Future global debris flow susceptibility considering climate change, wildfire probability, and glacier retreat

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Abstract. The present-day impact of climate changes on debris flow magnitude, frequency, and susceptibility has been demonstrated in North and South America, Europe, Asia, and New Zealand. Such impacts are expected to increase under future emission scenarios. Future global debris flow susceptibility models provide an international perspective on areas worthy of further, more detailed analyses with regard to geographic changes in global debris flow susceptibility. In this study, future global debris flow susceptibility models are developed under RCP 2.6 and 8.5 IPCC Climate Change Scenarios. These models were further augmented with wildfire probability, and areas of potential glacier retreat, both of which can act as amplifiers to debris flow susceptibility. The results are projected against future urban centers, for a spatial view on potential human vulnerability. Key findings are (1) wildfire acts as a significant amplifier in area and magnitude of debris flow susceptibility in all modeling scenarios, (2) greater than 50% of the studied glaciers reside within higher susceptibility zones when wildfire is not considered, and greater than 75% when wildfire probability is considered, (3) 76 of the studied glaciers are within 5 km of eleven urban centers, (4) 11% of these "urban" glaciers are in higher susceptibility zones when wildfire probability is not considered, and 51% are in higher susceptibility zones when wildfire is considered, (5) about 12% of future urban centers will reside within higher susceptibility zones under both future climate change scenarios. Consideration of these factors, together with traditional environmental factors and triggers, and findings by local and regional glacier-related debris flow researchers, suggests a new paradigm in modeling debris flow susceptibility, at any scale.

1 Introduction

Climate conditions (precipitation, temperature, aridity) may experience major changes in magnitude and geographic extent in the future. "The frequency and intensity of some extreme weather and climate events have increased as a consequence of global warming and will continue to increase under medium and high emission scenarios (high confidence)" [1]. Climatic variability will be manifested as significantly enhanced rainfall in some areas and marked desertification and enhanced wind erosion in others, operating at scales of tens to hundreds of years [2, 3]. The frequency and intensity of droughts are projected to increase in southern Africa, and the Mediterranean region, while frequency and intensity of extreme rainfall events are projected to increase in many other regions across the world.

Both changes in temperature and precipitation affect slope stability and potential debris flow susceptibility [4] by increasing sediment availability and from intense and/or prolonged rainfall triggers, rainfall totals, antecedent rainfall, and rain on snowmelt [1].

Changes in regional precipitation and temperature levels and patterns are the primary climate changes with a direct impact on soils, geomorphology, land use/landcover, and other environmental factors which influence the potential for debris flows. "Magnitude of debris flows could become larger due to larger amounts of sediment delivered to the channels and as a result of the predicted increase in heavy precipitation events." [5]. These factors can subsequently lead to debris flows in areas of frequent or intense rainfall [6] [4] [7] [8] [9].

Local and regional researchers have demonstrated the recent impacts of climate change on increased debris flow magnitude and frequency, and the correlation of increased debris flows with changes in seasonality, in North and South America, Europe, New Zealand, and Asia [4, 5, 10-14]. These recent observable results provide credibility for the potentiality of future impacts.

The future debris flow susceptibility models, developed herein, are based on projected climate trends worldwide for the decade 2100. The objective is to identify areas globally with the highest potential for debris flows. The purpose is not to predict, or provide early warning systems, but rather as a high-level preliminary view of the potential impact to society that can be used to determine areas to drill-down for more regional and localized research, and planning.

Frequently, debris flows occur post-fire from runoff-dominated progressive bulking of storm runoff with sediment eroded from hillslopes and channels, and to a lesser extent by infiltration-triggered failure and mobilization. In such areas, slope failures are in response to prolonged periods of rainfall, or prolonged rain fall in combination with rapid snowmelt [15-17]. With climate change and increasing temperatures, the likelihood of increased forest fires leads to an increased likelihood of post-fire debris flow frequency, in those burn areas where other debris flow predisposing factors exist [15] [17]; and rainfall amounts required to induce debris flows decrease [16, 18]. Given that debris flows may occur during the first rainy season post-fire, one to two years post-fire, and even up to 10 to 30 years [16], burned watersheds pose a significant potential threat to humans living in close proximity [19]. Thus, present-day, and future wildfire probability models from Moritz et al. [20] are coupled with

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the debris flow susceptibility models of this project, as a potential debris flow susceptibility amplifier.

While there are numerous factors which contribute to landscape instability and landslide susceptibility, such as precipitation, snow melt, temperature, seismic and volcanic activity, and anthropogenic changes to landscape, precipitation and snow melt are the most significant triggers for debris flows [9]. In mountainous regions, which are most susceptible to slope instabilities, increased temperatures can result in thawing of permafrost and interstitial ice in rock mass cracks, reducing the shear strength, and increasing the frequency and magnitude of rock falls and debris flows [14]. Glacier-related debris flows may occur during glacier retreat due to the availability and exposure of large quantities of unconsolidated sediments, which are mobilized with warming trends, increased precipitation, snowmelt, and glacial lake outbursts as triggering mechanisms [21]. The proximity of glaciers to populations within debris flow susceptible areas is modeled as an additional proxy for human vulnerability.

2 Methodology

A Maximum Entropy "present-day" global debris flow susceptibility model developed by Kurilla and Fubelli 2022 [22], with MaxEnt software [23] was used for derivation of factors and factor classes associated with an inventory of 5695 historic debris flow events. The "present-day" Maximum Entropy model is used to extract those factors with significance values > 1% and their factor classes which exhibit >= 90% predicted probability, as suitable debris flow environments. Table 1 lists the factors which met these criteria. These factors are used as input to the future models. The future models are developed in ArcGIS Pro. Representative Concentration Pathways (RCP) 2.6 and 8.5 projected monthly average precipitation [24] and Köppen-Geiger climate classification [25] data are used for the future models, extracting a subset based on the climate and precipitation factor classes which exhibited >=90% predicted probability in the "present-day" Maximum Entropy model. Each of the factor layers were weighted based on their "present-day" model Maximum Entropy significance value (relative contribution to susceptibility) and summed over each pixel. Each pixel of the resultant susceptibility map is equal to the sum of the weights of all environmental factors present at that pixel, therefore ranging from 0 (no factors present) to 99 (all factors present). Pixels with higher weighted sums represent higher susceptibility. The maps are classified using five equal intervals and qualitative labels of "Very Low", "Low", "Moderate", "High", and "Very High" susceptibility.

Next, future (2070-2099) projected wildfire probability data [20], at 0.5^{o} resolution, are summed with debris flow susceptibility values for each model, on a pixel basis, to identify areas where wildfire probability may increase, decrease, or have no impact on debris flow susceptibility. 214,429 glaciers with slopes >=20^{o} and <=35^{o} from the Randolph Glacier Inventory [26] were used for spatial overlay with future debris flow susceptibilities, with and without wildfire probability. These slopes are those most commonly associated with debris flows. ArcGIS "Buffer" and "Near" tools were used to provide a 5-km buffer around each glacier, and to determine the proximity to future urban centers. Future urban centers (a proxy for impact on both humans and economies), based on SSP5 (Shared Socioeconomic Pathway 5) data at 1-km resolution [27] are used as a spatial overlay in ArcGIS for the glacier proximity analysis.

Table 1. Susceptibility factors and significance values/weights

Environmental Factor	Significance Value/Factor Weight
Slope (deg)	27
Köppen-Geiger Climate Class	20
Landform	18
Soil Drainage	9
Soil Type	9
Fault Density (km/sq km)	6
Land Cover	4
Precipitation (Avg mo mm)	2
Soil Thickness (m)	2
Lithology	2

3 Results

The percentage area of each susceptibility zone for both future scenarios, with and without consideration of wildfire probability, is provided in Table 2, along with a reference comparison to the susceptibility zonation of the present-day model.

Table 2. Percent area of global debris flow susceptibility classification by model, with and without wildfire probability.

% Area susceptibility class by model	without wildfire /with wildfire		
	Present-day	RCP 2.6	RCP 8.5
Very Low	91.6%/27.6%	92.5%/21.4%	91.0%/23.7%
Low	5.2%/9.6%	5.2%/8.2%	6.7%/6.4%
Moderate	2.5%/27.8%	1.9%/32.4%	1.9%/32.1%
High	0.6%/23.4%	0.4%/25.6%	0.4%/23.7%
Very High	0.05%/7.4%	0.03%/8.7%	0.04%/10.9%
Extreme	0/4.2%	0/3.7%	0/3.2%

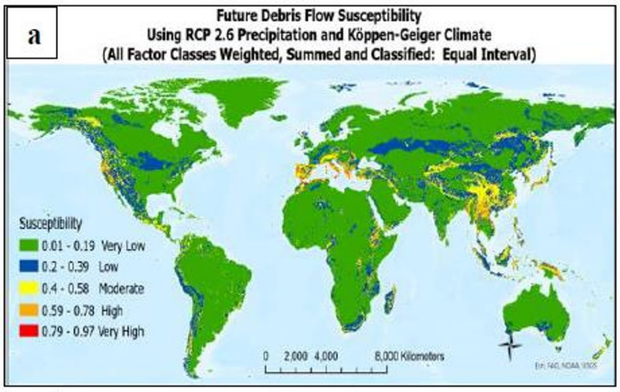
An additional susceptibility classification (Extreme) was introduced to accommodate the increase (> 100% probability) when wildfire probability is included. All susceptibility classifications increased in area, for all models, except "Very Low" when wildfire probability is considered. The change in the percentage area of each susceptibility classification per model, when wildfire is considered, is presented in Table 3.

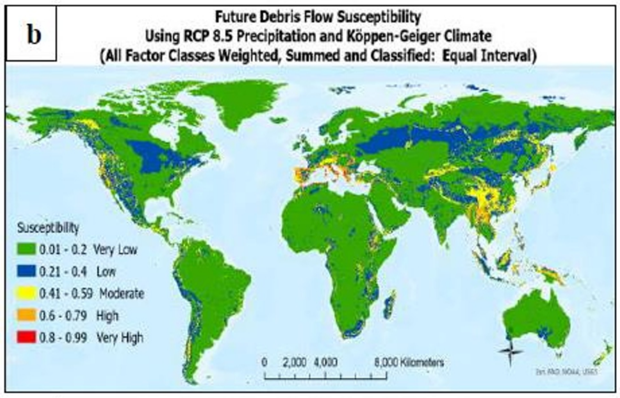
Figures 1a and 1b show future global debris flow susceptibility without considering wildfire probability for RCP 2.6 and 8.5, respectively. Figures 1c and 1d show future susceptibilities with wildfire probability for RCP 2.6 and 8.5, respectively.

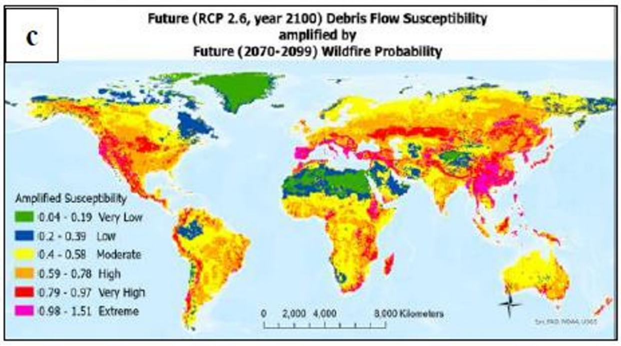
Table 3. Percent area change in susceptibility zone, by model, when wildfire probability is considered.

Debris Flow Susceptibility	% Susceptibility change with addition of wildfire		
Susceptibility Class	Current	RCP 2.6	RCP 8.5
Very Low	-62.1%	-75.8%	-74.2%
Low	27.0%	33.3%	30.5%
Moderate	23.6%	26.9%	25.5%
High	10.3%	10.8%	17.3%
Very High	1.2%	4.8%	0.9%
Sum of Moderate to Very High	43.8%	42.5%	35.1%

In studying the proximity of glaciers to debris flow susceptibility and urban centers, seventy-six of the studied glaciers were found to be within 5 km of eleven urban centers. 11% of these "urban" glaciers are in Moderate to Very High susceptibility zones under both future scenarios without wildfire consideration (Table 4), and greater than 50% when considering wildfire probability (Table 5).







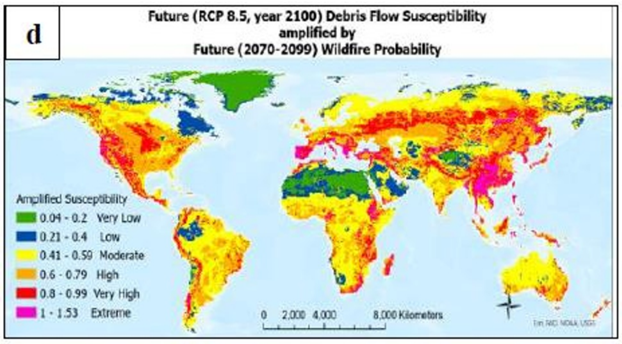


Fig. 1. Future susceptibility with and without wildfire consideration. a) RCP 2.6 without wildfire, b) RCP 8.5 without wildfire, c) RCP 2.6 with wildfire, RCP 8.5 with wildfire consideration

Table 4. Glaciers vis-à-vis susceptibility zones and urban centers, without wildfire

Debris Flow Susceptibility Class without wildfire probability (RCP 2.6 and 8.5)	# Glaciers	Population within 5km
Very Low	22	200,815
Low	46	218,358
Moderate	8	83,053
High	0	0
Very High	0	0
TOTALS	76	502,226

Table 5. Glaciers vis-à-vis susceptibility zones and urban centers, with wildfire

Debris Flow Susceptibility Class with wildfire (RCP 2.6 and 8.5)	# Glaciers	Population within 5km
Very Low	0	n/a
Low	37	184,996
Moderate	19	215,472
High	12	59,618
Very High	4	8,623
Extreme	4	46,786
TOTALS	76	515,495

4 Conclusions

Traditional environmental factors and triggers used for debris flow susceptibility modeling, based on historic debris flow events to-date, may no longer be sufficient for determining susceptibility under changing climatic conditions worldwide. A new paradigm may be needed which considers wildfire probability as well as potential cryosphere-related warming, when considering the potential human vulnerability.

The percentage of total land area with an increase in debris flow susceptibility classification under future scenarios RCP 2.6 and RCP 8.5 is small (1.49% and 3.14%, respectively) until wildfire probability is considered. When considering future wildfire probability, global debris flow susceptibilities are amplified in both magnitude and area across all models, present-day and future. Furthermore, it is demonstrated that human vulnerability may further increase where glaciers are coincident with higher debris flow susceptibility zones and within close proximity to urban centers.

Only time can be the real test of validity of this type of projection. There are many types and sources of uncertainty in any modeling effort, potentially resulting in spatial and/or classification uncertainty of the model. Given that there are few models at the global level, there are fewer opportunities to compare models. The credibility and known uncertainties of the underlying data (climate projections, wildfire probability, future urbanization) is critical in trusting this type of model. The future climate, urbanization, and wildfire researchers all constructed their final results through numerous (from 37 to 100) simulations and model comparisons, choosing those factors which had the highest confidence level across all simulations, on a pixel basis, and comparative analyses with other researchers' results at regional levels. They also consider coarser, long-term norms rather than short-term environmental fluctuations. One significant uncertainty in the future urbanization projections is not considering the impacts of climate change on urban growth [27]. Performing additional future global debris flow susceptibility models using different modeling approaches can allow for comparative analyses, and fine tuning. This research is based on the best (RCP 2.6) and worst (RCP 8.5) projections for greenhouse gas concentration, but only the worst case (SSP5) socio-economic scenario, of rapid and unconstrained growth in economic output and energy use. Including SSP1, which represents sustainability-focused growth and equality, would be a more complete representation of the two ends of a spectrum of potential outcomes

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