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

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I. 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 13 August 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 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.

II. Location & Background

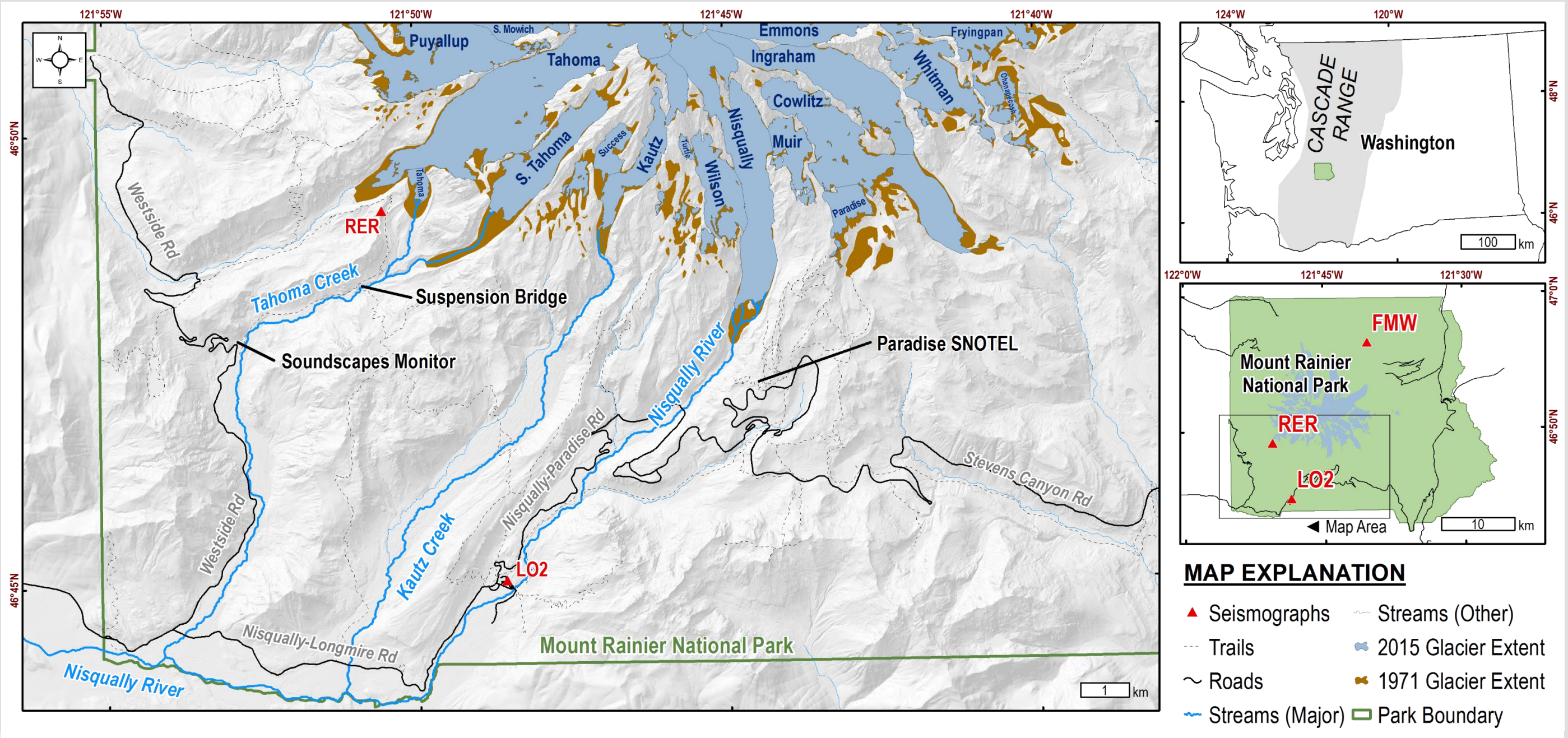

Fig. 1. Location map on the southwest side of Mount Rainier National Park. RER, LO2, and FMW refer to the Emerald Ridge, Longmire and Mt. Fremont Seismographs, respectively. Glacier change between 1971-2015 is shown.

- Mount Rainier is a 4,392 m active stratovolcano located in SW Washington State, USA. It lies 70 km and 90 km from Tacoma and Seattle, respectively (Fig. 1). The mountain can be seen from most of the state and occupies the entire 956 km^2 of Mount Rainier National Park (MORA).
- Volcanic hazards sourced from Mount Rainier are an issue of concern for much of the surrounding lowland areas. These include potential eruptive episodes, co-eruptive lahars capable of travelling up to 100 km, small debris flows localized to watersheds in MORA, and glacial outburst floods.
- Our monitoring focuses on the local debris flows and glacial outbursts. These events have the greatest frequency of the listed hazards and are the most likely to impact the park and visitors.
- The two main factors to prime the landscape for these events are the trends of enhanced glacial melt and subsequent exposure of glacial sediment stockpiles. Increases in glacial melt discharge increase potential for subglacial meltwater storage which can be released as an outburst flood, and the uncovering of glacial sediments makes available excellent materials for the mobilization of debris flows at glacier termini.
- Events on this scale led to the destruction and reconstruction of the Nisqually Glacier Bridge, the Kautz Mudflow of 1947 eradicated part of the Nisqually-Paradise Highway while completely filling the watershed, and Tahoma Creek witnessed over 31 debris flows in 48 years culminating in one of the greatest losses of natural resources and infrastructure yet catalogued in MORA.
- "Dry" events are preceded by less than four inches of rain in the last 18 days and correlate mainly to the June-September months, while "wet" debris flows dominate the remainder of the year.
- Evidence of small debris flows is often destroyed during the event making identification difficult, leading us to conclude that many have gone undocumented. Understanding the initiation trends and cataloging all such events is a major motivation for this study.

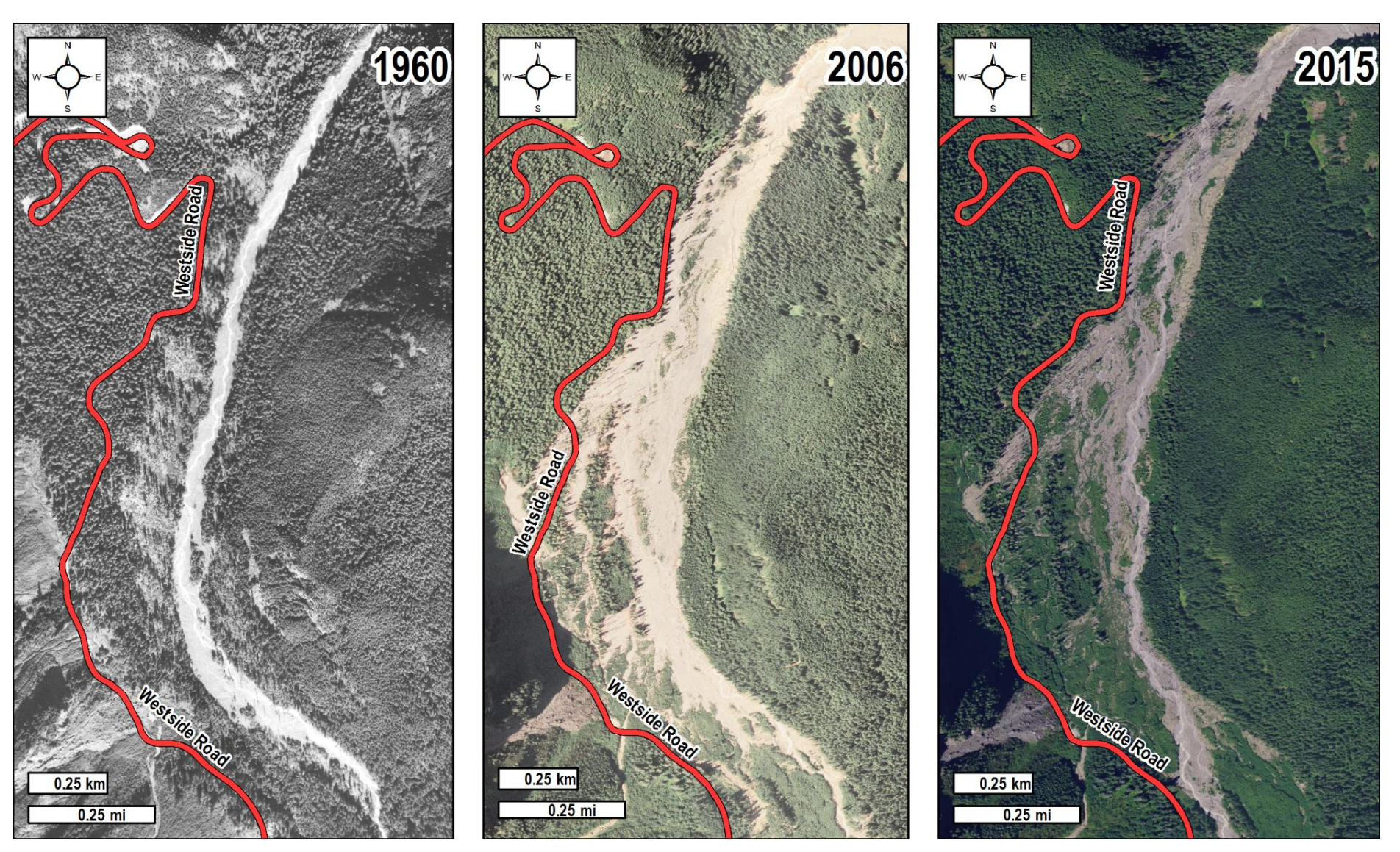

Fig. 2. Aerial photos showing the westward migration of Tahoma Creek along the West Side Road due to 31+ debris flows from 1967-2015.

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III. 13 August 2015 Debris Flows

- After a nine year lull in activity, on 13 August 2015, four separate debris flows occurred between 09:49 – 12:44 PDT (16:49 – 19:44 GMT).
- This event is the best documented debris flow in the park's history, recorded by:
  - Seismographs (RER),
  - Acoustic soundscape monitor,
  - Stream gauges (inside & outside park),
  - Park visitors, staff and volunteers.
- Aerial reconnaissance identified the source at the glacier terminus (Fig. 3).
- The event was first reported at 12:02 PDT (19:02 GMT) by park volunteer Yonit Yogev and a park visitor videoed DF #3.

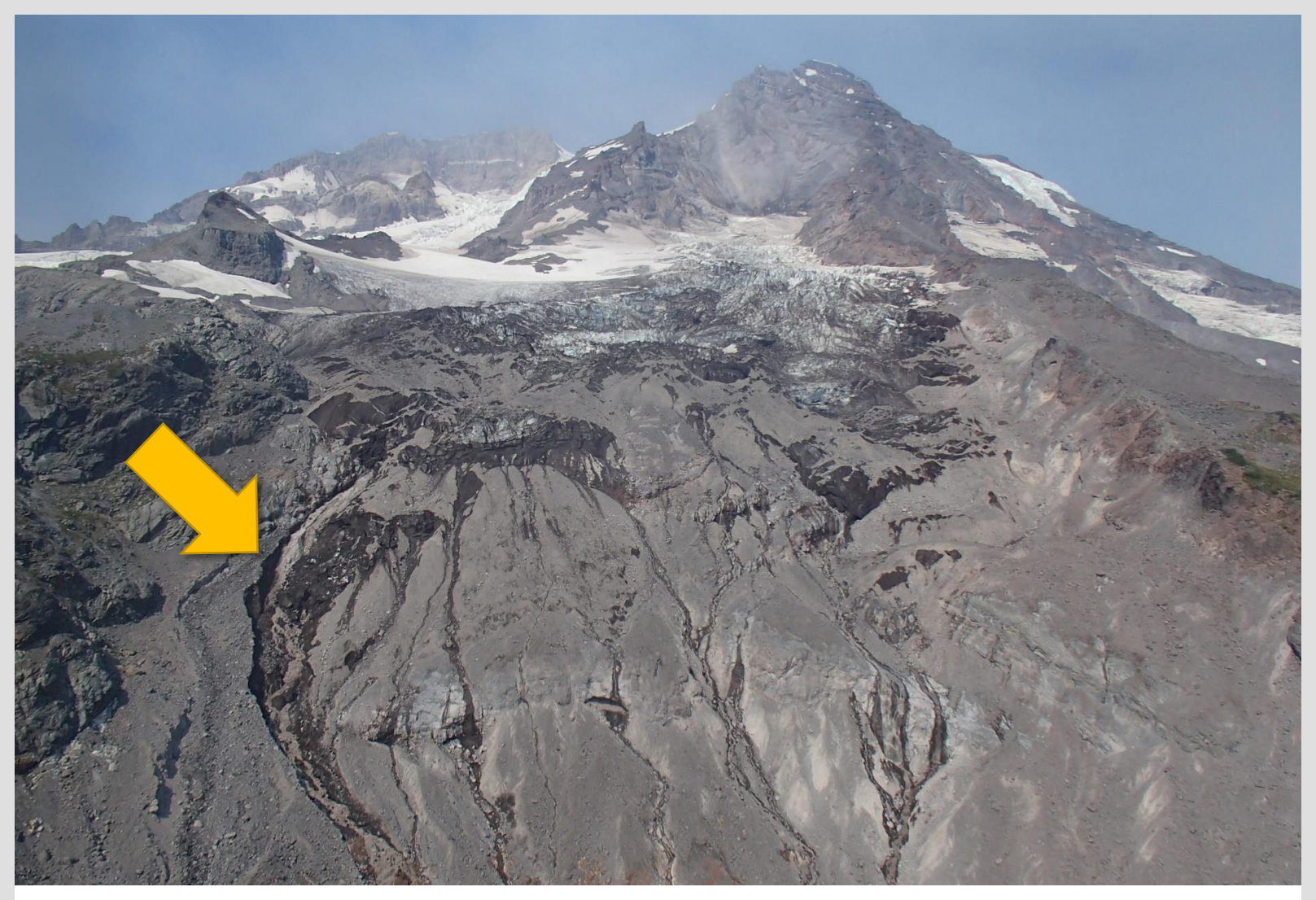


Fig. 3. Source area of the 13 August 2015 debris flows at the terminus of the South Tahoma Glacier. Orange arrow points to the initiation point at the debris-covered terminus.

- Acoustic soundscapes data (Fig. 4) recorded an unusual decrease in river noise before the first debris flow, which we postulate represented a physical blockage either downstream of or within the glacier, evidenced by the anomalous and steady decrease in river noise before 9:00 PDT (16:00 GMT).
- We postulate that the debris flows were initiated by this obstruction, as discharge finally overcame the blockages, then mobilized loose debris and bulked up as they moved downstream.
- **This event became the driving force for forecasting and detecting debris flows, especially because of the proximity of staff and visitors to the debris flows themselves.**

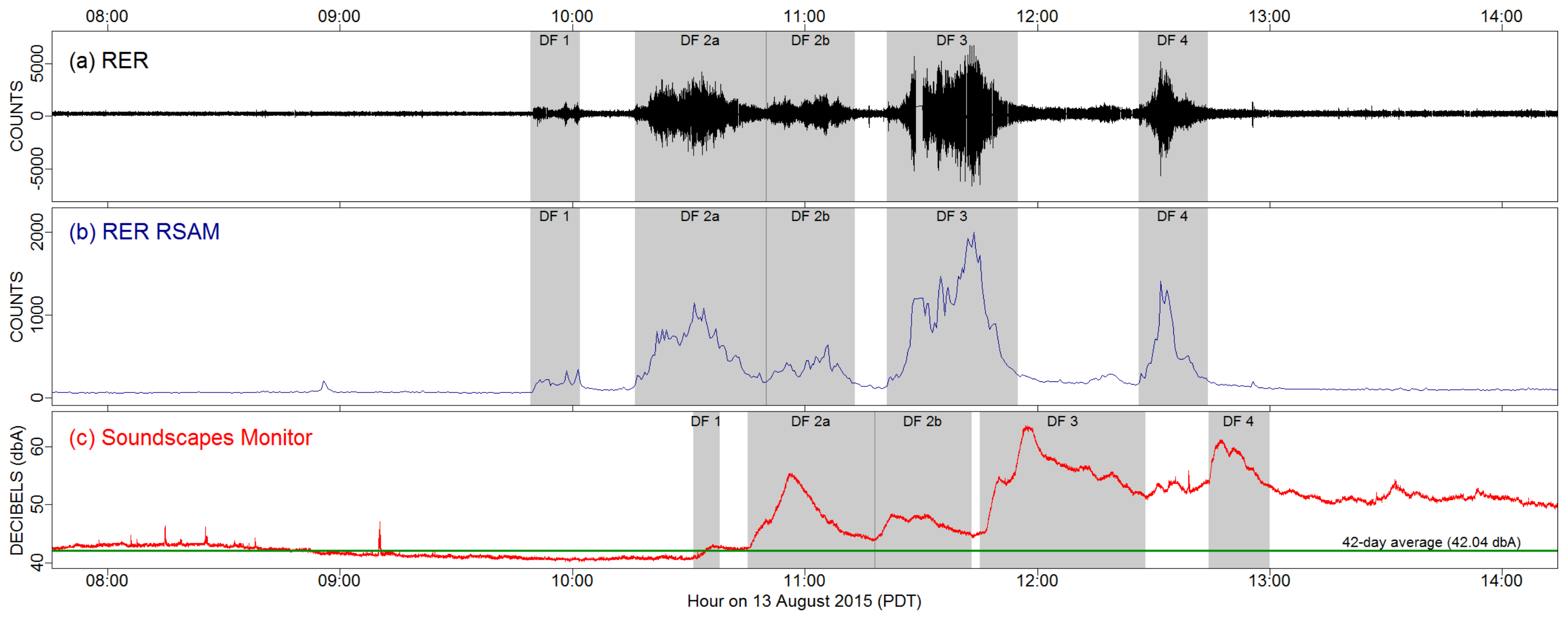
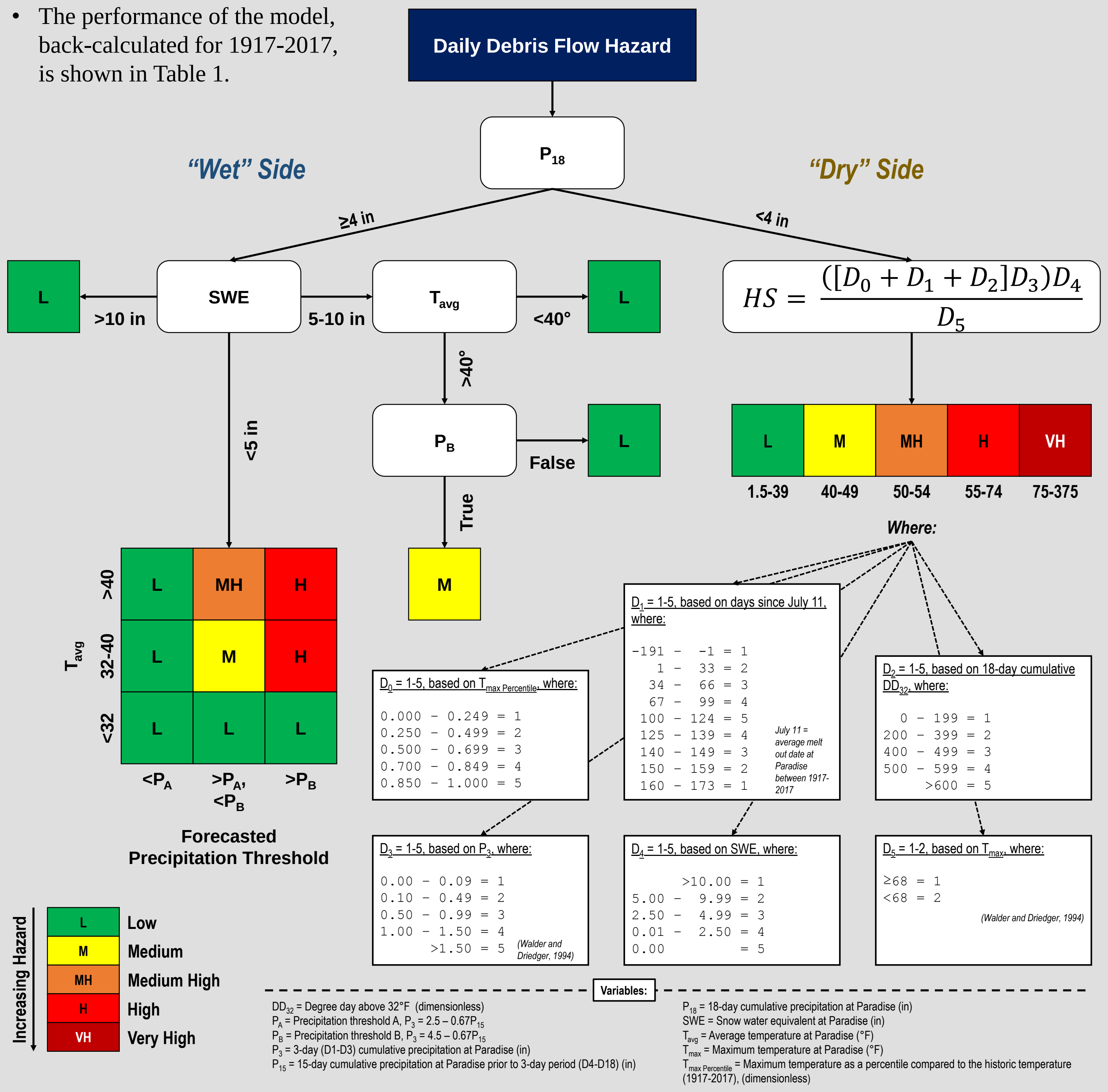


Fig. 4. Comparison of waveforms from (a) Emerald Ridge seismograph (RER), (b) Real-time Seismic Amplitude Measurement of the Emerald Ridge Seismograph (RER RSAM), and (c) Tahoma Creek Soundscape Monitor during the 13 August 2015 debris flow sequence. RER and RER RSAM are computed at the same geographic 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.

IV. Debris-Flow Forecasting

- The debris flow algorithm (shown below) addresses two seasonal populations of debris flows:
  - "Wet," rainy season events usually initiated by intense precipitation (Legg, 2015), and
  - "Dry," warm season events usually initiated by intense melt, using an equation derived from a Monte Carlo analysis of common meteorological conditions present on and leading up to debris flow days in the historic record at Mount Rainier.
- Debris flow sources primarily include: Walder and Driedger (1994a), Walder and Driedger (1994b), Walder and Driedger (1995), Driedger and Fountain (1989), and Copeland (2009).
- The model incorporates forecasted weather for the next seven days. The current data source is the hyper-local aggregated multi-source forecast from the DarkSky.net API. It is run every four hours.
- The performance of the model, back-calculated for 1917-2017, is shown in Table 1.



$$HS = \frac{([D_0 + D_1 + D_2]D_3)D_4}{D_5}$$

D_0 = 1-5, based on $T_{max\ Percentile}$, where:
0.000 – 0.249 = 1
0.250 – 0.499 = 2
0.500 – 0.699 = 3
0.700 – 0.849 = 4
0.850 – 1.000 = 5

D_1 = 1-5, based on days since July 11, where:
-191 – -1 = 1
1 – 33 = 2
34 – 66 = 3
67 – 99 = 4
100 – 124 = 5
125 – 139 = 4
140 – 149 = 3
150 – 159 = 2
160 – 173 = 1

D_2 = 1-5, based on 18-day cumulative DD_{32}, where:
0 – 199 = 1
200 – 399 = 2
400 – 499 = 3
500 – 599 = 4
>600 = 5

D_3 = 1-5, based on P_3, where:
0.00 – 0.09 = 1
0.10 – 0.49 = 2
0.50 – 0.99 = 3
1.00 – 1.50 = 4
>1.50 = 5

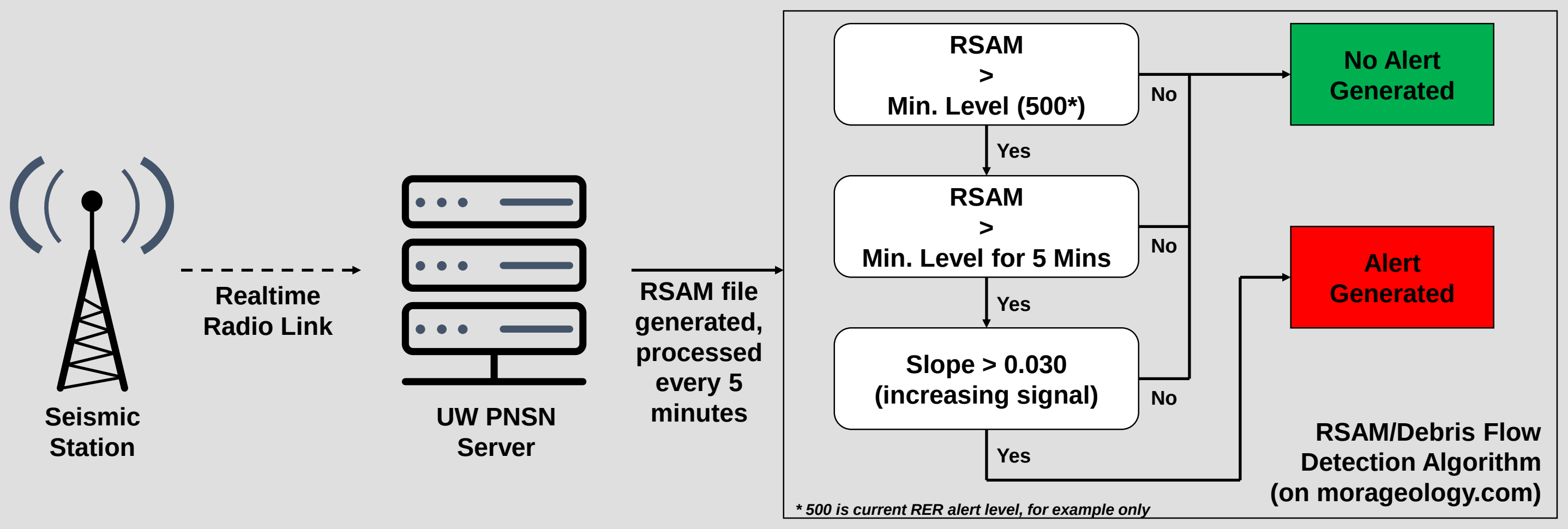
D_4 = 1-5, based on SWE, where:
>10.00 = 1
5.00 – 9.99 = 2
2.50 – 4.99 = 3
0.01 – 2.50 = 4
0.00 = 5

D_5 = 1-2, based on T_{max}, where:
≥68 = 1
<68 = 2

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)

V. Debris-Flow Detection

- Debris flows have a unique seismic signature – one that is especially distinctive when looking at the signal as run through the USGS Real-time Seismic Amplitude Measurement (RSAM) tool (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.
- 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."
- If these values are exceeded, an alert is sent out to park staff for analysis and hazard notification via cellphone text messages and emails.



* 500 is current RER alert level, for example only

- Current alert levels:
  - Emerald Ridge (RER) - RSAM count > 500, > 5 minutes, > 0.030 slope,
  - Mount Fremont (FMW) - RSAM count > 250, > 5 minutes, > 0.030 slope, and
  - Longmire (LON/LO2) - RSAM count > 75, > 5 minutes, > 0.030 slope
- Using these alert levels, 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 here) would have been detected on the Emerald Ridge (RER) seismograph with this system.
- **Importantly, this system would have detected DF #2 (Fig. 4) on August 13th at roughly 10:20 PDT (17:20 GMT), almost two full hours before park staff were alerted to the event on the radio.**
- Real-time debris-flow monitoring via the RSAM system is currently active on:
  - 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).
- Future seismic and infrasound implementation at MORA is being planned in the next five years which will help the co-location and debris flow detection ability in the park.

Table 1. Performance of current debris-flow hazard model (left) 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 indicates an inability to 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 Events (N = 31,647)	Wet:	12,633	980	539	1,083	-	942
	Dry:	11,608	984	618	1,001	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%**

VI. Conclusions

- Mount Rainier is ideally suited for debris-flow genesis and has a rich history of these events.
- Our work provides a forecast for debris-flow hazards 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 are exposed to seasonal storms and occasional outburst floods, which will continue the threat of debris flows to downstream areas.
- These systems 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 on these systems and will provide better warning to park staff and visitors in the park.

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