SURFICIAL ICE VELOCITIES OF THE LOWER NISQUALLY GLACIER AND THEIR RELATIONSHIP TO OUTBURST FLOOD HAZARDS AT MOUNT RAINIER NATIONAL PARK, WASHINGTON, UNITED STATES

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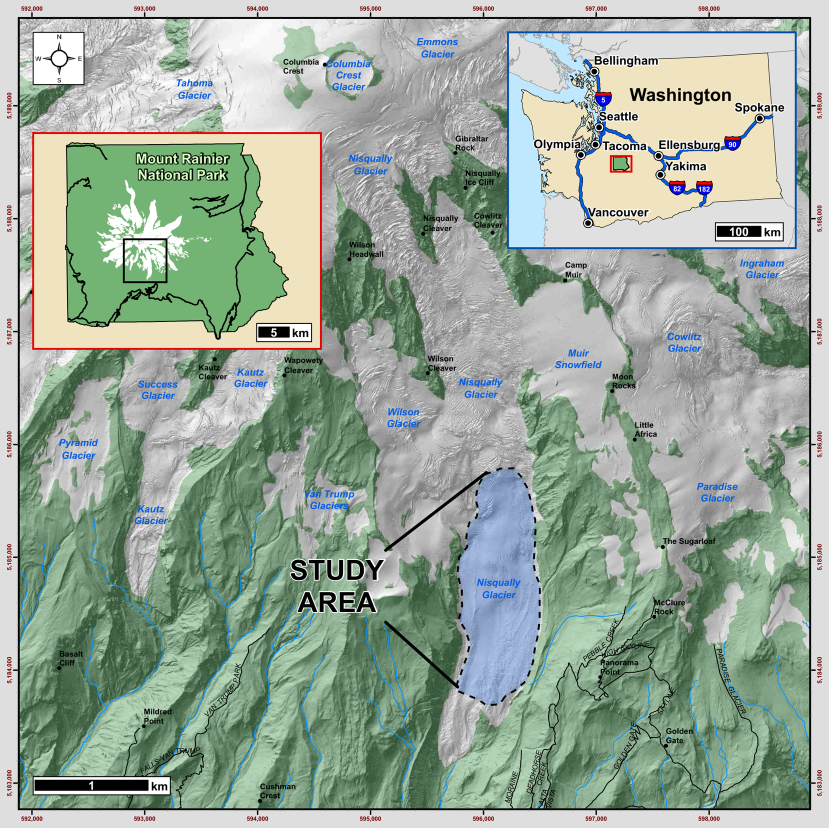
I. ABSTRACT

Mount Rainier, Washington is the tallest of a number of glacier-clad volcanic peaks within the Cascade Range. Standing at 4,392 m (14,411 ft) and having 25 major glaciers, it contains more glacial ice than any other single peak in the continental United States. Glaciers are the headwaters of a number of rivers emanating from Mount Rainier, many of which flow to the Puget Sound, approximately 60 km (37 mi) away. Glaciers on Mount Rainier have unleashed damaging outburst floods (jökulhlaups) in the past, often without warning. Previous observations have indicated an empiric link between changing glacial velocities and glacial outburst flood hazards. Specifically, the lower portions of the glaciers were often stagnant when outburst floods occurred. Additionally, the current Nisqually glacier extent is similar to glacial extent in the 1950s when an outburst flood impacted Longmire, one of the visitor destinations and work areas in the park.

This study explores whether the surficial velocity field of the Nisqually glacier is changing and if ice velocity changes can be used to indicate glacial outburst flood potential. Multiple sites on the lower Nisqually glacier were surveyed weekly during the summer/fall of 2011 and 2012. The surficial velocity field of the lower 1 km² (0.4 mi²) of the glacier was calculated from repeated measurements. Between 2011 and 2012, observed velocities in the upper portions of the study area accelerated while the lower portions of the glacier slowed or remained the same. Shortly after the on-glacier study concluded in October 2012, we observed a short-lived anomalous 1 m (3 ft) rise in river stage at Longmire during a rainstorm on the upper mountain. Field evidence corroborated the stage record and indicates a small outburst flood (approximately 15 m³/s (525 ft³/s)) was released from the glacier during this rain event.

Our work contributes to the understanding of glacial outburst floods and provides an additional line of evidence that changing ice velocities precede outburst floods. Further study of glacial velocity fields could provide a predictive methodology for glacial outburst floods in similar terrain. These results are critical for employee, visitor, and infrastructure protection in dynamic proglacial environments experiencing the effects of climate change, such as that at Mount Rainier.

II. LOCATION



Map showing the study area extent on the Nisqually Glacier on the southern side of Mount Rainier. The Nisqually Glacier is the largest south-facing glacier on Mount Rainier and it is the source for the Nisqually river, which parallels much of the main access road into the Park. Glacial velocity surveying occurred from the terminus, at approximately 1,580 m (5,180 ft), up to about the 2,190 m (7,180 ft) level (above the seasonal equilibrium line). The area surveyed is approximately 1 km² (0.4 mi²).

III. BACKGROUND

The Nisqually Glacier has one of the longest histories of scientific examination of any glacier in the United States, having been studied since the 1850s. Most historic studies on the Nisqually look at mass balance, glacial extent, or surface elevation while few have examined glacial velocity. Past research indicates that the lower Nisqually glacier has displayed varied glacial velocities throughout its measurement history. The available historic velocity data is presented in the table below.

Survey Interval	Location on Glacier	Maximum Velocity (mm/day)	Minimum Summer Velocity (mm/day)	Data Source
June - Sept 1968	Near ELA	380	210	Hodge, 1974
	Near Terminus	146	88	Hodge, 1974
May - Sept 1969	Near ELA	460	340	Hodge, 1974
	Near Terminus	130	68	Hodge, 1974
May 1970	Near ELA	740	660	Hodge, 1974
	Near Terminus	77	68	Hodge, 1974
1943 – 1949	~1,900 m	110*	70*	Meier, 1968
1950 – 1959	~1,900 m	315*	137*	Meier, 1968
1960 – 1966	~1,900 m (Near ELA)	452*	247*	Meier, 1968

* Meier's data is average yearly data, and thus averages out seasonal velocity changes

Empiric evidence suggests that jökulhlaups at Mount Rainier tend to occur when large amounts of stagnant ice are present in their lower reaches. Additionally, Hodge (1974) found that the summer ice velocity of the Nisqually glacier increased significantly in the vicinity of the equilibrium line (ELA), while slowing occurred toward the terminus (relative to the previous summer) just prior to the 1970 outburst flood.

He suggested that observed variations in ice velocity were correlated with the amount of liquid water temporarily stored within the glacier. This indicates that the presence of more englacial water leads to faster ice velocities and a higher potential for outburst floods, while the absence of large quantities of englacial water leads to slower glacial flow and fewer outburst floods. If this is consistently the case, annual glacial velocity measurement could be a powerful tool in the prediction of potentially devastating glacial outburst floods.

At least four major, damaging glacial outburst floods have been released from the Nisqually Glacier, along with many smaller outburst events. The floods of 1926 and 1934 damaged the bridge below the glacier terminus, and the floods in 1932 and 1955 destroyed it (Hodge, 1972). In Mount Rainier National Park, downstream tourist areas like Longmire are susceptible to flooding associated with glacial outburst floods, as evidenced in the 1955 event when the community was inundated with flood water. In addition, much of the main access road into the park parallels the Nisqually River.

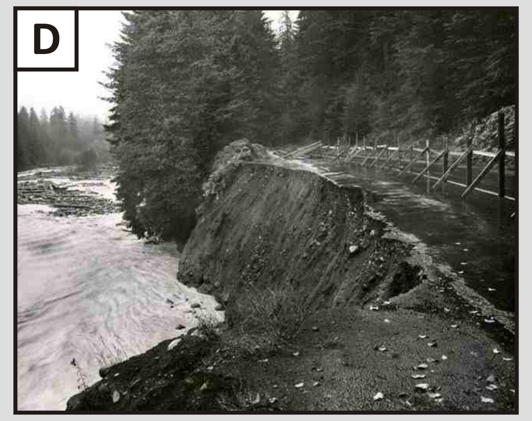
IV. HISTORIC OUTBURST FLOODS

A: Historic photo showing a "surge" of water pouring over the face of the Nisqually Glacier. In addition, accounts of glacial outburst floods include observations that the outburst can occur above the terminus of the glacier (possibly originating from the interface between active and stagnant ice) and sweep the glacial ice clean of debris.

B: Photo of a debris flow initiated by a glacial outburst flood on Tahoma Creek, Mount Rainier National Park.

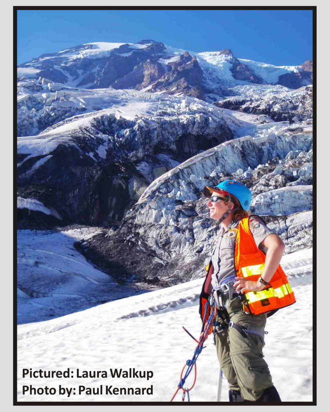
C: The Longmire maintenance area was inundated during the 1955 glacial outburst flood. In addition to its importance as the maintenance area for the park, this area is adjacent to other administrative buildings and visitor destinations such as the Longmire museum and the Longmire Inn.

D: Impacts of the 1955 outburst flood to the riverbank and park road between the main park entrance and Longmire.



V. METHODS

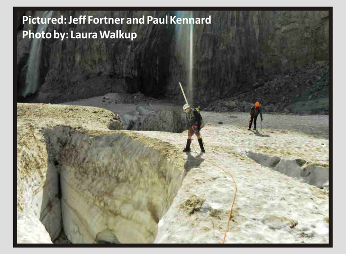
The change in position of rocks on/entrained in the glacial ice were measured weekly and used as a proxy to categorize total velocity of the glacier. These velocities also helped determine the aerial extent of the glacier that was moving rapidly versus barely moving. Surveying was conducted with a Topcon GPT-3105 5-second electronic total station using standard surveying practices.

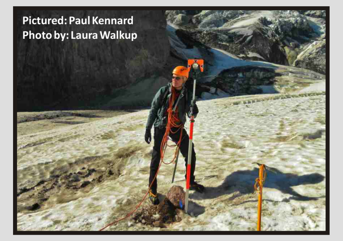


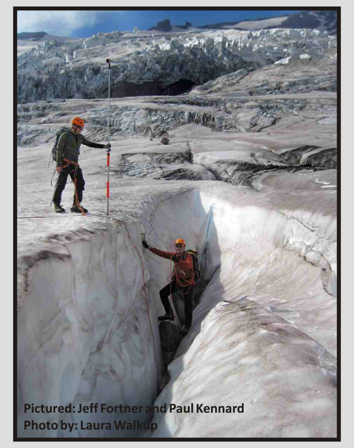
Safety equipment including versatile, high visibility clothing, a climbing helmet, harness, rope, ice axe, crevasse rescue gear, mountaineering boots, crampons, etc were required in order to safely survey much of the study area due to steep, icy, terrain and crevasse danger.

Rocks were chosen based on their location and likelihood of staying in place and survivability against rolling or falling into crevasses. Rocks chosen as survey points were labeled with a unique ID number. The location where the survey rod was placed was also marked on the rock in order to ensure that the same location was surveyed each time (so as not to introduce additional measurement error). Flags were placed in the ice adjacent to the survey point in order to provide a point of reference in case the rocks rolled or slid.

In addition to being measured and recorded by the Total Station, GPS positions of the rocks were also measured weekly using a handheld Garmin GPSMap 78. The exact placement of the flag and survey rods were photographed and recorded weekly. Rocks that were determined to have moved on the ice were surveyed where they were found, and the amount and direction of roll/slide was measured using the position of the flag (which nearly always stayed in place), photos from the week prior, a measuring tape, and a compass.



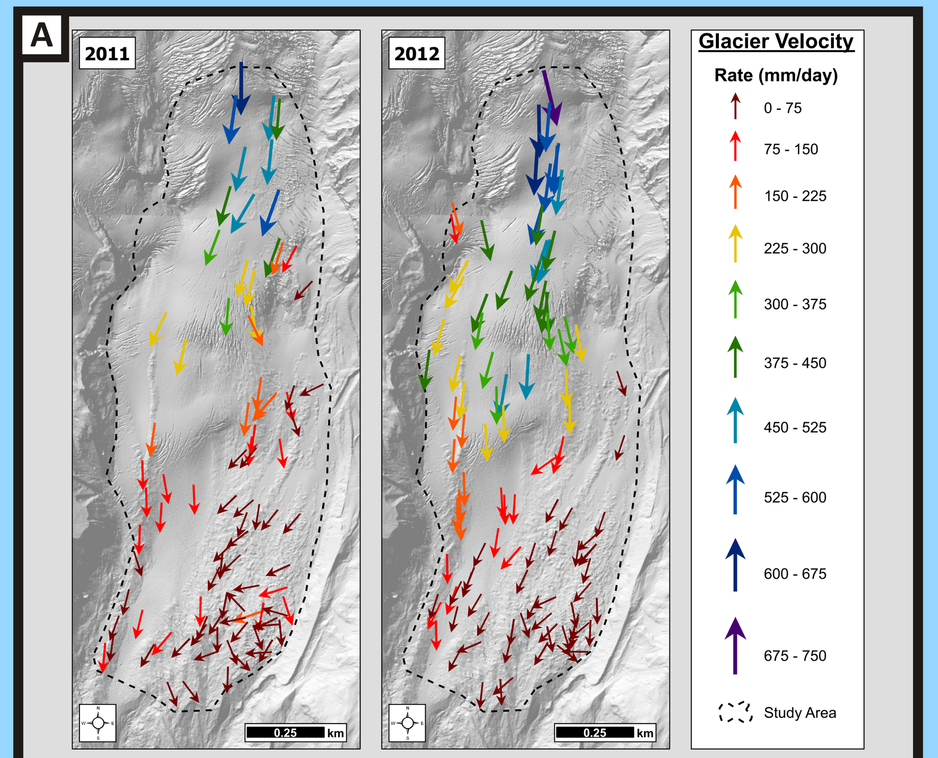




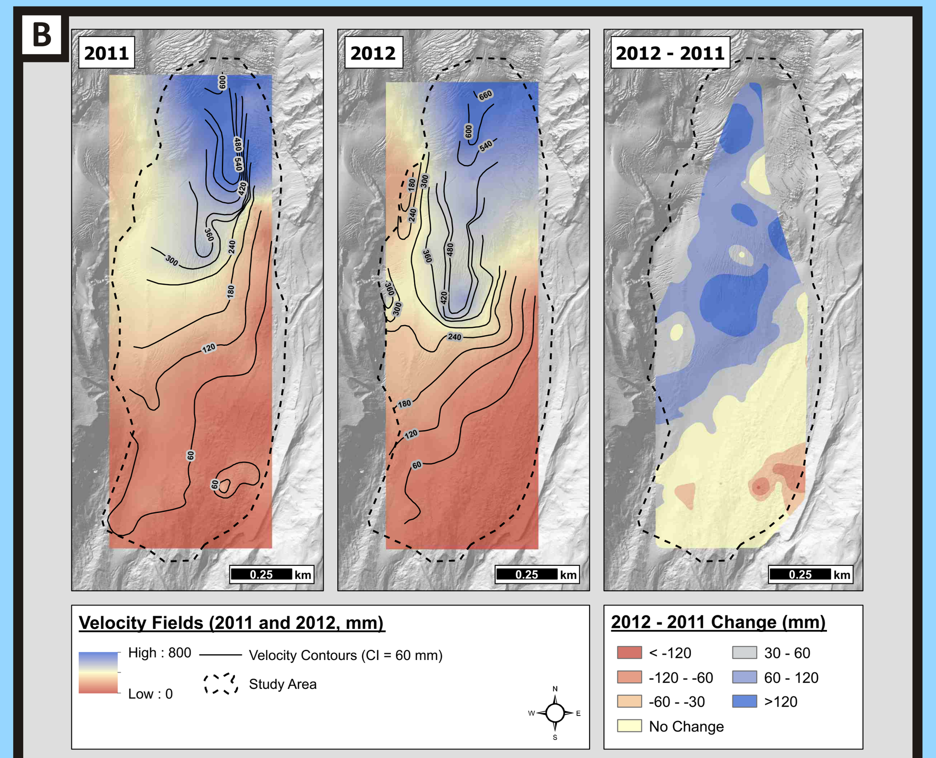
Normally if a rock falls into a crevasse that data point is lost, however, in this case the crevasse was closing and was relatively safe to venture inside. This measurement was assigned a high measurement error since it had clearly changed positions vertically. However, despite having dropped several feet down into the glacier, this rock was traveling at the same rate and in the same direction as nearby rocks.

VI. NISQUALLY GLACIAL VELOCITY RESULTS

2011 and 2012 Velocity Fields (Full Record)

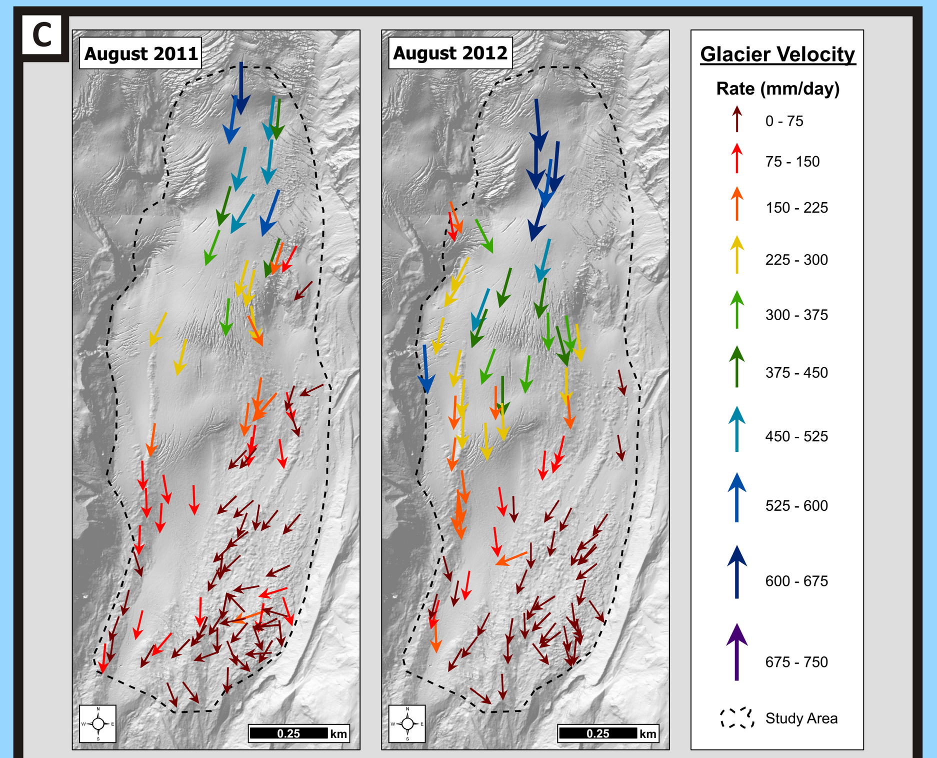


Measured data were post-processed and analyzed using ArcGIS 10.1 and Excel. A spreadsheet was designed to calculate direction of movement and positions of rocks that rolled/slid using field-measured values. Resultant data was imported into ArcGIS and used to create maps showing direction and magnitude of individual survey points on the glacier, as well as interpolated velocity fields in the survey area. In the above map, each arrow represents the average velocity of one measured point on the glacier. The 2011 data points were measured weekly from August 2011 through September 2011. The 2012 data points were measured weekly from July 2012 through October 2012.

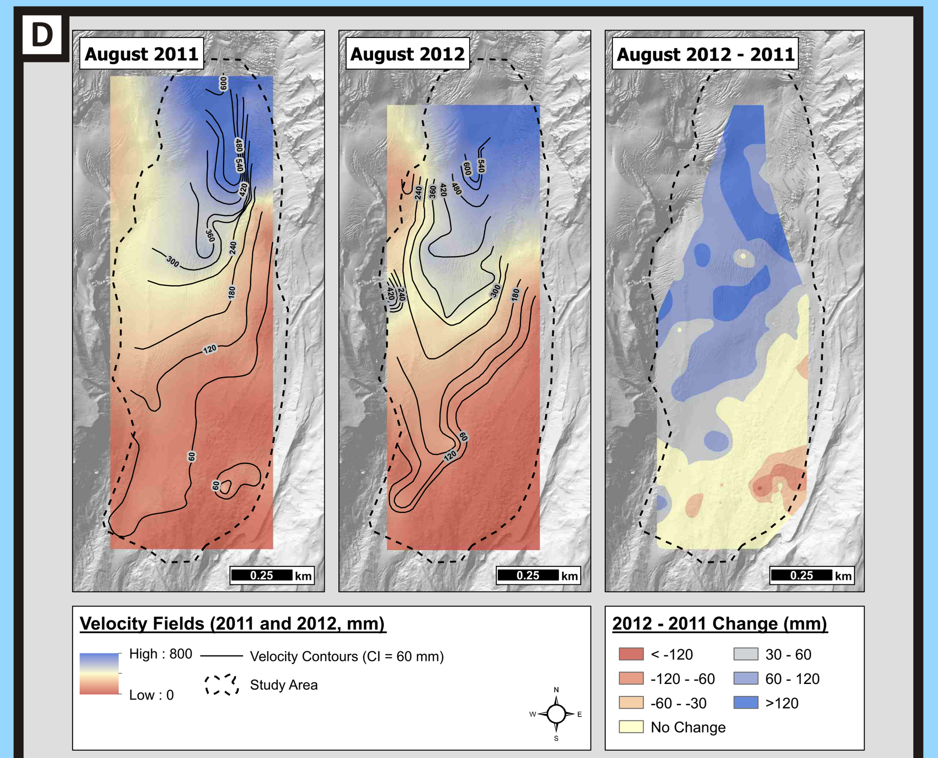


The above maps represent (from left to right) the average velocity field of the Nisqually glacier measured in 2011, the average velocity field measured in 2012, and the calculated difference between the two years. In general, the upper portions of the study area showed an increase in glacial velocity in 2012, and the lower portions either showed a decrease or no change in velocity between 2012 and 2011.

August 2011 and August 2012 Velocity Fields (Same time intervals)

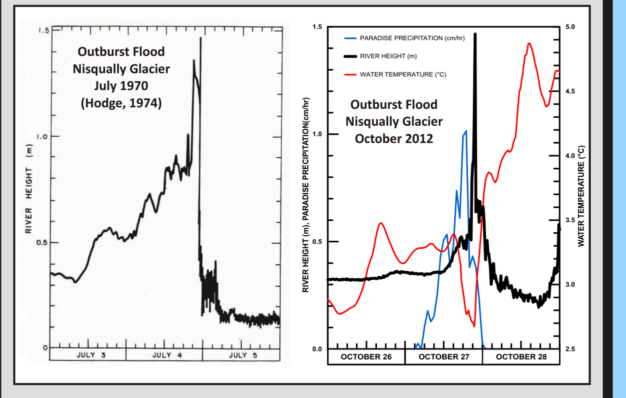


Comparison of glacial velocity between the same time periods in both 2011 and 2012. In this map, the 2012 data was limited to only include the measurements taken between the end of July and the beginning of September to correspond with the period of record from 2011. The scale is exactly the same as that in the earlier map showing the entire record.



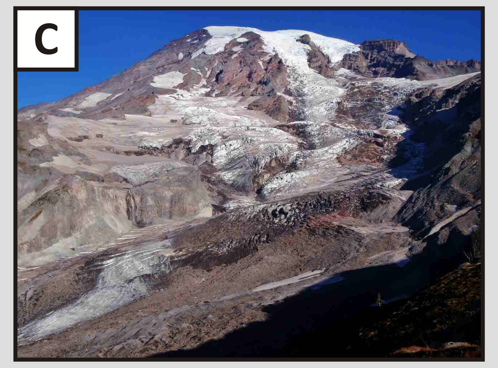
The above maps represent (from L to R) the average velocity field of the Nisqually glacier in 2011, the velocity field during the same period in 2012, and the difference between the two years. The upper portions of the study area showed an increase in glacial velocity in 2012, while the lower portions either showed a decrease or no change in velocity between 2012 and 2011, similar to the comparison between the full records (Fig VI-A). Despite slight differences between the full and limited 2012 velocity, the pattern is similar enough that our interpretation remains the same. This implies that a comparison of our data with previous surveys remains valid despite differences in survey timing.

VII. FALL 2012 GLACIAL OUTBURST FLOOD



On October 27, 2012, a small storm (RI = 1.04 yr) occurred at Mount Rainier, dropping 7.98 cm (3.14 in) of rain. Between 4:00 PM – 7:00 PM, rainfall intensity was between 0.6 – 1.0 cm/hr (0.24 – 0.40 in/hr). Starting at 8:00 PM, a stream gage in Longmire recorded a dramatic and anomalous rise in stream stage, from 0.51 m (1.66 ft) to 1.47 m (4.81 ft). The peak occurred at 9:45 PM, and employees living near the river reported hearing boulders rolling in the river and loud sounds from the river around that time. Within 15 minutes, the stream stage dropped back to around 0.6 m (2 ft). This 0.96 m (3.15 ft) rise in river level was not noted in other tributaries that feed into the Nisqually River. Additionally, stream temperature dipped noticeably during the peak flood, potentially indicating a glacial source of the surge.

The hydrograph from the October 2012 event (shown right) resembles an outburst flood hydrograph from Hodge (1974) (shown left).



Shortly after the October 2012 outburst flood was recognized in stream gage records, field reconnaissance was undertaken to find evidence for the event. Figure A shows a dramatic trim line approximately 1 m (3 ft) above the low flow of the Nisqually River near Cougar Rock, approximately 5.3 km (3.3 mi) downstream from the glacier. More evidence of a trim line (Figure B) was noted in Longmire farther downstream and a variety of other locations on the Nisqually River.

The exact source of the outburst flood on the Nisqually Glacier was not found; however, images of the Nisqually River shortly before (Figure C) and after (Figure D) the event show a band of ice that appears to have been "washed" by the event. The band begins just downstream of the confluence of the Wilson and Nisqually Glacier down to the terminus of the Nisqually. Winter weather precluded a comprehensive search for the source, however, it appears that the event was sourced on top of the glacier in the vicinity of the boundary between active, fast moving glacial ice and stagnating ice, as determined by the 2011 and 2012 surveys. This is consistent with historical accounts indicating that portions of the glacier were "swept clean" during outburst flood events (Richardson, 1968).

VIII. OUTCOMES

This study shows that measurable glacial velocity changes do occur between subsequent summers. Our data supports Hodge's observation of increased velocity in the vicinity of the ELA, concurrent with decreased velocity near the terminus prior to the occurrence of an outburst flood. If this trend is consistent and measurable, monitoring of glacial velocity would be a powerful tool in the prediction of outburst flood hazards.

Key Findings:

- Seasonal patterns of velocity exist
- Yearly velocity surveys could allow us to monitor glacier conditions and predict outburst flood hazard
- Real-time GPS tracking could potentially indicate glacier float and provide short-term outburst flood warning
- Stream gauge closer to terminus would monitor fluctuations in glacial discharge, and could allow us to detect smaller outburst floods that might be less noticeable on the stream gauges farther downstream

Continued Questions:

- What velocities are "normal" for the lower Nisqually?
- How has "normal" changed since Meier and Hodge did their studies?
- What is the outburst flood hazard now and what is it expected to be in the future?
- How will we know if outburst flood hazard changes?
- Do jökulhlaups occur when "active" ice overrides "stagnant ice?"
- Can kinematic waves cause outburst floods?
- Can kinematic waves reactivate stagnant ice and lower outburst flood hazard?
- How do velocities change in the winter?

Sources Cited:

Hodge, S.M., 1974. Variations in the sliding of a temperate glacier: Journal of Glaciology, Vol. 13, No. 69, p. 349-369.

Meier, M.F., 1968. Calculations of slip on the Nisqually Glacier on its bed: No simple relation of sliding velocity to shear stress. U.S. Geological Survey, Tacoma, WA, p. 49-57.

Richardson, D.T., 1968. Glacier outburst floods in the Pacific Northwest. Geological Survey Professional Paper, 600, 79.

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