# An assessment of hazards from rain-induced debris flows on Mount Rainier

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# Summary

Rain-induced debris flows initiated from Mount Rainier's upper flanks can inflict major damage to downstream areas, and therefore need to be incorporated into short- and long-term management decisions. This work provides tools that allow the National Park Service to assess the hazards from debris flow initiation in space and time. Hazard mapping provides tools to assess debris flow potential spatially, and a storm characterization and simple decision tree allow forecasting of debris flow hazards in time.

Hazard mapping involved separately mapping and then overlaying debris flow initiation potential and sediment availability. Initiation potential was mapped across drainage networks of Mount Rainier using measured slope and drainage area. Slope-drainage thresholds for debris flow initiation found for the November 2006 storm were used to identify segments of the drainage network with high initiation potential. Once initiated, debris flows can incorporate large volumes of sediment on Mount Rainier's upper slopes which in turn give debris flows greater potential to travel and inflict damage far downstream. Sediment availability is therefore an important factor in debris flow hazards. Geomorphic mapping roughly characterized sediment availability on Mount Rainier's upper slopes, so that areas with high initiation potential and sediment availability could be overlaid to develop hazard maps. A simple watershed-based hazard rating identifies relative debris flow hazards by major streams and rivers in the park. Maps can therefore be used to assess hazards from the scale of individual gullies to entire watersheds.

The storm characterization involved a simple accounting of storm conditions in past debris flow storms to in turn classify debris flow hazards in future storms. Precipitation, temperature, and snowpack measurements taken from 1980-2014 the Paradise SNOTEL station were used to characterize conditions during 11 known debris flow producing storms. All storms had less than 5 inches snow water equivalent (SWE), suggesting minimal antecedent snowpack is a requirement for debris flow initiation. Measured temperatures indicated that freezing levels were at or above the elevation range of high hazard areas mapped in the first section of the report, supporting the simple idea that rain needs to fall in order to produce runoff necessary for debris flow initiation. Finally, storm precipitation and antecedent precipitation were characterized using cumulative precipitation measured over 3 and 15 day periods. These periods allow comparison of debris flow producing storms to an existing landslide threshold for Seattle, Washington (Chleborad et al., 2006). Eight of the eleven storms exceeded that threshold. The seasonality of high hazard storms (those with minimal snow, high freezing levels, and rainfall exceeding the Seattle threshold) exclusively have occurred in late summer and fall months. The resultant forecasting methodology gives park officials a tool to forecast debris flow hazards three days in advance using weather forecasts for the same time period.

# Introduction

Slurries of mud, rock, and water known as debris flows that surge down Mount Rainier's slopes concern National Park Service managers and park visitors. Debris flows can inflict major damage to park infrastructure and threaten lives of visitors and park employees. For example, Mount Rainier's upper slopes unleashed at least 10 debris flows during a single storm in November 2006. Debris flows combined with flooding to cause over $36 million in infrastructure damage, resulting in a shutdown of Mount Rainier National Park (MORA) for multiple weeks. In addition to immediate damages, debris flows deposit large quantities of sediment that can reroute and restructure stream channels in ways that can last decades. Moreover, debris flows may occur more frequently in response to retreating glaciers, diminishing snow-packs, and changing storm characteristics in a warming climate. These consequences of debris flows require that we better understand their hazards within Park boundaries. This work provides tools for MORA officials to better forecast debris flows.

In order to better understand debris flow hazards, we need to know both *where* and *when* debris flows initiate. The *where* and *when* form the two main elements of this report. Where debris flows initiate is clearly important for understanding how debris flow hazards vary spatially around Mount Rainier, and corresponding risks to park infrastructure and visitor areas. Recent work by Legg et al. (2014) provides new insight into the processes and landscape characteristics responsible for recent debris flows. I use that work to map debris flow hazards around Mount Rainier. The focus on rain-induced debris flows means that the "when" depends on the meteorological and hydrological conditions during individual storms. The second major portion of this work performs a basic accounting of hydrological and meteorological conditions in previous storms. I then propose a simple forecasting methodology that could be combined with 3-day weather forecasts to in turn classify debris flow hazards.

# Scope

This report focuses exclusively on debris flows initiated from Mount Rainier during rainstorms. These debris flows primarily mobilize sediment sitting on Mount Rainier's flanks deposited by glaciers or other surface processes. Debris flows also can start when Mount Rainier's glaciers produce outburst floods that then mobilize sediment and become debris flows (Driedger and Fountain, 1989). However, debris flows induced by outburst floods are not a focus in this report because of our limited ability to measure the triggering conditions for outburst floods. Another type of debris flows, called lahars, initiate from collapse of Mount Rainier's bedrock edifice (Scott et al., 1995). Volcanic processes cause lahars, which mobilize huge volumes of rock that travel many miles from the mountain. Lahars have not been recorded in historical times on Mount Rainier, but numerous lahar deposits have been identified in its valleys (most notably the Osceola Mudflow which traveled to the Puget Sound Lowland (Vallance and Scott, 1997)). Lahars typically involve much greater volumes of rock and sediment than the rain-induced debris flows focused on here; however, rain-induced debris flows can and have reached volumes comparable to those of lahars. The one historic example is a large debris flow that initiated from the upper Kautz River valley in 1947, which resulted from catastrophic failure of a large glacial deposit during a rain storm (Grater, 1947).

This work focuses on debris flows that originate from the un-forested, upper flanks of Mount Rainier itself. Debris flows can also originate from forested and alpine areas of other mountains within park boundaries, but these debris flows often cause little damage and go unnoticed.

# Debris Flow Hazard Mapping

Debris flow hazard maps should allow for future planning and risk assessment of Park infrastructure. The hazard maps developed here address debris flow initiation on Mount Rainier's upper flanks. The hazard maps extend upon recent work by Legg et al. (2014) documenting landscape characteristics that led to debris flows initiating in the November 2006 storm. Their findings are used to map areas of Mount Rainier's flanks with high initiation hazard. Hazard maps are provided within the text as well as in GIS vector-based data.

## Background – Recent Debris Flow Initiation on Mount Rainier

The November 2006 storm is the best documented debris flow event on Mount Rainier due to its sheer magnitude and extent of damage. The number and distribution of debris flows that occurred in this one storm also provided an opportunity to identify the landscape characteristics common to debris flow initiation sites. Debris flow-causing storms prior to the one in 2006 typically had few debris flows identified, making it difficult to identify the variables important for debris flow initiation. For these reasons, Legg et al. (2014) focused on debris flows that occurred within the November 2006 storm.

The debris flows in November 2006 were found to have initiated in steep-sided gullies running through recently deglaciated areas dominated by glacial deposits (Copeland, 2009; Lancaster et al., 2012). Sediment recently deposited by glaciers is generally thought to be susceptible to rapid erosion, and thus logically may provide a source for debris flows (Church and Ryder, 1972; Moore et al., 2009). In many cases, the gullies where debris flows initiated widened appreciably as a result of debris flow passage, suggesting unstable gully walls composed of glacial deposits provided sediment to debris flows. Figure 1 shows an example of change in the gully below the Pyramid Glacier which is presumed to be the result of passage of the debris flow in 2006. More generally, the correspondence between debris flow initiation sites and recently deglaciated areas suggests glacial deposits important for debris flow initiation. Along these lines, a major step in this hazard mapping effort was to map sediment availability on Mount Rainier's upper slopes.

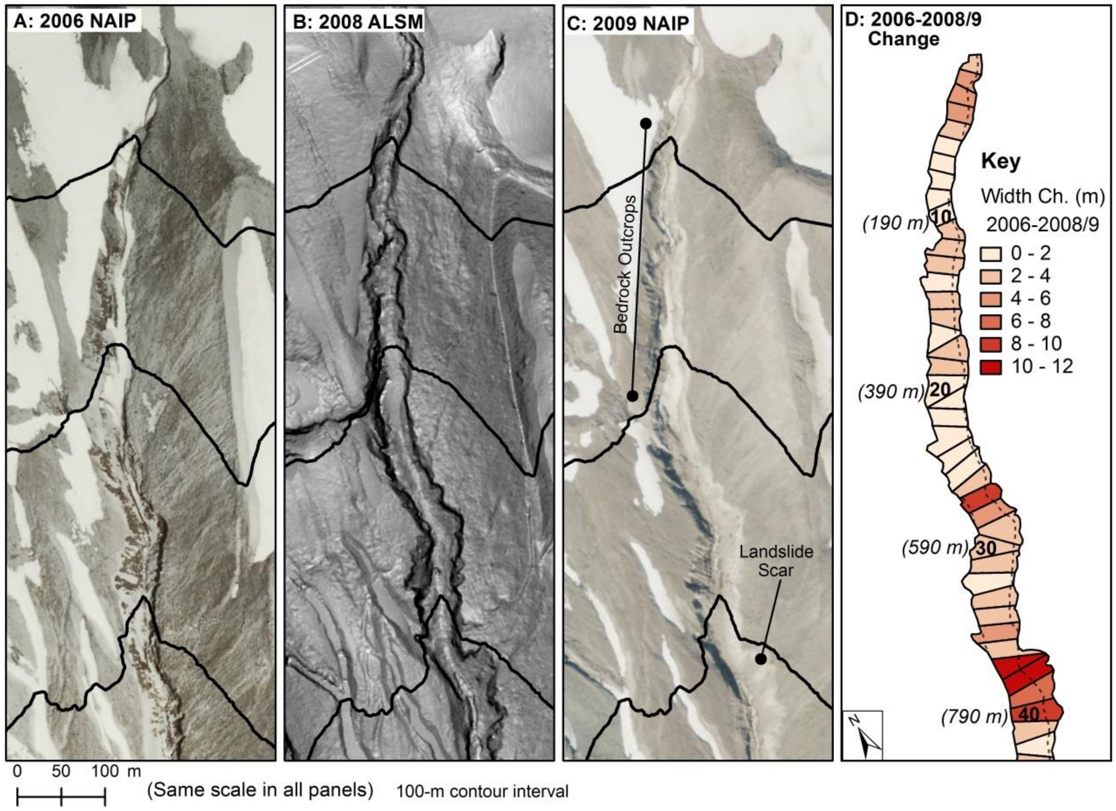


**Figure 1 Time-series of imagery showing change in the Pyramid gully as a result of the November 2006 debris flow. Note that the aerial photograph in panel A was taken in the summer prior to the November 2006 storm and debris flow. The high resolution elevation map (derived from LiDAR) in Panel B has a greyscale color scheme with low slopes in light and steep slopes dark. In panel D, 2006 (dashed) and 2008 gully (solid) outlines show gully expansion. Every tenth segment is labeled with distance downstream from the gully head and a segment number. Segments are colored by average width change.**

Thresholds for debris flow initiation that can be simply mapped across the landscape are the most important contribution of Legg et al. (2014)'s work. They found a common threshold defined by the slopes and drainage areas measured in gullies that initiated debris flows in the November 2006 storm. Slope and drainage area are commonly used in geomorphic studies to identify erosion thresholds (e.g. where gullies are likely to form as a result of forest practices (Montgomery, 1994)). Drainage area is a measure of how much land area drains to a particular point on the landscape, and corresponds to the amount of water flowing across that piece of land given some level of precipitation. It is generally expected that greater flows at larger drainage areas have greater potential to erode the land surface (with all else being equal). Slope - the second variable defining the debris flow initiation threshold - also relates to the power of flowing water to erode the land surface. Thus, we might expect that points on the landscape with combinations of steep slopes and large drainage areas to have a large potential for erosion. The debris flow initiation threshold found in the November 2006 storm defines the combinations of slope and drainage area where the debris flow initiation is a likely mode of land surface erosion. Figure 2 shows how that threshold is defined relative to slope-drainage area measurements.

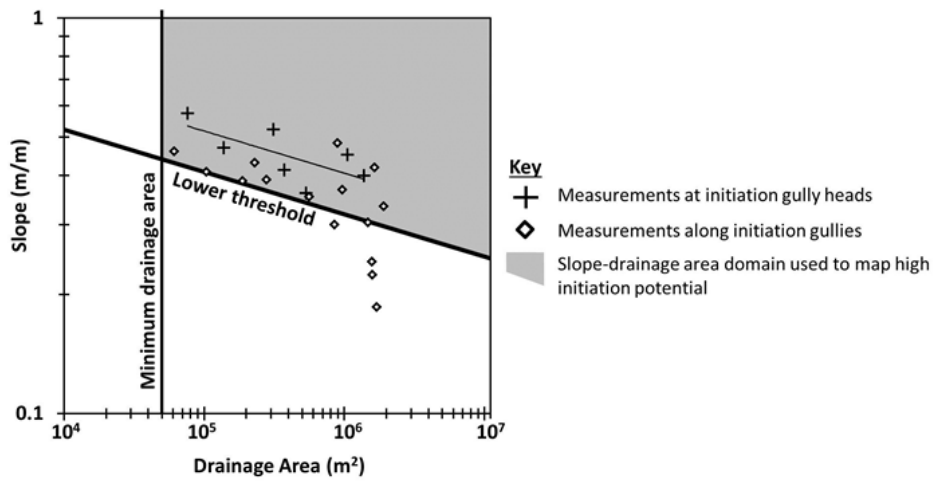


**Figure 2 Plot of slope versus drainage area showing the thresholds used to map high initiation potential gullies. Measurements by Legg et al. (2014) are the basis for the lower threshold shown. Slope (S) and drainage area (A) were measured at the heads and along gullies associated with the seven debris flows known (at the time of their study) to have initiated in the November 2006 storm. Three additional debris flows have since been discovered, and are discussed in sections below. The lower threshold was defined visually to encompass the slopes and drainage area measurements, and parallels the regression fit of gully head measurements (thin black line fit to crosses). The regression equation is $S = 1.769 * A^{-0.107}$ and the lower threshold used for hazard mapping is $S = 1.40 * A^{-0.107}$.**

The slope-drainage area observations also suggest a particular process of debris flow that has important implications for the hazard mapping approach used in this work. Legg et al. (2014) interpreted the slope-drainage area trends to be consistent with gully bed failure as the debris flow initiation mechanism (sensu Prancevic et al., 2014). Bed failure occurs in steep channels or gullies during flood flows, which induce rapid failure of the gully bed. Bed failure contrasts with another type of in-gully debris flow initiation where flood flows gradually incorporate sediment until they become a debris flow (e.g. Wells, 1987; Gabet and Bookter, 2008). If gully bed failure is the initiation mechanism for Mount Rainier's debris flows, it means that the expansion of gullies discussed above (also see Figure 1) is a consequence, rather than a cause of, debris flow initiation. This shifts the role of gully wall failure from being the causal factor, to the process that likely adds large sediment volumes to passing debris flows. Added sediment volume is important because volume often correlates with travel distance and destructive power of debris flows (Rickenmann, 1999). This sequence in with debris flows initiate on the gully bed and then incorporate additional sediment along steep gullies means that the conditions necessary for debris flow initiation and sediment entrainment can be mapped separately and then overlaid to identify high hazard areas. Thus, areas with the greatest debris flow hazards are considered zones where initiation potential is high (exceeding slope-drainage area threshold) and sediment availability is large (according to mapping described below). Figure 3 shows this concept in matrix form.

## Debris Flow Hazard Mapping Methodology

The mapping approach has two main steps: (1) mapping of debris flow initiation potential according to slope and drainage area of drainage networks, and (2) geomorphic mapping aimed at characterizing sediment availability for debris flow initiation. The conceptual matrix in Figure 3 shows how these two components inform our understanding of debris flow hazards. Each step is described below.

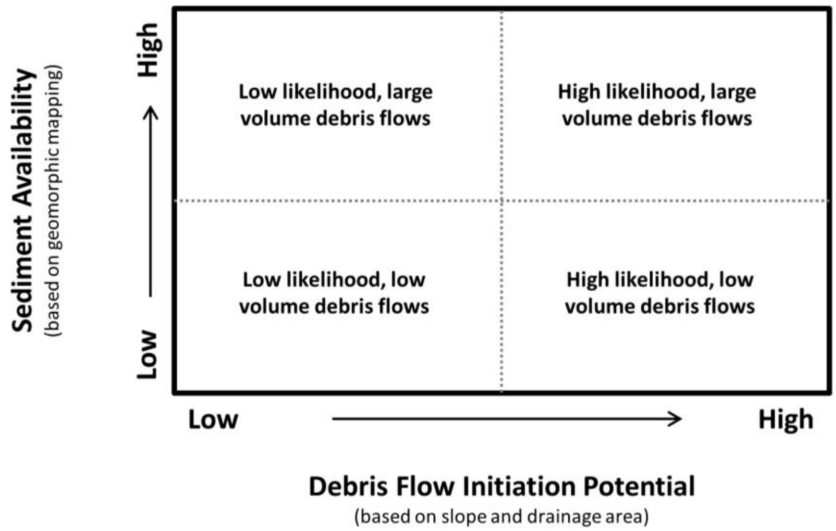


**Figure 3 Conceptual matrix showing how the two component hazard mapping approach identifies hazards of different types.**

### *Mapping Debris Flow Initiation Potential*

This step ultimately produced a map of drainage networks (represented by lines) on Mount Rainier's upper slopes. Drainage network lines are broken into segments that each has measured values of slope and drainage area which in turn allowed mapping of drainage network segments with high initiation potential. Mapping was performed in the Geographical Information System software called ESRI ArcGIS®. The main GIS steps included:

1. Generation of drainage network lines using ESRI ArcGIS standard Flow Direction and Flow Accumulation tools based on a 4-m gridded topography produced from the 2007-2008 LiDAR.
2. Segmentation of drainage network lines into lengths of 76.2 m (250 feet; note, some segments are less than 76.2 m in length because the segmentation algorithm divided segments that were not necessarily divisible by the 76.2 m).
3. Measuring longitudinal slope of each segment by differencing segment endpoint elevations and dividing by segment length. Elevations were extracted from high-resolution LiDAR elevation data collected for MORA in 2007-2008.
4. Extraction of drainage area from "flow accumulation" rasters (produced in step 1 above) at each segment's midpoint.
5. Identification of high initiation potential drainage network segments as those above the minimum slope-drainage area threshold and above the minimum drainage area of 50,000 $m^2$ shown in Figure 2.

### *Mapping Sediment Availability*

Using simple criteria, large areas of the park were first excluded from main mapping efforts. The debris flows of concern here initiate from the un-vegetated flanks of the Mount Rainier, typically near glaciers (Copeland, 2009). Therefore, a manually mapped vegetation line served as a lower cutoff for further geomorphic mapping. Note this lower-limit often extends well below tree-line near relatively low-elevation glaciers. The uppermost, un-glaciated slopes of the volcano are largely bedrock-dominated with rockfall as the dominant sediment transport process (Czuba et al., 2012). A trial-and-error process revealed that an elevation cutoff of 2,750 m (9022 ft) removed the primarily bedrock-dominated upper volcanic slopes. Debris flows also cannot initiate from the surfaces of glaciers that lack supraglacial sediment, so glacial ice areas above a mapped boundary of continuous supraglacial debris were eliminated from further mapping.

Within the remaining area, I mapped a series of units classified by their sediment availability based on geomorphic and previously mapped geologic characteristics. Mapping utilized four major geospatial datasets: (1) aerial images taken in 2011 and 2013 (National Agricultural Imagery Program, one-meter resolution); (2) high-resolution topographic data (LiDAR) collected from 2007-2008; (3) surficial geologic mapping by Crandell (1969); and (4) 2011 glacier outlines mapped by the National Park Service. Mapping was completed at an approximate 1:6,000 scale, so some generalization was required. The map units and their classified levels of sediment availability are listed below:

- <u>High sediment availability</u>
    - **Recently deglaciated areas dominated by glacial till:** Areas with minimal bedrock (<10%) exposed at the surface and dominated by glacial till or other glacially-derived deposits. Glacial landforms such as end and lateral moraines often bounded these areas, (Panel A in Figure 4 shows one example). Drainage features such as gullies were often visible, but not a required feature of the map unit. Tills were classified as recently deglaciated if they were upvalley of known Little Ice Age (LIA) moraines (Burbank, 1981; Sigafoos and Hendricks, 1972; Heliker et al., 1984; Legg, 2013) or mapped as “Young Garda Drift” by Crandell (1969). Many areas glaciated since the LIA now are vegetated and thus were not included in this category.
    - **Lateral glacier margin with drainage features:** Areas along the sides of glaciers can often have troughs that carry surface streamflow. These areas have high sediment availability due to delivery and sloughing of sediment from debris-covered glaciers and valley walls. This unit was mapped separately from the one above to identify different zones of debris flow hazards associated with different types of glaciers (e.g. valley versus cirque glaciers). A November 2006 debris flow initiation site along the west lateral margin of the Carbon Glacier is one example of this type of debris flow.
- <u>Medium sediment availability</u>
    - **Recently deglaciated area with mixed bedrock and till:** These areas had significant coverage of till (greater than ~50% but less than ~90%) and bedrock (less than 50%). Bedrock exposure at the surface suggests glacial deposits are generally thinner, and thus have less sediment volume available for debris flows. Surface age criteria were the same as above.
- <u>Low sediment availability</u>
    - **Lateral glacial margin with no visible drainage features:** These glacier margins transition directly from glacial ice to valley wall and have no visible drainage features. These areas were mapped to eliminate drainage lines generated by the automated drainage network

mapping procedure used in ArcGIS (e.g. the automated procedure only accounts for surface topography and does not recognize glacier ice.

- **Debris-covered ice with minimal surface drainage:** Debris covered ice was mapped visually within the 2011 glacier outlines using NAIP 2011 or 2013 aerial photographs. It included areas where surface debris appeared thick, or where it completely covered the ice below. Debris covered ice represents an area where abundant sediment is present, but where the lack of drainage features makes the sediment unlikely to initiate as debris flows that carry downstream into streams below. Note that a separate unit of debris-covered ice with visible surface drainage was planned, but was not mapped due to the general absence of supraglacial drainage observed.
- **Older glacial deposits:** Glacial deposits mapped by Crandell (1969) as "Old Garda Drift", on which he found Ash Layer W (deposited 1,482 AD (Yamaguchi, 1985)). These surfaces are presumed to be largely stable with low sediment availability.
- **Mixed bedrock and older glacial deposits:** Glacial deposits of the same age as above, but with frequent bedrock exposures.
- **Talus or alluvial cones:** Areas mapped as talus or alluvial cones by Crandell (1969) represent depositional areas unlikely to initiate large debris flows.
- **Bedrock dominated:** Areas with greater than 50 % bedrock exposed at the surface where sediment availability is low.

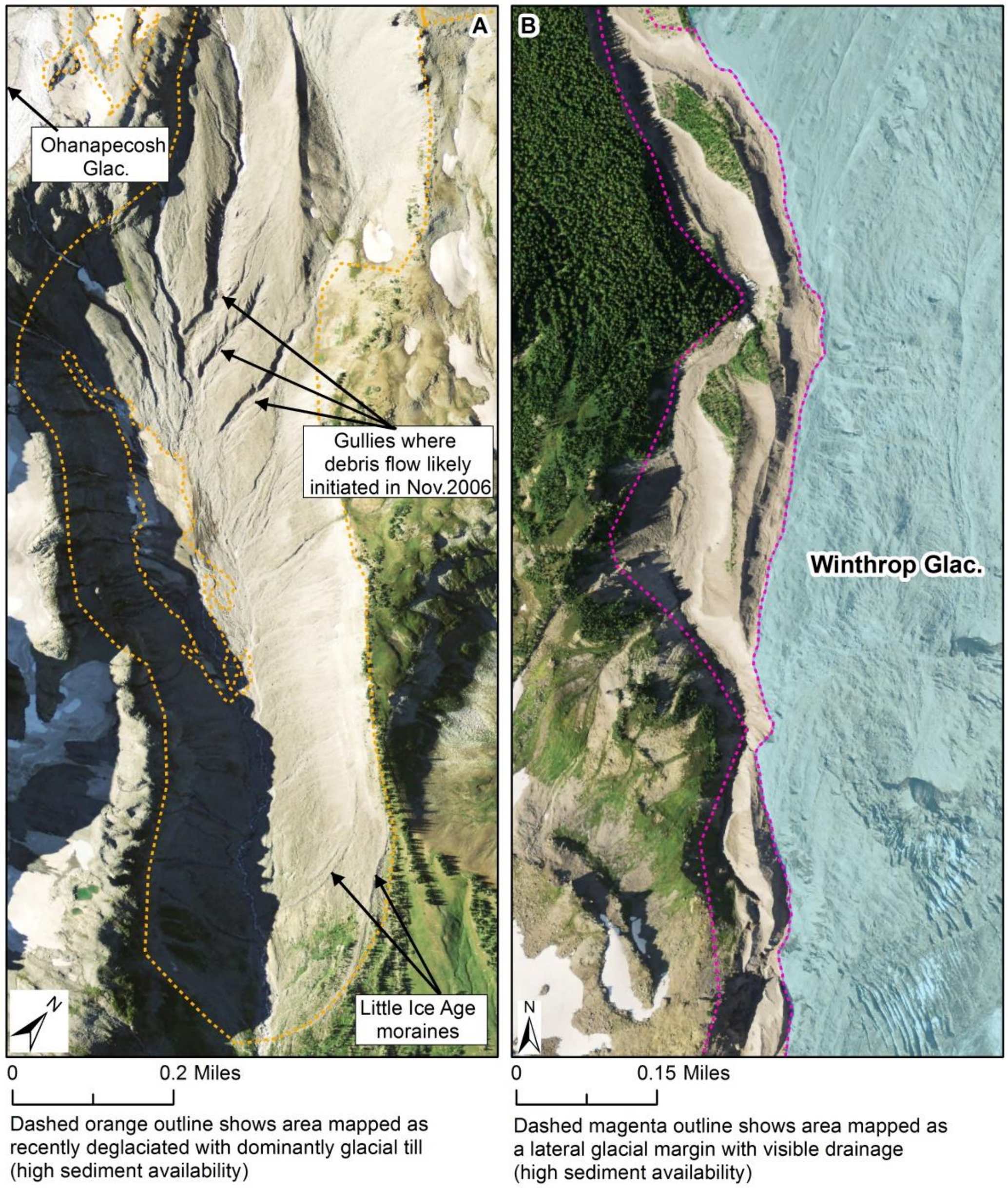


**Figure 4 Examples of areas mapped as having high sediment availability. Panel A shows an area mapped as "recently deglaciated and dominated by glacial till" in front of the Ohanapecosh Glacier. The Little Ice Age moraines marked were mapped and dated by Burbank (1981). The gullies marked were identified as sources for a debris flow in 2006 by Legg et al. (2014). Panel B shows an area mapped as a "lateral glacier margin with drainage features" along the Winthrop Glacier.**

### *Debris Flow Hazard Rating*

The hazard mapping can be used to identify individual gullies or sets of gullies with high debris flow potential; however, MORA park officials are likely concerned cumulative debris flow hazards within major streams draining Mount Rainier. A simple watershed-based hazard rating which incorporates both debris flow initiation potential and sediment availability was defined for the purpose of comparing hazards by stream. The rating is based on the cumulative length of high initiation potential drainage network segments (e.g. according to slope and drainage area in Figure 2) in each watershed, and scaled according to sediment availability at each segment. Drainage network segments are classified as having *high initiation potential* if their slope and drainage area plot within the grey zone in Figure 2. The metric requires measured length of high initiation potential segments mapped in high sediment availability map units ($l_H$) and medium sediment availability map units ($l_M$). The hazard rating (HR) is calculated using the following simple formula:

$$HR = l_H + 0.5 * l_M$$

As shown mathematically above, twice the weight is given to high initiation potential gullies with high sediment availability than to those with medium sediment availability to account for expected differences in potential debris flow volumes.

## Mapping Results and Discussion

### *November 2006 Initiation Sites Relative to Hazard Mapping*

The November 2006 debris flow initiation sites support the hazard mapping results to some degree. To identify the slope-drainage area threshold, Legg et al. (2014) used measurements made at seven debris flow initiation sites from November 2006 known at the time of their study (near the S. Tahoma, Pyramid, Kautz, Van Trump, Ohanapecosh, Inter, and Curtis Ridge (on ridge west of Winthrop) glaciers). It comes as no surprise that those seven initiation sites map as having high initiation potential (see Figure 5). Since their study, however, three additional debris flows that apparently initiated in November 2006 have been identified by Paul Kennard (NPS). Two of these debris flows initiated near the Puyallup glacier, and the other initiated along the west lateral margin of the Carbon glacier. As shown in Figure 5, all three of these initiation sites map near high initiation potential segments identified independently in this study, providing some support for the threshold for high initiation potential. The three initiation sites also map within areas classified as either moderate or high sediment availability, suggesting that geomorphic mapping at least broadly captured areas with sufficient sediment to fuel debris flows.

The relative volumes of the two debris flows near the Puyallup Glacier (in the N. Puyallup River watershed) also seem to corroborate mapping of sediment availability. During the field excursion to identify the two Puyallup Glacier debris flows, channel widening and damage along stream channels downstream of the initiation sites suggest the more northerly of the two was the larger volume debris flow. The northern and southern Puyallup Glacier initiation sites were mapped respectively as high and moderate sediment availability in this study (see Figure 5), suggesting that the northern initiation zone has a greater sediment volume to contribute to debris flows. These correspondences also seem promising for the mapping approach, but nonetheless represent only a few examples.

### *Spatial Distribution of Debris Flow Hazards*

Figures 6 and 7 show the results of watershed hazard ratings. The exact precision of the hazard rating is unknown, but it is likely that it can only resolve broad differences in debris flow hazards. For example, the hazard rating should not be used to resolve differences in two basins with very similar ratings (for example, Kautz and South Mowich), but the certainty increases with the disparity hazard rating. The hazard rating itself does not provide information on where debris flow hazards lie with respect to sediment mapping, but data in Figure 7 shows that certain basins have greater hazards from lateral margins of glaciers, as opposed to simply recently deglaciated areas (see paragraph below for more discussion).

The locations and levels of debris flow hazards vary with the type and size of glaciers. Glaciers and their surrounding environments take-on multiple characteristics that in turn influence the type and extent of debris flow potential. At their current extent, a majority of glaciers on Mount Rainier have their termini perched relatively high on the mountain (e.g. many of the south- and west-facing glaciers). Since slopes tend to become steeper with elevation (see Legg et al. (2014)), these glaciers tend to sit at steep slopes. As a result, debris flows tend to initiate from near the fronts of glaciers where there are abundant sediment and steep slopes. Conversely, Mount Rainier's valley-type glaciers (e.g. Carbon, Winthrop, and Emmons) cover much of the steep area located high on the volcano. As opposed to initiating from proglacial areas, debris flows are more likely to initiate from along lateral glacial margins (e.g. mapped lateral margins with surface drainage) that do extend to steeper zones prone to slope failure. These debris flows initiating from lateral margins either start in steep, lateral troughs along glaciers (e.g. the November 2006 Carbon debris flow) or from recently deglaciated areas on ridges (e.g. the November 2006 Winthrop/Curtis Ridge debris flow) separating major valleys.

Figure 8 also shows the raw area mapped in each geomorphic map unit for each watershed. The general classification reflects the mapping approach's ability to capture only broad differences in sediment availability.

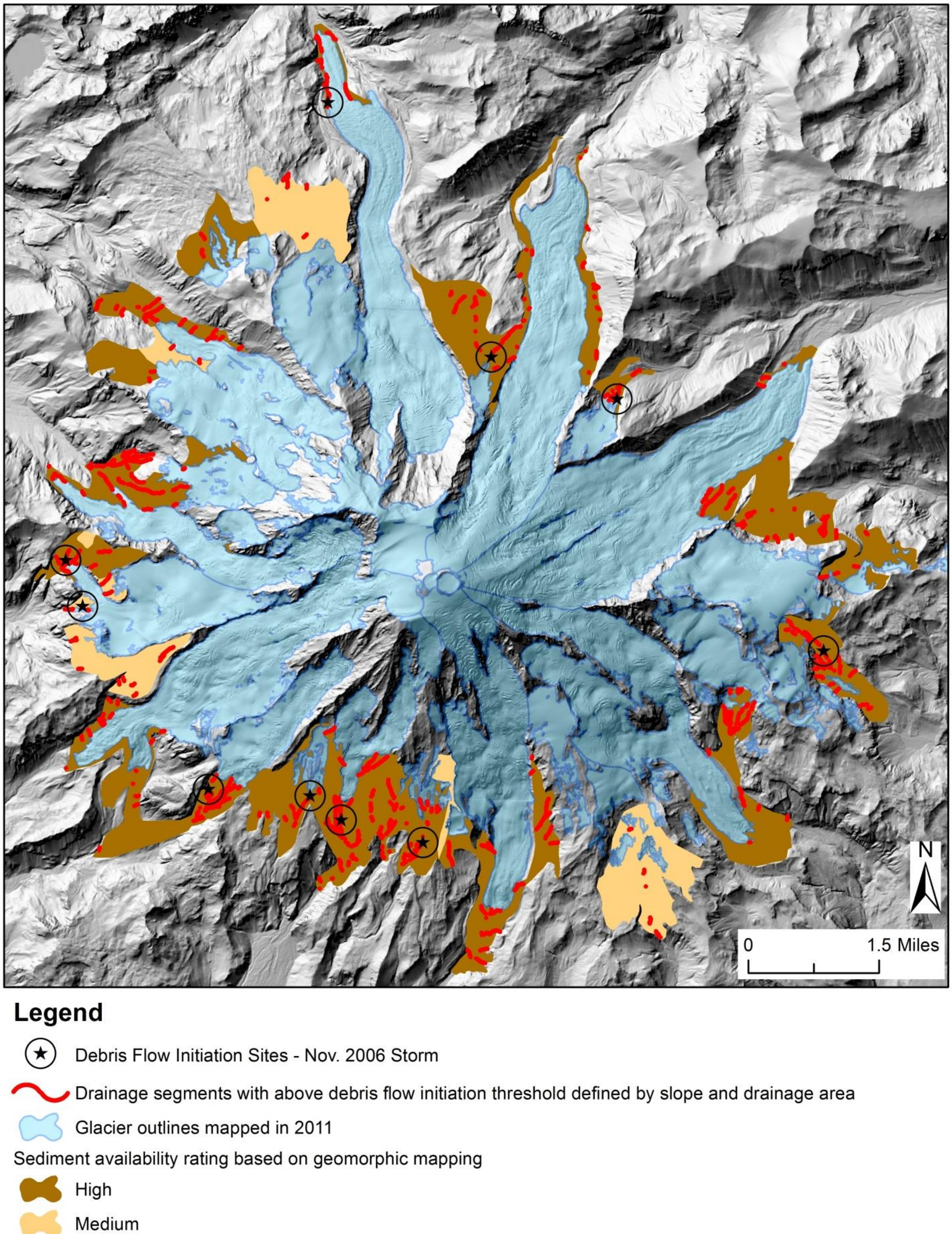


**Figure 5 Map of Mount Rainier showing high initiation potential segments of the drainage network within areas mapped as high and medium sediment availability. The map also shows known debris flow initiation sites in the November 2006 storm.**

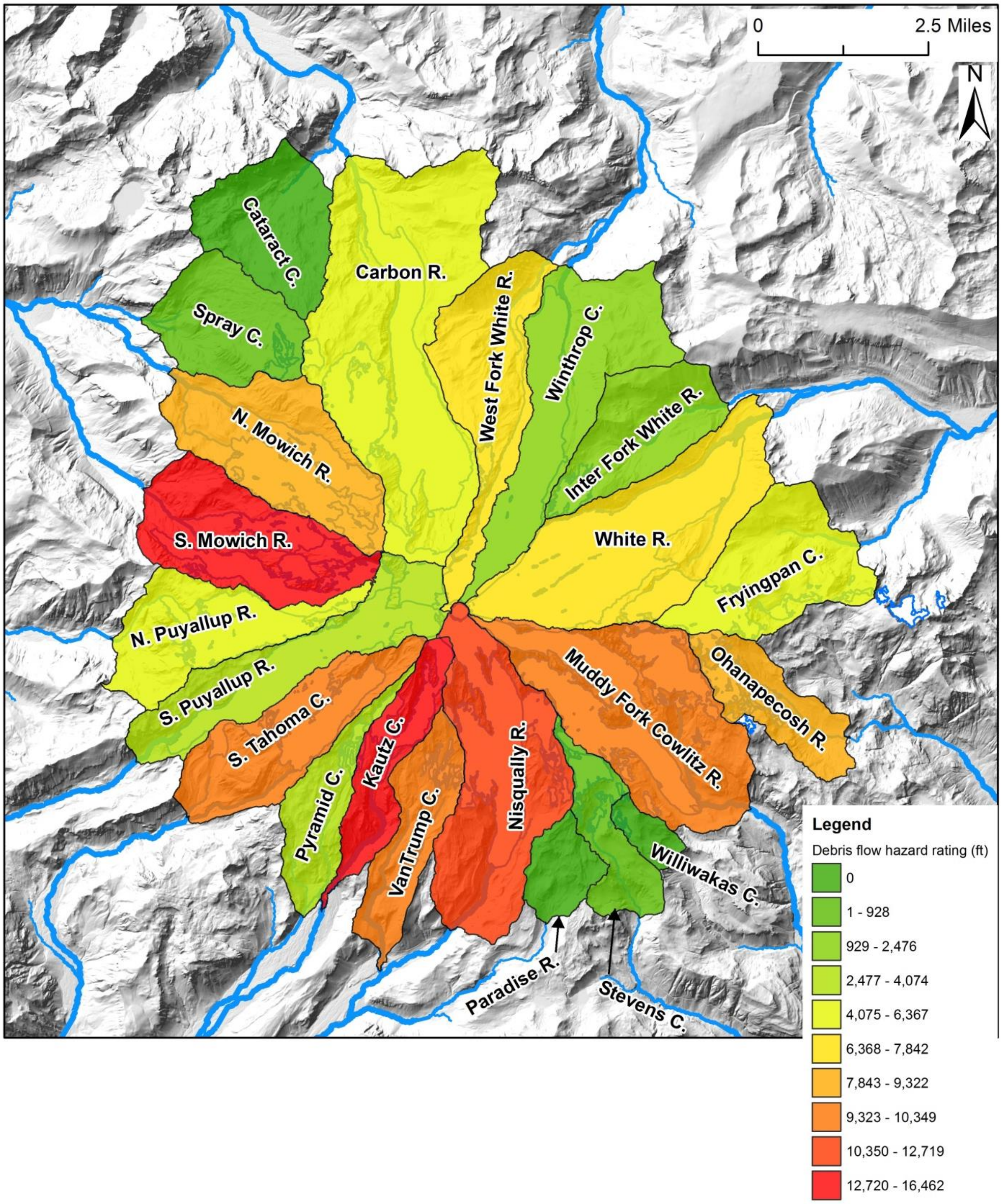


**Figure 6 Map showing watersheds of major streams and rivers draining Mount Rainier and their debris flow hazard ratings.**

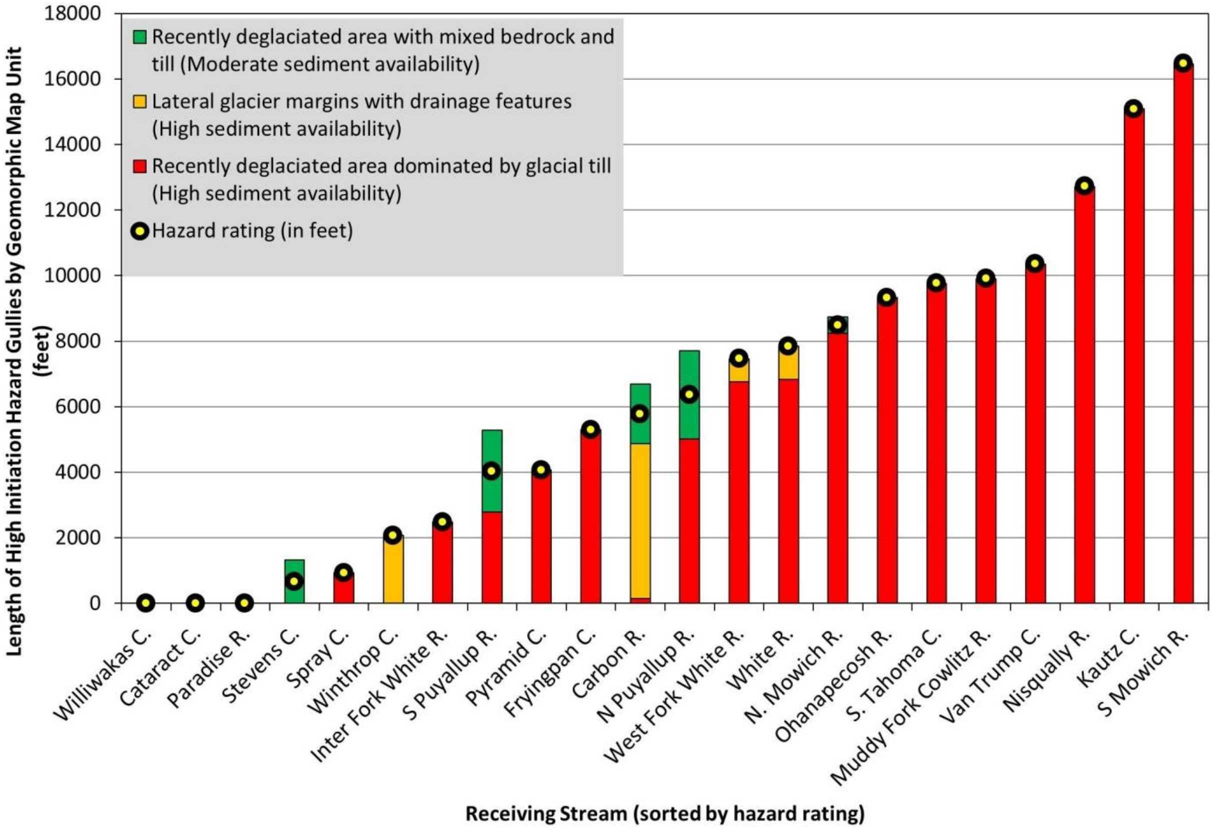


**Figure 7 Bar graph showing the total length of high initiation potential streams mapped in high and moderate sediment availability areas in each watershed.**

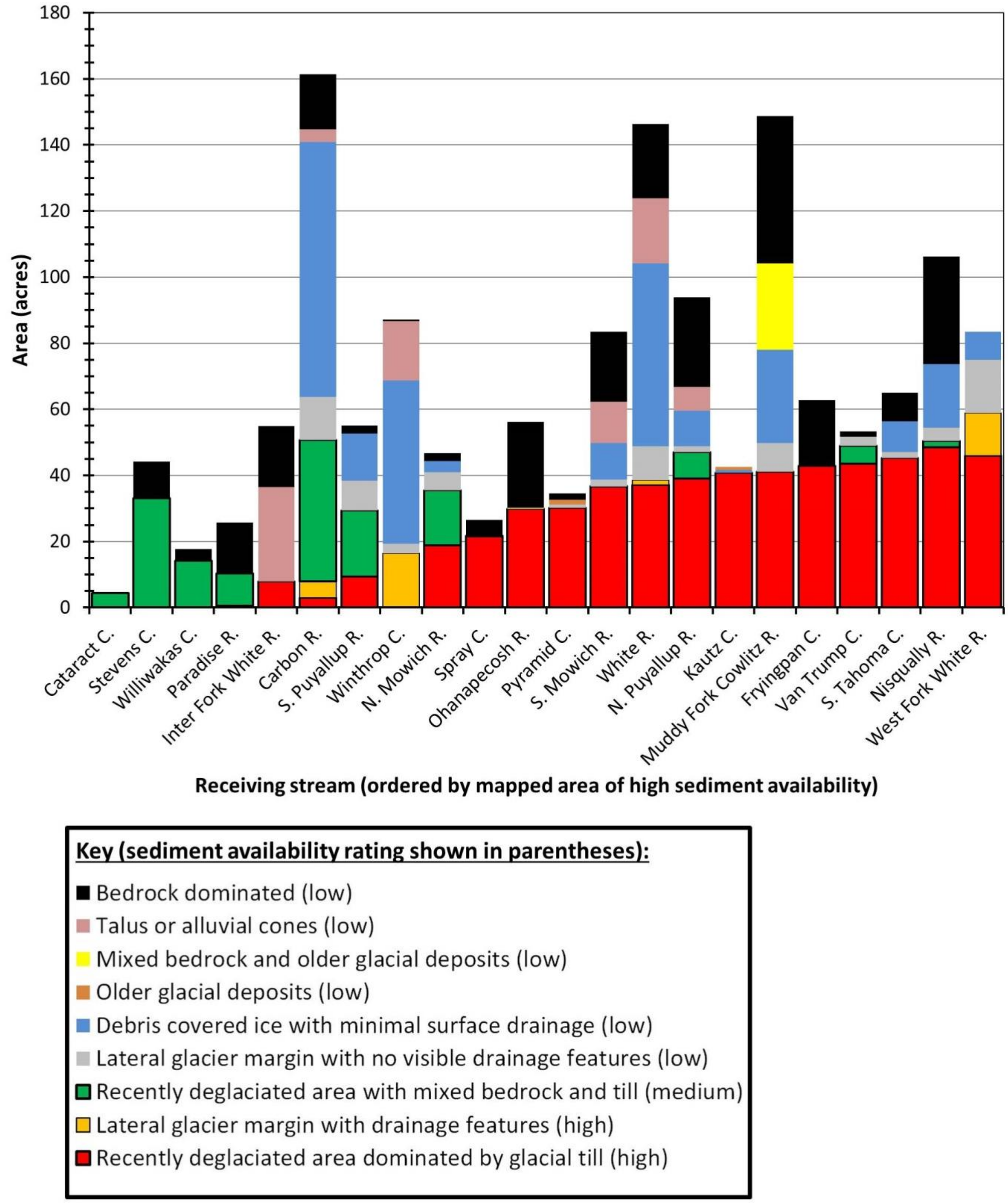


**Figure 8 Bar chart showing the mapped area of each geomorphic map unit in each watershed.**

# Storm Conditions Conducive to Debris Flow Initiation

To this point Mount Rainier National Park has lacked a systematic way to identify rain storms that have potential to initiate debris flows. We have general ideas about the storm conditions that lead to debris flows. Storms that bring warm temperatures and drop heavy rainfall when antecedent snowpack is minimal seem most prone to initiating debris flows – storms termed “atmospheric rivers” are often responsible for these conditions (Neiman et al., 2008). However, there has been only minimal effort to compile and document the conditions in past storms to identify the thresholds for debris flow initiation. Debris flow initiation thresholds can be combined with weather forecasts to create simple debris flow forecasting systems. Forecasting systems have been developed in landslide and debris flow susceptible areas around the world, as well as locally in Washington (e.g. Baum and Godt, 2010; Chleborad et al., 2006). Thresholds for debris flow initiation also could enable assessments of future risk to Park infrastructure under expected a warming climate, under which there area expected increases in the intensities and frequencies of the atmospheric river storms that bring warm and moist air to the Pacific Northwest (Warner et al., 2014). This work lays the initial groundwork for these future applications by assessing the storm conditions conducive to debris flow initiation in the historical record, and proposing a simple forecasting methodology.

## Historical Data

Historical records of debris flow events were compiled from 1980-2014 for the analysis of storm and antecedent conditions (Walder and Driedger, 1994a; Walder and Driedger, 1994b; Walder and Driedger, 1995; Driedger and Fountain, 1989; Copeland, 2009). Debris flows induced by rain and outburst flood were distinguished based on general descriptions of weather at the time of debris flow initiation. Outburst floods were identified as those that occurred in the absence of or with minimal precipitation, These events commonly occur during hot temperatures in the late summer and early fall (Walder and Driedger, 1995). The identified precipitation-induced debris flow events and their general hydrologic and meteorological conditions are shown in Table 1. The time of day of debris flow initiation is only known for one of the 11 debris flows events (the Van Trump debris flow on 9/29/2005 is known to have occurred at approximately 4:30 pm according to Kennard (personal communication)). The day of initiation is the most precise timing known for the remaining 10 events, so the subsequent analysis focuses on precipitation, temperature, and antecedent snow conditions recorded at daily intervals prior to and during debris flow events.

Nearly continuous daily measurements of temperature, precipitation, and snow water equivalent (SWE) were available from 1980-2014. The primary data source for these measurements was the Paradise Snow Telemetry (SNOTEL) station (ID 679) operated by the National Resource Conservation Service. The station is located at an elevation of 5,120 feet above sea level and has measured daily precipitation, temperature, and SWE nearly continuously from November 1980 to present, with exception of the period from October, 1981 to September, 1983 and occasional short outages (typically of a few days). Temperature and precipitation data from another weather station at the Paradise Ranger Station were also available through the Global Historical Climatology Network. These measurements were used to fill gaps in the SNOTEL data (however, the 1981-1983 gap was unavailable for both stations).

**Table 1 Information on rain-induced debris flows recorded from 1980-2014 on Mount Rainier.**

| | | | *Precipitation (in)* | | | *Temperature (F)* | | *Snow Water Equivalent (SWE, in)* | |
|---|---|---|---|---|---|---|---|---|---|
| Date | # Recorded Debris Flows | Glacier(s) near Initiation Site(s) | Day of Debris Flow | 3-Day Cumulative | 15-Day Cumulative (prior to 3-day) | Day of Debris Flow Average | 3-day Average | SWE at Debris Flow Day End | 3-Day Change in SWE |
| 10/26/1986 | 1 | S Tahoma | 1.2 | 4.5 | 0.0 | 45.5 | 47.5 | 0.0 | 0.0 |
| 7/14/1988 | 1 | S Tahoma | 0.1 | 1.1 | 1.4 | 40.0 | 41.2 | 0.0 | 0.0 |
| 10/16/1988 | 1 | S Tahoma | 2.8 | 7.8 | 0.6 | 47.9 | 44.0 | 0.2 | 0.0 |
| 11/9/1989 | 1 | S Tahoma | 1.9 | 5.0 | 7.1 | 40.3 | 34.7 | 3.2 | -0.7 |
| 10/3/1990 | 1 | S Tahoma | 4.1 | 4.9 | 0.1 | 39.4 | 38.1 | 0.0 | 0.0 |
| 11/5/1991 | 1 | S Tahoma | 1.8 | 4.5 | 5.4 | 38.5 | 37.9 | 2.9 | -1.0 |
| 9/8/1992 | 1 | S Tahoma | 1.6 | 2.1 | 0.8 | 42.8 | 39.7 | 0.0 | 0.0 |
| 9/20/1992 | 1 | S Tahoma | 0.6 | 0.6 | 3.0 | 47.5 | 47.0 | 0.0 | 0.0 |
| 10/20/2003 | 1 | Van Trump | 2.8 | 3.1 | 8.4 | 50.2 | 47.6 | 0.2 | -0.4 |
| 9/29/2005 | 3 | Kautz, S. Tahoma, Van Trump | 4.7 | 4.8 | 0.0 | 48.9 | 49.0 | 0.0 | -0.3 |
| 11/6/2006 | 10 | Carbon, Curtis Ridge (near Winthrop), Inter, Kautz, Puyallup (2), Ohanapecosh, Pyramid, S. Tahoma, Van Trump | 9.7 | 16.1 | 6.6 | 48.7 | 43.5 | 0.0 | -0.5 |

## Characterization of Storms with Known Debris Flows

The storm conditions analysis focused on precipitation, temperature, and snow levels at the time of debris flow initiation. The general approach was to identify triggering conditions based on the storms with known debris flows. Sub-sections on snowpack, temperature and rainfall below provide the background and logic for chosen metrics as well as the conditions observed in debris flow producing storms. Throughout the discussion, I identify thresholds on which to classify a storm's debris flow potential. These classification thresholds are used in subsequent sections to identify storms with similar conditions with no recorded debris flows. An accounting of these storms without debris flows gives us a better sense for frequency of hazardous storms as well as their seasonality.

### *Antecedent Snowpack*

Antecedent snow likely plays three major roles in debris flow initiation. First, existing snow on the ground can prevent debris flow initiation by absorbing and as acting as a reservoir for rain falling on its surface. Depending on factors such as the Snow Water Equivalent (SWE), holding capacity, and rainfall rate, antecedent snow delays or prevents generation of surface runoff (DeWalle and Rango, 2008). Without surface runoff, debris flow initiation is unlikely. Second, snow may stabilize the ground surface so that debris flow initiation is unlikely. The combination of the first two effects suggest that there may be a level of antecedent snow pack above which debris flows do not initiate. While only one measurement point, the Paradise SNOTEL site fortuitously sits within the elevation range of expected debris flow initiation and thus provides a useful estimation of antecedent snowpack (see Figure 9). Third, antecedent snowpack can melt in response to rainfall and warm temperatures during storms, thus generating surface runoff that increases potential for debris flow initiation. Snowmelt runoff has been identified in previous studies as a triggering condition for landslides and debris flows (Cardinali et al., 2000). Although snowmelt may be a factor in debris flow initiation, it is not addressed here as the

SNOTEL measurements have insufficient spatial coverage to assess the rates of snowmelt over the broad area and elevation range of Mount Rainier.

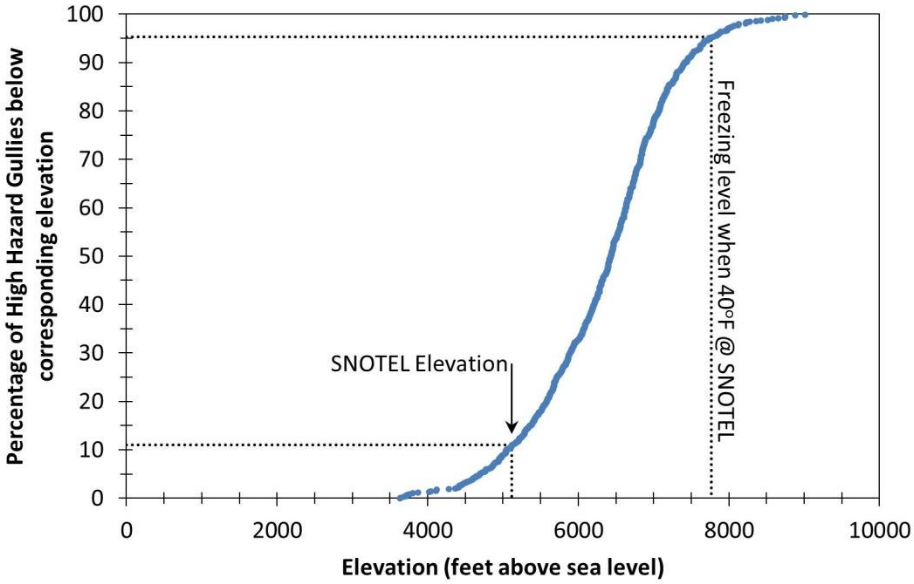


**Figure 9 Elevation distribution of high hazard gullies mapped in the hazard assessment (see above). High hazard gullies are those with high initiation potential within mapped areas of high sediment availability. The indicated elevations are used to divide storm classes. The freezing level shown suggests that rain (as opposed to snow) is likely falling on approximately 95% of high hazard gullies. The freezing level is calculated based on a measured temperature of 40°F at the SNOTEL station and an assumed 5.5°C per vertical kilometer lapse rate.**

Snowpack measured at Paradise was minimal in all of the debris flow-producing storms, with a maximum of 3.2 inches, and 0.2 inches SWE or less in 9 of the 11 storms (see Table 1). At a common snow density of 30%, the maximum observed value of 3.2 inches SWE is less than a foot snow depth. The minor amounts of snow support the expectation that relatively minor antecedent snowpack is a requirement for debris flow initiation. For the subsequent classification of storms, 5 inches SWE is used as a cut-off between storms with “Minor Antecedent Snow” with higher debris flow potential, and storms with “Significant Antecedent Snow” where debris flow potential is expected to be relatively low.

*Temperature*

Temperature was used to determine whether precipitation is falling as rain or snow across the elevation band where debris flow initiation is expected (based on hazard mapping above). Three-day average temperature measured at the Paradise SNOTEL site served as main temperature metric. To account for the fact that debris flow initiation can occur at a range of elevations (and thus temperatures measured at the SNOTEL site), storms were classified according to two temperature cutoffs. In general, the higher elevation the freezing level relative to zone of debris flow initiation, the greater surface runoff and likelihood of debris flow initiation. The first temperature cutoff of 32°C puts the average freezing level at the lower limit of the elevation band where debris flow initiation is likely (see Figure 9). Fluctuations above and below the average 3-day temperature should mean a mix of rain and snow falling on the zone of debris flow initiation. The second cutoff for 3-day average temperature is 40°F, putting an average freezing level at approximately 7,750 feet elevation near the top of the debris flow initiation zone (see

Figure 9). In this case, the calculated freezing level requires the assumption that the vertical temperature gradient is constant at 5.5°C per kilometer (wet lapse rate). Average freezing levels at these upper elevations suggest significant rain and runoff generation are occurring on and above the debris flow initiation zone, making conditions conducive for debris flow initiation.

Temperature conditions during debris flow-producing storms were expectedly warm so that rain was falling on upper volcanic slopes. Average temperatures measured over the day of the debris flow and a 3-day period were exclusively above freezing, with respective temperatures ranges of 38.5°-50.2°F, and 34.7° to 49.0°F (see Table 1). A strong majority of storms also had temperatures well above 40°F, meaning rainfall was falling over much or all of the elevation band expected for debris flow initiation (see Figure 9). The temperature component of the storm classification proposed below uses 32° and 40°F as boundaries separating Low (<32°), Medium (32°-40°F), and High (>40°) debris flow hazard classes.

*Rainfall Thresholds for Debris Flow Initiation*

Rainfall thresholds for debris flow initiation commonly incorporate measures of antecedent precipitation and precipitation intensity during a given storm (Caine, 1980; Guzzetti et al., 2008). Antecedent precipitation (i.e. precipitation that fell in some period prior to a storm) raises soil moisture and pore-water content so that diminished rainfall intensities are needed to initiate landslides and debris flows. Therefore, landslide thresholds defined by measures of antecedent precipitation and rainfall intensity typically have negative relationships. Given the relatively few known debris flow events on which to develop a threshold for Mount Rainier, precipitation measurements for debris flow-producing storms are compared to an existing rainfall threshold developed for Seattle area (Chleborad et al., 2006). The Seattle rainfall threshold depends on two measures of precipitation: 3-day cumulative precipitation (i.e. intensity) and 15-day cumulative precipitation prior to the 3-day period (i.e. antecedent precipitation), which are easily extracted from the SNOTEL data. The 3-day (72-hour) precipitation total is also a common period for weather forecasting (e.g. the National Weather Service's Quantitative Precipitation Forecasts http://www.hpc.ncep.noaa.gov/qpf/day1-3.shtml), which also enables park officials to forecast debris flow hazards 3 days in advance.

The 11 storms plotted by 3-day and 15-day precipitation do not form a clear lower threshold for debris flow initiation, making comparison with the Seattle landslide threshold the next best alternative for classifying debris flow hazards with respect to rainfall (see Figure 10). Rainfall thresholds for debris flows and landslides can vary with climate, soil types, and geological characteristics (Guzzetti et al., 2008), all of which differ between Seattle and Mount Rainier. Nonetheless, eight of the eleven storms plot above the rainfall threshold developed for Seattle (see Figure 10), suggesting it captures many of the known debris flow events that have occurred on Mount Rainier.

The three debris flow events plotting below the Seattle landslide all initiated below the terminus of South Tahoma glacier in a period of high debris flow activity, suggesting geomorphic conditions especially conducive to debris flow initiation may have temporarily lowered rainfall thresholds in that basin. That period of high debris flow activity was partially attributed rapid retreat and stagnation of a lower debris-covered portion of the S. Tahoma glacier. Retreat of the thickly debris-covered ice left huge quantities of steep, unstable sediment poised to fail (Walder and Driedger, 1994b). Since high debris flow activity ended in the early 1990s, the frequency of debris flows from the S. Tahoma glacier has decreased to the point that debris flows have only initiated in storms that generated debris flows in other valleys (the 2005 and 2006 storms in Table 1) suggesting that thresholds for initiation in the South Tahoma valley have diminished and become similar to thresholds on other parts of Mount Rainier. This is all to say that the three debris flows plotting below the Seattle threshold may be (but are not clearly) outliers with respect to present-day conditions on the mountain. This discussion also highlights the importance that on-the-ground knowledge of the constantly changing geomorphic conditions should play in debris flow forecasting on Mount Rainier.

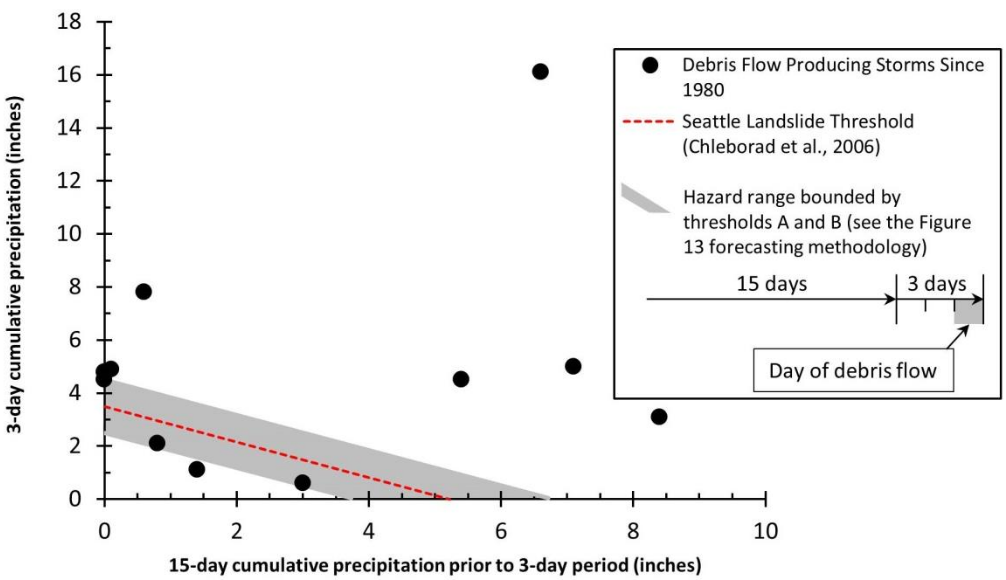


**Figure 10 Cumulative antecedent and storm rainfall for the eleven debris flow-producing storms since 1980. Storm rainfall is measured in the 3-day period including the day of the debris flow ($P_3$), and antecedent precipitation is measured during the 15-day period prior to the 3-day period ($P_{15,}$ see illustration above). The rainfall threshold for landslides in Seattle is $P_3 = 3.5 – 0.67*P_{15}$ (Chleborad et al., 2006). Thresholds A and B form the upper and lower bounds of the hazard range shown in grey and referred to in Figure 13. The respective equations for thresholds A and B are $P_3 = 2.5 – 0.67*P_{15}$ and $P_3 = 4.5 – 0.67*P_{15.}$**

## Past Storms with No Recorded Debris Flows

Storms with no recorded debris flows but with similar characteristics to debris flow-producing storms can provide additional insights into hazards. Precipitation events with the maximum 3-day cumulative precipitation in months without known debris flows were identified for a base dataset. Those precipitation events were then classified according to their antecedent snow, temperature, and precipitation levels in a stepwise manner using thresholds identified and discussed in the previous section. Graph A in Figure 11 shows the base dataset of 376 precipitation events plotted according to storm (3-day) and antecedent (15-day) precipitation, showing that a large number (n = 247) of precipitation events exceed the Seattle landslide threshold. However, removing events with greater than 5 inches SWE (e.g. those with “Significant Antecedent Snowpack” as discussed above) leaves far fewer precipitation events (n=115, see graph B in Figure 11) and results in a proportionally larger reduction in events (n=38) above the Seattle threshold.

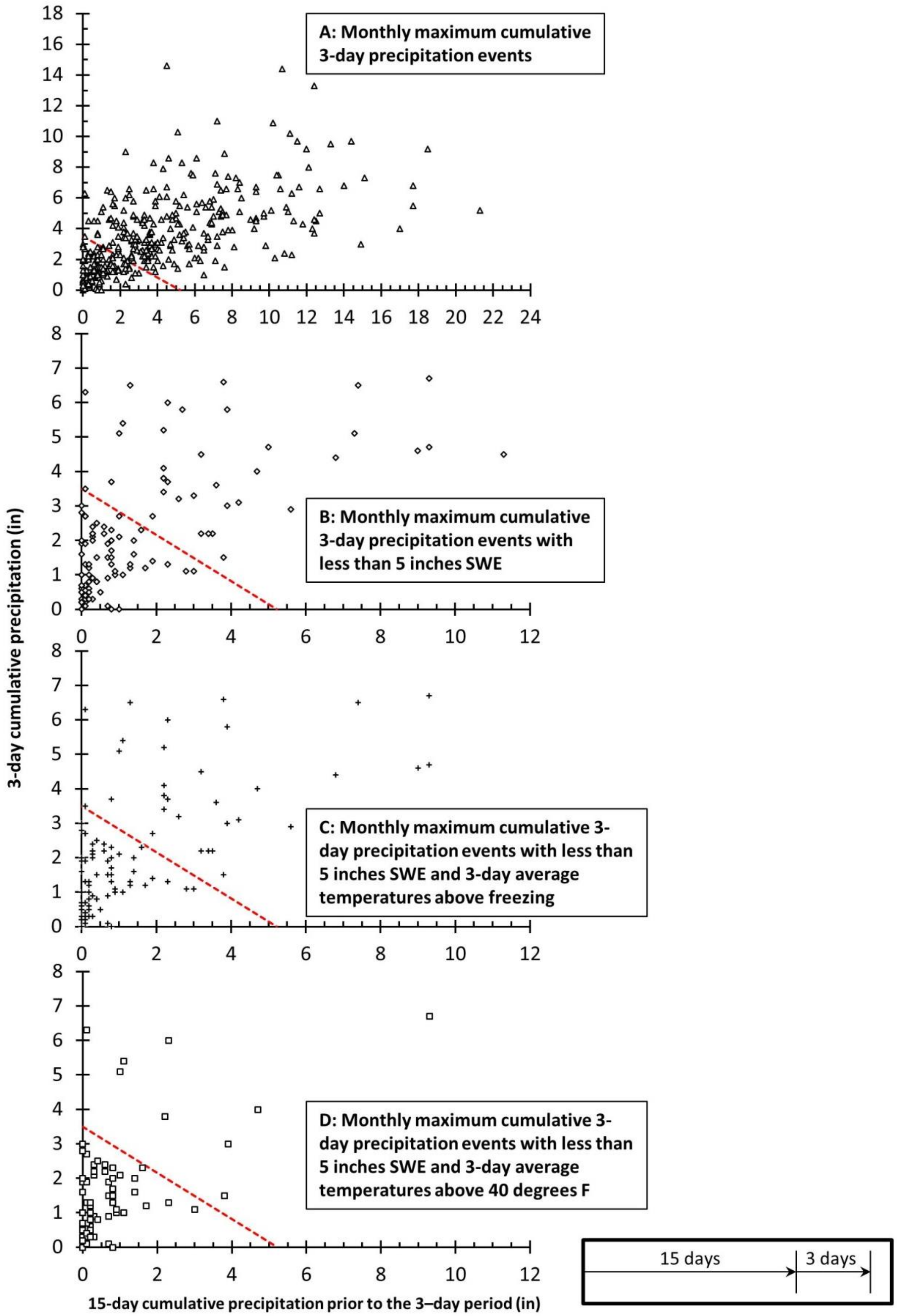


**Figure 11 Monthly maximum precipitation events for individual months with no known debris flows since 1980. Monthly maximum events are those with the maximum 3-day cumulative precipitation. Graph A shows all events, and subsequent graphs show subsets of that data according to the indicated criteria. In general, debris flow initiation is expected become more likely moving downward (from graphs B to D).**

Removal of events with 3-day average temperatures below freezing (at the Paradise SNOTEL) results in only a minor reduction in the number events (n = 108 total, with 33 above the Seattle threshold) as shown in graph C of Figure 11. Finally, removing precipitation events where the 3-day average temperature was below 40°F at the SNOTEL station results in 76 total events with only nine exceeding the Seattle precipitation threshold (graph D of Figure 11).

This exercise gives us the ability to better assess relative hazards between classes based not only on the storms with known debris flows, but also as a percentage of storms in each class. This is particularly helpful for assessing relative hazards of the intermediate and high temperature classes. For storms with precipitation above the Seattle threshold, there were respectively 24 and 9 precipitation events (without known debris flows) in the 32°-40°F, and >40°F temperature classes (see graphs C and D in Figure 11). For known debris flow producing storms there were respectively 3 and 5 storms in each of the classes. Thus, 3 of 27 total (11%) intermediate temperature class (32°-40°F) storms and 5 of 14 (36%) high temperature class storms generated debris flows. The higher percentage of debris-flow producing storms in the warm temperature class adds further support for temperature as a factor in debris flow initiation. The temperature classes are further supported by the fact that the two storm events with multiple debris flows (occurring in 2005 and 2006) had average temperatures well above 40°F (see Table 1).

Combining storms with and without debris flows indicates a strong seasonality to high hazard storms. Figure 12 shows that high debris flow hazard storms (those above the Seattle threshold with minimal snowpack and above freezing temperatures) almost exclusively arrive in the late summer and early fall.

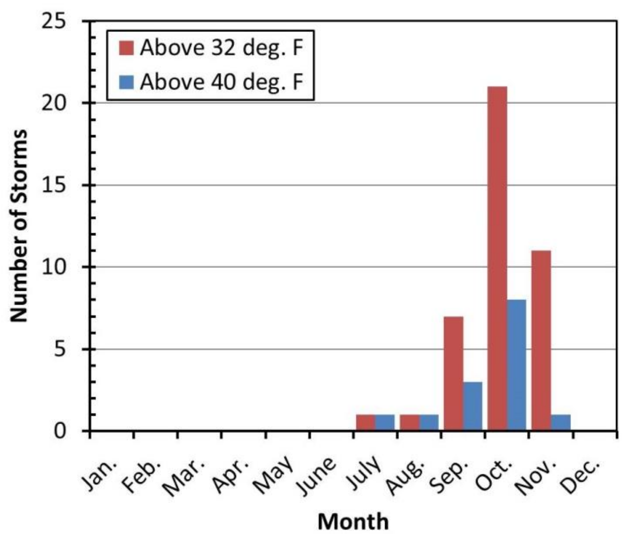


**Figure 12 Histogram of the month of high hazard rainstorms occurring from 1980 to 2014. High hazard storms are those where antecedent snowpack is below five inches on the day of the event, precipitation exceeds the Seattle rainfall threshold for landslides (Chleborad et al., 2006), and 3-day average temperature is at least 32°F at the Paradise SNOTEL. The histogram also shows a subset of high hazard events where the 3-day average temperature is above 40°F.**

## Preliminary Approach to Forecasting Debris Flow Hazards

The accounting of storm conditions in debris flow-producing storms forms a basis for the preliminary debris flow hazard forecasting approach shown in Figure 13. The approach classifies debris flow hazard potential 3 days in advance based on current snow measurements (at beginning of 3-day period) and forecasted temperature and precipitation for the next three days.

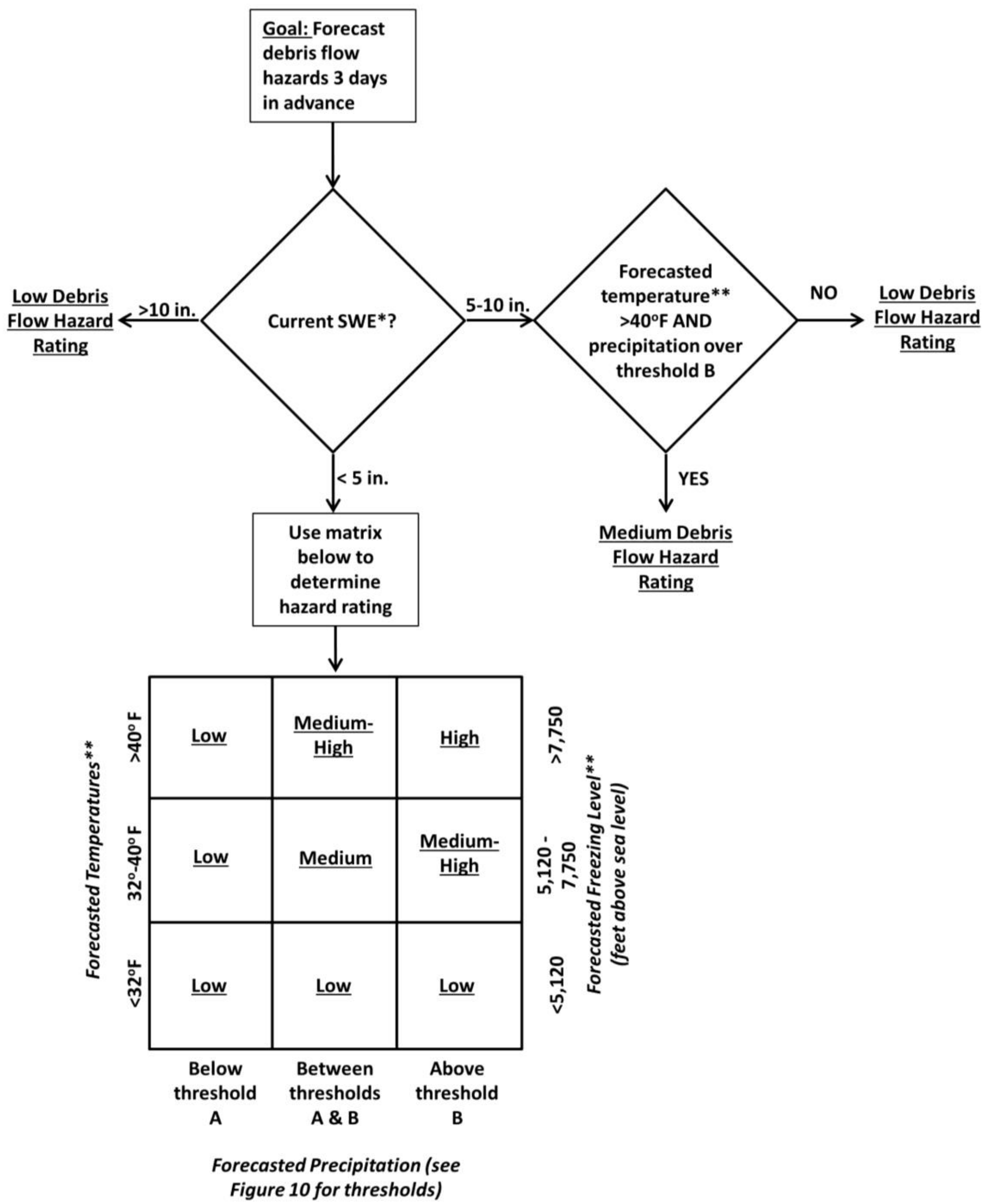


**Figure 13 Decision tree for forecasting debris flow hazards based on 3-day weather forecast. All SWE, temperature, and precipitation values shown are for the Paradise SNOTEL station (NRCS). *The current SWE value is measured at the beginning of the 3-day forecasting period. The cutoff value of 10 inches SWE allows for snowmelt during the 3-day forecasting period. ** The methodology uses the forecasted 3-day average temperature. Rainfall thresholds A and B are shown in Figure 10.**

### Errors and Limitations of the Forecasting Approach

The above methodology for categorizing storm hazards is preliminary in nature and could likely be improved with more sophisticated analyses or new data. Given the level of uncertainty, the classification was designed to be conservative in nature, meaning that false positives should be the more common error type (e.g. the methodology identifies high hazard storms that do not actually produce debris flows). That tendency should be somewhat apparent from the data in Figure 11 and its surrounding discussion, where a number of past storms without known debris flows have conditions suggesting high hazards. The lack of debris flows recorded in these events may in part be a product of observational bias; for example, debris flows are much more likely noticed in the major river valleys where Park infrastructure and high-use visitor areas concentrate. Debris flows also may not occur in these seemingly high hazard storms due to spatial and temporal variability in any number of landscape factors. The simple accounting of storm conditions performed here used measurements made in one area of the mountain, while precipitation, temperature, and snowpack all vary widely over Mount Rainier.

The intended conservatism of the forecasting methodology does not entirely eliminate the possibility of false negatives (e.g. storms with classified low hazards that induce debris flows and landslides). Debris flows can occur during unforeseen conditions or due to unexpected processes. Mount Rainier's dynamic landscape is one that we do not fully comprehend. This report does not provide any warrantees, express or implied.

## Recommended Future Work

In order to improve our understanding of debris flow hazards, future debris flows need to be identified and recorded as comprehensively and precisely as possible. A simple, low-cost monitoring system could be implemented to identify where and at what times debris flows occur during future storms. Turbidity meters installed in major streams and rivers in the park would identify spikes in sediment input indicative of potential debris flows. Such a network would enable prioritized post-storm field efforts to identify debris flows. Once debris flows are confirmed in the field, turbidity meters would also provide relatively precise constraint (within hours) on the timing of debris flow initiation. The meteorological conditions responsible for debris flow initiation could then be constrained on an hourly (as opposed to daily) basis to improve forecasting methodologies.

In line with the previous recommendation, records of debris flows in the past decade or two could likely be improved. A compilation of high-resolution aerial photographs would identify landscape change in response to large storms within intervening time periods. Debris flow deposits suspected from aerial imagery may remain preserved in valleys today, and thus could potentially be used to confirm debris flows suspected from aerial photograph analyses. Identified debris flows could then be used to refine the record of debris flows and hazard mapping and storm conditions analysis completed in this study.

This report largely addressed potential for debris flow initiation, but the distance a debris flow travels from its source is also a key variable in assessing risks to park infrastructure. Debris flow run-out (travel distance) can vary in response to a number of factors such as channel slope and debris flow volume. Future studies should assess debris flow run-out potential around the park.

Thresholds for debris flow initiation can potentially be integrated into probabilistic cost-benefit analyses to inform long-term planning of park infrastructure. For example, the risks of damage to a particular bridge could be projected based on debris flow thresholds, current storm probabilities, and future storm probabilities under a warmer climate.

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