What does landslide triggering rainfall mean?

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Abstract. Landslide-triggering rainfall thresholds are often subject to both false negatives (landslides where none are expected) and false positives (no landslides despite thresholds being exceeded). Debris flows and shallow landslides impact communities and infrastructures worldwide. Refinement of the relation between rainfall intensity and landslide occurrence would help remove the imprecise nature of this tool moving forward. Continuous 6-hour gridded precipitation data from over a five-year interval 900 km^2, combined with a complete, time-constrained, landslide data base over the same period, are used to derive relations for the probability of shallow landslides with rainfall intensity measured over 6-hour, 12-hour, or 24-hour durations. Previously published and widely used thresholds are quantified in terms of landslide probability per unit area and demonstrate, for different sized study areas, the likelihood that at least one landslide will be initiated at different intensities and durations. Probabilistic distribution of landslides for a given study area and rainfall intensity can be easily derived using the binomial method from these relations.

1 Introduction

Rainfall and shallow landslides relationships have been studied for the past 40+ years beginning with the work of Nel Caine [1]. Over time there have been strong connections established between rainfall and shallow landsliding [2]. Refining and honing this relationship have obvious societal impacts with regard to protecting lives, critical infrastructure, and properties [3].

The Caine threshold [1] first established a landslide triggering threshold for precipitation, over durations from one minute to 90 days, based on a worldwide database of 73 landslides for which rainfall data existed. Caine's work resulted in an envelope curve beyond which landslides were expected to occur, and took the form of an Intensity-Duration curve in the form:

$$\boldsymbol{I} = 14.82\mathrm{D}^{-0.39} \qquad (1)$$

Where I was rainfall intensity in mm/h and D was rainfall duration in hours.remains a widely used approach. However, it became obvious both that landslides were occurring at precipitation values below the threshold (false negatives) and that exceeding the threshold did not guarantee the occurrence of a landslide (false positives). This spurred researchers to use of larger datasets to create lower thresholds [4, 5, 6, 7] with limited success. Attempts to create better thresholds using antecedent conditions have also been derived [8, 9, 10] and continue today, but arguably make the thresholds more complex without making them more accurate.

Here, we present a well constrained probabilistic relationship between rainfall intensity and landslides. This relationship begins to quantify what the existing thresholds represent and permits relatively simple calculations regarding the potential impacts of different intensity storms.

2 Methods

The Klanawa study area (**Fig. 1**) is part of the Vancouver Island Ranges, comprised of glacially over-steepened volcanic and plutonic mountains extending from sea level to about 912 m. Precipitation at sea level is typically between 2,900 and 3,100 mm annually following almost exclusively as rain between October and March [11]. Further inland precipitation and percentage of snow increases with elevation.

The study area is in various stages of logged, juvenile forest, second growth, and old growth forest depending on logging history. Debris flows and shallow landslides are common [11].

A probabilistic relationship that can be deployed elsewhere requires a result that explains the likelihood of a landslide at a given rainfall intensity and duration, over a unit area. We therefore required: (i) a complete rainfall record for the area under investigation, and (ii) a complete landslide inventory for the same, as time constrained as possible.

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Fig. 1. The Klanawa 90,259 ha study area on the west coast of Vancouver Island. Red dots indicate landslide locations.

2.1 Rainfall Data

The number of intensity-duration rainfall events (ID-area pairs) that did not trigger landslides at a particular area will overwhelm those that did. Each data point contains and ID-area pair and a landslide count (0, 1, 2, …*n*).

We collected 6-hour gridded rainfall (2.5 km^2 grid) from the Canadian Surface Prediction Archive [12] for the period between Feb 02, 2018, and Jan 18, 2023. These data were processed and up-sampled (interpolated between points) to generate hourly gridded ID-area pairs one ha in size (**Fig. 2**).

Altogether we generated more than 0.5 billion ID-area (1 ha) pairs for each of three durations (6-hours, 12-hours, and 24-hours). The 12-hour and 24-hour tests ran on a moving 6-hour window.

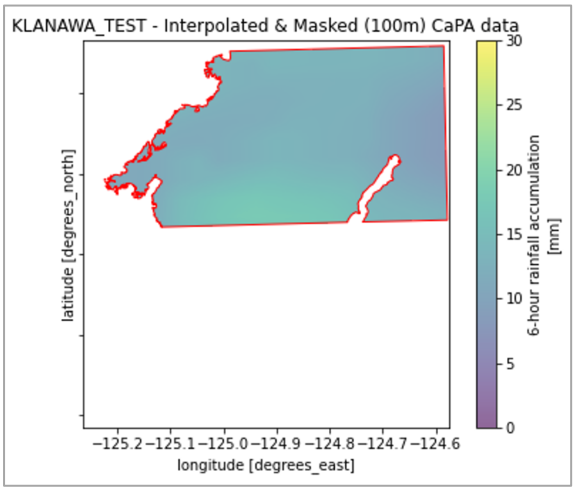

Fig. 2. Up-sampled 1 ha resolution rainfall data.

2.2 Landslide Data

Planet Fusion data were used to collect and acquire landslide occurrences in the study area over our period of record. These data provide daily cloud-free orthorectified imagery, at 3 m resolution. Landslides were discovered by running a change detection process between the first and last images of approximately 1,500 images, separating landslides from other surface changes, and determining the first and last definitive images that bracketed the observed landslides (**Fig. 3**).

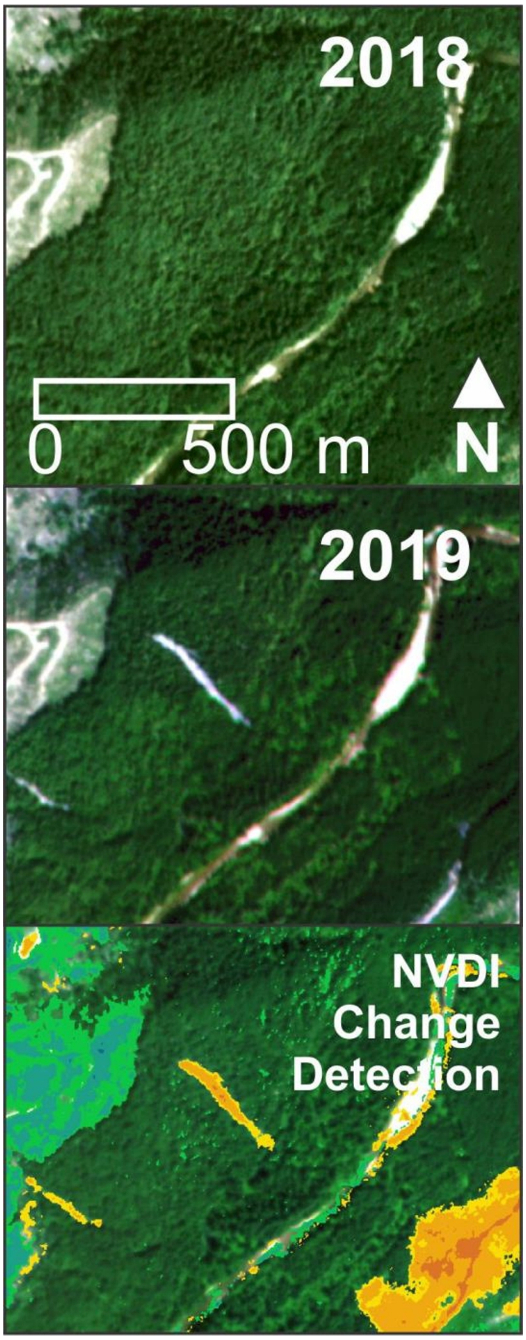

Fig. 3. Example landslide change detection between image sets from PlanetFusion.

Image quality varied dramatically across dates, which meant considerable persistent uncertainty about the presence of landslides on transition images. Landslide dates were constrained, on average, within a 65-day period and assumed to be a result of the most intense rainfall (6-hour, 12-hour, or 24-hour) over that period.

Fifty landslides were identified between 2018 and 2022. Landslide counts were assigned to the ID-area pairs at their specific location and assigned a time based on the maximum intensity for that duration.

ID-area pairs were then grouped into 1 mm intensity bins where each bin contained the total landslide count from about 0.54 billion possible ID-area pairs (the exposure time).

Probability was determined by dividing landslide counts in each intensity bin by the exposure time.

3 Results

Probabilities were plotted for 6-hour, 12-hour, and 24-hour. Here we graphically present the results for the 6-hour for conservation of space (**Fig. 4**). The widely referenced Caine [1], Crosta and Frattini [5], Jakob and Weatherly [6] and Guzzetti et al. [4] thresholds are also plotted within the **Fig. 4**.

Landslides are both possible and observed at lower rainfall intensities (Table 1) but their probability of occurrence is much lower. The Caine threshold [1] results in about a one percent chance (0.01) of at least one landslide per 100 km^2 for the intensity-durations measured here.

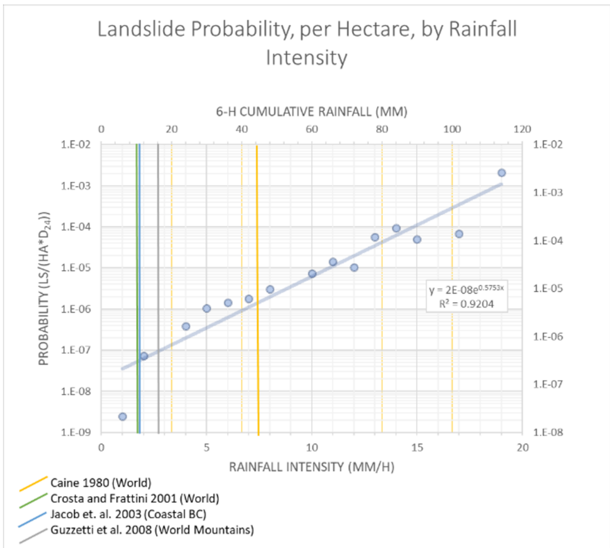

Fig. 4. Probability of landslides/ha by 6-hour rainfall intensity.

4 Discussion and Conclusions

The relationship between rainfall intensity and landslide occurrence are robust. The correlation coefficients for all three curves are strong (0.92, 0.99, and 1.0 for D6, D12, and D24 respectively) and we argue that the relations have high explanatory power irrespective of duration and antecedent conditions.

Table 1. Probability of landslides per unit area for different durations and intensities

Intensity (mm/h)	Cumulative Rainfall	Probability of at least one landslide per ha	1 km^2	10 km^2	100 km^2
	24 h				
3.13	75	2.8E-07	0.000028	0.00028	0.00277
4.17	100	6.7E-07	0.000067	0.00067	0.00664
5.21	125	1.6E-06	0.000160	0.00160	0.01588
6.25	150	3.8E-06	0.000384	0.00384	0.03772
8.33	200	2.2E-05	0.002217	0.02195	0.19901
9.38	225	5.3E-05	0.005317	0.05191	0.41322
	12 h				
2.1	25	1.2E-07	0.000012	0.00012	0.00115
4.2	50	6.7E-07	0.000067	0.00067	0.00664
6.3	75	3.8E-06	0.000384	0.00384	0.03772
8.3	100	2.2E-05	0.002217	0.02195	0.19901
10.4	125	1.3E-04	0.012726	0.12021	0.72217
12.5	150	7.4E-04	0.071273	0.52260	0.99939
	6 h				
4	25	2.2E-07	0.000022	0.00022	0.00220
8	50	2.4E-06	0.000242	0.00241	0.02387
13	75	2.7E-05	0.002652	0.02621	0.23322
17	100	2.9E-04	0.028769	0.25317	0.94602
21	125	3.2E-03	0.274804	0.95977	1.00000

Future work is required by others to test the broader applicability of these relationships. Broader applicability may be subject to differences in land use, geology, regional climate, and bio-geomorphic regimes. Similar approaches performed in post-wildfire scenarios indicate shows a higher occurrence of debris flows when compared to the relationships presented here.

The findings show, for the first time, what published thresholds mean for a given storm. The relations demonstrate that different size study areas produce a different a likelihood of at least one debris flow is initiated under different rainfall intensities and durations.

Despite the recognition that the broader application of these relationships need to be determined, we nevertheless expect these have broad applicability.

References

1. N. Caine, Geografiska Annaler. Series A, Physical Geography **62**, 1-2 (1980)

2. F. Guzzetti, S. L. Gariano, S. Peruccacci, M. T. Brunetti, M. Melillo, *Rainfall and Landslide Initiation*, in Rainfall. Modeling, Measurement and Applications, Elsevier (2022)

3. D. Petley, *Geology* **40**, 10 (2012)

4. F. Guzzetti, S. Peruccacci, M. Rossi, C.P. Stark, Landslides **5** (2008)

5. G.B. Crosta, P. Frattini, *Rainfall thresholds for triggering soil slips and debris flow*, in Proceedings of the 2nd EGS Plinius Conference on Mediterranean Storms, Siena (2001)

6. M. Jakob, H. Weatherly, Geomorphology **54**, *3-4* (2003)

7. M. T. Brunetti, S. Peruccacci, M. Rossi, S. Luciani, D. Valigi, F. Guzzetti, Natural Hazards and Earth System Sciences **10** (2010)

8. M. Church, M.J. Miles, *Meteorological antecedents to debris flow in southwestern British Columbia; Some case studies*, in Debris Flows/Avalanches: Process, Recognition, and Mitigation, The Geological Society of America (1987)

9. M.J. Crozier, Earth Surface Processes and Landforms **24** (1999)

10. G.F. Wieczorek, T. Glade, *Climatic factors influencing occurrence of debris flows*, in Debris-flow Hazards and Related Phenomena, Berlin, Springer (2005)

11. T. Rollerson, D. Maynard, S. Higman, E. Ortmayr, *Klanawa landslide hazard mapping pilot project*, in Joint Conference of IUFRO 3.06 Forest Operations under Mountainous Conditions and the 12th International Mountain Logging Conference, June 13-16, Vancouver (2004)

12. J. Mai, K. C. Kornelsen, B. A. Tolson, V. Fortin, N. Gasset, D. Bouhemhem, D. Schafer, M. Leahy, F. Anctil, P. Coulibaly, Bulletin of the American Meteorological Society **101**, 3 (2020)