New Chronologic and Geomorphic Analyses of Debris Flows on Mount Rainier, Washington

By Ian Delaney

Abstract

Debris flows on Mount Rainier are thought to be increasing in frequency and magnitude in recent years, possibly due to retreating glaciers. These debris flows are caused by precipitation events or glacial outburst floods. Furthermore, as glaciers recede they leave steep unstable slopes of till providing the material needed for mass-wasting events. Little is known about the more distant history and downstream effects of these events. Field observations and/or aerial photograph of the Carbon River, Tahoma Creek, and White River drainages provide evidence of historic debris flow activity. The width and gradient of the channel on reaches of streams affected by debris flows is compared with reaches not affected by debris flows. In all reaches with field evidence of debris flows the average channel width is greater than in places not directly affected by debris flows. Furthermore, trends in width relate to the condition of the glacier. The stable Carbon Glacier with lots of drift at the terminus feeds the Carbon River, which has a gentle gradient and whose width remains relatively consistent over the period from 1952 to 2006. Conversely, the rapidly retreating Tahoma and South Tahoma Glaciers have lots of stagnant ice and feed the steep Tahoma Creek. Tahoma Creek's width greatly increased, especially in the zone affect by debris flow activity. The rock-covered, yet relatively stable Emmons Glacier feeds White River, which shows relatively little change in channel width.

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Introduction

Mount Rainier holds great cultural and environmental significance in the Pacific Northwest. As an active volcano it garners great attention, due to its proximity to Seattle and other nearby urban centers. Furthermore, its massive size and high peak elevation of 4,392 meters makes Mount Rainier National Park a popular destination.

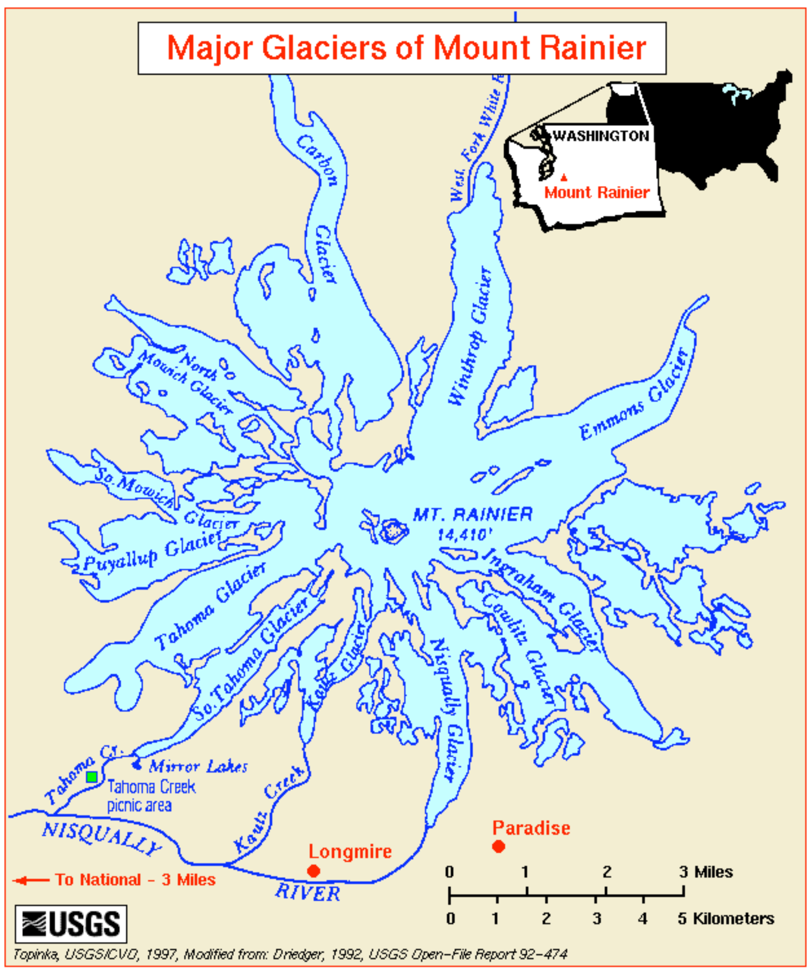


Figure 1. Glaciers of Mount Rainier. 25 glaciers cover 88 square kilometers on Mount Rainier (Driedger, 1986). Figure from Topinka.

Debris Flows Background

Three main factors influence the initiation of debris flows: moisture, abundance of fine-grained sediment, and slope. On South Tahoma Glacier, which feeds Tahoma Creek on Mount Rainier, debris flows initiate through rapid saturation of sediment, almost always as a result of glacial outburst floods (Driedger and Walder, 1994). Such floods usually occur in stagnant ice where water can build up in cavities within the ice and then release quickly, saturating the surrounding till and initiating a debris flow. Rainfall is also an important trigger; rainfall caused debris flows in 2003, 2005 and 2006 (Copeland, 2009).

As glaciers retreat they leave behind large amounts of lodgment and ablation till with a large component of fine-grained sediment; in some cases a steep slope can form. The combination of these factors provides ideal places for debris flows to initiate (Copeland, 2009).

Debris flows differ from flooding events and hyperconcentrated flows in their physical properties. Pierson (1985) describes the physical characteristics of debris flows; as debris flows move downstream, they do not behave as Newtonian fluids; they have internal shear along with high density and viscosity (Fig. 2). The shear strength in debris flows comes from electrochemical interactions between the fine-grained sediments and the friction with larger particles. Should the debris flows become diluted, the shear strength will decrease; the interactions between fine-grained sediments and the friction associated with the larger sediments will subside and the flow will become hyperconcentrated. Two phases exist in hyperconcentrated flows: a liquid phase, composed of water, clay and silt, and a solid phase consisting of larger particles. Due to the velocity of the flow, large particles can be either entrained or transported by bedload. A debris flow may be followed by a hyperconcentrated flow, which in many cases destroys evidence of debris flow deposits by washing out the fine-grained matrix that distinguishes debris flow deposits from other fluvial deposits. The project focused on the geomorphic implications of debris flows.

Figure 2. A debris flow on Tahoma Creek, Mount Rainier in 1988. Photo from Parker.

Study Area

There are 25 glaciers at Mount Rainier National Park, covering roughly 93 square kilometers. Overall, these glaciers have been retreating, losing 18% of their mass since 2003 (Paul Kennard, personal communication, Feb. 25, 2010).

Tahoma Creek flows down the southwest side of Mount Rainier; it is fed by the Tahoma and South Tahoma Glaciers (Fig. 1). With the exception of 2003, the Tahoma and South Tahoma Glaciers have steadily retreated (Paul Kennard, personal communication, Feb. 25, 2010). In August of 1967 a glacial outburst flood originating at 2133 m cut the South Tahoma Glacier in two parts, causing the lower part to turn to stagnant ice (Driedger, 1986) In retreating, it has left huge amounts of unconsolidated sediment. Furthermore, the stream exhibits a steeper gradient than the other drainages studied. According to Copeland (2009) known debris flows have occurred every year since 1967 with the exceptions of 1972, 1985, and 2001 to 2004.

The Carbon Glacier on the north side of Mount Rainier supplies the Carbon River with sediment and water (Fig. 1); the Carbon River's mean annual discharge is 12 cubic meters per second (US Geological Survey, 2003). The Carbon Glacier is the third largest glacier on the mountain by area, and the largest by volume (0.834 cubic kilometers, Driedger, 1986). Between the 1760s and 1960s it retreated only half a mile; as a result, it has the lowest terminus of any glacier in the contiguous United States at 1,066 m above sea level (Driedger, 1986). Even in recent years as glaciers on the rest of the Mount Rainier shrink, the Carbon Glacier remains stable; the mountain to the north protects the glacier from the sun, while tons of rock and ice falling from the Willis Wall insulate the glacier and keep its mass in balance. In turn, although there is abundant rock on the terminus, the stability of the glacier has prevented the accumulation of steep slopes of lodgment till (Driedger, 1986).

The Emmons Glacier, the largest glacier in the contiguous United States by area (11.13 square kilometers, Driedger, 1986), lies on the northeast side of the mountain and feeds the White River (Fig. 1). Of the drainages examined in this study, the White River has the greatest mean annual discharge at 24 m^3/sec (USGS, 2010). About 5 ka, the Osceola mudflow significantly altered the Emmons Glacier and the White River drainage. An avalanche of rock originating at the summit crater originally covered 668 square kilometers surrounding Mount Rainier (Crandell, 1971). In December 1963 a massive rockfall from nearby Little Tahoma Peak dropped 113 million cubic meters of rock onto the glacier and area below. This huge amount of rock provides an insulating layer on the glacier preventing retreat (Dreidger, 1986). However, mass balance measurements show ice loss (Paul Kennard, personal communication Feb. 25, 2010).

Little historical record exists of debris flows on many of the streams radiating off of Mount Rainier. In this study we use a chronological set of aerial photographs, along with field observations , to examine the geomorphic effects of debris flows on stream channels. As the glaciers on the mountain retreat, they leave large amounts of unconsolidated till ready to initiate debris flows (Copeland, 2009). Debris flows can destroy riparian vegetation and add material to the braided stream drainage; the combination of these effects will widen the channel.

Methods

In order to determine the geomorphological changes of the streams with respect to debris flow activity and time, a combination of aerial photographs and field observations were used.

Field Observations

During the summer of 2009, field observations were made on Tahoma Creek and the Carbon River, looking for evidence of debris flows. In order to differentiate between fluvial deposits and debris flow deposits, we used the criteria of Pierson (2009). Briefly, debris flow deposits are matrix supported andvery poorly sorted, contain angular clasts, deposit convex formations, lack imbrication or cross-bedding, and are often piled up around standing trees, snags, or downed logs (Fig. 3). Conversely, fluvial deposits, originating either from flooding events or by normal fluvial activity in a braided stream channel, were differentiated from debris flow deposits by bedding, sorting, and clast supported structure. Due to the proximity to glaciers, the abundance of sediment, and the fact that floods or hyperconcentrated flows usually follow a debris flow event, determining the mode of deposition for a particular deposit can be extremely difficult or impossible. For example, a flood subsequent to a debris flow can destroy the deposit, or wash the matrix out, making a debris flow deposit appear like a fluvial one.

On Mount Rainier, channels have widened even in drainages primarily affected by fluvial activity (Beason, 2007). Furthermore, differentiating between debris flow deposits and fluvial deposits in such a sedimentologically immature environment can be difficult or impossible. Only relatively unequivocal debris flows deposits were identified as such.

Figure 3. Debris flow deposits. Debris flow deposits can be differentiated from fluvial deposits by the angular clasts, supporting matrix, and poor sorting, and little stratification (left). They also can create levies on the sides of the flow (right). Left Photo: DePauw University. Right Photo: Ian Delaney

Aerial Photograph Analysis

We used a chronological set of aerial photos to determine the geomorphic changes in areas affected by debris flow activity over time. Using ArcGIS, aerial photos from 1950, 1960, 1970, 1979, 1984, 1989, 1996, and 2006 were georeferenced to a U.S.G.S. 7.5 minute topographic map. After georeferencing, the width of the channel from dense vegetation and forest on one side of the channel to dense vegetation and forest on the other side was determined along various points roughly 500 meters away from each other down the channel (Fig. 4). If the channel split around a vegetated bar only the width of the non-vegetated area was taken. The reaches of stream were separated into the areas above debris flow deposits, and those below based on field observations. For the White River, we did not have field observations, so we estimated the extent of the debris flow zone by identifying the part of the White River channel where the channel slope matched the debris flow zone slope we observed on the Carbon River and Tahoma Creek. Essentially we divided the channel into an area directly affected by debris flows, and an area not directly affected by debris flows (Fig. 5). With this data we graphed average width of the stream in the respective areas with respect to time.

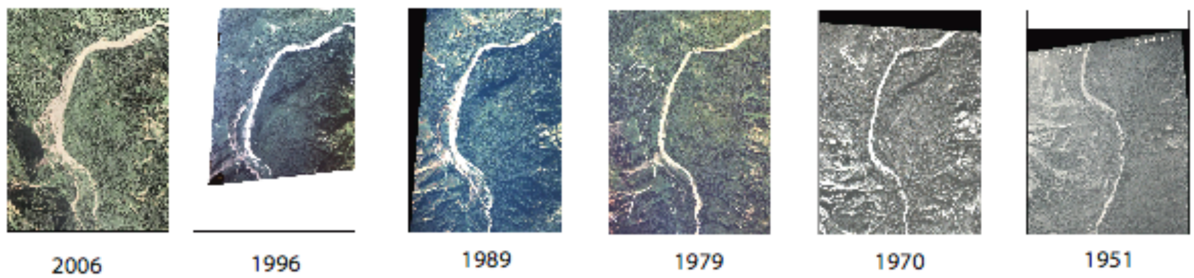


Figure 4. Consecutive photographs on Tahoma Creek. By measuring the width of the channel we established some of the effects of debris flows. Note the trend in widening.

Fieldwork was not completed on the White River. In order to determine the zone where debris flows could affect channel characteristics, a topographic profile of the channel was taken. The debris flow zone was created based upon the gradient of the debris flow zones on the Carbon River and Tahoma Creek. The zone where debris flows could come to a stop is called the “End zone.”

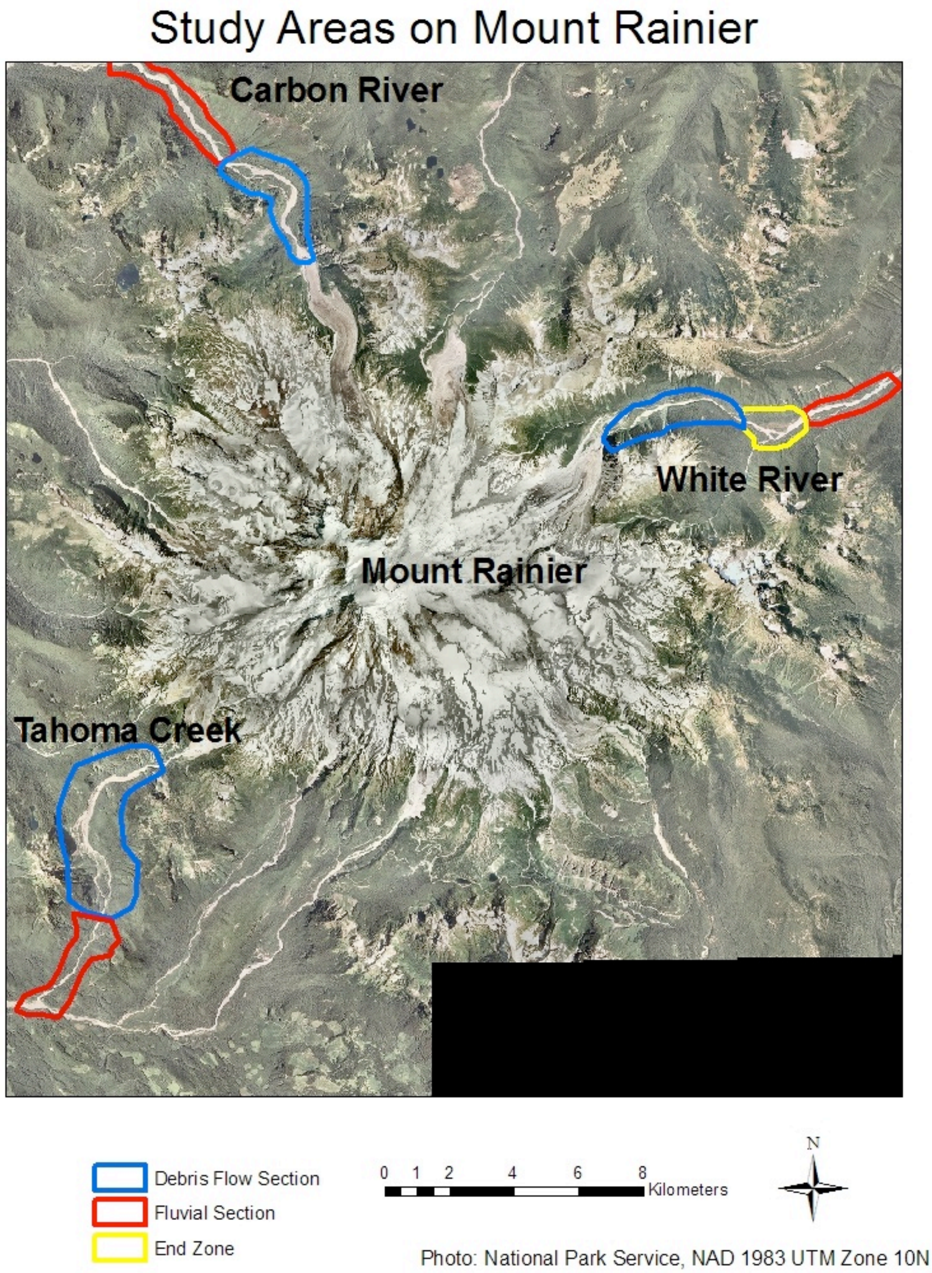


Figure 5. Zones affected by debris flows on Carbon River, Tahoma Creek and White River, Mount Rainier.This project examined channels on the three labeled drainages. By dividing the drainages into reaches with evidence of debris flow activity we hoped to identify the effects of debris flows. No fieldwork was done on the White River, so the debris flow zone was identified using a topographic profile of the drainage, and correlating it to the gradients of reaches with debris flow activity on other drainages.

Results

Figure 6. Width verses time in debris flow and non-debris flow zones.

All three channels grew in width from 1951 to 2006 (Fig. 6). This includes both the debris flow and non-debris flow sections of the channels. The debris flow zones on the upper reaches of the Carbon River and Tahoma Creek increase in width more than those along the lower part of the channel. This widening is most pronounced along Tahoma Creek (Fig. 6). The debris flow width of the section on the Tahoma Creek increases an average of 160 m from 1951 to 2006, compared to the fluvial section which widened 73 m over the same period.

The average width of the Carbon River increased by 34 meters in the non-debris flow zone and 33 meters in the debris flow zone. Also, in recent years, the width of the debris flow zone is decreasing in width with respect to that of the lower channel.

The White River behaves as a normal fluvially-controlled drainage that widens downstream. The debris flow section of the river is the narrowest reach of channel. However, the White River is widest in the "End Zone."

	Gradient (upper section) (degrees)	Gradient (lower flow section) (degrees)	Amount of fine sediment available	Mean annual discharge (cubic-meters/second)	Channel width change (upper section) (meters)	Channel width change (lower section) (meters)	Historic events
Tahoma Creek	-4.392	-1.855	High	Lowest	+160	+72	Debris flows every year except 1972, 1985, 2001, and 2004 ***
Carbon River	-3.467	-1.884	Medium	12*	+33	+34	None known
White River	-3.069	-1.624	Low (drift by rock fall debris)	24**	+20	+22	1963 (rock avalanche)

Table 1. Summary of Data. *US Geological Survey 2005, ** U.S. Geological Survey, 2010, ***Copeland, 2009.

Discussion

Fluvial Processes vs. Debris Flow Process

Two main geomorphic processes control channel width in drainages on Mount Rainier: fluvial processes and debris flows. In a fluvially controlled drainage the channel gets wider from source to bottom. In Tahoma Creek, the channel is much wider in the upper reaches where we observed debris flow deposits. Thus channel widening in the upper reaches of the drainage, where debris flow deposits are present, can be attributed to debris flow activity. The reason debris flow processes may dominate on the upper reaches may be attributed to sediment source, gradient and water discharge—all of which will be discussed below.

In contrast, the White River does not experience the same amount of widening characteristic of Tahoma Creek, and gets increasingly wider downstream (with the exception of the "End Zone"). Because of these characteristics, it is likely that fluvial processes dominate the geomorphology of the White River.

The Carbon River displays widening characteristic of both debris flow processes and fluvial processes. The debris flow section, on the upper reaches of the drainage, is wider than the rest of the channel; however, in recent years, the width of the downstream reach and the upstream reach have become similar. The lack of widening in the debris flow section, although the section is wider, and the widening of the fluvially controlled reaches, suggests that debris flow activity may have once influenced channel width to a greater degree then at present.

Influence of Gradient

Gradient is important, along with water, and fine-grained sediment needed for debris flows to be initiated. With a gradient of 4.39° in the debris flow section (2.44° in the debris flow end zone), Tahoma Creek is far steeper than the Carbon River, -3.47° in the debris flow section (2.22° in the debris flow end zone), and the White River, -3.07° in the debris flow section (1.66° in the debris flow end zone) (Fig. 9). The steeper gradient of Tahoma Creek most likely contributes to its increased channel widening in the debris flow zone.

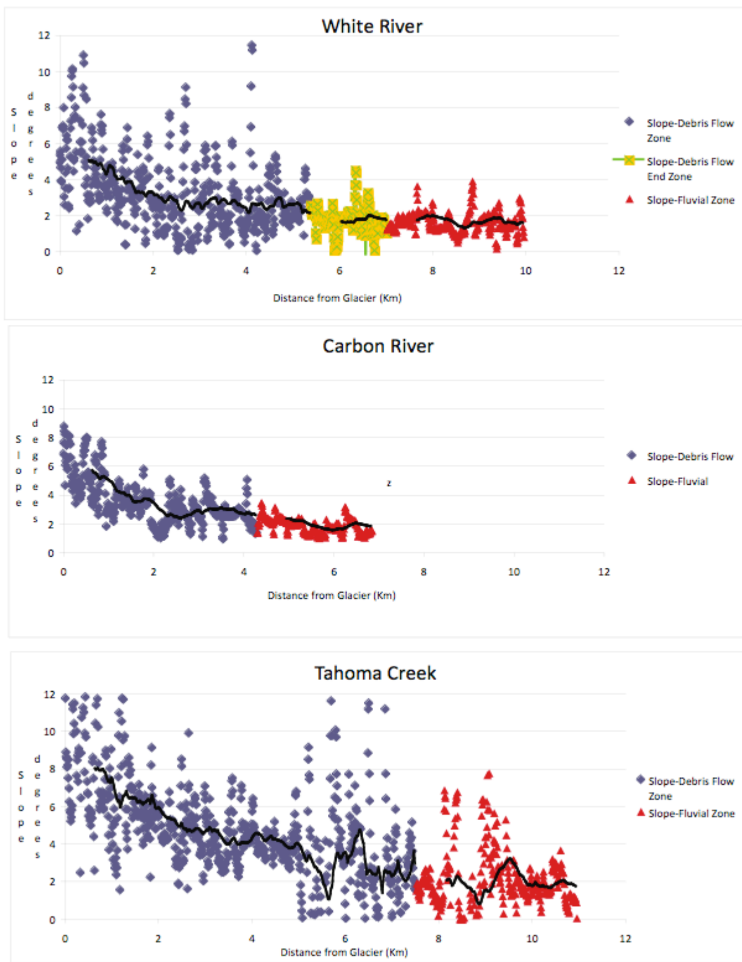


Figure 7. Profiles of Drainages. A Digital Elevation Model determined the profiles. The gradients of the White River and the Carbon River are not as steep as Tahoma Creek.

1988 2009

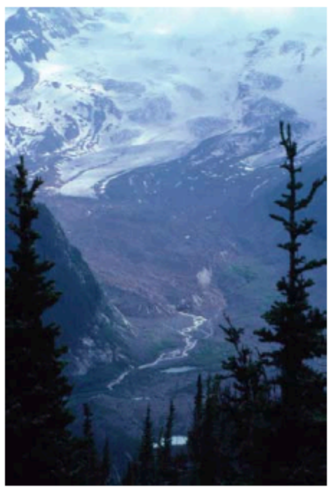
Figure 8. Upvalley from the Wonderland Bridge on Tahoma Creek. Notice the steep slopes and change in quantity of material in the foreground on the right and in the background on the left of each photo. 1988 photo by Robert Carson**;** 2009 photo by Ian Delaney.

Influence of Sediment Supply

Silt and clay-sized particles are required for debris flows to be initiated (Driedger and Walder, 1994). The Emmons Glacier, feeding the White River, experienced a massive rock fall from Little Tahoma Peak in 1963, covering the terminus of the glacier. This layer of rock insulates the glacier, preventing glacial retreat (Driedger, 1986); however, the Emmons has a negative mass balance (Kennard, personal communication, Feb 25, 2010). Furthermore, the rockfall debris covering the glacier most likely lacks the fine-grained sediment required for debris flow activity. The Carbon Glacier also experiences a great amount of rock fall from the Willis Wall at its head. As the glacier melts out toward the terminus, the rock provides an insulating layer. Consequently, the glacier has retreated very little, and little fine-grained sediment exists near the terminus (Driedger, 1986).

The Tahoma and South Tahoma glaciers, retreated greatly in the past 50 years (Driedger, 1986). As they retreated they left steep slopes of ablation and lodgment till (Fig. 8). Drift, with abundant fine sediment, provides the material needed for the debris flows to be initiated. Furthermore, steep unstable gullies exist below the glacier; Copeland (2009) showed thatdebris flows initiated on their steep sides. In contrast, the Emmons and Carbon Glaciers, feeding the White and Carbon Rivers, have not retreated as rapidly, and the rivers below them have not been subject to debris flows as much as Tahoma Creek.

Carbon Glacier 2007



Emmons Glacier 1963

South Tahoma Glacier 2009

Figure 9. Termini of the glaciers. The veneer of rock fall debris on the Carbon Glacier and Emmons Glacier has insulated the glacier and prevented retreat. Notice the steep slopes and massive amount of sediment on the South Tahoma Glacier. 1963 Photo: Robert Carson; 2007 Photo: Scurlock; 2009 Photo: Ian Delaney.

Influence of Water Discharge

In the three drainages studied, drainages with greater discharge exhibited downstream widening more characteristic of fluvial activity. The White River gets wider downstream. Conversely, Tahoma Creek, the creek with the smallest discharge, is widest upstream.

The Carbon River, with moderate discharge, shows characteristics of both debris flow activity and fluvial activity. With larger stream discharge, fluvial processes could dominate over any effects caused by debris flows. However, both the White River and Carbon River differ from Tahoma Creek in gradient, amount of sediment, and condition of the feeding glacier, which could suggest that debris flows could be less frequent or less devastating than on Tahoma Creek.

Implications for Glacial Recession

All glaciers on Mount Rainier are retreating (Kennard, personal communication, Feb 25, 2010). As a result, if the characteristics of the Tahoma Creek drainage are true of other drainages on the mountain, there will probably be an increase in debris flow activity, especially in drainages with a steep gradient and abundant drift. Glaciers that retreat rapidly, leaving large amounts of drift, will be more subject to debris flows.

Conclusions

Due to the great amount of widening on Tahoma Creek in the debris flow section, debris flows contribute greatly to the geomorphology in this drainage. Conversely, although the White River and the Carbon River widened over the study period, the debris flow zone did not differ from the fluvial zone to the same degree as along Tahoma Creek. The difference can be attributed to the greater slope and sediment source on Tahoma Creek, although, the greater discharge on the Carbon River and White River could mask some of the debris flow activity in those drainages.

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