7th International Conference on Debris-Flow Hazards Mitigation

Forecasting and seismic detection of debris flows in pro-glacial rivers at Mount Rainier National Park, Washington, USA

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Abstract

The glaciated Mount Rainier volcano in Southwestern Washington State (USA) has a rich history of outburst floods and debris flows that have adversely impacted infrastructure at Mount Rainier National Park in the 20th and 21st century. Retreating glaciers leave behind vast amounts of unconsolidated till that is easily mobilized during high precipitation intensity fall storms and during outburst floods during warm summer months. At least 60 debris flows and outburst floods have been documented between 1926 and 2017 at Mount Rainier. Debris-flow activity has led to the closure of campgrounds and visitor destinations, which has limited visitor access to large swaths of the park. After a relative lull in activity between 2006 and 2014, the historically debris-flow-prone South Tahoma Glacier released two separate sequences of debris flows in 2015, possibly signaling a reawakening in activity. The August 13, 2015 debris flow was especially well documented by park visitors, seismographs and, most interestingly, a soundscape monitor which recorded an anomalous decrease in river noise prior to the arrival of the first debris flow. The seismograph near Tahoma Creek accurately recorded the passage of each debris-flow surge. Using the day of and historic antecedent weather conditions on past debris-flow days, we have developed a debris-flow hazard model to help predict those days with a higher relative hazard for debris-flow activity park-wide based on prevailing and forecasted weather conditions. Debris flows are detected in near-real-time using the USGS Real-time Seismic Amplitude Measurement (RSAM) tool. If an event is detected, we can then provide alerts to employees and visitors working and recreating in the areas downstream to evacuate. Our goal is to accurately forecast the hazard of a debris flow up to seven days ahead of time and then use RSAM to detect debris flows within minutes of their genesis.

Keywords: Debris flows; outburst floods; hazard mitigation and monitoring; hazard forecasting; Real-time Seismic Amplitude Measurement

1. Introduction

Mount Rainier is a 4,392 m (14,410 ft) stratovolcano located in southwest Washington State, USA, approximately 70 km (43 mi) southeast of Tacoma and 90 km (56 mi) south-southeast of Seattle (Fig. 1). The volcano occupies most of the 956 sq. km (369 sq. mi) Mount Rainier National Park (MORA) and is visible from much of western Washington State. MORA has been episodically active in the last 500,000 years, including at least 10-12 eruptions in the last 2,600 years (Sisson and Vallance, 2009). Eruptions have initiated large lahars that have inundated areas of the Puget lowland as far as 100 km (62 mi) from the volcano (Crandell, 1971). Because of its far-reaching lahar hazards MORA has a “very high” threat and ranks as the third most hazardous volcano in the nation (Ewert et al., 2008).

Debris flows initiated during intra-eruptive periods at MORA are generally much smaller in magnitude and impact than the large lahars that have occurred during eruptive periods (Pierson and Scott, 1985; Vallance and Scott, 1997; Vallance, 2005). This species of debris flow is initiated when surges of water recruit additional sediment and transform into slurries of coarse sediment (Scott et al., 1995). These surges originate from within a glacier, referred to as glacial outburst floods, or during periods of intense and prolonged precipitation. Debris flows of this type attenuate rapidly and the deposits are often reworked by subsequent event runoff, leaving them nearly identical to overbank flood deposits. Sometimes, these debris flows often go unnoticed in remote reaches of the park. Understanding the initiation

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characteristics and thus cataloging all events at MORA is one of the prime motivating factors in the development of the real-time detection efforts described in this paper.

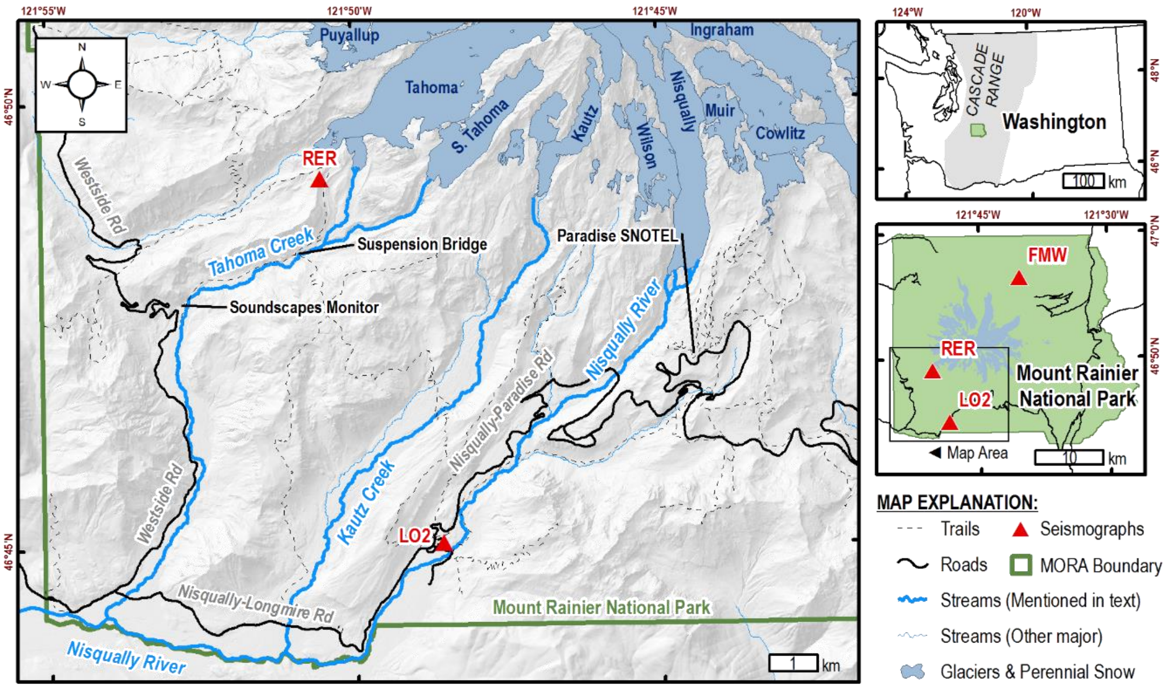

Fig. 1. Location map of the southwest side of Mount Rainier National Park in Washington State, USA. RER, LO2 and FMW refer to the Emerald Ridge, Longmire, and Mt. Fremont seismographs, respectively. Locations listed in text are shown on the detail map.

The glaciers in MORA are one of the strongest controlling influences on the park landscape. MORA has 29 named glaciers which cover a total of 78.76 ±1.11 km^2 (30.41 ±0.43 mi^2), and encompass a total volume of 3.22 ±0.31 km^3 (0.77 ±0.07 mi^3) as of 2015 (Beason, 2017; George and Beason, 2017). Studies show that the glacial ice on MORA has decreased in area by 39.1% from 1896 to 2015 (0.44 $km^2 \cdot yr^{-1}$ avg.), and in volume by 45% from 1896 to 2015 (0.02 $km^3 \cdot yr^{-1}$) (Driedger and Kennard, 1986; George and Beason, 2017). Glacial recession contributes to increases in glacial melt runoff and, through mechanisms not yet understood, subglacial water storage, both of which have been observed to cause glacial outburst floods and many of the debris flows recorded in the park. As such, quantifying changes in these glaciers and the impacts of newly uncovered glacial sediment stockpiles must be considered if we are to understand the hazards discussed here.

2. Brief history of debris flows at Mount Rainier

The first recorded debris flow in the park occurred in the Nisqually watershed on October 16, 1926. This event was initiated by the first heavy rain at the end of the summer season (Richardson, 1968). Prior to the event it was noted that there was 33 cm (13 in) of snow at Paradise on October 13, all of which had melted by October 16. After this melt, a warm rain event brought in 9.9 cm (3.9 in) of rain on the day of the 16th. Between 1932 and 1976, at least six outburst floods or debris flows occurred in the Nisqually River, originating from the Nisqually Glacier. Most of these events were induced by precipitation, which varied from 6-25 cm (2.4-9.9 in). Four of the events occurred in October and two occurred in June and July. On October 14, 1932, visiting engineers from the Bureau of Public Lands witnessed a precipitation-induced debris flow, described as “a wall of water 25 ft high and 125 ft wide” and “similar to a huge mixture of concrete except darker in color” (Richardson, 1968). The force of this event moved the entire old Nisqually Glacier Bridge over 0.8 km (0.5 mi) downstream from its original location. Some of the debris-flow events were well witnessed, including the October 25, 1955 and July 3, 1976 events (Samora and Malver, 1996; Richardson, 1968). An event in 1955 had six pulses in 45 minutes, had an estimated velocity of 6.1 $m \cdot s^{-1}$ and a discharge of 2000 $m^3 \cdot s^{-1}$, and was estimated to be 70% sediment by volume (Richardson, 1968). This event also lead to the construction of the current tall Nisqually Glacier Bridge that exists to this day.

There are an additional five events cataloged on the Nisqually during the park's history which behave similarly to the events listed, but were much smaller and had negligible impacts on park infrastructure. These five data points contain three glacial outbursts and two "other hydrologic events." Two of the outburst floods are wet events that were preceded by notably intense rainfall in a short period beforehand, with the other being a dry event that took place in July. Of these, only the dry event was noted to have multiple surges. The "other hydrologic events" were noted for increases in stream stage, but not significant enough to cause any lasting damage to infrastructure or mobilize mass wasting events. The most recent event recorded in the Nisqually River was a precipitation initiated outburst flood on October 27, 2012 (Beason, 2012), which caused a 1 m (3 ft) increase in river stage at Longmire, approximately 7.9 km (4.9 mi) downstream of the glacier.

2.1. 1947 Kautz Mudflow

The largest recorded debris-flow event in the history of MORA is the 1947 Kautz Mudflow, which had an estimated volume of 3.8x10^7 m^3. In the 24 hours prior to the event, 15 cm (5.9 in) of heavy rain and high freezing levels were seen in the Kautz watershed (Driedger and Fountain, 1989). These conditions resulted in the collapse of the lower 1.6 km (1 mi) of the Kautz Glacier and a rapid release of water stored within the glacier (Scott et al., 1995). The surge of water entrained glacial outwash material transforming into a clay-poor debris flow. Placement of the Kautz mudflow deposits occurred over several days and included multiple pulses of water. Debris flows were noted in other drainages during this event, including the Nisqually River.

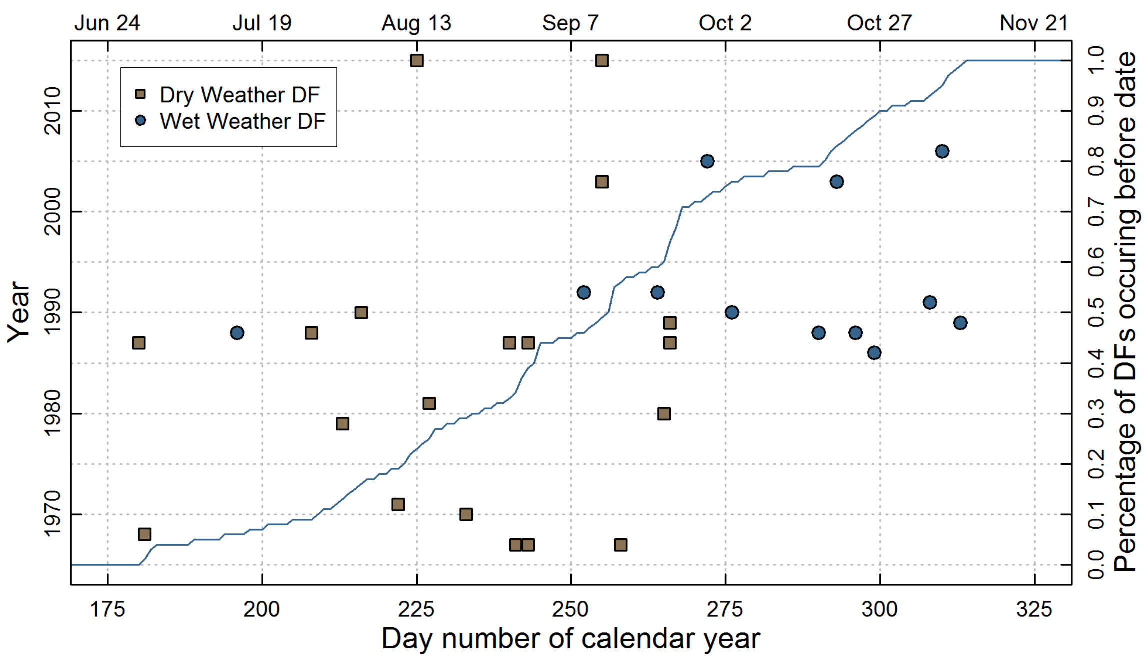

Fig. 2. Seasonal timing of debris flows in Tahoma Creek from 1967 to 2015. Dry weather flows refer to those not induced by heavy precipitation.

2.2. South Tahoma Glacier activity

Recent debris-flow activity began in the Tahoma Creek valley during the summer of 1967. The summer of 1967 was noted as exceptionally warm and dry. On August 29, a short-lived outburst flood destroyed a footbridge 1.9 km (1.2 mi) below the South Tahoma Glacier. The stream rose about 0.5 m (1.5 ft) at the Tahoma Creek Campground, ~5.6 km (3.5 mi) downstream of the glacier. Two days later an outburst flood roared down Tahoma Creek (Richardson, 1968). Fortunately, the campground was already closed due to fire danger.

Between 1967 and 2015, at least 31 distinct events have occurred (Fig. 2). Walder and Driedger (1994a) note that the record for debris flows in Tahoma Creek does have some gaps, specifically between 1967 and 1985. This is due to poor record-keeping during this time. Crandell (1971) notes that "Floods not associated with rainfall also moved down the [Tahoma Creek] valley from time to time during the summer of 1968." Walder and Driedger (1994a) note that debris flows from the years of 1971 to 1985 are described "only sketchily" in park records. Debris flows that occurred between 1986 and 1992 are well documented, largely owing to increased awareness among NPS staff (Walder and Driedger, 1994a).

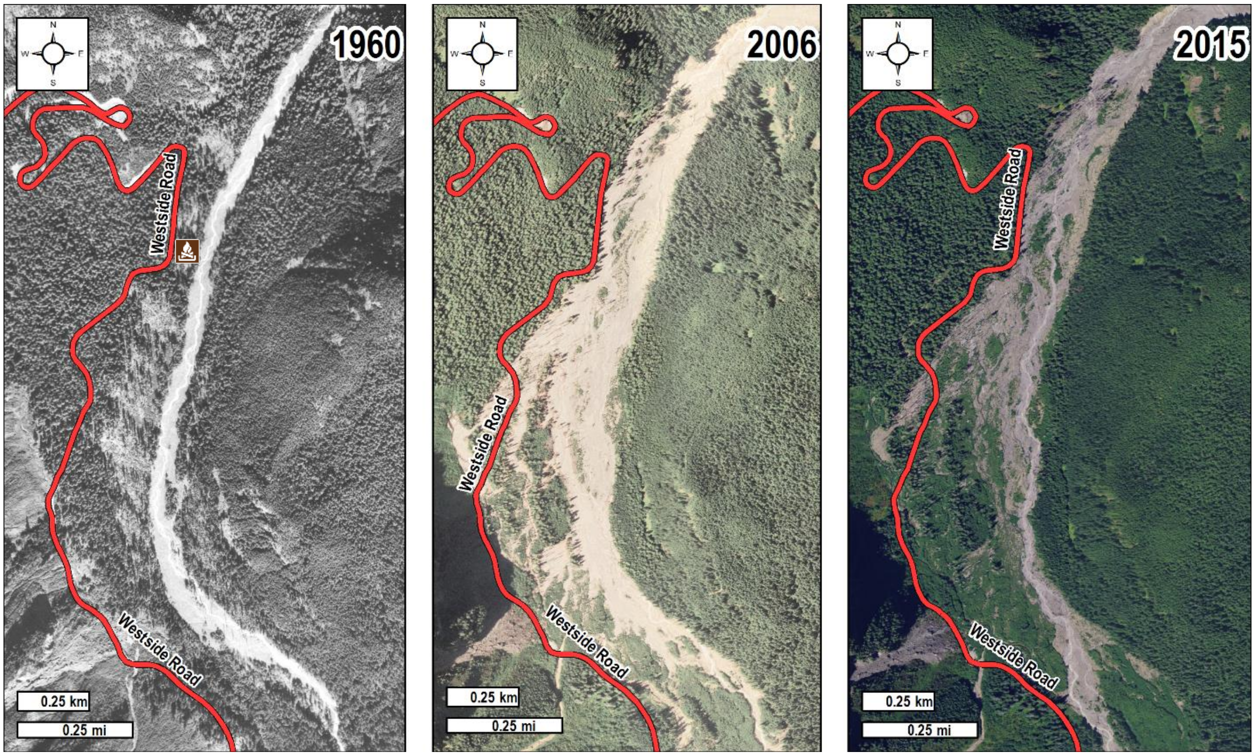

Fig. 3. Aerial photos from 1960, 2006, and 2015 showing the westward lateral migration of Tahoma Creek along the West Side Road due to debris-flow activity. Brown campfire sign in 1960 image indicates approximate position of former Tahoma Creek Campground.

The cumulative impact of over 30 debris flows in less than half a century and a major flood event in 2006 (Bullock et al., 2007) has been remarkable to the built infrastructure in the Tahoma Creek valley. The 24 km (15 mi) West Side Road was closed to vehicular traffic at mile post 3 in 1988. The sudden increase in debris-flow deposition forced the westward lateral migration and avulsion of Tahoma Creek, completely decimating an old-growth forest in the process (Fig. 3). Portions of the West Side road in Fig. 3 have had to be repaired numerous times due to the combined effects of debris flows and seasonal floods. The reduction in vehicular traffic and thus foot traffic on the West Side Road lead to a rapid and dramatic decrease to the recreational use of the trails and campgrounds on this side of the park since the late 1980s.

3. Debris flows in 2015 – Direct Observations and Monitoring Results

After a lull in debris-flow activity in the Tahoma Creek basin between 2006 and 2015, four separate debris-flow sequences occurred between 09:49 AM - 12:44 PM PDT (16:49 - 19:44 UTC) on 13 August 2015 (dry season). Each individual sequence was identified in seismic records from the Emerald Ridge (RER) seismograph, located near Tahoma Creek (Fig. 4; location in Fig. 1). This event is the best documented debris flow in the park's history. Seismic monitors, a soundscape monitor, and stream gages downstream all recorded data relevant to each debris-flow surge, while numerous park visitors, volunteers and employees all witnessed and photographed the event. Several visitors, including a geology professor at Pacific Lutheran University, recorded photos and videos of individual flows. A park volunteer in the upper Tahoma Creek basin accurately recorded and documented hyperconcentrated flow surges after the four debris flows (not recorded on the seismograph); recording a total of 12 individual hyperconcentrated flows.

The first debris flow issued by the South Tahoma Glacier was witnessed by visitor Croil Anderson. Anderson described the event as being "louder than a jet" at a distance of 2.5 km (1.5 mi) from the glacier (Anderson, personal communication, 2015). Anderson also stated that the first debris flow was an "incredibly large surge of black water, ice and rock" from the terminus. Claire Todd, a geology professor from Pacific Lutheran University, was on the Tahoma Creek suspension bridge as the DF 2a and 2b moved down the watershed (Fig. 4). When arriving at the bridge she noted "a very high water/mud mark on wall of channel" quickly followed by a "loud roar and terrific ground shaking" (Todd, personal communication, 2015). Continuing to observe the scene she noted "a ~1.5 m boulder is exposed in the channel" as the flow passes, and within another minute "roar and shaking resumes, a second flow passes, just as thick as the first -completely obscuring the large boulder again." Professor Todd witnessed the wave pass "exposing all of the large boulder again." Lastly she recorded "a thin flow of hyperconcentrated water is passing… and a view upstream shows another low wave of hyperconcentrated flow approaching," noting that "these minor flows are not producing the roar or shaking that the first two offered."

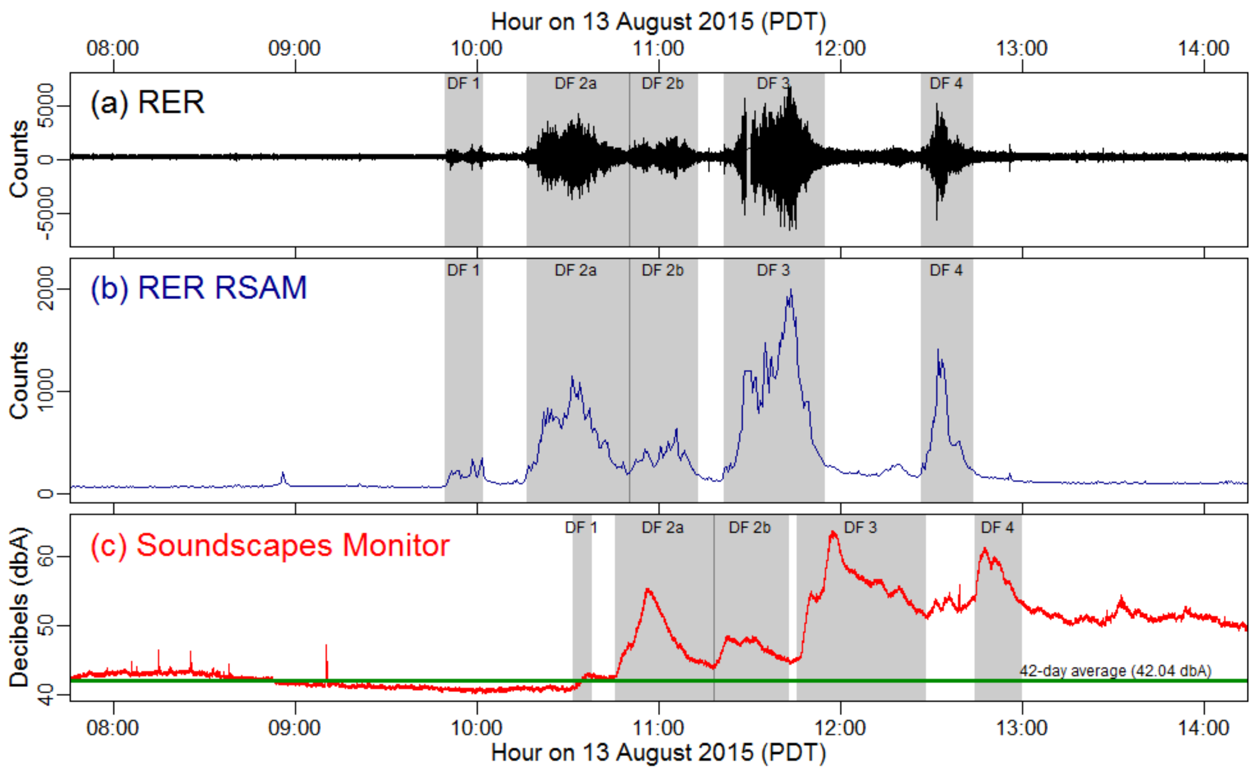

Fig. 4. Comparison of waveforms from (a) Emerald Ridge seismograph (RER), (b) Real-time Seismic Amplitude Measurement of the Emerald Ridge Seismograph (RER RSAM), and (c) Tahoma Creek Soundscape Monitor during the 13 August 2015 debris flow sequence. RER and RER RSAM are computed at the same geographic location, whereas the soundscapes monitor was approximately 3.7 km (2.3 mi) downstream, which accounts for the lag in arrival times for that instrument. The green line in plot (c) is the 42-day background average of 42.04 dbA.

The Emerald Ridge seismograph (RER, Fig. 1) is located approximately 1 km (0.6 mi) from Tahoma Creek and accurately recorded the passage of each debris-flow surge. Using the seismic data as an input, after the event, we calculated the USGS Real-time Seismic Amplitude Measurement (RSAM) signature (Fig. 4) (Endo and Murry, 1991). RSAM summarizes seismic activity for characterizing a volcano's changing seismicity in real time. We use it to downsample the seismic signal to an average amplitude over a set time, in this case, 30 seconds. The combination of the seismic data and RSAM calculations (Fig. 4 (b)) show the passage of each debris-flow surge clearly.

One of the most interesting findings from the August 13 debris-flow sequence is the analysis of the soundscapes data in Fig. 4 (c). The soundscapes monitor is a research effort by the National Park Service to understand the natural and unique soundscape of the park (NPS, 2018). Equipment emplaced along Tahoma Creek in 2015 fortuitously recorded the background noise on the months prior to and day of the debris flow. The monitor recorded an anomalous decrease in river noise from the background level approximately 1.5 hours before the arrival of the first debris-flow surge. Each successive surge was recorded and the river was relatively louder after the last debris-flow surge. This coincides with visual observations that the river was flowing much more vigorously after the event than before.

Park staff became aware of the debris-flow event at 12:02 PM when park volunteer Yonit Yogev called the MORA dispatch center on the radio reporting an outburst flood at Tahoma Creek trailhead. Yogev described the event as "telltale sounds of a rumbling train, a huge amount/sounds of trees, and a huge amount of water coming over the road out of the creek bed" (Yogev, personal communication, 2015; NPS Dispatch Records). A park visitor, Zachary Jones, videoed the passing debris-flow surge (DF 3 in Fig. 4) with his cellphone which provided visual evidence of the flow.

Based on all observations and data observed from this event, we postulate that this event began as a physical blockage in the normal discharge of the glacier, perhaps as either a collapse of ice within the glacier or a small landslide just downstream of the glacier. This is evidenced by the anomalous and steady decrease in river noise from the soundscapes monitor just before 09:00 AM, showing that the total input to the river had dropped below the normal background level.

4. Debris-flow hazard forecasting

The impetus for generating the debris-flow hazard forecast is to avoid having park staff and visitors in debris-flow-prone areas when likely events could occur – like those conditions seen on 13 August 2015. The debris-flow hazard forecasting approach at MORA is based on two separate models combined, which have different variables for dry, warm weather debris flows and cool, wet weather debris flows. The full model is shown in Appendix A.

4.1. Cool, wet weather debris flows

In recent decades, warm rain storms occurring with low snowpack have been anecdotally associated with debris flows on MORA. These storm and debris-flow events typically occur in late fall, when "Atmospheric River" storms bring intense tropical moisture from mid-latitudes and drop voluminous rain high on the volcanic flanks (Neiman et al., 2008). Prior to this study there had been no systematic characterization of debris flow occurrence with respect to meteorological and antecedent hydrologic conditions. In practice, such a characterization could be paired with weather forecasts and in-situ monitoring to classify current debris-flow hazards. This specific phase of our study focused on characterization of past storms and their associated debris-flow potential.

Past debris-flow events were compiled from multiple sources and included in our analysis if the debris flow's timing was known within a day, was associated with measurable precipitation, and occurred within the monitoring record of the snow telemetry (SNOTEL) station at Paradise (NRCS Site 679, elevation 1,640 m) on the southern flank of MORA. Debris-flow sources include Walder and Driedger (1994a), Walder and Driedger (1994b), Walder and Driedger (1995), Driedger and Fountain (1989), and Copeland (2009). This SNOTEL station lies at the lower elevation range of mapped drainage networks and gullies identified as having high potential for debris-flow initiation using slope-drainage area thresholds (Legg et al., 2014). This station broadly characterizes precipitation, temperature, and antecedent snowpack in the elevation band of potential debris-flow generation on MORA's flanks. For each debris-flow event, precipitation, temperature, and snowpack measurements were compiled for 1-, 3-, and 15-day periods on and prior to the day of the debris flow. These metrics were also compiled for all monthly maximum precipitation events for the full SNOTEL record to compare the known debris-flow producing storms to the broader population of storms.

This data compilation effort resulted in a total of eleven debris-flow producing storms that occurred between 1979 and 2014. All eleven storms had daily average temperatures above freezing, and all but two events had daily average temperatures above 40° Fahrenheit. Based on a typical vertical lapse rate of 5.5°C/1,000 m, a temperature of 40°F at the SNOWTEL station indicates temperatures above freezing for the full elevation band of high hazard gullies, suggesting rainfall and potential surficial runoff generation in the zone of likely debris flow initiation. All debris-flow producing storms also had limited antecedent snowpack, suggesting antecedent snowpack inhibits debris-flow generation by limiting runoff and/or stabilizing surficial colluvium. Additionally, there were negligible reductions in snowpack in the 3 days leading up to the eleven debris-flow events, suggesting snowmelt-derived runoff as an unlikely ingredient for debris-flow generation.

Precipitation quantities were further compared to an intensity-duration threshold for the nearby Seattle, Washington area developed by Chleborad et al. (2006), which is based on 3-day and 15-day cumulative precipitation totals in inches. Initial comparisons to this landslide threshold found that eight of the eleven known debris flow producing storms exceeded the Seattle threshold; however, 247 of 376 monthly maximum storms (without known debris flows) from 1979-2014 also plotted above the threshold. These results suggest landslide threshold alone is a poor predictor of debris flow potential on MORA. To explore potential refinements to the model, we then removed monthly maximum storms with greater than 5” SWE and/or 3-day average temperatures less than freezing. In the remaining group, 33 monthly maximum (non-debris flow producing) storms exceeded the Seattle threshold, in addition to the 8 debris flow-producing storms. These numbers indicate ~20% (8 of 41) of these storms (with above-freezing temperatures and low snowpacks, while exceeding Seattle threshold) generated debris flows. A similar calculation utilized a temperature threshold of 40°F instead of 32° and revealed that 5 of 14 storms (36%) storms exceeding the Seattle threshold produced debris flows. The increased proportion of debris flow producing storms indicate warm temperatures (i.e. high freezing levels) are indeed a requirement for debris flow generation. Overall, these results highlight the need for temperature and snowpack information to be coupled with landslide thresholds in order to increase predictive capability of our wet debris flow model.

The above analysis informed development of a simple decision tree approach to hazard classification as a planning tool for MORA (Legg, 2015). The approach uses 3-day precipitation and temperature forecasts in concert with measurements of SWE and 15-day precipitation totals to classify and forecast debris flow hazards into low, medium and high hazard categories over a coming 3-day period. More broadly, this effort represents an example of hazard forecasting in an alpine setting where seasonal temperature and snow fluctuations are major drivers of debris-flow potential.

4.2. Dry, warm weather debris flows

The method for forecasting dry weather debris flows is an expansion of Legg’s (2015) model. A total of 35 debris-flow events which occurred in a dry season (i.e., no rain and relatively warm temperatures [average high temperature of ~65°F]) were compiled from the various sources mentioned in Section 4.1. From that list, antecedent weather information for the day of event and the days leading up to the event itself were calculated from the Paradise SNOTEL station and other weather sources in the vicinity. A Monte Carlo analysis was completed on each weather variable to determine its relative importance to the overall detection of a debris flow. Once the relative weighting of each variable was completed, all days in the historic record were run to determine the debris flow hazard scores on those days (this includes the wet weather debris flows) (Table 1).

Table 1. Performance of current debris-flow hazard model based on all available weather data for the period of 1917-2017 at the Paradise SNOTEL station. Event type categories are split out on known debris flow and outburst flood days from the historic record. The undefined category means that weather conditions were not available to adequately calculate the debris-flow hazard score for that day.

Event Type	Model Type	Low	Medium	Medium High	High	Very High	Undefined
Debris Flow (N = 42)	Wet:	0	0	1	12	-	0
	Dry:	3	4	6	11	5	0
	TOTAL:	3	4	7	23	5	0
Outburst Flood (N = 8)	Wet:	2	0	0	0	-	0
	Dry:	3	1	0	1	1	0
	TOTAL:	5	1	0	1	1	0
Debris Flow + Outburst Flood (N = 50)	Wet:	2	0	1	12	-	0
	Dry:	6	5	6	12	6	0
	TOTAL:	8	5	7	24	6	0
No Debris Flow or Outburst Flood (N = 31,647)	Wet:	12,633	980	539	1083	-	942
	Dry:	11,608	984	618	1001	540	719
	TOTAL:	24,241	1,964	1,157	2,084	540	1,661
	TOTAL:	**24,249**	**1,969**	**1,164**	**2,108**	**546**	**1,661**
		76.50%	**6.21%**	**3.67%**	**6.65%**	**1.72%**	**5.24%**

The specific variables of interest for the dry side of the model are: P_{18}, or 18-day precipitation total at Paradise, which is necessary to determine whether to run the dry side or wet side of the model; T_{max}, which is the maximum daily temperature observed at Paradise; $T_{max\ Percentile}$, which is the maximum temperature expressed as a percentile based on the historic maximum temperatures (1917-2017); *DS0SP*, which is “days since zero snow pack”, a relative variable used to determine when debris source areas will be snow free – for the model, this variable is assumed as days since July 11th, which is the average “melt out” date at Paradise in the historic (1917-2017) record; $DD32_{18}$, or the 18-

day cumulative degree days above freezing; P_3, or the 3-day precipitation total, a key dry-weather variable defined by Walder and Driedger (1994a); and *SWE*, or snow water equivalent. Each variable is given a numeric score between 1 and 5 (see Appendix A) and the debris-flow hazard score is calculated by the model when it is run.

At this time, the method is still being refined as more data is uncovered about the antecedent weather conditions and as more debris flows occur in the park. Additionally, an improved Monte Carlo approach is being undertaken to improve the model. The performance of the model for all available dates between 1917 and 2017 is shown in Table 1. In general, those days with a debris flow or outburst flood from the historic record should have a higher score, whereas those days with no event should have a lower score for the model to be considered truly calibrated successfully.

4.3. Combination forecast and data sources

The combination forecast (Appendix A) utilizes both the wet and dry sides into a simple decision tree based on calculated weather factors. Weather information is downloaded every hour from the DarkSky.net API. DarkSky provides a free ensemble forecast for individual locations throughout the park that is easily incorporated into the debris-flow hazard model. Every four hours, these weather variables and antecedent weather observations are automatically compiled based on the wet or dry forecast and then run through the decision tree algorithm (Appendix A). A qualitative score (Low, Medium, Medium High, High, or Very High) is generated for the day of interest and next seven days. This is then reported on a website for monitoring and decision-based analysis by park staff. Hazard scores are tied to weather forecasts and will change as forecasts are updated. While this process is automated, park staff still must monitor the model every day to determine the future relative risk for debris flow activity.

5. Real-time debris flow monitoring

The final piece in the debris-flow hazard system at MORA is the ability to detect debris flows as they occur. As shown in Section 3, debris flows like those in 2015 have a seismic and RSAM signature that is distinctive. With assistance from the University of Washington's Pacific Northwest Seismic Network (UW PNSN), seismic data is run through the USGS RSAM program and binned into 30 second values. At five-minute intervals, an automated computer script then downloads the RSAM values and runs through the data file looking for a "debris-flow-like signature." A debris flow signature is defined as an increasing signal above a set point over a set amount of time. If these values are exceeded, an alert is sent out to park staff for analysis and hazard notification via cellphone text messages and emails.

As an example, at the Emerald Ridge (RER) seismograph, the relevant variables are an RSAM value greater than 500 counts for over 5 minutes with a RSAM value that is increasing (slope > 0.030), on average, over those 5 minutes. Using this definition, three of the four debris flows on 13 August 2015 (2a/2b, 3 and 4) and an additional debris flow that occurred in Tahoma Creek on 12 September 2015 (not discussed in this paper) would have been detected with this system. Additionally, this system would have detected the second debris flow on August 13th at roughly 10:20 am, almost a full two hours before park staff were alerted to the event on the radio.

Real-time debris-flow monitoring via the RSAM system is currently being run on the Emerald Ridge (RER) seismograph (Puyallup, Tahoma and South Tahoma Glaciers), Mt. Fremont (FMW) seismograph (Emmons, Inter, and Winthrop Glaciers), and Longmire (LO2) seismograph (Kautz, Nisqually, Pyramid, Success, Van Trump, and Wilson Glaciers). Most of the major glacial streams at MORA now have some sort of seismic monitoring; those without, with the exception of the Carbon Glacier, do not have extensive infrastructure development in their watershed boundaries.

The overall performance value of the RSAM system in detection of debris flows is not yet available since the park has yet to experience a confirmed debris flow since the system's inception. There have been several false positive readings, almost exclusively due to wind noise (especially at RER). Local, regional, and teleseism earthquake events are such short period and punctuated that they are excluded in the analysis and rarely generate alerts. When false positives have been detected, staff is able to quickly analyze real-time seismic data to determine if the event is truly a debris flow or some other event. In this sense, the system is semi-automated and still requires human intervention in order to take the step from an alert generation to an alert being broadcast to the field. Lastly, we are not yet able to co-locate exact drainages where a debris flow due to a paucity of seismic stations. However, a strong signal in one seismograph and relatively weak signals in others (as was the case in the August 2015 event) can help determine a narrower geographic location of the event. Future seismic implementation at MORA is being planned in the next five years which will help the co-location ability of this system.

6. Conclusions

Mount Rainier is an environment that is ideally suited for debris-flow genesis and has a rich history of these events. With our work, we have been successful in providing a forecast for debris-flow hazard based on past antecedent weather conditions on prior debris-flow days up to seven days in advance. We then can detect individual debris flows using in situ seismometers and the RSAM system. As glaciers continue to retreat, new sediment sources will be exposed to annual storms and occasional outburst floods – all of which will continue the threat of debris flows to downstream areas. The forecasting and detection systems we have in place now are in their infancy and will be further refined as more events occur. Additional seismic installations planned in the next decade at MORA will only improve these systems and will provide better warning to park staff and visitors working and recreating at the park.

Acknowledgements

This work is greatly indebted to the following individuals for their observations, photos, videos, and assistance during and after the 2015 debris flows, including, but not limited to: Anthony "Scott" Anderson, Croil Anderson, Jenni Chan, Carolyn Driedger, Maxine Dunkleman, Terry Flower, Jeff Gardner, Sara Hall, Mitch Haynes, Steve Hughes, Zachary Jones, Dave Keltner, Paul Kennard, Glenn Kessler, Rebecca Lofgren, Steve Malone, Kendra Martinez, Seth Moran, Dave Morgan, Casey Overturf, Heather Rogers, Heather Sharp, Kurt Spicer, Trisha Stanfield, Karen Thompson, Claire Todd, Dave Turner, and Yonit Yogev. Finally, thank you to Kate Allstadt and Abigail Michel who provided critical review to this manuscript prior to submission.

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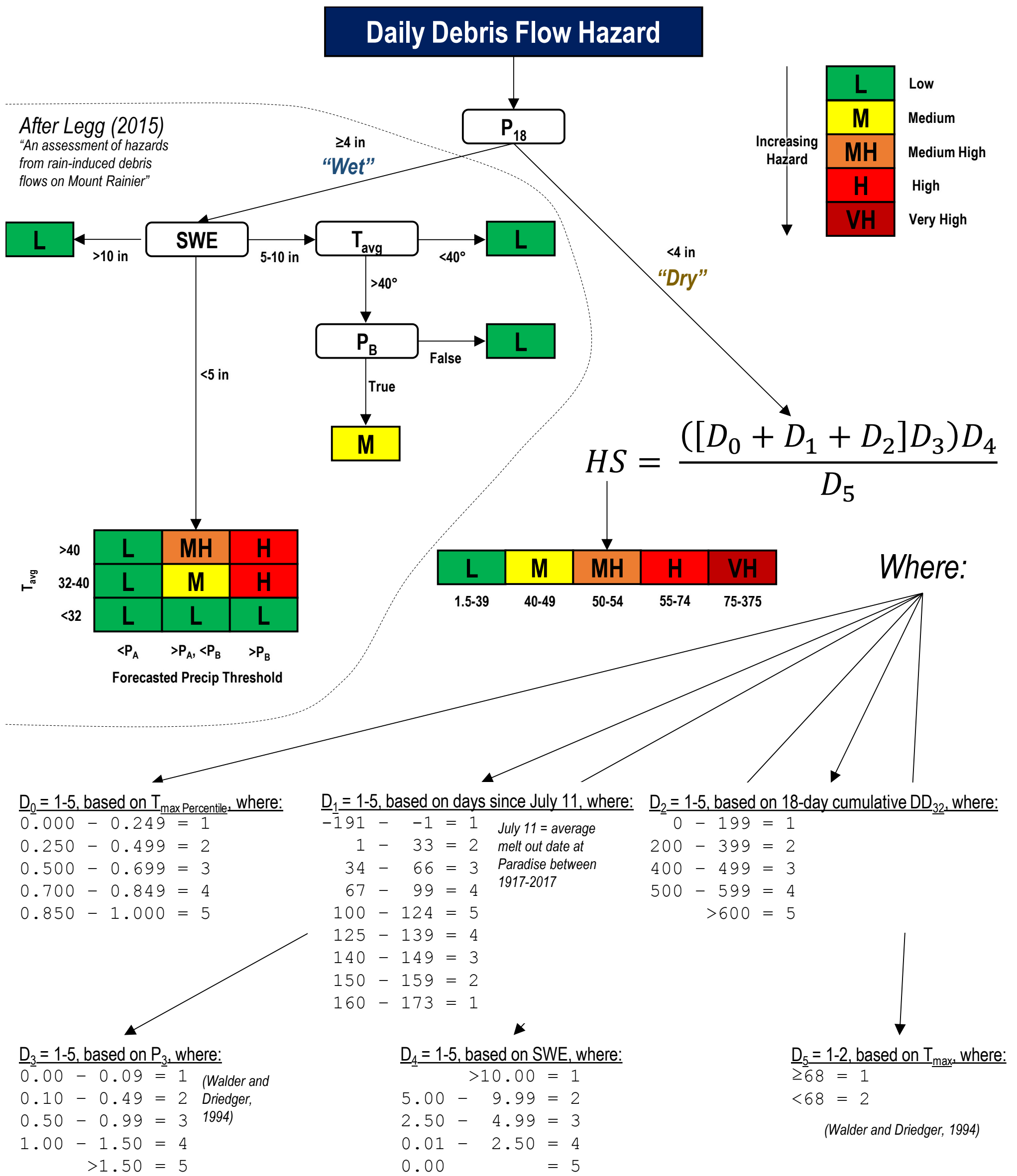
Appendix A. Debris flow hazard forecast model at Mount Rainier



Variables:

DD_{32} = Degree day above 32°F (dimensionless)
P_A = Precipitation threshold A, $P_3 = 2.5 – 0.67P_{15}$
P_B = Precipitation threshold B, $P_3 = 4.5 – 0.67P_{15}$
P_3 = 3-day (D1-D3) cumulative precipitation at Paradise (in)
P_{15} = 15-day cumulative precipitation at Paradise prior to 3-day period (D4-D18) (in)
P_{18} = 18-day cumulative precipitation at Paradise (in)
SWE = Snow water equivalent at Paradise (in)
T_{avg} = Average temperature at Paradise (°F)
T_{max} = Maximum temperature at Paradise (°F)
$T_{max\ Percentile}$ = Maximum temperature as a percentile compared to the historic temperature (1917-2017), (dimensionless)