Addendum to "The Mud Creek Debris Flow of September 20, 2014, on Mount Shasta"

Steve Romero, Steve Bachman, Juan de la Fuente, Brad Rust
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(Presented by Carolyn Napper, USFS
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Contents

BACKGROUND

Due to recent mudflow activity at Mud Creek this addendum to the report documenting the large 2014 event entitled "The Mud Creek Debris Flow of September 20, 2014, on Mount Shasta" was developed to characterize immediate and future relative risk and elaborate on possible mechanisms for the mudflows on Mud Creek.

Periodic large debris flows and floods have occurred historically at Mud Creek. These floods often carry large volumes of soil and rock with them which are deposited on the Mud Creek alluvial fan that includes Pilgrim Creek Road. Given the primary deposition zone is an alluvial fan the pathways for water flow and deposition are relatively random shifting with each event.

Baseline and historic conditions are covered extensively in the 2014 report.

OVERVIEW OF POSSIBLE DEBRIS/MUDFLOW MECHANISMS

Over the past 100 years there have been approximately nine major events at Mud Creek. The 2014 report outlines several mechanisms that could generate debris flows on Mud Creek. The most likely are summarized as follows,

Summer Convective Storms (small to medium size) – The most common. These include thunderstorms. The resulting debris flows are relatively small. The recurrence interval for this mechanism was estimated at approximately 10 to 20 years in the 2014 report.

Warm Summer Frontal Storms (medium size) - The recurrence interval was estimated at 50 years in the 2014 report.

Glacial Melt/Outbursts (medium to very large size) – 2014 was the last major event. The recurrence interval is estimated at 50 to 100 years in the 2014 report. A hypothetical failure mechanism is described in this addendum.

Warm Winter Storms (small to medium size) - Winter storms can produce warm rain up to 10,000 feet in elevation which have triggered debris flows at Mount Shasta. The recurrence interval is estimated at 30 years in the 2014 report. A similar event occurred in 1997 along a tributary of Cascade Gulch.

Less likely mechanisms were described in the 2014 report which include seismically triggered and volcanic. Both are described on as follows,

Seismically triggered events – Though earthquakes occur regularly around Mount Shasta the peak ground accelerations are low and lack the energy to cause major impacts like large landslides and rockfalls in most instances. However, a complicating factor is the topography of Mount Shasta which is essentially a cone. Like an ear trumpet that focuses sound waves topographic cones focus seismic energy. In general terms the effect of topology on the seismic response at any location is called 'topographic effects. For longer earthquake recurrence intervals (greater than 2500 years) topographic effects could increase spectral accelerations to 1 g or more at Mount Shasta. The high spectral accelerations coupled with relatively unstable geologic formations could trigger a large landslide or rockfall. Due to the large amount of energy imparted to seismically triggered landslides many would have the potential to transition to debris flows especially if saturation levels are high. As an example, the 1959 Hebgen Lake earthquake triggered a massive landslide that caused 28 fatalities and dammed the Madison River forming Quake Lake in Montana.

Volcanic triggered events – A volcanically triggered event could cause catastrophic, rapid, melting of existing glaciers on Mount Shasta. The resulting debris flows could be much larger than what has been observed in more recent history. The estimated recurrence interval is greater than 10,000 years.

Secondary mechanisms include,

Landslides – Due to unstable, over steepened slopes, landslides occur frequently along the entire Mud Creek alignment. When they occur most pinch the stream alignment temporarily impeding flow with no significant water storage upstream of the slide. The stream erodes the landslide debris until natural armoring stabilizes the stream channel. During large floods increased flow velocity and flow density (which is increased by suspended sediment and rock) can entrain large boulders transporting them downstream. As indicated in the 2014 report scour occurs along the entire Mud Creek alignment to varying degrees during large floods. Scour can trigger additional slides/debris flows on the channel slopes that may temporarily dam the creek. This is especially true during large storm events which can increase soil saturation levels. When these natural dams fail, they cause a surge in flow and debris downstream. Thus, landslides are probable contributor to debris and mud flow impacts downstream.

CLIMATE CHANGE IMPACTS ON DEBRIS FLOW MECHANISMS

A warmer atmosphere holds more water vapor. Increased atmospheric water vapor content enhances moisture convergence and rainfall intensity in storm systems. Additionally, as the atmosphere warms there is increasing evidence that average wind speeds are slowing globally leading to longer duration storms. This trend points to larger storm driven debris flows in the future around Mount Shasta.

2014 OBSERVATIONS AND ESTIMATES

The sheer volume of the debris/mudflows on Mud Creek require a tremendous amount of liquid water to transport. Critical observations were made in the 2014 report. Blocks of ice measuring 100 feet wide, 200 feet long, and 20 feet deep had dislodged from the toe of Konwakiton glacier. Two narrow outflow tracks were also observed leading from the toe of the glacier – 20 feet and 40 feet wide approximately. Slopes where the outflow tracks occurred were estimated at 55%. With that information peak outflows from the glaciers could have been in excess of 15,000 cubic feet per second using open channel flow assumptions and an average channel depth of at least 3 feet. Total sediment deposition on the alluvial fan at Pilgram Creek Road was estimated at 800,000 cubic yards. Assuming most of the sediment was transported as debris flows and a sediment/rock concentration by volume of approximately 50% at least 800,000 cubic yards of water would have been required to transport the deposited soil and rock. It is doubtful that amount of water could be stored by Kowakiton Glacier. Water contributions from antecedent soil moisture, scoured frozen soil along the stream alignment, entrained ice from the glacier, and entrained/melting ice/snow along the channel were likely contributors to the total water volume in the debris flows. The hypothesis of several of these additional water sources was supported by observations made in 2014. As seen in Figure 1 scoured frozen soil embankments were observed along the debris flow path. Additionally, the Forest Service team that surveyed the debris flow reported chunks for ice entrained in the flow. As seen in Figure 2, contributions from the Red Banks above Kowakiton glacier could have also contributed water since flow and erosion tracks are visible and appear to discharge into the glacier below.

HYPOTHETICAL GLACIAL MELT/OUTBURST MECHANISM

Due to their location the glaciers at the headwaters of Mud Creek receive significant solar radiation. Over the summer months the glaciers gradually lose mass as ice melts. With the loss of mass, the albedo of the glaciers can decrease which can lead to an increase in heat absorption and melt. Crevasses penetrate the existing glaciers from the surface to the underlying bedrock/soil. Ice along the alignment of the glaciers is in different states of lateral compression and extension. In zones of extension the crevasses are open allowing meltwater to flow from the surface of the glacier to the base. Water may flow along the contact with bedrock at atmospheric pressure or under head to the glacier toe. The flow condition would depend on incoming melt flow rates and on the flow capacity of the pathway which likely varies along the glacier alignment. A portion of the flow likely seeps into the underlying rock/soil. The flow of water causes advective heat transfer increasing the melt rate throughout the glacier. As the rate of melt increases large blocks of the glacier can shift. The shift is caused by a decrease in contact area between the glacier and underlying bedrock as the ice melts from flowing water along the glacial slide plane. The decrease in contact area increases the normal and shear stresses in the remaining ice eventually leading to failure and localized collapse. Collapses can constrict or cutoff the natural drainage pathways in the glacier. With restricted drainage liquid water storage in the glacier could increase dramatically increasing hydrostatic pressure under the glacier upstream of the constriction. As seen in other glaciers storage occurs in the Crevasse's. The additional hydrostatic pressure could unplug the drainage pathway leading to a sudden release of water from the glacier. The dislodged blocks of ice observed in 2014 could have been such an event.

An additional complication from the increased hydrostatic pressure is uplift on the glacier potentially leading to a sudden local or general movement in the glacier. Sudden movements could cause pressure transients substantially increasing hydraulic pressures in the glacier possibly leading to a local or general collapse and sudden release of liquid water. Such movements are called surges. The glaciers at the headwaters of Mud Creek are on relatively steep slopes which impart significant static shear stress in the ice at the contact with bedrock/soil. The high static shear stress and lack axial confinement make surges a real possibility.

As previously mentioned, some of the flowing water below the glacier likely seeps into the underlying bedrock/soil. Water in the bedrock/soil is probably frozen forming a bedrock/soil glacier. Advective heat transfer into the bedrock/soil would cause zones of liquid water to exist in the soil and rock. If the geologic formation under the glacier is open with high permeability large amounts of liquid water could be stored and released suddenly once the frozen colluvial soil on the slope face thaws. There is no evidence this has previously occurred but the mechanism is possible.

The hypothetical glacial mechanisms are portrayed in Figure 3.

GENERALIZED PROPERTIES OF MUD AND DEBRIS FLOWS

For reference Table 1 includes the generalized properties of sediment laden, mud, and debris flows. Estimated hazard levels have been included.

RECENT ACTIVITY AND POSSIBLE PREDICTIVE RELATIONSHIPS

Debris flow activity from all sources has increased in recent years at Mud Creek. Mud Creek experienced debris flows in 2002, 2014, 2015, 2021, and 2022 – a much greater rate than the historical record. Convective storms were responsible for debris flows in 2002 and 2015. Glacial outbursts were responsible for debris flows in 2014, 2021, and 2022. In addition, multiple glacial outbursts occurred in both 2021 and 2022. Given that debris flow activity over past two years coincided with periods of extreme to exceptional drought the drought record was investigated for similar trends.

A review of the historical drought record over the short and long term appears to show a strong correlation between drought severity and debris flows at Mud Creek. Figure 5 is the short-term drought severity over the past 20 years in the McCloud watershed which Mud Creek is a part of (Figure 4). Figure 6 shows the long-term drought severity since 1895 in the Upper Sacramento watershed. Vertical lines on both figures are occurrences of debris flow events. The primary metric both plots use is the Palmer Drought Severity Index (PDSI). There are several forms of the metric (and related factors) which are used to estimate long term drought severity. The PDSI was originally intended for agricultural use but has been extended to estimate long term drought conditions in most watersheds by the U.S. Drought Monitor and West Wide Drought Tracker. The PDSI is calculated using precipitation, temperature, and local available soil water content (computed using runoff and water flux in and out of the soil). The U.S. Drought Monitor is produced through a partnership between the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture and the National Oceanic and Atmospheric Administration. The West Wide Drought Tracker is produced by a partnership between the University of Idaho, Western Regional Climate Center, and the Desert Research Institute.

There appears to be a good correlation between drought severity and conditions on the glaciers at the headwaters of Mud Creek that lead to outbursts. As can be seen in Figure 5 over the past 20 years outbursts have occurred during periods of extreme or exceptional drought conditions in the McCloud watershed. An interesting aspect of the observation is that extreme drought conditions over 100% of the watershed seem to be required for outburst risk to be elevated. Also, extreme drought conditions may need to persist at least a few months to increase outburst risk. An attempt was made to estimate glacial stability and debris erosion/deposition processes in Figure 5 based on field observations and available data.

A similar correlation is seen for the longer record in Figure 6 for the Upper Sacramento watershed which the McCloud watershed is part of. Over the past 128 years when severe/extreme drought occurs in the Upper Sacramento watershed (PDSI < -3) there was a high probability that an outburst on Mud Creek would occur. In some instances, there appears to be a delay between when severe drought conditions are met and the eventual outburst. This could be due to several factors which might include,

- A lesser correlation of the larger watershed to local conditions in the McCloud watershed.
- Convective storms.
- Structural instabilities that developed during extreme drought conditions and eventually failed during the next warming cycle.

As was seen in 2021, 2022, and (possibly) the 1920's debris flow events when a glacial outburst occurs the risk of additional outburst is significantly elevated. It is likely that multiple debris flows occurred during periods of glacial outburst activity but were never recorded.

In both the long and short records extreme drought conditions appear to significantly increase the likelihood of a glacial outburst Mud Creek.

CONCLUSION

Short term risk and recommendations

Over the past 100 years there have been about 9 significant debris flow events/periods at Mud Creek from all mechanisms. Periods include multiple debris flow events over the same season. Based on available data and assuming a binomial distribution the likelihood of a significant debris flow event occurring at Mud Creek over the next two years is about 16%. If a debris flow event occurs there is a 44% chance at least one more event will occur during the same year. The likelihood of a significant debris flow event occurring in the next 5 years is about 31%.

Glacial outburst activity and the associated debris flows appear to be strongly correlated to drought severity with probability of debris flow events increasing significantly when drought conditions in the McCloud watershed are extreme or exceptional.

The available data suggest Pilgram Creek road should be closed when drought conditions in the McCloud watershed are extreme or exceptional or when significant storm events are forecast. If the road is reopened signage indicating the potential risk is a critical component of risk management. Similar signage exists for areas where there is significant natural hazard risk along transportation corridors including, but not limited to, rockfall, landslide, debris flows (in general), avalanche, flooding, tsunami...etc...

Long term risk

Rising global air temperatures will likely exacerbate storm and glacial caused debris flows on Mount Shasta.

If the described hypothetical glacial outburst mechanism is reasonably accurate it could indicate increased downstream risk in the future from glacial outburst generated debris flows as glaciers become more unstable.

Increasing global temperatures increase the capacity of the atmosphere to hold water. Increasing temperatures may be slowing winds globally. Thus, precipitation events in the future will have the potential to be more intense and of longer duration leading to larger storm generated debris flows on Mount Shasta. A changing hydrologic landscape from increased wildfire activity will compound the situation by increasing the risk of amplified post fire runoff and debris flows during the recovery period after fires. Post fire recovery of the landscape could extend far longer than predicted during periods of persistent drought. Thus, the risk of larger storm generated debris flows will increase in the future resulting in increased impacts downstream.

ADDITIONAL REFERENCES

Aiguo, D. (2011) *Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008.* Journal of Geophysical Research, Vol. 116, D12115

Bradley, J.B. (1986). *Hydraulics and bed material transport at high suspended sediment concentrations* (140 pp) Ph.D. Thesis, Colorado State University

Chudley, T. R., Christoffersen, P., Doyle, S. H., Dowling, T. P. F., Law, R., Schoonman, C. M., et al. (2021). *Controls on water storage and drainage in crevasses on the Greenland Ice Sheet.* Journal of Geophysical Research: Earth Surface, 126, e2021JF006287.

De la Fuente, J., Mikulovsky, R., Bachman, s., Courtney, A., Schneider, F., Meyers, N., Coots, F., Dooley, M., Veich, D., Rust, B., (2014) *The Mud Creek Debris Flow of September 20, 2014 on Mount Shasta.* USDA Forest Service

Dodgshun, J. (2017) *The stilling: global wind speeds slowing since 1960,* European Union Horizon Magazine.

Kotlyakov V.M., Osipova G.V., Tsvetkov D.G. (2008) *Monitoring surging glaciers of the Pamirs, Central Asia from Space.* Annals of Glaciology, vol. 48, pp. 125-133

Kotlyakov V.M., *Global warming and surging glaciers,* UN Chronicle

Palmer, W. C. (1965), *Meteorological drought, Rep. 45,* 58 pp., U.S. Dept. of Commerce, Washington, D. C.

Robbins, J. (2022) *Global 'Stilling': Is climate change slowing down the wind?,* Yale Environment 360, Yale School of the Environment.

Zheng, W. (2022) *Glacier geometry and flow speed determine how arctic marine-terminating glaciers respond to lubricated beds.* The Cryosphere, 16, 1431–1445

FIGURES AND TABLES

TABLE 1: Characteristics of Sediment Laden, Mud, and Debris Flows (Modified and adapted from Bradley, 1986)

<table>
<tr><td colspan="8">Flow Bulking Factor</td></tr>
<tr><td>0</td><td>1.11</td><td>1.25</td><td>1.43</td><td>1.67</td><td>2.00</td><td>2.50</td><td>>3.33</td></tr>
<tr><td colspan="8">Sediment Concentration by Weight (100% by weight = $1x10^6$ ppm)</td></tr>
<tr><td>0</td><td>23</td><td>40</td><td>52</td><td>63</td><td>72</td><td>80</td><td>87 to 100</td></tr>
<tr><td colspan="8">Sediment Concentration by Volume (specific gravity of suspended material = 2.65)</td></tr>
<tr><td>0</td><td>10</td><td>20</td><td>30</td><td>40</td><td>50</td><td>60</td><td>70 to 100</td></tr>
<tr><td colspan="2">Normal Stream Flow</td><td colspan="2">Hyperconcentrated flow</td><td colspan="2">Debris/Mud Flow</td><td colspan="2">Landslide</td></tr>
<tr><td colspan="2">Newtonian</td><td colspan="2">Non-Newtonian</td><td colspan="2">Non-Newtonian</td><td colspan="2">Non-Newtonian</td></tr>
<tr><td colspan="2">Utilize depth x velocity curves to determine hazard</td><td colspan="2">High Hazard at any depth</td><td colspan="2">High Hazard at any depth</td><td colspan="2">High Hazard at any depth</td></tr>
</table>

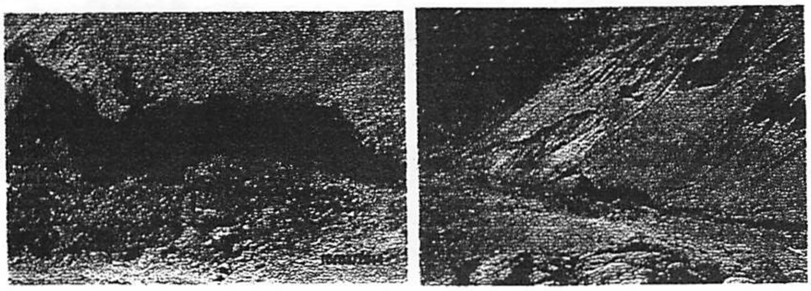

FIGURE 1: Scour of frozen soil embankment by glacier outburst flood in 2014

FIGURE 2: Water erosion and tracks from Red Banks into Konwakiton Glacier

FIGURE 3: Hypothetical Glacier Outburst Mechanism (see attachment)

FIGURE 4: McCloud Watershed

FIGURE 5: Drought Monitor vs Mud Creek Debris Flows Since 2000 (see attachment)

FIGURE 6: Drought Monitor vs Mud Creek Debris Flows Since 1895 (see attachment)