Glacier Peak and the Chocolate Factory: Recurring debris flows from the eastern flank of Glacier Peak stratovolcano, North Cascades, Washington State, USA

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Glacier Peak and the Chocolate Factory: Recurring debris flows from the eastern flank of Glacier Peak stratovolcano, North Cascades, Washington State, USA

By

Edward M. Fordham

Accepted in Partial Completion of the Requirements for the Degree Master of Science

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Edward M. Fordham

April 2022
Glacier Peak and the Chocolate Factory: Recurring debris flows from the eastern flank of Glacier Peak stratovolcano, North Cascades, Washington State, USA

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Edward M. Fordham
April 2022
Abstract

Alpine mass wasting events can have wide ranging impacts that extend past their headwater origins reaching down to lowland population centers. The Suiattle River, which drains the eastern flank of Glacier Peak in the North Cascades of Washington State, is a dominant contributor of suspended sediment in the region. Normalized for drainage area, the Suiattle River supplies more suspended sediment than nearly any other river in the region and more than twice as much as the White Chuck River, which drains the western flank of the volcano. Despite its known importance to the regional sediment budget, the specific geomorphic drivers of the anomalous sediment load on the Suiattle have received relatively little attention in the literature. In this study, I build on previous work to explore the magnitude, timing, triggering mechanisms, and the spatial distribution of sediment loading events in the Suiattle River Basin.

My historical analysis shows that major debris flow activity initiated in the late-1930s, with a total of nine historic debris flows since then (RI = 9.3 years). One previously unreported circa late-1940s debris flow was identified from reanalysis of dendrochronology (Slaughter, 2004) and historical aerial imagery. From topographic differencing, I placed a minimum bound of ~4.9 M m³ (±0.6 M m³) on the material incised from the most recent valley filling debris flow deposits. Historical accounts suggest that major debris flows happen at the hottest times of the year in the absence of precipitation, with two eyewitness accounts of debris flows triggered by glacial outburst floods. Historical photos, remote sensing, and field measurements of terrace heights suggest that incision into historic debris flow deposits occurs soon after deposition and tapers after the first few years.
To examine smaller more recent debris flows, I created a framework to automatically extract debris flow timing, duration, and magnitude from USGS turbidity and discharge data over the period 2011 to 2020. I identified 28 individual debris flow events that occurred in every year in the record. To evaluate triggering mechanisms, I calculated prior day maximum temperature anomalies for all non-debris flow days and for days when a debris flow started. Debris flow start days were shown to be statistically warmer than non-debris flow days (mean of -0.21 °C and 2.48 °C, respectively; ks test, $d_m = 0.314$, $p = 0.007$). This suggests that minor debris flows are triggered by high temperatures and, like the historical major debris flows, points to glacier outburst floods as the primary initiation process. I estimate suspended sediment loads attributable to minor debris flows, anomalous sediment flushing events following debris flows, and suspended sediment loads outside of these categories. Together debris flows and flushing account for ~21% of the mean annual load on the Suiattle.

At Glacier Peak, Chocolate Glacier is unique. Its high propensity for glacier outburst floods makes it the dominant source of debris flows and suspended sediment, vastly outweighing contributions from other glaciers on the mountain. The frequency and magnitude of debris flows from Chocolate Glacier bare similarities to South Tahoma Glacier at Mount Rainier.

Combined, my findings show that debris flows deliver large quantities of sediment to the mainstem river at both annual and decadal timescales. This work is a step toward understanding how sediment supplied from alpine mass wasting events shapes downstream geomorphic processes. My findings have implications for how ongoing climate change may alter cascading hazards in these systems.
Acknowledgments

As a student of geomorphology, I have been fortunate to have learned from many inspirational scientists and I would like to acknowledge the contributions of all my past teachers here. Specifically, I thank my advisor, Dr. Allison Pfeiffer, for sharing her ideas and for showing me the tools and helping me build the skills necessary for becoming a fluvial geomorphologist. During data analysis sessions where we ‘dove into the data’, Allison showed me that it is possible to have a bit of fun even while tackling complex problems. Allison’s positive attitude, patience, and persistence helped make this research possible. I thank my committee members Dr. Colin Amos, Dr. Andy Bunn, and Dr. Doug Clark for the guidance and support they provided and for hanging in there with me through a thesis that was completed mostly during the turmoil of the COVID-19 pandemic. I am grateful to the entire faculty and staff of the Western Geology department who were always welcoming and helpful. I thank Scott Anderson for sharing his time, data, and equipment to help a student accomplish a goal. Pilot John Scurlock graciously provided aerial imagery. Jim Vallance shared resources from his work at Glacier Peak.

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# Table of Contents

Abstract .......................................................................................................................................... iv

Acknowledgements ......................................................................................................................... vi

List of Tables and Figures ............................................................................................................... ix

Introduction ........................................................................................................................................ 1

My Study ........................................................................................................................................... 6

Terminology ....................................................................................................................................... 8

Study Area ......................................................................................................................................... 10

Geographic and hydrologic setting ................................................................................................. 10

Historic accounts of geomorphic change in the Suiattle ................................................................. 12

Methods ............................................................................................................................................ 14

Dating historic debris flows .............................................................................................................. 14

Field observations of debris flow terraces ....................................................................................... 15

Dendrochronology ............................................................................................................................ 15

Interpolated surface differencing .................................................................................................... 18

Sediment conversions ....................................................................................................................... 20

Contemporary debris flow analysis .................................................................................................. 20

Contemporary debris flow meteorological triggers ......................................................................... 22

Estimating suspended sediment loads ............................................................................................ 23

Results .............................................................................................................................................. 24

Historical imagery ............................................................................................................................ 24

Identifying terraces ........................................................................................................................... 25
List of Tables and Figures

Table 1: Dendrochronology samples .................................................................67
Table 2: Summary statistics for debris flow temperature anomalies ..................67
Table 3: Summary statistics for prior day precipitation ......................................67
Table 4: Suspended sediment loads per water year ...........................................68
Table 5: Cumulative suspended sediment loads .................................................69
Table 6: Major debris flows .............................................................................70

Figures

Figure 1: Study area map ..................................................................................71
Figure 2: Glacier Peak stratovolcano annotated satellite image .........................72
Figure 3: Lower Sauk gauge as a proxy for suspended sediment on the Suiattle ....73
Figure 4: Discharge and turbidity relationships ..................................................74
Figure 5: Suiattle Basin in western Washington State map ..................................75
Figure 6: Geology and topography map .............................................................76
Figure 7: Photos from Miners Ridge ..................................................................77
Figure 8: Circa 1956 photo of the upper Suiattle Valley .....................................78
Figure 9: Interpolated differencing methods......................................................79
Figure 10: Turbidity residual analysis methods ..................................................80
Figure 11: Turbidity residuals vs. time ...............................................................81
Figure 12: Frequency distributions of turbidity residuals ....................................82
Figure 13: Field and LiDAR identified debris flow terraces ...............................83
Figure 14: Terrace height example profile and profile locations .......................84
Figure 15: Field and LiDAR measured terrace heights .........................................................85
Figure 16: Dendrochronology minimum surface ages ..........................................................86
Figure 17: Locations of dendrochronology samples ............................................................87
Figure 18: Photographs of crossdated standing dead ‘ghost tree’ .........................................88
Figure 19: Interpolated surface differencing results ............................................................89
Figure 20: Interpolated surface differencing uncertainty ......................................................90
Figure 21: Contemporary debris flow analysis results ..........................................................91
Figure 22: Temperature anomaly frequency distribution .....................................................92
Figure 23: KS test for temperature anomalies ......................................................................93
Figure 24: Precipitation frequency distributions ..................................................................94
Figure 25: KS test for precipitation ......................................................................................95
Figure 26: Suspended sediment budget for the Suiattle Basin ..........................................96
Figure 27: Cumulative suspended sediment with debris flows and flushing time series .........97
Figure 28: Historical aerial imagery analysis ........................................................................98
Figure 29: 1950s photos of post debris flow impacts ..........................................................99
Figure 30: Debris flow scarp historical aerial imagery 1944 and 1950 ...............................100
Figure 31: Confluence of Suiattle River and Dusty Creek 1944 and 1950 .........................101
Figure 32: Reanalysis of Slaughter (2004) dendrochronology ...........................................102
Figure 33: Confluence of Suiattle River and Dusty Creek 1974 and 1979 .........................103
Figure 34: Aerial imagery of Chocolate Creek and Chocolate Fan ....................................104
Figure 35: Debris flow, flushing, and other suspended sediment bar graph .....................105
Figure 36: Incision along Chocolate Creek since 2003 .....................................................106
Figure 37: Conceptual model of debris flow sediment export in the upper Suiattle ..........107
Introduction

Steep, geomorphically active headwater streams deliver the majority of sediment supply to larger downstream basins (Anderson and Pitlick, 2014); their effect on basin-scale sediment supply is often disproportionate relative to their drainage area (Milliman and Syvitski, 1992). Geomorphic disturbances in alpine headwaters can cause drastic increases in sediment supply which can be expressed as periods of anomalously high suspended sediment concentration downstream, and discrete pulses of coarse sediment influxes in the headwaters.

Identifying sediment sources and the geomorphic processes responsible for sediment delivery in headwater basins can help to explain the sediment supply regime of downstream basins and provide insight into future sediment loads, which is crucial information for river management, restoration efforts, and hazard mitigation (Czuba, 2012; Anderson and Pitlick, 2014; Pfeiffer et al., 2017; Pfeiffer et al., 2019). Understanding how basins respond to sediment supply disturbances from alpine headwaters is becoming increasingly important as ongoing anthropogenic climate change threatens to alter sediment production and transport in alpine systems (Czuba, 2012; Mauger et al., 2015; Jaeger et al., 2017).

Alpine mass wasting events are common in the Pacific Northwest. They vary in rheology, magnitude, and frequency of occurrence and are driven by a wide range of triggering mechanisms. There is a growing body of literature linking climate change to shifts in the magnitude and frequency of alpine mass wasting events (e.g., Coe et al., 2018; Bessette-Kirton and Coe, 2020; Friele et al., 2020; Morino et al., 2021; Shugar et al., 2021). Mass wasting events
can vary in size, from events that fill river valleys, stripping or burying mature forests, to smaller events that, although destructive in the headwaters, do not cause large-scale geomorphic change in the valleys downstream. One type of mass wasting event particularly important for sediment delivery is debris flows (e.g., Czuba et al., 2012). Debris flows are highly mobile slurries of sediment and water (Pierson and Costa, 1987) and their long runout distances often result in direct sediment delivery from alpine slopes to river channels (Czuba et al., 2012). On the upper end of the mass wasting spectrum, the August 6th, 2010 Mount Meager landslide in the Coast Mountains of southwest British Columbia mobilized ~ 50 x 10^6 m^3 of volcanic sediment and rock from partially glaciated slopes. It transformed into a debris flow, delivering large volumes of sediment to the downstream Lillooet River (Guthrie et al., 2012; Huggel et al., 2012). On the lower end of the mass wasting spectrum, the August 13, 2015 debris flow on the upper Suiattle River, identified from a downstream turbidity spike (Jaeger et al., 2017) and later by topographic differencing at the source zone (S. Anderson USGS, pers. comm., 2020), left little valley scale geomorphic change in its wake.

Climate change has the potential to increase the frequency of alpine mass wasting hazards due to glacial debuttressing (e.g., Evans and Clague, 1994), glacier retreat (e.g., O’Connor and Costa, 1993; Stoffel and Huggel, 2012), and rock-permafrost degradation (e.g., Coe et al., 2018). Additionally, a shift in precipitation from snow to rain in alpine regions (e.g., Mauger et al., 2015), reduced snowpacks (e.g., Mauger et al., 2015), and increasing intensity of rainfall (e.g., Salathé, 2006; Warner et al., 2014) can also contribute to a higher frequency of alpine mass wasting events (Major et al., 2021). The 2010 Mt. Meager landslide was preceded by weeks of high temperatures reaching up to 20°C (Guthrie et al., 2012; Huggel et al., 2012). This event
provides a regional example of how climate drivers causing glacier retreat (Oerlemans et al., 1994) and permafrost degradation may trigger high magnitude alpine mass wasting events (Huggel et al., 2012). Smaller events, too, have been connected to alpine warming. The August 14, 2001 Van Trump debris flow from the Kautz Glacier at Mount Rainier initiated when high temperatures contributed to accelerated melting (Vallance et al., 2002). Ultimately, a meltwater diversion triggered a debris flow in unconsolidated glacial sediments.

Glacier outburst floods can also trigger debris flows. These outburst floods are observed predominantly in the summer and early fall (Richardson, 1968; Scott et al., 1995) during both rainless, hot weather periods and during periods of heavy rains (Walder and Driedger, 1995). Both triggers lead to the buildup of water within as well as below the glacier (Walder and Driedger, 1995). Such melt-water triggered debris flows are particularly well studied on Mount Rainier, Washington. National Park infrastructure provides easy access, and the debris flow chronology is likely more complete than at any other Cascade volcano (Copeland, 2009). In a study of debris flows in the Tahoma Creek Valley at Mount Rainier spanning 1967 to 1992, Walder and Driedger (1995) found that 15 out of 23 debris flows occurred on hot, dry days. These debris flows predominantly emanated from South Tahoma Glacier; all but one were attributed to glacier outburst floods (Walder and Driedger, 1995). Two common debris flow triggering mechanisms, high summer temps and intense rainfall, are both expected to become more frequent under anthropogenic climate change (Mauger et al., 2015).

Debris flows typically originate on steep slopes in loose, poorly sorted sediment (Iverson, 1997). At Mount Rainier, initiation occurs in steep gullies cut into Quaternary pyroclastic and morainal
deposits, fed by glacial meltwater (Lancaster et al., 2012). These initiation points tend to be located in proglacial zones exposed by glacial retreat within the last century (Lancaster et al., 2012). Studying a 2006 atmospheric river event, Legg et al. (2014) found that gullies were more likely to produce debris flows when they had steeper slopes and greater lengths, suggesting that the debris flows in this setting initiate when the channel bed fails, and increase in magnitude via sediment bulking from down-valley gully wall failure.

Sediment pulses often result from alpine mass wasting events delivering sediment directly into the fluvial network. The fate of this material has implications for downstream hazards and ecosystem function. The post-eruption fluvial response at Mount St. Helens is a well-studied example of river evolution in the wake of extreme sediment loading (e.g., Gran et al., 2011; Major et al. 2019; Major et al., 2021). The debris avalanche and pyroclastic flows triggered by the May 18, 1980 eruption at Mount St. Helens buried the North Fork Toutle River locally to a maximum of ~150 m (Uhrich et al., 2021). Lahars sourced from the Toutle River Basin transported sediment all the way down to the Columbia and deposited about $28 \times 10^6$ m$^3$ of sediment in less than 24 hours, making the Columbia’s navigational channel unpassable for large ships (Hubbell et al., 1983). In the upper reaches of the North Fork Toutle River, in the first few years immediately following the eruption, channels reestablished primarily through rapid vertical incision of tens of meters into the debris avalanche deposit and through lateral widening of the channel (e.g., Major et al., 2018). In the decades following channel reestablishment, channels have become more stable and lack the initial drastic changes seen earlier on, but sediment export from the North Fork Toutle River remains 10 times greater than pre-eruption levels, owing largely to erosion from the channel (Major et al., 2021). Although sediment loads at Mount St.
Helens have decreased since the 1980 eruption, the expected duration of the elevated sediment loads, and associated engineering and management challenges, remains less well constrained (Uhrich et al., 2021).

Glaciated volcanoes are the dominant contributors of sediment to the Salish Sea (Czuba et al., 2011), and therefore likely drivers of lowland river change – even in the absence of syneruptive sediment loading. Hydrogeomorphic studies have investigated glaciated Cascades Volcanoes to determine sediment sources, quantify sediment loads, and develop baselines for understanding future fluctuations from climate change (e.g., Czuba et al., 2010; Czuba et al., 2012; Curran et al., 2016; Jaeger et al., 2017). Excess coarse sediment sourced from alpine headwaters can fill in channels, thereby reducing the channel’s capacity to contain high discharge events. This aggradation can result in an increased frequency of flooding (Slater, 2015). Recent work in the Pacific Northwest found that channels with glaciers in upstream catchments are subject to more dramatic aggradation and incision than rivers draining unglaciated catchments (Pfeiffer et al., 2019). Although it seems likely that alpine mass wasting sediment pulses play a role in this river channel variability, the pervasiveness of this connection remains uncertain.

The recent removal of several major dams in the region has created opportunities to study the fluvial response to abrupt increases in sediment supply, and the likelihood of future dam removals motivates further work to understand these processes. Unlike alpine mass wasting, dam removals are planned events that typically occur further downstream in river systems and are well suited to detailed observational study. Intensive monitoring of geomorphic response to dam removal at two dams in the Cascades Range, Marmot Dam on the Sandy River in Oregon (Major
et al., 2012), and at Condit Dam on the White Salmon River in Washington State (Wilcox et al., 2014), showed rapid export of the reservoir sediment in both cases despite differences in the grain size of the trapped sediment deposit (~50% gravel and 50% sand; 60% sand, 35% silt and clay, 5% gravel; respectively). On the Elwha River, in the Olympic Mountains of Washington State, phased removal of the Elwha and Glines Canyon Dams resulted in ~90% of the impounded sediment being transported through the river and reaching the sea within the first two years following the start of the dam removal process (Warrick et al., 2015). Observations of geomorphic response to immense sediment influx following dam removal can help to inform expected geomorphic responses to sediment loading in natural systems. In turn, natural systems can add insight into expected responses at dam removals. Thus, both settings can help to fill in knowledge gaps about river response to extreme sediment loading and the underlying geomorphic processes in a wide range of settings.

My Study

The Suiattle River drains the northeast flank of Glacier Peak, a remote stratovolcano in the North Cascades of Washington State (Fig. 1). Chocolate Creek a headwater tributary of the Suiattle feeds the system with glacial meltwater from Chocolate glacier (Fig. 2). The Suiattle is a dominant source of suspended sediment to the Skagit River, which is the greatest contributor of sediment to the Salish Sea (Czuba et al., 2011; Czuba et al., 2012; Jaeger et al., 2017). The unusually high sediment loads have been attributed to mass wasting events in the headwaters by Jaeger et al. (2017).
Jaeger et al. (2017) used three United States Geological Survey (USGS) gauging stations that measure discharge and turbidity to estimate the suspended sediment flux from the Sauk river and its two main tributaries, the Suiattle and White Chuck rivers, during the period from October 2011 to September 2016 (Fig. 1). The distribution of gauges within the Sauk Basin allowed them to use the difference between a mid-basin gauge and lower basin gauge as a proxy for sediment flux exiting the Suiattle Basin (Jaeger et al., 2017; Figs. 1 and 3). Based on seasonal trends in turbidity and discharge at the Lower Sauk gauge, Jaeger et al. (2017) concluded that whereas wintertime discharge and turbidity largely track each other, in the summertime turbidity was largely independent of discharge, suggesting that glacial processes (e.g., relatively low magnitude outburst floods or meltwater events) and/or episodic sediment pulses controlled turbidity magnitude, timing, and duration in the summer (Fig. 4).

Previous work has pointed to large debris flows in the mid- to late- 20th century, along with smaller contemporary debris flows, as a likely source of suspended sediment in the upper Suiattle (Ford, 1959; Richardson, 1968; Beget, 1982; Slaughter, 2004). Outburst Canyon, draining Chocolate Glacier, has been named as a likely source of the recurrent debris flows (Fig. 2). The Jaeger et al. (2017) study found that a debris flow that occurred on August 13, 2015 in the upper Suiattle basin contributed up to 20% of the entire suspended sediment load delivered to the Sauk over a 5-year monitoring period that took place from 2011 to 2016. Topographic differencing in the headwaters of Chocolate Creek located the debris flow source area at the terminus of Chocolate Glacier and constrained the volume of material eroded to a minimum of ~400,000 m³ (Jaeger et al., 2017; S. Anderson USGS, pers. comm., 2020). Other debris flow events reported throughout the 20th and 21st centuries caused changes to downstream river
morphology, damage to infrastructure, extensive debris flow terrace deposits, and abnormally elevated suspended sediment levels (Ford, 1959; Richardson, 1968; Slaughter, 2004). Suspended sediment sourced from the Suiattle accounts for ~80% of the total annual load of the Sauk River Basin (Jaeger et al., 2017). Jaeger and others (2017) estimated that the majority of the suspended sediment exiting the Suiattle originates from Chocolate Creek in the upper basin, which drains the eastern flank of Glacier Peak (Jaeger et al., 2017; Figs. 1 and 2).

Despite its importance in the regional sediment budget (Czuba et al., 2010), the geomorphology of the upper Suiattle has received little attention in the published literature. Glacial sediment production (Jaeger et al., 2017), debris flows (Slaughter, 2004; Jaeger et al., 2017), and a generally sediment-rich environment related to the basin’s Quaternary volcanic and glacial histories (Jaeger et al., 2017) have all been named as possible explanations for the anomalous sediment load on the Suiattle. However, the magnitude, frequency, and triggers of sediment loading events in the upper Suiattle remain poorly constrained. In this study, I build on previous work by beginning to constrain the geomorphic processes responsible for the high sediment load, including: the magnitude and timing of sediment loading events, triggers, and the spatial distribution of the sediment loading in the basin.

**Terminology**

Debris flows can be defined by having a very high proportion of sediment (70-90% by weight) to water in their flow (Costa, 1988). At these sediment proportions, water and sediment move as a single homogenous body, and the competence of the flow is powerful enough to buoy and
transport boulders at high velocity for several kilometers (Pierson and Scott, 1985; Pierson and Costa, 1987; Costa, 1988; Czuba et al., 2012). Debris flows are often differentiated by their clay content, where flows with greater than ~3 to 5% clay by weight are cohesive and flows with less than ~3 to 5% clay are noncohesive (Scott et al., 2001). In contrast to true debris flows, hyperconcentrated flows of water and sediment carry ~40 to 70% sediment by weight (Costa, 1988). During actual events, mass flows commonly occur in surges with varying sediment concentrations that transform between true debris flow concentrations and hyperconcentrated flows (Scott and Yuyi; 2004). Debris flows discussed here can be considered sediment rich and likely fall along a gradient of sediment concentration from debris flows to hyperconcentrated flows.

All debris flows discussed in this study are volcanic debris flows in that the source material is volcanic tephra from the eastern flank of Glacier Peak stratovolcano. Technically, any debris flow emanating from the flanks of an active volcano can be described by the term ‘lahar,’ regardless of the presence of a volcanic triggering mechanism (Crandell, 1971; Pierson and Scott, 1985; Vallance and Scott, 1997; Czuba et al., 2012). I do not use the term lahar to describe these volcanic debris flows to aid in differentiating them from older, syneruptive lahar deposits present in the study area.
Study Area

Geographic and hydrologic setting

The study area lies in the Mount Baker – Snoqualmie National Forest with the upper Suiattle River falling completely within the Glacier Peak Wilderness (Fig. 5). The lower 50 km of the Suiattle River are protected as a part of the Skagit Wild and Scenic River System. These legal protections have aided in the Suiattle basin remaining one of the last undammed river networks draining alpine terrain in Washington State (Jaeger et al. 2017). As such, the area remains relatively pristine, supporting a robust evergreen forest ecosystem and a genetically distinct salmon population, the Suiattle Spring Run Chinook (Beamer et al., 2005). The basin also serves as a source of fresh water for downstream communities (Slaughter, 2004). The remote setting of the Suiattle – Glacier Peak Study area and Glacier Peak’s lack of visibility from major metropolitan areas have led to its tendency to be understudied in terms of geology and hazards when compared to other stratovolcano areas in the Pacific Northwest (Mastin and Waitt, 2000).

After descending the eastern flanks of Glacier Peak, the Suiattle River joins the Sauk River, which flows into the Skagit River, eventually draining into the Skagit Bay southwest of Mt Vernon, WA (Fig. 5). The Skagit Bay is connected to the Salish Sea. Drainage area for the entire Suiattle Basin is roughly 890 km², of which proglacial zones on the eastern flank drain ~60 km². Elevation in the study area ranges from ~ 3214 m at the summit of Glacier Peak to ~93 m downstream on the Sauk River (Fig. 1). Average precipitation increases with elevation in the basin from about 80 cm/year in the lowland valleys to over 460 cm/year around Glacier Peak (Beechie et al., 2001). Precipitation falls primarily as snow at higher elevations and as rain at
lower elevations, with portions of the alpine basins wavering between receiving rain or snow (NSD, 2014). The mean annual hydrograph exhibits two peaks in discharge corresponding to high magnitude spring snowmelt and a fall rainy season (Jaeger, et al. 2017). The study area is about 20 miles east by road from the town of Darrington, Washington (Fig. 5). In 2015, a 1-meter resolution LiDAR dataset covering Glacier Peak and its drainages down to the Sauk was compiled and made publicly available (lidarportal.dnr.wa.gov; Fig. 1).

Bedrock geology in the North Cascades is bisected by the Straight Creek Fault (Fig. 6). A wider range of rock types exists west of the fault, including low-grade metamorphic, sedimentary, metasedimentary, tertiary volcanic, and metavolcanic rock units, whereas intrusive and medium to high-grade metamorphic rocks dominate to the east in the Crystalline Core (Tabor et al., 2002). Alpine glaciers likely extended ~30 to 40 km down the Suiattle River valley during the Fraser alpine glacier maximum (Evans Creek Stade; Riedel, 2017). Following recession of the alpine glaciers from their maxima, the Puget Lobe of the Cordilleran Ice Sheet reached its maximum (~16.3 ka; Riedel, 2017) extending ~30 to 35 km up the Suiattle River Valley from the confluence with the Sauk River (Riedel, 2017) and started its retreat after a few centuries (Porter and Swanson, 1998). Therefore, maximum ice coverage from the earlier alpine glaciation and the later Puget Lobe probably had some spatial overlap in part of the valley ~35 km downstream from the Suiattle River’s confluence with Chocolate Creek (Fig. 1), but the valley was not completely glaciated from alpine or Puget Lobe glaciers at any time during the Fraser Glaciation. Glacier Peak has experienced at least three major post-glacial eruptive episodes which included high magnitude tephra eruptions, dome collapses, and lahars that reached all the way to the Salish Sea (e.g., Beget, 1982; Mastin and Waitt; 2000; Stanton and Dragovich, 2009). The well
stratified Suiattle fill, a prominent volcanic apron in the upper Suiattle, is the result of a dome collapse (~5500-5000 yr BP) on the eastern flank of the volcano (Tabor and Crowder, 1969; Beget, 1982, Slaughter, 2004; Stanton and Dragovich, 2009). Minor eruptive activity has been reported as recently as the early 19\textsuperscript{th} century (Beget, 1982; Stanton and Dragovich, 2009). At present, Glacier Peak supports ten named alpine glaciers, the largest being Chocolate Glacier, which drains into Chocolate Creek on the eastern flank of the volcano. Since their Little Ice Age maxima all glaciers at Glacier Peak have retreated ~1640 m on average (Pelto, 2013).

\textit{Historic accounts of geomorphic change in the Suiattle}

Few historic accounts of the upper Suiattle exist before ~1940. A photo from Miners Ridge Lookout (~12 km northeast from Glacier Peak summit), taken in 1935, shows the upper Suiattle Valley. The channel is cloaked by a mature conifer forest growing tightly along the banks (Fig. 7). In the summer of 1938, the Ptarmigans Mountaineering party ended an alpine traverse in the area, reporting: “The thirteenth and last day we stormed over Suiattle Pass, down Miners Ridge, down the Suiattle valley, stirring the volcanic dust into great choking clouds that required us to walk at intervals of a hundred yards.” (\textit{the Mountaineer}, 1958). A photo by Phillip Hyde taken in ~1956 showcases the Suiattle River Valley upstream of Dusty Creek (Fig. 8). Although cast in shadow, the Suiattle appears as a light-colored strip with sweeping unvegetated banks of exposed sediment. Ford (1959) provides the first documented accounts of ‘floods’ in spring of 1931 or 1932 and again in 1938 that were associated with silt deposition down the Suiattle Valley. Although useful, ambiguity surrounds the terminology, timing, and geomorphic impact of ‘floods’ reported by Ford (1959) for the 1930s.
In the spring of 1941, after a water year plagued by persistent problems with stream gauging operations due to aggradation of fine sediment along the Sauk and Suiattle Rivers, the USGS wrote to the United States Forest Service (USFS), inquiring about the possibility of mass wasting and/or intense rainfall (‘cloudburst’) events causing their downstream aggradation problems (Supplementary Material). The USFS district ranger on the Sauk responded by pointing the USGS to a flooding-mass wasting event that occurred on about September 26, 1940, in the absence of any ‘cloudburst or heavy rain,’ but rather was likely due to the ‘slipping of a glacier’ in the headwaters of Chocolate Creek. On July 9, 1941, the USFS also mentions that large volumes of sand were still being transported down the Suiattle, Sauk, and Skagit Rivers as a result of the same event from the previous September (Supplementary Material).

Over a ten-minute period, during a USFS fire observation flight on August 15, 1963, H. C. Chriswell watched as an outburst of muddy water emerged from the terminus of Chocolate Glacier, propagated down Chocolate Creek as a debris flow, and continued down the Suiattle river. Chriswell estimated the debris flow snout to stand 6 to 12 m high in the area around the confluence of Chocolate Creek and the Suiattle River (Fig. 1). The 1963 debris flow destroyed the Skyline Bridge spanning the Suiattle River ~13 km downstream from the terminus of Chocolate Glacier and caused significant morphological change and silt deposition in the upper Suiattle. Accumulation of silt was also reported down through the Sauk River. Notably, there was no precipitation in the vicinity of Glacier Peak that day (Richardson, 1968; Slaughter, 2004).

A second debris flow was witnessed emanating from Chocolate Glacier during a USFS flight on July 30, 2003. The pilot watched the debris flow descend Chocolate Creek until a dust cloud
disrupted his view (Slaughter, 2004). Impacts from the 2003 debris flow were observed in the field by Slaughter (2004) and included drainage reorganization of Chocolate Creek, draping of fines outside the channel, and devastated riparian vegetation. Extremely turbid water from the 2003 debris flow clogged water filters and was observed on the Skagit River at Mount Vernon about 150 km downstream (Slaughter, 2004).

Methods

Dating historic debris flows

Historical aerial imagery, records of eyewitness accounts, remote sensing, dendrochronology, and field observations were used to date major debris flow events that have occurred over the past century in the Suiattle.

To constrain the timing of debris flows, I downloaded historical aerial images from USGS Earth Explorer (https://earthexplorer.usgs.gov/). Some of the images came pre-georeferenced while others did not. The accuracy of the initial georeferencing of images varied, with some images poorly aligned. In order to ensure that my area of focus was properly aligned, I georeferenced the images in ArcGIS Pro, focusing my efforts on accurately locating features around the mouths of Chocolate and Dusty creeks, the centers of debris flow deposition. To augment the older USGS historical aerial imagery I downloaded more recent images from Google Earth and georeferenced them to the USGS images. Additional oblique photos were obtained, though not georeferenced, from Eric Willhite (http://www.willhiteweb.com) and regional pilot John Scurlock (pers. comm., 2022) to provide further constraints on the timing of debris flow events.
Field observations of debris flow terraces

I evaluated debris flow terrace morphology and measured terrace heights in the field on three campaigns during August of 2019, July 2020, and August 2020. Terraces bounding Chocolate and Dusty creeks and the areas around their confluences with the Suiattle River are distinct in the LiDAR and aerial imagery (Fig. 1). One prominent terrace stands out above the channels and the terrace height tapers downstream from the confluences. In the field, to confirm that the terrace features observed in the imagery are indeed debris flow terraces, I recorded matrix supported clasts, the presence of megaclasts and wood, and inverse grading (Major et al., 2005) that were observed in exposures of terrace risers. In addition to deposit texture and bedding I used evidence of debris flows recorded in vegetation to confirm debris flow origins for various terraces. For example, terraces with buried standing dead trees that had noticeably battered upstream trunks provided further evidence of a debris flow. To help constrain the timing and extent of incision into debris flow deposits, I measured terrace heights above the active channel and compared the field measurements to terrace height measurements from the 2015 LiDAR.

Dendrochronology

To date the debris flow terraces, I applied two distinct methods of dendrochronology: (1) counting the rings of living trees actively growing on recent depositional landforms, which provide minimum surface ages; (2) crossdating of regional datasets to tree rings of a standing dead ‘ghost tree,’ killed by a major debris flow, which provides a calendric date for that event.
I constrained minimum surface ages for terraces along Chocolate and Dusty creeks following the work of Pierson (2007). The largest tree found on a terrace was cored with an increment borer at a height of about 1.4 m above ground. I only cored living trees with a noticeable root crown at the surface indicating that the tree had not been buried after initial growth. I subtracted ring counts from the year the tree was cored and adjusted by a known colonization time gap (CTG), the time required for the tree to colonize a freshly exposed surface and grow to coring height (Pierson, 2007) to arrive at minimum surface age. In this study, I assumed a CTG of 10 years, based on a study of Douglas fir colonization on young surfaces (<60 years) of known age at Mount Rainier, Mount St. Helens, and Mount Hood (Pierson, 2007). Surfaces at Mount Rainier used to generate the CTG are located in the same geographic region (Western Washington Cascades Range) and at ~750 m share comparable elevations with my sampling sites at Dusty and Chocolate creeks (~900 m, ~1200 m, respectively). Additionally, sampling sites at Mount Rainier are located in the 1947 Kautz Creek debris flow deposit which would share similar substrate growing conditions (well drained, gravelly sand with minor silt and clay) with my Glacier Peak debris flow sites (Pierson, 2007). Although similar, my dendrochronology sites are at higher altitude and latitude than the sites used by Pierson (2007) and this may impact the accuracy of results due to changes in the CTG between sites. Uncertainties associated with minimum surface ages are calculated following Pierson (2007), from the sum of error involved with counting rings (±2 years, false or light rings, missing rings, and off-center cores), using the largest tree as a proxy for the oldest (+13 years, the largest tree is not always the oldest), variability in year of seedling establishment (±3 years, from standard deviation of site means), and trees cored at breast height (±2, standard deviation of seedling growth rates). It is important
to note that the largest source of uncertainty comes from using the largest tree as a proxy for the oldest tree on a surface. The largest tree on the surface might not be the oldest given the ability of a stressed tree to continue along in stunted growth and not express that as being the largest tree. Although imperfect, the largest tree method allowed me to estimate surface ages without using a much wider sampling scheme that would better identify the oldest tree.

I constrained the calendric date of one major debris flow event through analysis of a wood slab removed from a standing dead ‘ghost tree’ located along Chocolate Creek. This tree is visible in many of the historical air photos, going back to 1944. The slab bears a long record (>100 years) of tree growth from the outer section of wood located directly under the remaining bark. The sampled tree lacked a visible root crown, indicating that the base of the tree had been buried following a period of undisturbed growth. I polished the slab until individual wood cells could be discerned through a microscope. I measured ring widths manually from the wood using a microscope with a crosshair and a measuring stage controlled by a screw (Velmex TA, 0.001 mm precision), producing a record of ring widths pinned to the sample via a floating chronology drawn on the wood. I measured two ring cross-sections per slab to ensure accurate ring counts and widths.

Tree ring widths vary from year to year due to environmental factors that control tree growth including drought and abnormal temperature (Shroder, 1980). Coincident patterns in ring width occur among tree populations subjected to common environmental conditions (Douglas, 1941; Struble et al., 2019), allowing tree rings to be dated via comparison to a known ‘master chronology’ for that tree species and region.
The sequence of measured ring widths from the slab was compared to a master chronology through crossdating to date the sample at annual resolution. Littell et al. (2008) developed a dated master chronology from Douglas fir cores collected from north facing aspects in North Cascades National Park near Park Creek, which is geographically close to, and shares a similar elevation with, my sampling location. I crossdated the slab to the master chronology using open-source software, xDateR, which identifies the segment of the master chronology that is best correlated to the sample through a process of incrementally lagging the sample forward and backward in time across the entire master chronology (Bunn, 2008; Bunn, 2010). This crossdating method yields ‘best fit’ calendric dates for the sequence of measured tree rings. I inferred the timing of a debris flow event from drastic qualitative changes in ring width/growth patterns in the slab (Shroder, 1980). The process of debris flow deposition can result in a growth suppression response that is recorded in the wood (Shroder, 1980). I qualitatively assessed the growth pattern and attributed the observed change in growth pattern to a debris flow event. Crossdating of the tree rings allowed me to match the beginning of suppressed growth to a specific dated tree ring.

*Interpolated surface differencing*

To place a minimum bound on the volume of material eroded from historic valley-filling debris flow deposits, I used topographic differencing between an interpolated ‘pre-erosional’ surface and a recent LiDAR DTM (Digital Terrain Model; Campbell and Church, 2003; Perroy et al., 2010; James et al., 2022). I recreated a ‘pre-erosional’ debris flow surface by interpolating
between debris flow terrace edges in the 2015 DTM (Fig. 9). Informed by evidence from the field, historical accounts, and visual interpretation of the DTM surface, I created points in GIS software (ArcGIS Pro; ESRI, 2020) along established and inferred terrace edges. I extracted elevation data from the terrace edge points and mapped a polygon defining the extent of the fill surface to be interpolated. Then I used the Spline with Barriers tool (cell size = 1, smoothing factor = 0) to interpolate between the terrace edge points, creating a surface raster of elevation that caps the void between incised terrace edges throughout the study area. The 2015 DTM was subtracted from the interpolated surface to generate a DEM (digital elevation model) of difference (DoD), where each raster cell represents the depth of incision ($D_i$) at that point (Fig. 9). The sum of the 1m x 1m cells in the DoD provides an estimate of the volume ($m^3$) of material eroded throughout the area of interest (e.g., Báčová et al., 2018). Before summing the volume from differencing, boundaries of the interpolated surface that stand above the terrace edges were removed by setting differencing values < 0 to no data. This step eliminated the small number of spurious negative value cells at the boundary between the terrace edge and the interpolated surface, resulting in a difference raster with only positive values of incision. In this analysis, I assumed that the rivers have not incised past the base of the debris flow deposits. My interpretation is supported by the absence of a discernable deposit base in the debris flow terraces. Field observations of incision depth were compared to depth in DoD cross sections to provide ground truth to my estimates of incision and thus volume.
Sediment conversions

After calculating the volume of material eroded from topographic differencing, I converted the eroded volume to a flux in metric tons (t) per year for comparison with suspended sediment load (SSL) results from other sediment sources in this study. To estimate exported fines from the material eroded, I used 22% as the initial fines content of debris flow deposits in the Suiattle Basin (Pfeiffer et al., 2020). Previous work has demonstrated that the abrasion of low-density vesicular volcanic clasts, which are the primary lithology in the deposits, is an important process for the partitioning between coarse and fine sediment fluxes in this system (Pfeiffer et al., 2020). Accordingly, I estimated that 50% of the remaining coarse material from debris flow deposits is converted to fines through abrasion during fluvial transport between the debris flow source and the confluence of the Suiattle and Sauk Rivers. I used a bulk density of 2 metric tons per cubic meter, reported for similar mass wasting deposits in the region (Scott and Collins, 2021), to convert from debris flow volume to mass. Finally, I divided mass by the time elapsed since deposition to arrive at an average suspended sediment flux in metric tons per year for material eroded from historic debris flow deposits.

Contemporary debris flow analysis

To identify contemporary debris flow events in the absence of long-lived debris flow deposits I relied on 15-minute time series data of turbidity and discharge collected by the USGS along the Sauk River above and below the confluence with the Suiattle (gauges 12187500 and 12189500, respectively). The location of the gauges within the Sauk Basin allowed us to use the difference
between SSL on the Lower Sauk and Middle Sauk gauges as a proxy for SSL in the Suiattle Basin (Jaeger et al., 2017; Figs. 1 and 2).

I exploit the difference in the turbidity-discharge relationship between seasons (Fig. 4) to automate the identification of summer debris flow events in the upper Suiattle. I fit a linear regression to the wet season (November through June) relationship between turbidity and discharge and calculate turbidity residuals from the best fit line for all of the data (January to December; Fig. 10). Turbidity residuals represent the deviation from the expected wet season relationship (i.e., high turbidity values at low discharge result in high turbidity residuals). I set a turbidity residual threshold ($\log_{10}$ turbidity residual $> 1.5$; Fig. 10), where extreme values of turbidity for a given discharge are interpreted as debris flow events. I arrived at the $\log_{10}$ turbidity residual $> 1.5$ value through inspection of the data and comparison of known debris flow timing (Jaeger et al., 2017) to the $\log_{10}$ turbidity residual. Furthermore, I found that the $\log_{10}$ turbidity residual $> 1.5$ occurs predominantly during my expected debris flow months (July through October, Fig. 11) and that the frequency distribution of $\log_{10}$ turbidity residuals for all the data is bimodal with a spike in frequency peaking at $\sim 1.5$, suggesting a distinct geomorphic process is responsible for these turbidity residual values (Fig. 12).

In the weeks following anomalous sediment load delivery by debris flows, precipitation events drive increases in discharge that function to flush the anomalous sediment load from the basin (Jaeger et al., 2017). To quantify the magnitude of this anomalous sediment flushing I employed my turbidity residual framework and set a bound on residuals from the region of the plot where flushing occurs: $\log_{10}$ turbidity residual from 0.75 to 1.49 (Fig. 10). These bounds were applied
to select for turbidity and discharge values outside of the debris flow and expected wintertime relationship ranges. By definition, my flushing events are related to higher discharges, so the region in the plot from 0.75 to 1.49 turbidity residual was further restricted to discharges greater than 250 m$^3$/s ($\log_{10}$ discharge $> 2.39$; Fig. 10). I selected the discharge threshold of 250 m$^3$/s to avoid incorporating a snowmelt signal in July and August that can occur, on rare occasions, during late snowmelt years.

**Contemporary debris flow meteorological triggers**

To explore the driving mechanisms of contemporary debris flows on the Suiattle River, I used my turbidity residual analysis and daily USGS data to compare meteorological variables to debris flow occurrence for the period 2011-09-23 to 2020-10-31. I identified debris flow start days as the first day when a debris flow signal was indicated at the Lower Sauk gauge. Unique events begin at the debris flow start day and end after the debris flow signal ceased for greater than one day between individual events. To focus on months when debris flows are known to occur in the North Cascades during summer and early fall (e.g., Richardson, 1968; Walder and Driedger, 1994; Slaughter, 2004) I selected debris flow start days only for the months July to October. I calculated temperature anomalies from 30-year maximum temperature normals and daily maximum temperatures (°C) both collected at the USFS Darrington Ranger Station (Fig. 1) and downloaded from the National Oceanic and Atmospheric Administration’s Applied Climate Information System (NOAA ACIS [http://scacis.rcc-acis.org/]). I used the prior-day maximum temperature anomaly to compare the frequency distributions of prior day anomalies from two independent populations, debris flow start days and non-debris flow days. I also applied this
analysis to the distributions of prior-day precipitation for debris flow start days and non-debris start days, using daily precipitation data from the Darrington Ranger Station.

*Estimating suspended sediment loads*

My goal is to calculate how much of the total suspended sediment load (SSL) on the Suiattle is transported during summertime debris flow events, how much is transported during post debris flow anomalous sediment flushing events, and how much is attributable to neither debris flows nor flushing. I calculate the total SSL, as well as SSL attributable to debris flows and anomalous sediment flushing using regression models generated by Jaeger et al. (2017) and 15-minute USGS data from the Lower and Middle Sauk gauges (Fig. 1):

Middle:  \[ SSC = 0.35Tu^{0.968}Q^{0.442}bfc \]  \textit{Equation 1}

Lower:  \[ SSC = 0.323Tu^{0.928}Q^{0.533}bfc \]  \textit{Equation 2}

\[ SSL = Q \ast SSC \ast k \]  \textit{Equation 3}

where,

- \( SSC \) is suspended sediment concentration in mg/L;
- \( Tu \) is turbidity in FNUs (Formazin Nephelometric Units);
- \( Q \) is discharge in m\(^3\)/s;
- \( bcf \) is a bias correction factor (1.06);
- \( SSL \) is suspended sediment load in tons (t) per 15-minute time interval; and
- \( k \) is a unit conversion equal to 0.0009 L*t*s/m\(^3\)*mg*15 min.
Summing 15-minute SSL values over a period of time gives us SSL in tons per time elapsed, for instance, tons per year.

To isolate sediment coming from the Suiattle Basin from other upstream sources in the main-stem Sauk River, I used the difference between SSL on the Middle Sauk and Lower Sauk gauges as a proxy for SSL from the Suiattle (Jaeger et al, 2017; Figs. 1 and 3). This simplification is discussed above in the Contemporary Debris Flow Methods and was previously established by Jaeger et al. (2017). I sum SSL from the Suiattle Basin and attribute estimates of SSL to debris flow and anomalous sediment flushing events in the upper Suiattle Basin.

**Results**

*Historical imagery*

Seven USGS aerial images document geomorphic change in the Chocolate Fan area from 1944 to 1984. Individual years of the USGS imagery include 1944, 1950, 1953, 1956, 1974, 1979, and 1984. One georeferenced Google Earth image documents the same area in 1998. An additional USGS aerial image from 1979 provides coverage of the Dusty Creek confluence for comparing change at that location between 1974 and 1979. A second 1950 georeferenced USGS aerial image was used to show change at the terminus of Chocolate Glacier between 1944 and 1950. Two oblique photos from John Scurlock (pers. comm., 2022) provide further information on the morphology of the Chocolate Fan and Outburst Canyon in May of 2003. Two photos taken from Miners Ridge Lookout, one from 1935 and one from 2015, capture change along the Suiattle River downstream from the confluence with the Dusty Creek.
Identifying Terraces

Field observations confirm that terraces identified in LiDAR and air photos are debris flow deposits (Fig. 13). Field measurements of debris flow terrace heights align reasonably well with measurements made using the 2015 LiDAR (Figs. 14 and 15). Terrace heights measured in the 2015 LiDAR were within 1 m of measurements taken in the field at nine out of 14 sites. On average, change in measured terrace heights between the 2015 LiDAR and the 2019 field measurements was ~0.2 m across all sites, suggesting that minor change occurred in the four years between datasets.

Dendrochronology:

Cores from living trees on terraces along Chocolate and Dusty creeks provide minimum surface ages ranging from 8 to 222 years (Table 1, Fig. 16). The oldest sample comes from a tree growing on a high, heavily vegetated terrace along Chocolate Creek and provides a minimum surface age of 1800 C.E. (Fig. 17; Sample #10). Among the remaining samples, there is a group of surface formation dates beginning in 2004 (Sample #s 1-4) located near the confluence of Dusty Creek and the Suiattle River (Table 1; Figs. 16 and 17).

I removed a slab from a partially buried standing dead tree along Chocolate Creek (Fig. 18). The tree is ~1 m in diameter, with a remaining height of ~36 m above the terrace surface. It is the largest standing dead tree along Chocolate Creek. The extracted slab, which covers only a small
portion of the tree’s radius, contains ~180 rings, including a region of suppressed growth (Fig. 18). The suppressed growth section is ~0.5 cm wide (measured perpendicular to the rings). Tree rings from this section appear very thin, lack distinct darker winter rings, and display intermittent irregularities with lense like morphology. Crossdating of this slab against the master chronology for the region (Littell et al., 2008) dates the onset of these thin rings to 1941 C.E. (Table 1; Figs. 17 and 18), and places tree death at ~1996 C.E.

*Interpolated surface differencing*

I performed interpolated surface differencing to place a minimum bound on the volume eroded from historic debris flow deposits. The total volume of material eroded from valley filling debris flow deposits in the upper Suiattle Basin amounts to ~ 4,857,000 m³ ± 590,000 (Fig. 19). Incision into valley fill deposits reaches a maximum depth of ~12.1 m in the upper most reaches of Chocolate Creek (Figs. 2 and 19). The largest volumes of material have been exported from the steepest reach along Chocolate Creek, and at the confluences of the Suiattle River with Chocolate and Dusty creeks (Fig. 19).

The most likely source of uncertainty in my volume estimate arises from differences between the roughness of my interpolated surface and the roughness of the original debris flow surface. In other words, the interpolated surface is relatively smooth, whereas the original debris flow surface was likely rough due to the turbulent process of deposition and the wide range of clast sizes in the debris flow material. To account for this uncertainty, I used the surface roughness of a region of relatively pristine debris flow deposit as a proxy for the original debris flow surface.
roughness. I calculated the surface roughness of the remaining deposit as the standard deviation of elevation values in a 9x9 cell moving window. The mean standard deviation across the remaining debris flow surface was 0.27 meters (Fig. 20). This value was substantially higher than the bare earth vertical accuracy reported for the LiDAR DTM at -0.015 meters (Quantum Spatial, 2015). To test the effect of surface roughness and to place a bound on the uncertainty associated with my volume estimate I created a new DoD where 0.27 m was subtracted from every cell, essentially negating possible error associated with initial debris flow surface roughness (Fig. 20). The difference in volume estimates between my two DoDs was ~590,070 m³ or ~12% decrease in the initial volume estimate.

Contemporary debris flows

Working with the 15-minute USGS measurements of turbidity and discharge along with my turbidity residual framework, I automatically extracted the timing, duration, and magnitude of debris flow events. I summed suspended sediment loads (SSL) from contemporary debris flows and present those results in the Suspended Sediment Load section below. In any given year, I limited this analysis to my expected debris flow season July to October. SSL during time periods when the debris flow signal was picked up ranged from 0.25 to 1441 t/15-minutes. Turbidity ranged from 7.6 to 2093 FNUs. The highest magnitude SSL signal from a debris flow occurred on 10/11/2015. The maximum turbidity value associated with a debris flow signal occurred on 8/19/2015, at 2093 FNUs, in the days immediately following the 8/13/2015 debris flow noted by Jaeger et al. (2017). Year to year variability in the timing, magnitude, and duration of debris flow signal throughout this analysis was high. Debris flow turbidity spikes, independent of discharge,
are apparent in every year. 2019 is a representative year from the period of this analysis (2011-09-23 to 2020-10-10), with no previously reported debris flows (Fig. 21).

Contemporary debris flows and meteorological triggers

I identified 28 unique debris flows, evidenced by spikes in turbidity that are independent of discharge, spread through all 10 years of the daily turbidity and discharge record at the Lower Sauk gauge (Table 2). Based on historical accounts and preliminary evidence, I restricted my debris flows registered by this analysis to those occurring from July to October. There was only one debris flow start date picked up outside of this range: on June 27, 2015.

Compared to non-debris flow days, the distribution for debris flow start days is shifted to the right with higher frequencies of prior day temperature anomalies at higher magnitudes (Table 2; Fig. 22). Following the work of Walder and Driedger (1995), I used the Kolmogorov – Smirnov test to address the question: What is the probability that the population of debris flow start days is drawn at random form the population of non-debris flow days (Fig. 23)? The test statistic $d_m$ is the greatest difference between the two distributions ($d_m = 0.314$). At the location of $d_m$ in the plot, the probability that non-debris flow temperature anomalies are lower than ~2.3 °C is ~70% compared to a probability of ~38% for debris flow start days. From my p-value ($p = 0.007$), I suggest that it is highly unlikely that debris flow start days are drawn at random from non-debris flow days.

The above-mentioned analysis was also performed on the distributions of prior day precipitation for debris flow start days and non-debris flow days (Fig. 24). I found that the distributions with
regard to prior day precipitation are not statistically different ($d_m = 0.107; p = 0.90$; Fig. 25).

Debris flow start days were characterized by low to no precipitation with a debris flow start day prior day precipitation mean value of 0.17 cm (Table 3), thus eliminating precipitation as a driving mechanism of debris flows in the upper Suiattle Basin.

**Suspended sediment loads**

Suspended sediment associated with summertime debris flows accounts for ~10.6% of the mean annual suspended sediment load (SSL) in the Suiattle Basin (Table 4). Flushing of anomalous debris flow sediment represents a similar proportion: 10.7% of the mean annual load. Together these two processes, both attributable to contemporary debris flows emanating from the upper Suiattle Basin, account for ~21% of the mean annual load on the Suiattle (Fig. 26). Mean annual load on the Suiattle over the period of record (2011-09-23 to 2021-04-13) was estimated at 667,948 t ($\pm 117,559$) per water year (Table 4; Fig. 26).

The cumulative sum of SSL on the Suiattle during the period of record was 5,547,594 t ($\pm 976,376$; Table 5). Cumulative SSL sums for summertime debris flows and sediment flushing were 512,563 t ($\pm 102,513$) and 650,587 t ($\pm 129,174$), respectively. Compared to the mean annual load, cumulative SSL export during the period of record from flushing events represents roughly 1 year of SSL on the Suiattle. Over the period of overlap between Middle Sauk data and Lower Sauk data (2011-10-29 to 2015-12-07), Middle Sauk which does not include the Suiattle Basin represented only ~25% of SSL exported past the Lower gauge on average across the 5 years (Table 5; Figs. 1 and 27).
Uncertainties in SSL relate mainly to uncertainties in the regression equations used to calculate SSC from turbidity and discharge measurements. The range of uncertainty in computed SSC can be defined as the range of SSC values that fall within a 90% certainty interval. Jaeger et al. (2017) used this method to calculate uncertainty associated with SSL for the water years 2012 to 2016. I used the average error calculated by Jaeger et al. (2017) over their study period to approximate the error associated with my estimates of SSL. Uncertainties of 12.6%, 13.4%, 17.6%, and 20% were applied to sediment loads estimated for the Lower Sauk, Middle Sauk, Suiattle Basin, and debris flows and flushing, respectively (Tables 4 and 5).

Debris flow and incision chronology

Historical accounts and aerial imagery along with field observations provide a basis for interpreting a chronology of debris flows and incision events in the upper Suiattle. Historical photographs taken from a fire lookout positioned above the Suiattle River show a valley bottom tightly bound by mature forest that lacks bright patches characteristic of recently deposited and exposed volcanic sediment, constraining the onset of extreme sediment loading by debris flows to after the early 1930’s (Slaughter, 2004; Fig. 7).

The earliest aerial photograph found for this study, from 10-7-1944, shows thinned clusters of conifer forest standing in a broad sediment plain with prominent terraces flanking the channels (Fig. 28). Upstream from the confluence of Chocolate Creek with the Suiattle River (Figs. 1 and 4), a debris fan, known as the Chocolate Fan, evolves through time from recurring debris flows
and incision events, as depicted from eight aerial photographs spanning 1944 to 1998 (Fig. 28). My dendrochronology Sample # 7, collected from a standing dead Douglas fir, provides an event date and a stable point of reference, being clearly visible (e.g., see distinct shadow from tall trunk cast over the channel) from 1944 to present in the available imagery (Fig. 28).

Catastrophic fluvial geomorphic changes along Chocolate Creek and down the mainstem Suiattle River including devasted forests and debris flow terraces ~ 1.5 m thick were first attributed to flooding events occurring in the 1930s by Ford (1959). Ford (1959) provides images taken at some point between 1954 and 1958 (Fig. 29) documenting the geomorphic change that he observed in the upper Suiattle. From historical accounts, given by USFS Darrington Ranger District employees and local residents, Ford (1959) tied the geomorphic change to the year 1938. Ford (1959) also notes accounts of ‘floods and silting conditions’ occurring in the spring of 1931 or 1932, adding ambiguity to the earlier dates. From the firsthand accounts, early hypotheses about the source of the ‘silting’ material focused on the formation and failure of landslide dams in the upper Suiattle (Ford, 1959). In the text, ‘1938?’ is consistently used by Ford (1959) when referring to the timing of the 1938 event. I interpret the presence of the question mark following 1938 throughout the report to imply that there was generally a low confidence in this date and that the evidence was largely circumstantial.

Building off Ford’s (1959) report, Slaughter (2004) used historical accounts, field observations, and dendrochronology to attribute the mid-century geomorphic changes in the upper Suiattle to a 1938 glacier outburst flood and a subsequent catastrophic debris flow. Destroyed mature conifer forests, a bare fill deposit on the broad valley floor, and debris flow terraces standing ~3 to 5 m
above the Suiattle River that extend ~17 km downstream were all interpreted by Slaughter (2004) to have been caused by the 1938 event. Terraces from the 1963 debris flow that covered earlier mid-20th century terraces for at least 2 km downstream of the Chocolate Fan (Slaughter, 2004) were the only other debris flow terraces that he did not attribute to the 1938 event.

In 1940, a debris flow overtopped the fan and buried Sample #7 to an unknown depth. This interpretation is supported by abrupt suppressed growth visible in the tree rings beginning in 1941 (Fig. 18) and is consistent with a correspondence between the USGS and USFS regarding silt deposition interfering with discharge measurements at the Suiattle gauge (1218900) in the fall of 1940 (Supplementary Material). Following burial by debris flow, peak flows on the Suiattle in fall of 1941 likely incised into the 1940 deposit exposing the roots of Sample #7, probably contributing to the observed suppressed growth pattern. Supporting incision and exposure of roots, the 1944 image (Fig. 28) displays Sample #7 standing near the edge of a terrace, directly abutting a distinct incised channel to the north where the roots were exposed. In similar systems, rapid sediment loading by debris flow and volcanic processes is often followed by swift fluvial incision through the unconsolidated deposits (Major et al., 2018).

From the tree rings, the 1944 image, the written correspondence between federal agencies, and hydrographs from this period on the Suiattle I have high confidence that a debris flow on about 9/26/1940 is responsible for the burial of Sample #7 and at least some of the depositional features in the 1944 photo (Fig. 28). Because Sample #7 does not record an earlier disturbance (Fig. 18) I infer that the 1938 event described by Ford (1959) and Slaughter (2004) is of lower relative magnitude than the 1940 event. The 1940 event would require a higher magnitude than
the 1938 event to overtop terraces and blanket a larger surface that included Sample # 7. About 3 km downstream from the confluence of the Suiattle River with Dusty Creek, in July of 1938, the Ptarmigans Mountaineering club describes kicking up a choking volcanic dust cloud while walking down the Suiattle Valley bottom (Manning, 1958). The Ptarmigans’ report suggests that the 1938 debris flow deposited fine sediment ~20 km downstream from the summit of Glacier Peak, giving us some sense of the relative magnitude of this event. However, I generally have low confidence in attributing relative magnitude to the 1938 event other than my assertion that it was smaller than the 1940 event.

Between 1944 and 1950, deposition attributed to a previously unreported circa late-1940s debris flow appears to have created a new debris flow depositional surface located to the north of the 1940 terrace along Chocolate Creek (Fig. 28). Clusters of standing dead trees appear significantly thinned between the 1944 and 1950 historical aerial images. A significant scarp at the terminus of the Chocolate Glacier, in the potential proglacial source zone (Fig. 30), increased in extent and shifted upslope into the ice between 1944 and 1950. Individual lobes of the 1944 scarp have coalesced in the west and potentially a large area against a lateral moraine to the north has lost ice coverage in the 1950 image (Fig. 30). Downstream at the confluence of the Suiattle River and Dusty Creek (Fig. 31), razing of vegetation at the center of the images and a substantial increase in visibly exposed sediment along the channels points to extreme sediment loading by debris flow events. Significant change on Dusty Creek and the Suiattle River upstream of their confluence indicates unique sediment loading events occurring on both streams (Fig. 31). Additionally, a reanalysis of dendrochronology samples collected by Slaughter (2004) using the previously described method for living trees applied in this study, helps to constrain the
timing of debris flow surface formation on the Suiattle in the reach extending ~ 8 km below the Dusty Creek confluence with the Suiattle (Fig. 32). Evidenced by multiple sets of photographs showing exceptional geomorphic change and dendrochronology from downstream deposits that covered previous debris flow terraces, I assign a high relative magnitude to the Suiattle event. My confidence in this interpretation is lower than that expressed for the 1940 event because I lack historical accounts. On Dusty Creek the evidence is more limited, accordingly my confidence in estimating the timing and magnitude of the Dusty Creek event is low. I assign a high relative magnitude to the Dusty Creek event based solely on channel change between the 1944 and 1950 images.

The images from 1944 and 1950 show evidence of incision during this period of time (Fig. 28). Dark shadows highlight terraces that have been cut into debris flow deposits through the process of incision. More specifically, in the 1950 image, the terrace supporting Sample # 7 has been cut away on its northeastern side (Fig. 28). Incision into the fan appears to have continued from 1950 to 1956 (Fig. 28).

Geomorphic change between 1956 and 1974 aerial images is dramatic. Chocolate Creek abandoned its former channel hugging the Suiattle Fill to the northwest, where it ran parallel to the Suiattle in the 1956 image, for ~1 to 2 km through the sediment plain, to take a more direct route across the fan to meet the Suiattle (Fig. 28). A new depositional surface appears in the 1974 image extending north from Sample #7 towards Chocolate Creek and south along the Chocolate Fan (Fig. 28) I attribute the rerouting of Chocolate Creek and the new depositional surface observed in the 1974 image to the 1963 event noted by Richardson (1968) and rank the
1963 debris flow as a medium to high relative magnitude event based on geomorphic change from the images and the eyewitness report of the event. The eyewitness account of the 1963 event provides a high level of confidence in attributing magnitude here.

During the period between 1974 and 1979, images from the confluence of Dusty Creek and the Suiattle River support Beget’s (1982) report of a 1978 debris flow event on Dusty Creek (Fig. 33). In 1974, the area northwest of the confluence is heavily vegetated with alder brush. In the 1979 image of that area, much of the brush up to 2.5 km upstream from the confluence along Dusty Creek is noticeably thinned and Dusty Creek has cut a new channel to the west of the Suiattle extending its course by at least 500 m and leaving an island of green vegetation between the older and newer confluences (Fig. 33). I suggest a probable low to medium relative magnitude for the 1978 Dusty Creek debris flow based on aerial imagery, field observations, and Beget’s (1982) initial report.

Images taken between 1974 and 1984 show no evidence of major debris flows along Chocolate Creek (Fig. 28). The 1979 image of Chocolate Creek is washed out. However, vegetation on the fan and sediment plain appears to have increased relative to the 1974 image, which I associate with a period of stability (i.e., lack of flooding and/or debris flow events overtopping previous debris flow terraces). In the 1984 image of the Chocolate Fan, the vegetation is more extensive than the 1979 image. In addition, Chocolate Creek clearly continues its more direct course through the fan (Fig. 28).
The next available image, from 1998 (Fig. 28), indicates that Sample # 7 was to the south of a new depositional surface that extends north towards the Suiattle Fill for about 40 m and continues upstream and downstream along the fan. Chocolate Creek has abandoned its channel from the 1974 image and has retaken the northwest channel following the edge of the Suiattle Fill. The former channel cutting through the fan is non-distinct, alder brush has been cleared from the lower fan near the Suiattle, and a cluster of conifer forest on the southeast of the fan is now standing dead. I attribute changes observed between the 1984 and 1998 images to a debris flow event reported by Slaughter (2004) which is known to have occurred in 1992. Judging by the extensive vegetation clearing on the fan, resurfacing of the fan, and channel rerouting, I consider this event to be of at least medium to high relative magnitude. Little is known about the source of information for this date provided by Slaughter (2004), so my confidence in attributing event timing to the changes described between 1984 and 1998 is relatively low.

Aerial surveys by pilot John Scurlock of Cascades glaciers on May 27th and 29th, 2003 provide the next set of images (Fig. 34). In the 2003 images, the entire fan surface appears draped with fresh sediment, there is minimal alder shrub vegetation with few remaining conifers, and Chocolate Creek has been rerouted, pushing its confluence with the Suiattle further downstream (Figs. 28 and 34). The draping of fresh sediment interpreted from changes between the 1998 and 2003 images and the rerouting of lower Chocolate Creek hint at an event occurring between 1998 and 2003, for which I do not have other record. Importantly, incision into the fan along the southern edge of the Suiattle Fill appears to be at a minimum in the 2003 images, over my period of investigation (Figs. 28 and 34).
After the 2003 images were taken, a debris flow noted by Slaughter (2004) deposited additional material on July 30th of the same year. During a USFS fire spotting flight, the 2003 debris flow was witnessed descending Chocolate Creek before a dust cloud interrupted the spectacle (Slaughter, 2004). Slaughter (2004) conducted field work in the upper Suiattle Basin before and after the 2003 debris flow and noted that the 2003 event overtopped its banks throughout Chocolate Creek and caused rerouting of the channel. The 2003 deposition was followed by the flood of record at the Lower Sauk gauge, which occurred on October 10, 2003, likely causing substantial incision in the upper Suiattle. Primarily from field reports (Slaughter, 2004) and available imagery I assign a low relative magnitude to the 2003 debris flow. Uncertainty about the relative magnitude of this event is high due to several factors, including that I lack good photographic evidence capturing post-event debris flow deposition.

In 2015, a debris flow was identified in turbidity and discharge data and further corroborated by topographic differencing (S. Anderson USGS, pers. comm., 2020) that revealed a source area at the terminus of Chocolate Glacier (Jaeger et al., 2017). The 2015 event is considered to be of a higher relative magnitude than the 2003 event, but lower than 1992 event. I have relatively high confidence regarding the magnitude of the 2015 event, primarily due to topographic differencing (S. Anderson USGS, pers. comm., 2020) placing the volume deposited near the confluence of Chocolate Creek and the Suiattle River at ~200,000 m³.
Discussion

The goal of this work is to better understand the specific geomorphic drivers of the Suiattle Basin’s anomalously high suspended sediment load. Results from this study show debris flow processes are major components of the suspended sediment budget on the Suiattle. Historic, major debris flows have occurred with a 9.3 year recurrence interval ($n = 9$; inter-event time range: 2 to 16 years) since they began in the mid-20th century. Lower magnitude debris flows are common throughout my contemporary analysis, which spans the past decade. Fall flushing events, following summertime debris flows function to export debris flow sediment from the basin. Combined, high and low frequency debris flows function to increase basin scale sediment supply at both annual and decadal timescales.

High magnitude, low frequency debris flows recorded in debris flow terraces and tree rings, and noted in historical accounts, deposit large quantities of sediment throughout the upper Suiattle Basin. Material deposited from these events overwhelms and displaces channels, buries vegetation, and is subsequently eroded by fluvial incision feeding an elevated basin scale sediment supply at decadal timescales. Over the study period, a pattern of major depositional events followed by incision has repeated itself multiple times. The greatest incision is located where Dusty and Chocolate creek valleys meet the Suiattle. The volume eroded tapers over ~3 km downstream (Fig. 19). A total of five historic, valley filling debris flows with source areas at the head of Outburst Canyon were identified along Chocolate Creek (Table 6; Fig. 2). A previously unknown high magnitude debris flow that coursed down from Chocolate Creek depositing material down to ~ 8 km past the mouth of Dusty Creek was identified in this study.
using historical imagery and a reanalysis of previously collected (Slaughter, 2004) dendrochronology samples (Fig. 32). One major event has previously been reported on Dusty Creek (Beget, 1982; Table 6) and was corroborated by aerial imagery. Compared to Chocolate Creek, debris flows from Dusty Creek augment sediment supply on the upper Suiattle to a lesser extent (Ford, 1959; Beget, 1982; Slaughter, 2004).

Debris flow deposits along the Suiattle almost certainly overprint older debris flow events (Copeland, 2009). Additionally, deposits from smaller debris flows could be rapidly eroded leaving no trace of their existence (Copeland, 2009). In some cases, debris flows can be insufficient to fully overprint prior terrace surfaces, rather a later debris flow will spill out and deposit a lobe only locally on the fan as seen in 1998 to 2003 where the channel is only partially rerouted (Figs. 28 and 34). Although there may be evidence of consecutive debris flow deposition over decades recorded in debris flow terraces, analysis of terrace stratigraphy was not a focus of my field campaigns. Because debris flows can generate pulses with changing rheology and thus changing stratigraphy of the resulting deposits (Major et al., 2005), it would be difficult to confidently differentiate changes in stratigraphy that happened over days or hours from changes that resulted from a different event many years later using field observation alone (Slaughter, 2004). Overprinting and erosion of smaller deposits may have caused events to be left out of my chronology and makes comparing overall event magnitude challenging. Thus, the ~9.3-year recurrence interval of major debris flows along the Suiattle since 1938 should be considered a maximum bound.
Lower magnitude and higher frequency debris flows, which result in summertime turbidity spikes, occur multiple times every summer. I identified 28 smaller debris flows over the roughly 10 years of my turbidity and discharge analysis, with at least one event in every year of record. While striking in the turbidity data and apparent in the color of the river, in the field, and in aerial imagery (Fig. 3), low magnitude debris flows are not directly responsible for a very large portion of the total SSL measured at the Sauk gauge (Tables 4 and 5; Fig. 35). Fall flushing events that follow summer debris flows more than double the suspended sediment contributed from low magnitude debris flows, bringing the total contribution from this process to a more substantial proportion. Debris flow and fall flushing SSL can be thought of as a short-term signal, immediately accounted for as they pass the gauge. The coarsest fraction of material deposited by a debris flow would contribute to the SSL but would require higher recurrence interval precipitation to initiate a high magnitude discharge required for bed load transport.

There is consistency between meteorological data from contemporary debris flows and historical accounts that attribute debris flows in the upper Suiattle Basin to glacier outburst floods. Evidence points to both historic and contemporary debris flows occurring on hot, dry summer days. Eyewitness reports from two fire spotting flights and other historical accounts tie high magnitude debris flows to periods of hot and dry weather. Analysis of contemporary debris flows shows that smaller debris flows also happen during the hottest times of the year, typically in the absence of precipitation. It should be noted that the analysis of meteorological debris flow triggers takes place during the dry season at the warmest time of the year in the North Cascades. In contrast to other regions like the Rocky Mountains the North Cascades do not receive summer
monsoon rainstorms and even in the event of a rare rainstorm there would be little antecedent moisture on the volcano’s flanks that could lead to a slope failure.

_Historic volcanic activity at Glacier Peak (?)_

A few reports suggest volcanic activity at Glacier Peak as recently as the 18th century (Majors, 1980; Beget, 1982). Early European explorers were not aware that Glacier Peak existed or even that it was an active volcano until they received reports (circa mid-1850s) from Native Americans that Glacier Peak had ‘smoked’ in the recent past (Majors, 1980; cited in Beget, 1982). Ash and pumice deposited on top of young glacial moraines support Native American accounts of this recent activity (Beget, 1982). An eruptive event as recently as the 18th century from the glaciated peak raises questions about a possible syneruptive lahar descending at least one of the canyons draining Glacier Peak. My dendrochronology Sample # 7 (Fig. 18) with its long growth record is useful for establishing the timing of catastrophic lahars along Chocolate Creek. Assuming a constant growth rate of 15 rings per centimeter in trunk diameter, established from the region of normal growth in Sample # 7, the tree would be about 750 years old. However, early growth most likely exceeded later growth (i.e., early rings were wider; Sillett et al., 2018). A more reasonable estimate for tree age would be about 300-500 years, 500 years being on the long end of the spectrum for such a dynamic environment. Therefore, I can conservatively exclude Chocolate Creek as a possible lahar route during at least the last 400 years. Dendrochronology Sample #10 (Fig.17) marks the location of a lone, high lahar terrace (~14 m above the channel), covered by mature conifer. Based on this height alone, this terrace appeared to be a possible piece of evidence for recent volcanic activity from Glacier Peak.
However, its position upstream and elevated above the Chocolate Fan precludes any catastrophic lahar from descending Chocolate Creek while Sample # 7 stands vulnerable downstream. The age of the terrace from Sample #10 (1800 C.E.) initially pointed to a volcanic trigger roughly corresponding to Native American accounts. However, it is highly unlikely that Sample # 7 would have survived, let alone continued uninterrupted growth, after a valley filling event of this magnitude. Thus, any high magnitude syneruptive lahars from Chocolate Creek would have to be older than Sample #7. The minimum surface age of Sample #10 of 1800 C.E. is too young based on the timing constraints from Sample #7. I suggest that the 1800 C.E. age of Sample # 10 is related to a local landslide that could have reset the age distribution of trees on the lahar terrace centuries after the lahar occurred. It may be that there was not a syneruptive lahar related to the smoking of Glacier Peak reported by Native American people as recently as ~200 to 300 years ago, or an alternative hypothesis is that the syneruptive lahar took a different route down the mountain other than Chocolate Creek.

*Debris flows from other Cascades Volcanoes*

The large magnitude, historic debris flows along the Suiattle bear similarity to other non-eruption related debris flows emanating from volcanoes in the region. Ford (1959) reported that deposits he observed at Mount Rainier from the 1947 Kautz Creek debris flow were very similar in nature to the debris flow terraces that he attributed to the 1938 Chocolate Creek debris flow at Glacier Peak. While the Kautz Creek debris flow and the historic debris flows from Glacier Peak have noncohesive texture in common (Scott et al., 1995; Slaughter, 2004), the Kautz Creek debris flow deposited an unusually large volume of sediment ~38 to 50 x 10⁶ m³ (Scott et al., 1995) and
unlike most historic debris flows from Glacier Peak it was triggered by intense rainfall (Richardson, 1968). It is probable that the Kautz Creek debris flow was at least an order of magnitude larger than the highest magnitude historic debris flow from Glacier Peak. The June 1927 Deming Glacier debris flow at Mount Baker likely shares a more similar volume to the largest historic debris flows from Glacier Peak at an estimated deposit volume of ~10 x 10^6 m^3 (Tucker et al., 2014). The triggering mechanism for the Deming Glacier debris flow remains unknown because meteorological monitoring in 1927 at that remote location was inadequate to attribute a trigger (Tucker et al., 2014). Deposits from the Deming debris flow were also noncohesive and the formation of distinct and continuous debris flow terraces perched several meters above the channels is shared with Kautz Creek and Glacier Peak events. The common noncohesive deposit texture supports evidence from both settings that these debris flows were not volcanically triggered, as syneruptive debris flows usually carry higher clay content and are cohesive (Scott et al., 1995). Non-cohesive flows are usually triggered by water floods incorporating debris from the surface that has a lower initial clay content (Vallance and Scott, 1997; Legg, 2014). Although precipitation has triggered the highest magnitude events at Mount Rainier (Scott et al., 1995), debris flows on Glacier Peak happen on clear weather days with little antecedent rainfall. One of the more important diagnostic commonalities among these high magnitude Cascades debris flows is that their source areas experienced 20th century glacial recession and that they all occurred during or immediately following warming temperature trends (Slaughter, 2004, Tucker et al., 2014). Additionally, the debris flows all resulted from glacier outburst floods transitioning to debris flows (Richardson, 1968; Tucker et al., 2014).
Lower magnitude more frequent debris flows as reported here from Glacier Peak have counterparts at other Cascades volcanoes as well. Smaller debris flows have been documented at Mount Baker (Tucker et al., 2014), Mount Hood (Swanson, 1989) and at Mount Rainier (e.g., Richardson, 1968; Walder and Driedger, 1994; Scott et al., 1995). Mount Rainier is the most well studied of low magnitude high frequency debris flow producing volcanoes in the Cascades. Specifically, the debris flow record from the more accessible South Tahoma Glacier at Mount Rainier with its high propensity to produce glacier outburst floods is ideal for comparison to debris flows at Glacier Peak. From 1967 to 2006 there were 27 debris flows reported from South Tahoma Glacier (Copeland, 2009; Anderson and Pitlick, 2014). During a study spanning 1985 to 1992, Walder and Driedger (1995) found that 15 out of 23 debris flows occurred during dry weather days and concluded that outburst floods were the primary triggering mechanism during their study. I found 19 out of 28 debris flows happened during dry days over my period of record and also infer a glacier outburst trigger mechanism. The August 13, 2015 debris flow happened on a dry weather day and the week preceding the event gave no precipitation. At Mount Rainier, one glacier, the South Tahoma Glacier, has been identified as the standout, producing small recurrent debris flows at a higher rate than any other glacier at Rainier. Similarly, at Glacier Peak, from historical accounts and aerial imagery, it appears that Chocolate Glacier is the glacier most prone to producing debris flows from outburst floods. In the contemporary debris flow analysis, I make a general assumption that smaller more recent debris flows are predominantly sourced from Chocolate Glacier as well. This assumption is based on the evidence from major debris flows and is supported by my historical analysis; however, further work is required to directly attribute smaller debris flows identified from the gauge record to outburst floods emanating from Chocolate Glacier.
Despite a few reports of landslides initiating debris flows at other Cascades volcanoes, they do not appear to be a significant triggering mechanism at Glacier Peak. For example, the 1980 Polallie Creek event at Mount Hood started as a small landslide and bulked up to a relatively small (76,000 m³) debris flow (Swanson, 1989). The May 31st (~100,000 m³) and June 6th, 2013 debris flows from Mount Baker also started as slope failures (Tucker et al., 2014). Interestingly, turbidity signals from these debris flows were recorded at a downstream gauge (Tucker et al., 2014) and turbidity magnitudes from these events were on par with events from Glacier Peak. However, landslide triggering has not been reported from the eastern flank of Glacier Peak and I have not seen convincing evidence of landslide triggers in this study. Further support for excluding landsliding as triggers in the upper Suiattle comes from similar systems with unconsolidated moraines and volcanic sediment in the proglacial source zone. Walder and Driedger (1994) reported that during the summer only a small proportion of source zone sediment would be saturated, and that the vast majority of sediment would be much too dry to slump and mobilize a debris flow. Additionally, Walder and Driedger (1994) report that landslide and slump-damming is not a likely water source for debris flows. Small headwater dams cannot produce enough water to explain the observed debris flow discharges providing additional evidence that higher frequency debris flows at Glacier Peak are not likely to be initiated by this mechanism either. Overwhelmingly, glacier outburst floods related to retreating glaciers and higher temperatures over multiple timescales seem to be the root cause of lower magnitude higher frequency debris flows at Cascades Volcanoes.
Topographic differencing from Mount Rainier can help to put incision into debris flow deposits from Glacier Peak into context. Walder and Driedger (1994) estimated that \(\sim 2 \times 10^5 \text{ m}^3/\text{yr}\) of sediment was exported from upper Tahoma Creek from 1970 to 1991. From 2003 to 2015 I found that \(\sim 1 \times 10^5 \text{ m}^3/\text{yr}\) of sediment was exported from the incising reach of Chocolate Creek (Fig. 36). Although the period of incision was longer, the yearly exported volume from incision was on the same order of magnitude at Mount Rainier compared to Glacier Peak.

**Potential implications for climate change**

In the 21\(^{\text{st}}\) century the Puget Sound region is expected to see double the warming experienced in the 20\(^{\text{th}}\) century (Mauger et al., 2015). Average summer temperatures in the Skagit River Basin are predicted to increase by as much as 5.8 to 6.7 °C by the 2080s (Mauger et al., 2015; CMIP5 RCP 8.5). Considering the ongoing effects of climate change, the results from the prior day temperature anomaly analysis may have implications for future debris flow frequencies. As climate continues to warm, I might expect that the magnitude and frequency of temperature anomalies would also increase. Based on this analysis I may see the frequency of debris flows in the Suiattle increasing in the coming years as temperatures rise from ongoing anthropogenic climate change. This mirrors the findings from other basins with stagnant and retreating glacial termini in their headwaters (O’Connor and Costa, 1993; Walder and Driedger, 1994; Copeland, 2009; Huggel et al., 2011; Lancaster et al., 2012; Stoffel and Huggel, 2012; Legg et al., 2014). In the Sauk River Basin, the area covered by glaciers decreased by 23% from 1959 to 2009 (Riedel and Larrabee, 2016). Most glaciers are predicted to be lost from the North Cascades by 2100 (Pelto, 2018). Because debris flows in the Suiattle depend on outbursts from these glaciers,
debris flow hazards will very likely begin to diminish by late in this century, if not sooner. However, before the glaciers are gone, their ongoing retreat may provide a punctuated increase in the magnitude and frequency of these events owing to readily available meltwater and increased unconsolidated sediment freshly exposed in proglacial environments.

*Where is the rest of the suspended sediment coming from?*

Using my suspended sediment budget for the Suiattle Basin I can begin to weigh the importance of sediment contributed from identified geomorphic sources and evaluate other potential sources in the basin (Fig. 26). Jaeger et al. (2017) estimated the anomalous suspended sediment load sourced from “proglacial point sources on the eastern flank of Glacier Peak” by subtracting an estimated background rate of sediment production from the calculated Suiattle sediment load. The sediment yield from basins draining the western flank of Glacier Peak were assumed to be baseline sediment production in the Suiattle Basin and measured SSL above the baseline on the Suiattle was attributed to the upper Suiattle (Jaeger et al., 2017). They found that about 60% of SSL on the Suiattle is ‘anomalous sediment load’, which they attribute to proglacial zones on the eastern flank. Using their work as a baseline, I can estimate the proportion of the total ‘anomalous sediment load’ that is explained by through-flowing debris flow material as well as fall ‘flushing’ of material deposited in the channel by these minor debris flow events. I can also put the volume of material eroded from the 2003 deposit (Fig. 36) in the context of the basin sediment budget to get an estimate of the relative magnitude of these events in the sediment budget of the basin.
In the lower basin, prominent sediment sources include retreating Holocene lahar bluffs on the mainstem Suiattle, and downstream tributaries of the Suiattle which transport sediment from the hillslopes to the mainstem (Fig. 26). These sources are considered part of the background rate estimated from the western flank of Glacier Peak. Previous work attributes 96,793 t/year to Holocene bluff retreat which represents ~14% of material from the lower Suiattle (Novak, 2021; Scott and Collins, 2021). Downstream tributaries that are known to run clear for the majority of the year account for some portion of the remaining ~26% of sediment load on the lower Suiattle. Further work is required to adequately address specific hillslope processes contributing to sediment flux in downstream tributaries. Hillslope processes that convey soil down slope and into channels from forested slopes would be dominated by soil creep which consists mainly of wetting and drying of the soil, tree throw, and bioturbation (Dietrich and Dunne, 1978). Rates of soil creep could be estimated from previous work in similar environments (e.g., Dietrich and Dunne, 1978). Fluvial processes including lateral migration and incision would function to periodically transport sediment from tributaries to the mainstem (e.g., Cianciala et al., 2020). In addition to these sources, rock-flour production beneath the glaciers should play a role, although to a lesser extent than in the Chocolate and Dusty basins, where the glaciers are larger. Unvegetated volcanic surfaces in proglacial zones would also contribute sediment, particularly during the snow melt season and during rainfall runoff events. While there are glaciated basins within the lower Suiattle Basin it is important to note that these basins are less geomorphically active (e.g., the glaciers are smaller, slopes are less steep in the proglacial zone, the proglacial zone sediment is probably less connected to channels through debris flow processes) and the extent of Quaternary unconsolidated volcanic deposits in the lower basin is much lower than in the upper basin.
Differentiating sediment delivery by process and timing

Air photo evidence and historical accounts suggest that the most recent minimum of incision into the Chocolate Fan surface follows the 2003 debris flow event. Therefore, incision into the 2003 deposit has formed the prominent terrace, and the resulting volume eroded represents material transported since 2003-7-30 (Fig. 36). Since deposition in 2003, ~1,728,547 t (±207,426) has been transported out of the upper Suiattle from incision into valley fill deposits in the upper basin. This volume, over the 12 years of incision, is more than 2 times the mean annual load on the Suiattle (Fig. 26).

Although there is some overlap between SSL from contemporary debris flow processes and from incision into historic deposits, the volume from historic deposits is not directly accounted for in my sediment budget (Fig. 26). My sediment budget only accounts for debris flow suspended sediment that is directly picked up in my contemporary debris flow analysis from the gauge during the period from July through October (Fig. 37). The coarse fraction of material introduced by debris flows certainly contributes to the annual SSL even though my analysis does not account for it directly (Fig. 37). From my sediment budget, up to ~38.7% of mean annual SSL could be accounted for by abrasion of the coarse fraction and incision in the upper basin outside of the debris flow and flushing time range (Fig. 26). I elaborate on the seasonality of the SSL analysis and on suspended sediment sourced from abrasion of the coarse fraction below.
The discrepancy between SSL from contemporary debris flow processes and long term incision into historic deposits is complicated by the fact that debris flows are not only mechanisms of deposition, they can also erode the bed (e.g., Benda and Dunne, 1987) and bulk up from steep channel margins (e.g., Lancaster et al., 2012; Legg et al., 2014), thus the sediment signal from contemporary debris flows could potentially include material that was eroded from the 2003 terrace (Fig. 36).

Channel response after the 1980 eruption of Mount St. Helens (MSH), though much more dramatic, can provide context for the pace of channel incision into debris flow deposits along the Suiattle River. If I look at the roughly 21% of mean annual SSL represented by contemporary debris flows and flushing on the Suiattle, it would take about 12 years for small debris flows and flushing to match SSL inputs from incision into historic deposits since 2003 (~1,728,547 t; Figs. 26 and 36). However, data from channel cross sections in the upper North Fork Toutle River Valley at MSH suggest that the majority of incision took place rapidly, occurring within the first 3 to 6 years after deposition (Major et al., 2018; Major et al., 2019; Major et al., 2021). During this channel reestablishment phase at MSH annual SSL was extremely elevated, hundreds of times above pre-eruption levels, and it quickly declined as initial incision accompanied by widening declined in the mid-1980s (Major et al, 2021). The analogy to MSH is supported by the fact that field measurements of terrace heights made in 2019 along the Chocolate Fan closely match the heights I measure from the 2015 LiDAR (Figs. 14 and 15). Together, the timing of incision at MSH and the stable terrace heights along Chocolate Creek between 2015 and 2019 suggest that SSL coming from the upper Suiattle would have been greatly elevated in the first few years immediately following deposition from historic debris flows.
Future work will focus on fine-tuning my contemporary debris flow analysis to better differentiate between discrete debris flow events and insignificant periods of very low turbidity and discharge. My contemporary debris flow analysis relies on a threshold value of the turbidity residual to automatically identify the timing, magnitude, and duration of debris flows as well as initiate the summation of debris flow SSL (Fig.10). From Figure 21, it is clear that this threshold value needs to be increased to more accurately and precisely differentiate debris flow processes from other processes occurring in the summer. Future work will seek to fine-tune the turbidity residual threshold to limit the extent of summertime SSL attributed to debris flows. Adjusting the turbidity residual threshold, used here to define debris flows, will certainly improve the identification of discrete summer debris flow events (Fig. 21). However, it is unlikely to have a profound impact on the amount and proportion of debris flow SSL reported here because by definition increasing the turbidity residual threshold will remove time periods of the lowest turbidity values included in the debris flow dataset (Fig. 21). Turbidity spikes, independent of discharge, occur every year over in my contemporary debris flow analysis (Fig. 27). The summer of 2019 is a representative year from my dataset in which I identified multiple debris flow events not previously reported (Fig. 21). Although adjusting the turbidity residual threshold will improve results presented in Figure 21, it is very unlikely to change major interpretations presented here.
**Seasonality of the analyses**

Suspended sediment from minor debris flow events that arrive at the downstream gauge outside of the late summer and early fall are not resolved in my contemporary debris flow analysis. In the summer, suspended sediment from contemporary debris flows is being supplied during low discharge (Fig. 37). Additional sediment exceeding transport capacity is likely stored along channel margins in areas of reduced velocity (Major et al., 2018). Some of this material would be transported during recorded flushing events, but it is possible that the coarsest remaining sediment could only be transported at the highest flows (Fig. 37). This transport of contemporary debris flow sediment would contribute to overall upper basin SSL outside of contemporary debris flows and flushing inputs estimated here (Figs. 26 and 37).

My definition of flushing is a conservative one. Despite having a flushing threshold at discharges above 250 m$^3$/s, small increases in discharge have a powerful effect on SSL accumulation and exceptional discharges are not necessary for flushing events to occur. The winter following extreme sediment loading in summer 2015 had extraordinary SSL without particularly unusual discharge (Fig. 27).

High magnitude discharge recorded at the Lower Sauk gauge does not always coincide with high discharge in the upper basin. In the late fall and winter months when the highest flows typically occur, higher elevation basins including Chocolate and Dusty Basins waver in the transient zone
near the snowline elevation threshold between receiving rain or snow (NSD, 2014). Rain events would lead to higher magnitude discharge, incision, and higher SSL, while snow would not.

During winter and spring, the presence of a snowpack in alpine basins or lack thereof would also have consequences for the hydrological response of the broader Suiattle Basin including changes to the rates of erosion and sediment transport (Mauger et al., 2015; Major et al., 2021). Snowpack can function to protect hillslopes from runoff and erosion by acting as a stabilizing layer (e.g., Lancaster et al, 2012; Major et al., 2021). Hillslopes lacking a snowpack would be more susceptible to erosion and runoff. Thus, a higher snowline elevation could expose a larger area of unconsolidated hillslopes to erosion and runoff due to both rain falling on a greater area and unconsolidated material being unprotected by snow cover (e.g., Huggel and Clague, 2012; Fig. 37).

Discharge and SSL from higher elevation basins within the Suiattle Basin may increase in the future due to several factors, all driven by climate change. Subtle changes in temperature can move the snowline upslope and expose a greater area to rainfall and reduce the depth and extent of snowpack. The majority of peak flows in the Sauk Basin result from atmospheric rivers in the late fall and winter (Neiman et al., 2011). Atmospheric rivers are bands of moist warm air transported from tropical regions to cooler regions at higher latitudes (Warner et al., 2014). In the Pacific Northwest atmospheric rivers move east off the Pacific Ocean and crash into the Cascades delivering extreme rainfall and higher than normal temperatures (NSD, 2014). The combined effect can cause rain-on-snow events where warm rain falling at higher elevations rapidly melts snowpack and often generates annual peak flow level discharges. One such
an atmospheric river event, on February 1, 2020, drove 15-minute SSL values recorded at the Lower Sauk gauge to above 8,500 t/15-minutes at discharges exceeding 1400 m³/s (Fig. 27). This single winter event contributed ~400,000 t to the annual load for 2020 (Table 4). The storm delivered 7.8 cm of rain over one day with a maximum daily temperature of 55°C (12.4°C above the 30-year normal) at the Darrington Ranger Station. Global warming is predicted to significantly increase the frequency and intensity of extreme atmospheric river events along the West Coast of North America by the end of this century (Warner et al., 2014). Changes to alpine snow and rain dynamics driven by warming are likely to influence the timing and magnitude of discharge, incision, and SSL in the upper Suiattle throughout the coming century.

Could wintertime debris flows be happening, and I am just not picking them up? On one hand, winter debris flows are not impossible, but due to higher winter discharges the turbidity signal at the downstream gauge would probably not be registered by my analysis due to dilution. Despite the possibility of winter debris flows, unfavorable proglacial source zone conditions including persistent freezing temperatures and potentially a deep protective snowpack would inhibit most triggering events.

Role of abrasion in elevated suspended sediment loads

My suspended sediment load analysis captures only fine sediment, yet the debris flows carry sediment as large as boulders. During the debris flows themselves, the boulders are likely only transported a short distance down the mainstem channel. Boulder transport for the 2003 event likely ceased within the first few kilometers downstream of Chocolate Creek (Fig. 36). Beyond
that point in the channel, a portion of the fine sediment from the debris flow continued down the Suiattle and was registered as a high SSL signal at the gauge (Fig. 37).

We consider, now, the fate of the coarse debris flow material. Production of fines via the process of abrasion during high flow events represents another possibly substantial source of suspended sediment in the upper Suiattle (Fig. 37). Low density vesicular dacite clasts make up ~78% of the debris flow source material and resultant gravel bar sediment near the confluence of the Suiattle River and Chocolate Creek (Pfeiffer et al., 2020). The softer material, dominating sediment supply in the upper Suiattle, is highly susceptible to transport dependent abrasion processes (Attal and Lavé, 2009). Abrading clasts transporting as bedload during high flows would experience significant volumetric losses which would be proportional to increases in suspended load resulting from the products of abrasion (Fig. 37). Increased SSL from abrasion would occur during high flow events, outside of summertime debris flow periods (Figs. 26, 27, and 37).

*Continued incision into Holocene volcanic deposits*

In addition to recurring inputs from contemporary and historic debris flows, continued vertical and lateral incision into the Suiattle Fill would represent another principal sediment source in the upper Suiattle. Extreme sediment loading at Mount St. Helens (MSH) resulting from the 1980 eruption has been well studied (e.g., Lipman and Mullineaux, 1981; Criswell, 1987; Fisher, 1990). Following syneruptive deposition, a long-term study of cross sections on the North Fork Toutle River showed that the dominant response of the fluvial system was incision (Major et al., 2018). The products of this incision at MSH are clearly evident in the elevated SSL exiting
basins following the eruption (Uhrich et al., 2021). Like MSH, Glacier Peak has experienced extreme sediment loading from pyroclastic flows and dome collapse. At ~5,500 ybp (Beget, 1982), an eruptive episode deposited ~ 4 km³ (Tabor and Crowder, 1969) of material throughout the upper Suiattle, forming the broad volcanic apron referred to as the Suiattle Fill. Evidently a large proportion of SSL, outside of debris flow processes, is potentially sourced from ongoing incision into the abundant Suiattle Fill (Figs. 4 and 6). The idea that volcanic fluvial systems in the Cascades remain perpetually disturbed following catastrophic eruptions (J. Major, pers. comm., 2021), not reaching an equilibrium state at societally important timescales from centuries to millennia, likely applies to both MSH and Glacier Peak. Initial volcanic input at Glacier Peak is on the same order of magnitude as the 3.3 km³ (Uhrich et al., 2021) reported at MSH. After ~5,500 years, legacy volcanic sediment continues to drive elevated sediment loads at Glacier Peak. Thinking broadly about Glacier Peak as a space-for-time substitution for incision processes into post-eruptive alluvial fills at MSH, excess sediment loads sourced from the 1980 eruption could persist for millennia to come.

Abrupt increases in sediment supply, like the valley filling debris flows from the upper Suiattle, can cause channel widening and increased braiding (East et al., 2018). On the Suiattle, an increase in active channel width was accompanied by reduced roughness of the floodplain and channel by removal of forests and deposition of fine material over the former channel. The overall effect functioned to increase connectivity between the channel and the steep, unconsolidated bluffs of the Suiattle Fill. Subsequent floods can result in substantial geomorphic change when the channel has high connectivity to tall banks (Major et al., 2021). Increased active channel width in concert with increased connectivity to bluffs represents a feedback by
which debris flows in the Suiattle could have triggered drastic increases in sediment yield from the basin following the onset of major debris flows in the late 1930s.

**Conclusions**

My goal was to constrain the geomorphic processes in the upper Suiattle responsible for the anomalous suspended sediment load. I find that debris flows of widely varying magnitude are predominantly triggered by high temperatures in the late summer. Major debris flow activity initiated in the late 1930s with 9 major debris flows occurring since 1938. Through reanalysis of previous dendrochronology samples and historical aerial imagery, I found one unreported debris flow responsible for drastic geomorphic change in the late-1940s. Based on my historical analysis, Chocolate Glacier has a high propensity for producing outburst floods that lead to debris flows. Its contribution to the sediment supply of the Suiattle is likely to vastly outweigh other glaciers of the volcano including Dusty Glacier, which produced only one higher magnitude debris flow and one lower magnitude debris flow. Smaller, contemporary debris flows are recorded every year at the downstream gauge. Recurring debris flows of varying magnitudes combined with high magnitude floods work sequentially to deliver sediment from the seemingly endless volcanic sediment source in the proglacial zone to the mainstem river. This work is a step toward understanding how sediment supplied from alpine mass wasting events shapes downstream geomorphic processes, with implications for how climate change may alter cascading hazards in these systems.
References


**Tables**

Table 1. Dendrochronology samples ordered from downstream to upstream.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Minimum Surface Age (Calendar Years C.E.)</th>
<th>Uncertainty</th>
<th>Stream</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2007</td>
<td>-7, +12</td>
<td>Suiattle River</td>
<td>Alder</td>
</tr>
<tr>
<td>2</td>
<td>2009</td>
<td>-7, +10</td>
<td>Suiattle River</td>
<td>Alder</td>
</tr>
<tr>
<td>3</td>
<td>2004</td>
<td>-7, +15</td>
<td>Dusty Creek</td>
<td>Alder</td>
</tr>
<tr>
<td>4</td>
<td>2011</td>
<td>-7, +8</td>
<td>Dusty Creek</td>
<td>Alder</td>
</tr>
<tr>
<td>5</td>
<td>1980</td>
<td>-7, +20</td>
<td>Suiattle River</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>6</td>
<td>1969</td>
<td>-7, +20</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>7</td>
<td>1940</td>
<td>N/A</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>8</td>
<td>1956</td>
<td>-7, +20</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>9</td>
<td>1959</td>
<td>-7, +20</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>10</td>
<td>1800</td>
<td>-7, +20</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>11</td>
<td>1978</td>
<td>-7, +20</td>
<td>Chocolate Creek</td>
<td>Douglas fir</td>
</tr>
</tbody>
</table>

Table 2. Summary statistics for the frequency distributions of the prior day maximum temperature anomalies (°C) for debris flow start days and non-debris flow days used in the meteorological analysis.

<table>
<thead>
<tr>
<th>Class</th>
<th>Number (n) in Sample</th>
<th>Mean (°C)</th>
<th>Median (°C)</th>
<th>Standard Deviation (°C)</th>
<th>Minimum (°C)</th>
<th>Maximum (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Flow Start Days</td>
<td>28</td>
<td>2.48</td>
<td>2.78</td>
<td>3.67</td>
<td>-6.67</td>
<td>10.0</td>
</tr>
<tr>
<td>Non-Debris Flow Days</td>
<td>757</td>
<td>-0.21</td>
<td>-0.56</td>
<td>4.06</td>
<td>-11.67</td>
<td>12.22</td>
</tr>
</tbody>
</table>

Table 3. Summary statistics for the frequency distributions of prior day precipitation (cm) for debris flow start days and non-debris flow days use in the meteorological analysis.

<table>
<thead>
<tr>
<th>Class</th>
<th>Number (n) in Sample</th>
<th>Mean (cm)</th>
<th>Median (cm)</th>
<th>Standard Deviation (cm)</th>
<th>Minimum (cm)</th>
<th>Maximum (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Flow Start Days</td>
<td>28</td>
<td>0.17</td>
<td>0.0</td>
<td>0.38</td>
<td>0.0</td>
<td>1.57</td>
</tr>
<tr>
<td>Non-Debris Flow Days</td>
<td>761</td>
<td>0.44</td>
<td>0.0</td>
<td>1.17</td>
<td>0.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Table 4. Middle and Lower Sauk Suspended Sediment Load (SSL) is calculated from 15-minute interval USGS time series data (Sauk River near Darrington, 12187500; Sauk River near Sauk, 12189500). The difference between Lower Sauk and Middle Sauk is used as a proxy for SSL in the Suiattle Basin. Middle and Lower Sauk only overlap for the period 2011-10-29 to 2015-12-07 because turbidity monitoring was discontinued at Middle Sauk on 2015-12-07. SSL on the Suiattle, outside of the period of overlap, was estimated by calculating a baseline as the percentage of Middle Sauk SSL showing up at the Lower Sauk gauge (~25% for WYs 2012 to 2016). Years where Suiattle Basin SSL was adjusted using the 25% metric are denoted by the ‘ † ’ symbol. Debris flow and flushing SSL was calculated using the turbidity residual analysis described above. Years with a ‘*’ have incomplete data and were not incorporated into averages for mean annual load calculations for Middle and Lower Sauk. The mean annual load on the Suiattle was calculated as the difference between mean annual load on the Middle and Lower. Percentage of Suiattle debris flow and flushing SSL were calculated as the percentages of mean annual load for the Suiattle, shown in the table (667,948 t). No data were recorded for 2017.
Table 5. Cumulative Suspended Sediment Loads (SSL) estimated from 15-minute turbidity and discharge records. Period of record for each category is listed and varies between categories. The Suiattle basin SSL is the difference between Lower Sauk and Middle Sauk during the period of overlap.

<table>
<thead>
<tr>
<th>Category</th>
<th>Period of Record</th>
<th>Cumulative SSL Sum over Period of Record (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Sauk Gage</td>
<td>2011-09-23 to 2021-04-13</td>
<td>6,418,167 (±808,689)</td>
</tr>
<tr>
<td>Middle Sauk Gage</td>
<td>2011-10-29 to 2015-12-07</td>
<td>870,573 (±116,656)</td>
</tr>
<tr>
<td>Suiattle Basin</td>
<td>2011-09-23 to 2021-04-13</td>
<td>5,547,594 (±976,376)</td>
</tr>
<tr>
<td>Suiattle Basin Debris Flow</td>
<td>2011-09-23 to 2020-10-10</td>
<td>512,563 (±102,513)</td>
</tr>
<tr>
<td>Suiattle Basin Debris Flow Flushing</td>
<td>2011-09-23 to 2020-10-10</td>
<td>645,870 (±129,174)</td>
</tr>
</tbody>
</table>
Table 6. List of major debris flows in the upper Suiattle.

<table>
<thead>
<tr>
<th>Count</th>
<th>Date</th>
<th>Relative Magnitude</th>
<th>Stream</th>
<th>Source(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>~9/26/1940</td>
<td>High</td>
<td>Chocolate Creek</td>
<td>Dendrochronology (this study); USGS station notes and correspondence with USFS 4/4/1941 to 7/10/1941 regarding questions about damaged gauges</td>
<td>USFS author suggests about 9/26/1940 for event timing, speculates about a Chocolate Creek source, &quot;large quantities of sand still being washed down Suiattle, Sauk, and Skagit as a result of this flood&quot;; Supported by dendrochronology, suppressed growth in Sample 7 beginning in 1941.</td>
</tr>
<tr>
<td>3</td>
<td>circa late-1940s</td>
<td>High</td>
<td>Chocolate Creek</td>
<td>USGS aerial imagery, reanalysis of dendrochronology samples from Slaughter, 2004</td>
<td>Previously unreported event. Reanalysis of previous dendrochronology (Slaughter, 2004) points to a late 1940s event. Air photo evidence from 1944 and 1950 shows formation of a new depositional surface along Chocolate Creek, vegetation thinning on fan, changes at the confluence of Dusty Creek and the Suiattle, and an outburst scarp at the glacial terminus.</td>
</tr>
<tr>
<td>4</td>
<td>circa late-1940s?</td>
<td>High?</td>
<td>Dusty Creek</td>
<td>USGS aerial imagery</td>
<td>Significant channel widening, rerouting, and dev egetation on Dusty Creek upstream of the confluence with the Suiattle River observed in air photos between 1944 and 1950.</td>
</tr>
<tr>
<td>9</td>
<td>8/13/2015</td>
<td>Low to Medium</td>
<td>Chocolate Creek</td>
<td>Jaeger et al., 2017, Anderson et al., (2018)</td>
<td>Observed in turbidity discharge record and supported by topographic differencing at the glacial terminus (Jaeger et al., 2017). Anderson et al. (2018) estimated &gt;400,000 m³ eroded from proglacial zone, ~200,000 m³ deposition near the Suiattle River’s confluence with Chocolate Creek.</td>
</tr>
</tbody>
</table>
Figures

Figure 1. Location of the Suiattle Basin study area, Washington State, USA. (A.) The Suiattle Basin is outlined in a thick black line. The Sauk Basin is outlined by a thin black line. Locations of the USGS gauges are marked by white triangles. The meteorological station located at the USFS Darrington Ranger Station is marked by the black dot. (B.) 1-meter 2015 LiDAR, Chocolate Fan at the confluence of the upper Suiattle River and Chocolate Creek, distinct terraces are visible. Extent of Panel B is shown in Panel A by a red rectangle. (C.) Satellite imagery of Glacier Peak showing glaciers and drainages to the Sauk River. Extent of Panel B is shown in Panel C by a red rectangle.
Figure 2. Satellite composite image of Outburst Canyon, eastern flank of Glacier Peak Stratovolcano (Google Earth, https://earth.google.com/web/@48.12074977,-121.04564909,1643.94760829a,9372.61103029d,35y,-89.41937595h,59.54197481t,0r). The image is looking to the southwest. Outburst Canyon is located in the center of the image. Chocolate Glacier is perched directly above the canyon and Chocolate Creek drains the glacier descending past the Chocolate Fan in the lower left before meeting the Suiattle River in the central foreground of the image.
Figure 3. The Lower Sauk USGS gauge as a proxy for turbidity on the Suiattle River: (A.) contrast in turbidity between the Suiattle River and the Sauk River (Planet Satellite Imagery, captured 2014-08-18, 5 m/pixel); (B.) 15-minute USGS data recorded at the Middle Sauk USGS gauge for August through September 2014; (C.) 15-minute USGS data recorded at the Lower Sauk USGS gauge for the same time period in B. Red arrows in B and C correspond to the timing of the imagery in A. Note that the magnitude of turbidity is lower in B compared to C, and that B lacks spikes in turbidity seen in C.
Figure 4. Discharge and turbidity relationships from 15-minute data for the Sauk River Basin (Lower Sauk, 12189500). (A.) Full 2020 water year demonstrating differences in discharge and turbidity relationships between winter and summer months. (B.) Winter data showing scaling pattern between discharge and turbidity. (C.) Summer data illustrating increases in turbidity that are independent of discharge. Black lines in panel A highlight locations of panels B and C in the water year.
Figure 5. Study area map showing the location of the Suiattle River Basin in the North Cascades Mountain Range of western Washington State. The map also highlights the relationship between the Suiattle River, the Skagit River, and the Puget Sound which are all part of important habitat for multiple threatened salmonid species. The extent of Wild and Scenic and Wilderness protections is also depicted in the map. Map data sources: 30m DTM Hillshade-Washington State Department of Natural Resources (http://data-wadnr.opendata.arcgis.com/), Wild and Scenic Corridor and Glacier Peak Wilderness- U.S. Forest Service Geospatial Data Discovery (https://enterprisecontentnew-usfs.hub.arcgis.com/datasets/national-wild-and-scenic-river-lines-feature-layer?geometry=136.025%2C46.638%2C-94.211%2C51.662).
Figure 6. Study area with geology and topography. Inset maps highlight the upper Suiattle Basin geology (including streams and the Suiattle Fill) as well as glacial deposits near the mouth of the Suiattle River. Map data sources: Washington Department of Natural Resources LiDAR and Geologic Information Portals (Geologic Units-https://geologyportal.dnr.wa.gov/, LiDAR DTM-https://lidarportal.dnr.wa.gov/#48.20317:-121.20255:11).
Figure 7. Photos from Miners Ridge USFS Fire Lookout (Photo source: Eric Willhite [http://www.willhiteweb.com/washington_fire_lookouts/miners_ridge/tower_326.htm]): (A.) 1935 image showing pre-disturbance valley bottom (Photo credit: G.B. Clisby); (B.) 2015 image (Photo credit: Will White) overlain on top of and justified to the 1935 image showing the modern, exposed and widened valley bottom. The yellow arrow points to the same point in both A and B. Note that the bright volcanic sediment from Glacier Peak is clearly visible in B, but is not distinct in A.
Figure 8. Circa 1956 photo of the upper Suiattle Valley taken from Miners Ridge Fire Lookout (Photo credit: Phillip Hyde). View is looking upstream past the confluence of Dusty Creek and the Suiattle River. The Dusty Creek channel is visible to the lower right. The Suiattle River channel is visible in mid-left. The Suiattle Fill, the densely forested fan slope with bright exposures where incised, features prominently in the center of the image.
Figure 9. Panel A shows the valley fill debris flow deposit in tan over a 2015 1 m LiDAR DTM. Remnants of the deposit extend downstream along the Suiattle for at least 10 km. The cross-section A to A’ is located ~7km downstream from the summit of Glacier Peak along Chocolate Creek near its confluence with the Suiattle River. Panel B depicts the cross-section with estimated debris flow deposit thickness of ~5m. The interpolated raster surface is depicted by a red dashed line. All dashed lines imply inferred contacts. A queried contact at the base of the valley fill debris flow deposit implies that the deposit thickness likely extends below the channel thalweg and was not identifiable in the field. Panel C shows the valley fill surface alongside an orange polygon representing the area of material eroded due to channel incision. DEM differencing of the interpolated surface and the LiDAR DTM (Panel B, solid black line in cross-section) result in a raster dataset composed of erosional difference values ($D_i$). Summing the $D_i$ values from the erosional difference raster yields a net volume of material eroded from the initial deposit.
Figure 10. Turbidity residual analysis. All data are from 15-minute USGS turbidity (FNU) and discharge (m$^3$/s). Gray data points represent the expected relationship between turbidity and discharge, winter data. All data are colored by turbidity residual. Turbidity residuals were calculated from the black, winter fit, best fit line. Turbidity residual values above the flushing threshold (shown in blue) for discharges greater than 2.39 (log$_{10}$ units) and below the debris flow threshold 1.5 (log$_{10}$ units) are considered flushing signal. Debris flow signal is collected above the debris flow threshold 1.5 (log$_{10}$ units) shown in red.
Figure 11. $\log_{10}$ turbidity residuals colored by month as a function of time. Turbidity residuals were calculated from 15-minute USGS turbidity (FNU) and discharge (m3/s) over the period of record. The debris flow turbidity residual threshold $> 1.5$ is shown by the black line. Months above the threshold correspond to months where we expect to see debris flows.
Figure 12. Frequency distributions of log_{10} turbidity residuals. Residuals above the 1.5 threshold are considered debris flows and are shown in red. The bimodal distribution suggests that a change in process drives the second peak with a maximum near 1.5.
Figure 13. Field and LiDAR identified terraces. Locations of the photographs are shown in Panel B and in the inset, Panel C. Location of Panel B is shown in C by the red box. (A.) Prominent debris flow terrace with boulders at the surface. Photo is looking upstream on Chocolate Creek. (D.) Exposure of debris flow terrace riser displaying megaclasts, large wood inset within the deposit, matrix supported clasts, and inverse grading. Photo is looking downstream on Chocolate Creek. (E.) Debris flow terrace riser with standing dead trees killed by the debris flow in the background. Photo is looking across the Suiattle River below the confluence with Dusty Creek. (F.) Example of a channel adjacent tree with a severely battered trunk caused by recurrent debris flows. The tree is located along Chocolate Creek. Field book for scale.
Figure 14. Comparison between field measured terrace height and terrace height extracted from the LiDAR: (A.) Locations where measurements were taken in the field and in the LiDAR; (B.) LiDAR elevation profile demonstrating that field measured terrace height was consistent with terrace height measured from the 2015 LiDAR DTM.
Figure 15. 2019 field measured terrace height (m) vs. 2015 LiDAR terrace height (m). Data points are labeled corresponding to their profile locations in Figure 14. Black line represents a 1:1 relationship between the axes. Points above the black line indicate aggradation after 2015 and points below the line indicate incision after 2015. Nine out of 14 sites show a change in terrace height of less than 1 meter between the 2015 LiDAR and the field measurement indicating relatively little incision or aggradation over the four years between measurements.
Figure 16. Minimum surface ages from dendrochronology samples are represented by dots colored by stream. Samples are numbered from downstream (1) to upstream (11). Samples from living trees have an uncertainty of -7 and +20 years shown in blue. The crossdated slab (Sample #7) does not have associated uncertainty.
Figure 17. Locations of dendrochronology samples in the upper Suiattle Basin. Extent of A is shown in red and the extent of B is shown in black in Panel C. Samples marked in green represent the oldest core from any given surface. Brown dots mark a group of cores from living trees, where the oldest core was used as the minimum age or unutilized slabs taken from trees killed by debris flows.
Figure 18. Photographs of dendrochronology Sample #7, the standing dead Douglas fir, located along Chocolate Creek. (A.) Crossdated slab showing dated rings and the region of suppressed growth. (B.) Field assistant extracting sample. The tree is about 1 m in diameter. (C.) Sampled Douglas fir standing ~36 m above a debris flow terrace. (D.) Aerial photo of Sample #7 highlighted by a distinct shadow cast over the terrace surface.
Figure 19. Interpolated Surface DoD map for incision on Chocolate Creek and the Suiattle River. Polygons on the map break up the volume eroded from each 750 m section. Volume eroded from each section is plotted against distance downstream from the first polygon boundary. Blue arrows in the plot and in the map denote the locations of tributary junctions.
Figure 20. Surface roughness, considered here to be the standard deviation of elevation, was calculated using a 9x9 cell moving window, for every cell within the red Roughness Polygon (Panel A). The average roughness over the red polygon area was 0.27 meters. Our volume estimate was recalculated excluding all values below 0.27 meters. Essentially, subtracting the first 0.27 m from the initial DoD surface (Panel B). The recalculation resulted in a decrease in the volume estimate of about 12% of the total volume.
Figure 21. Gauge records of turbidity (FNU) and discharge (m$^3$/s) from the Lower Sauk gauge showing 15-minute data for summer and early fall 2019. The lower two panels show estimated suspended sediment loads and cumulative suspended sediment loads (t) for the Suiattle Basin during our contemporary debris flow analysis. In the turbidity panel, time periods when the debris flow signal was picked up are highlighted in red and the debris flow flushing signal is highlighted in violet.
Figure 22. Relative frequency distribution of prior day maximum temperature anomalies (°C) for debris flow start days in red and non-debris flow days in blue. Maximum temperature anomalies were calculated from 30-year normals and daily maximum temperatures collected at the Darrington Ranger Station. Meteorological analysis is limited to months July through October for the time period 09-23-2011 to 10-31-2020.
Figure 23. Cumulative distribution functions of prior day maximum temperature anomalies (°C) for debris flow start days and non-debris flow days. The Kolmogorov-Smirnov test showed that the two distributions are statistically different ($d_m = 0.314$, $p = 0.007$).
Figure 24. Relative frequency distributions of prior day precipitation (cm) for debris flow start days in red and non-debris flow days in blue. Precipitation measurements were collected at the Darrington Ranger Station. Meteorological analysis is limited to months July through October for the time period 09-23-2011 to 10-31-2020.
Figure 25. Cumulative distribution functions of prior day precipitation for debris flow start days and non-debris flow days. The Kolmogorov-Smirnov test showed that the two distributions are not statistically different ($d_{km} = 0.107$, $p = 0.90$).
Figure 26. Suspended sediment budget for the Suiattle River subdivided into the upper Suiattle (headwater basins draining the eastern flank of Glacier Peak) and the Lower Suiattle. *Arrived at 40% from Jaeger et al. (2017) who demonstrated that neighboring basins can be used to calculate a baseline rate of sediment production for the lower Suiattle. **Remaining mass from the upper Suiattle likely receives substantial SSL contributions from incision into extensive historic debris flow deposits outside of our debris flow and flushing SSL summation periods and from long term incision into legacy volcanic material. Additionally, some proportion is likely accounted for by storage in the system.
Figure 27. Cumulative SSL in $1\times10^6$ t for the Middle and Lower Sauk gauges from 15-minute data. Discharge for Lower Sauk in light blue. Time periods when the summertime debris flow and anomalous sediment flushing signals are picked up in our turbidity residual analysis and summed are plotted in red and blue, respectively.
Figure 28. Eight historical aerial images of the Chocolate Fan, running along Chocolate Creek, upstream of the confluence between Chocolate Creek and the Suiattle River (1944 to 1984: USGS Earth Explorer, 1998 Google Earth). Images depict history of deposition and incision. Annotations indicate changes discussed in the text. Flow direction of Chocolate Creek and the Suiattle River are depicted by arrows on the 1953 image. Chocolate Creek as depicted is roughly 5 km downstream from the terminus of Chocolate Glacier.
Figure 29. Debris flow deposit photographs from Ford (1959) taken during field work between 1954 and 1958: (A.) Looking up the Suiattle River on the eastside of the Chocolate Fan, recurring debris flows have forced the Suiattle east into the adjacent forest; (B.) Upstream end of the Chocolate Fan, debris flow deposit (right side of image) stands about 1.5 meters above Chocolate Creek; C. Lower Chocolate Fan, Chocolate Creek has eroded much of the debris flow deposit leaving a debris flow terrace (right side of image) with standing dead trees killed by the debris flow.
Fig 30. Historical images from the terminus of Chocolate Glacier providing support for a circa late-1940s event (USGS Earth Explorer). The red arrow is stable in both photos and points to the scarp of interest and the general direction of flow. In the 1944 photo, the scarp at the glacier terminus is much smaller in extent. In the 1950 photo, lobes from the 1944 scarp, in the northwest, have coalesced, covering a larger surface area and advanced upslope into the ice-covered area visible in 1944. The elliptical insets are enlarged to highlight changes in the scarps.
Figure 31. Images of Dusty Creek Confluence with the Suiattle River from 10-6-1944 and 8-17-1950 (USGS Earth Explorer) providing evidence of drastic changes including razing of mature conifer stands on the channel margins and significant addition of sediment to the floodplain. Supports a major circa late-1940s event.
Figure 32. Reanalysis of Slaughter (2004) dendrochronology: (A.) Slaughter (2004) dendrochronology samples (22.9 to 13.6) plotted as minimum surface ages; (B.) locations of dendrochronology samples.
Figure 33. Historical aerial imagery from 1974 and 1979 of the confluence of the Suiattle River with Dusty Creek (USGS Earth Explorer). Change in vegetation and channel re-routing provide evidence for the 1978 Dusty Creek debris flow.
Figure 34. Oblique air photos of the Chocolate Fan taken on May 27\textsuperscript{th} (B.) and 29\textsuperscript{th} (A.), 2003 (Photo Source: John Scurlock). Photos point to the summer of 2003 being a period of minimal incision into the Chocolate Fan over the period of study. Photo A is looking to the north over the Chocolate Fan upstream of the confluence between Chocolate Creek and the Suiattle River. Photo B is looking to the west towards Glacier Peak.
Figure 35. Suspended sediment loads per water year from 15-minute data for the Suiattle Basin broken up into debris flows, flushing, and total annual SSL. Water years with incomplete data were excluded from the plot.
Figure 36. Topographic differencing map for incision (minimum bound of material eroded) into debris flow deposits along Chocolate and Dusty Creeks and the Suiattle River: (A.) shows the full extent of estimated incision in the study area; (B.) is zoomed in on the Chocolate Fan. Black dashed line represents the area of the Chocolate Fan incised since 2003. Red dashed line represents the area of Dusty Creek incised since 1978.
Figure 37. Conceptual model of debris flow sediment export in the upper Suiattle. (A.) A summer day debris flow occurs during low discharge. The turbidity signal is picked up by our automatic analysis and SSL is summed as contemporary debris flow SSL. The majority of suspended sediment is transported down past the gauge while some amount deposits on banks and bars. (B.) Precipitation in the late summer to early fall increases discharge, partially incising headwater debris flow deposits and transporting some of the sand deposited on banks and bars past the gauge where SSL is attributed to anomalous sediment flushing. (C.) Major rainstorms drastically increase discharge causing significant incision into debris flow deposits. Abrasion during bed load transport generates additional fines from the course fraction of the debris flow deposit material. The coarse fraction makes up ~ 78% of the initial deposit of which about half is converted to fines through abrasion. Processes in Panel C explain up to 38.7% of the mean annual load from the upper Suiattle.
### Appendix A

Table A.1. Terrace height profile locations with initial 2015 LiDAR measurements, field terrace measurements, and the difference (LiDAR – Field).

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<th>Profile</th>
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<th>*Northing</th>
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<th>LiDAR Terrace Height (m)</th>
<th>Difference [LiDAR – Field] (m)</th>
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*Locations were measured with consumer grade GPS and are only accurate to within ± 5 m.
Supplementary Material

The Supervisor
Mt. Baker National Forest
Bellingham, Washington

Dear Sir:

Our gaging stations on Suquathie River and Suiattle River below the Suquathie have been affected by large movements of sand in the rivers since last September.

Have you had any report of large slides or intense rain of possibly cloudburst proportion occurring in the Suquathie River Basin during September of last year? We should like to have any available information as an aid in interpreting results at our gaging stations.

Very truly yours,

F. H. Veatch
District Engineer

July 8, 1941

1100 Washington Building
Tacoma, Washington
April 4, 1941
12-1890

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
Mount Baker National Forest

ADDRESS REPLY TO
FOREST SUPERVISOR
AND REFER TO
E
COOPERATION- Mt. Baker
Geological Survey

BELLINGHAM, WASHINGTON
April 15, 1941

U.S. FOREST SERVICE

Mr. F. W. Veatch,
District Engineer, U.S. Dept. of Interior,
1100 Washington Building,
Tacoma, Washington.

Dear Sir:

We have decided to refer your letter of April 4 to District Ranger Hugh Ritter at Sauk for more details as to the approximate dates and nature of the heavy rains or cloudburst occurring on the Suilsite River last fall. We recall that the storm was quite severe, sufficiently so as to wash out several of our trucktrail bridges, but have no record here at this time of the dates. We will write you more fully as soon as we hear from Ranger Ritter.

Very truly yours,

CHAS. H. FLORY, Forest Supervisor,

Acting.
Mr. F. W. Veatch,
District Engineer, U.S. Dept. of Interior,
1100 Washington Building,
Tacoma, Washington

Dear Sir:

The follow up reply to your letter of April 4 appears to have been overlooked in this office.

As stated in our letter of April 15, your inquiry was referred to District Ranger Hugh Ritter at the Sauk station. He replied on April 16 and his statement is being quoted in full as follows:

"In connection with your inquiry relative to dates, damage, etc., of a flood which occurred on the Tulallite River last fall please refer to my memorandum, E-Improvements of October 15, 1940.

The exact date of the flood is not known, but I believe it was on September 26. Anyway it was the last week in September as stated in my memo.

I do not believe the flood occurred as a result of a cloudburst or even a heavy rain but, from a landslide on the headwaters of Chocolate Creek. It may have been aggravated by the slipping of a glacier. We may have an opportunity to learn more about the course of the flood during the ensuing field season.

It is hoped that the information given here in addition to what may be gotten from the memo referred to previously will enable you to fully reply to the Geological Survey peoples letter.

You may be interested to know that large quantities of sand are still being washed down the Tulalite, Sauk and Skagit River as a result of this same flood."

Very truly yours,

CHAS. M. FLORY, Forest Supervisor,
By [Signature]
Acting.