposure to adverse performance from geohazard processes. The approach can quickly accommodate improvements to climate modelling as they emerge 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 an entire region. The proposed process enables infrastructure owners and operators to make proactive, risk-informed asset management decisions in response to predicted changes in temperature and precipitation.

Acknowledgements

The authors would like to acknowledge the U.S. Federal Highway Administration and CDOT for sponsoring the study and contributing to the work; climate specialists from US National Center for Atmospheric Research for input on climate models and uncertainties, and the firm AEM for reducing climate model output for use in the event trees.

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The paper was published in the proceedings of the Geo-Resilience 2023 conference which was organized by the British Geotechnical Association and edited by David Toll and Mike Winter. The conference was held in Cardiff, Wales on 28-29 March 2023.