ANALYZING TURBIDITY, SUSPENDED-SEDIMENT CONCENTRATION, AND PARTICLE-SIZE DISTRIBUTION RESULTING FROM A DEBRIS FLOW ON MOUNT JEFFERSON, OREGON, NOVEMBER 2006

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Abstract A debris flow and sediment torrent occurred on the flanks of Mt Jefferson in Oregon on November 6, 2006, inundating 150 acres of forest. The massive debris flow was triggered by a rock and snow avalanche from the Milk Creek glaciers and snowfields during the early onset of an intense storm originating near the Hawaiian Islands. The debris flow consisted of a heavy conglomerate of large boulders, cobbles, and coarse-grained sediment that was deposited at depths of up to 15 ft and within 3 mi of the glaciers, and a viscous slurry that deposited finer-grained sediments at depths of 0.5 to 3 ft. The muddy slurry coated standing trees within the lower reaches of Milk Creek as it moved downslope.

Continuous turbidity measurements have seldom been made during debris flows from the high western Cascade Range because the hyperconcentrations of fluvial sediment, high-flow velocities, and violent nature of such debris flows have prohibited instream monitoring. As the debris flow and sediment slurry worked their way downstream to the larger North Santiam River, the stream velocities became less destructive and dilution from the higher mainstem streamflow lowered the turbidity to measurable levels. Continuous instream turbidity was measured in the North Santiam River at a streamflow gaging station (*North Santiam*) 10 mi downstream from where the sediment slurry entered the North Santiam River. By using the continuous turbidity data, the timing and extent (beginning and end points) of the sediment slurry were determined. Continuous streamflow data also were recorded at *North Santiam* and suspended-sediment samples were collected over the entire event, which allowed suspended-sediment loads (SSL) to be estimated.

The additional debris flow water-discharge volume was estimated by comparing streamflows from *North Santiam* with those in the adjoining Breitenbush River basin. The average debris-flow suspended-sediment concentration (SSC) that entered the North Santiam River, about 8 mi downstream of the Mt Jefferson summit, was 130,000 milligrams per liter (mg/L), probably much lower than what occurred in the upstream debris flow area. Peak turbidity from the slurry at *North Santiam* was estimated to be near 55,000 Formazin Nephelometric Units with a peak SSC of 35,000 mg/L.

Field reconnaissance identified the likely scenario of how the debris flow and sediment torrent traveled downslope. Several pulses of sediment releases occurred as newly formed debris levees and temporary log and rock dams were created and later collapsed or were overtopped by the sediment slurry. The main portion of the sediment torrent eventually amassed at a point downstream of the entire debris-flow area. The sediment slurry quickly breached this obstruction and diverted Pamelia Creek 300 ft southward, where it carved a new channel. This final release of material caused the highest spike in turbidity and SSC as recorded at *North Santiam*, where the daily-mean turbidity increased by over 2 orders of magnitude. The estimated peak debris-flow SSC (peak 30-minute SSC) from Milk and Pamelia Creeks was estimated to be 350,000

mg/L (29% by weight). The November 6 SSL at *North Santiam* was 23,200 tons, which probably was derived entirely from Pamelia Creek, as little suspended-sediment came from other subbasins. Also, sediment deposition may have occurred within the North Santiam River channel downstream of Pamelia Creek, although most all the slurry was lighter, fine-grained material that likely was carried downstream by the higher volume and velocity of the North Santiam River.

As the fluid matrix was released from the log jam and flushed downstream, the percentage of fine sediment consistently decreased throughout November 6–7. The sediment flux returned to a more coarse-grained regime as an increase in streamflow, resulting from a subsequent storm, re-entrained sediment initially laid down by the debris flow and eroded sediment from other upstream subbasins. At the beginning of the event, the amount of sediment finer than sand was 99%. By the end of the 22-hr event, this classification had declined to less than 80%. The same trend was evident in the remaining fine-sediment categories from silt to clay. As the volume of glacial water released in Milk Creek decreased, the larger material was deposited in the lower debris-flow area, where the gradient lessened. Based on a geographic information system analysis of the field mapping, the active Milk Creek channels had scoured, 2–3 years after the debris flow, over 10% of the recently deposited fine-grained material. By using an estimated 0.5 to 3 feet of fine-sediment deposition, the surveyed area of the Milk Creek channel, and velocity estimates of 10–20 ft/s from previous Cascade debris-flow studies, the slurry was deduced to be hyperconcentrated as it traveled in the Milk Creek channels and ramparts, with 250 to over 5,000 times more sediment than water.

INTRODUCTION

The U.S. Geological Survey (USGS) has monitored water quality, including turbidity, in the North Santiam River basin (fig. 1) since October 1998 (Bragg and Uhrich, 2004). The sensors also record streamflow as well as other water-quality parameters and transmit all data in near real time for display on the study Web site (http://or.water.usgs.gov/santiam/). Mt Jefferson is a dormant stratovolcano situated at the crest of the Western Cascades in Oregon with a history of glacially induced debris flows (O'Connor and others, 2001). Milk Creek is a small watershed of 2.5 mi^2 on the steep western slope of Mt Jefferson that feeds into Pamelia Creek, a tributary to the upper North Santiam River. Milk Creek was the primary conduit for a massive debris flow and sediment torrent on November 6, 2006, that sent large fluvial sediment loads into the North Santiam River by way of Pamelia Creek. Milk and Pamelia Creeks do not have continuous turbidity monitoring, but turbidity and suspended sediment from their basins can be detected at the North Santiam River below Boulder Creek streamflow gaging and water-quality monitoring station (14178000, herein abbreviated *North Santiam*) about 10 mi downstream (fig. 1). Turbidity recorded at *North Santiam* helped to define the timing and extent (beginning and ending points) of the debris flow after correcting for the time of travel from Pamelia Creek to *North Santiam*.

The autumn of 2006 was unusually dry and sunny in the upper North Santiam River basin. From September to October 2006, an average of less than 4 in. of precipitation (20% below the monthly average) had fallen at three U.S. Natural Resource Conservation Service stations (Hogg Pass, Santiam Junction, Marion Forks) in the Upper Cascades near Mt Jefferson (http://www.wcc.nrcs.usda.gov/snotel/Oregon/oregon.html). After this dry period, subtropical

moisture from the Pacific Ocean entered the Western Cascades in early November 2006 dropping 5 in. of rain over 5 days from November 4 through 8. Because the November 2006 precipitation event occurred after such a dry period, there was little snow cover to buffer runoff and minimize soil erosion. In addition, air temperatures near Mt Jefferson also increased by 10°C for several days in early November. This caused precipitation throughout the area to fall mostly as rain and melt much of the existing snow.

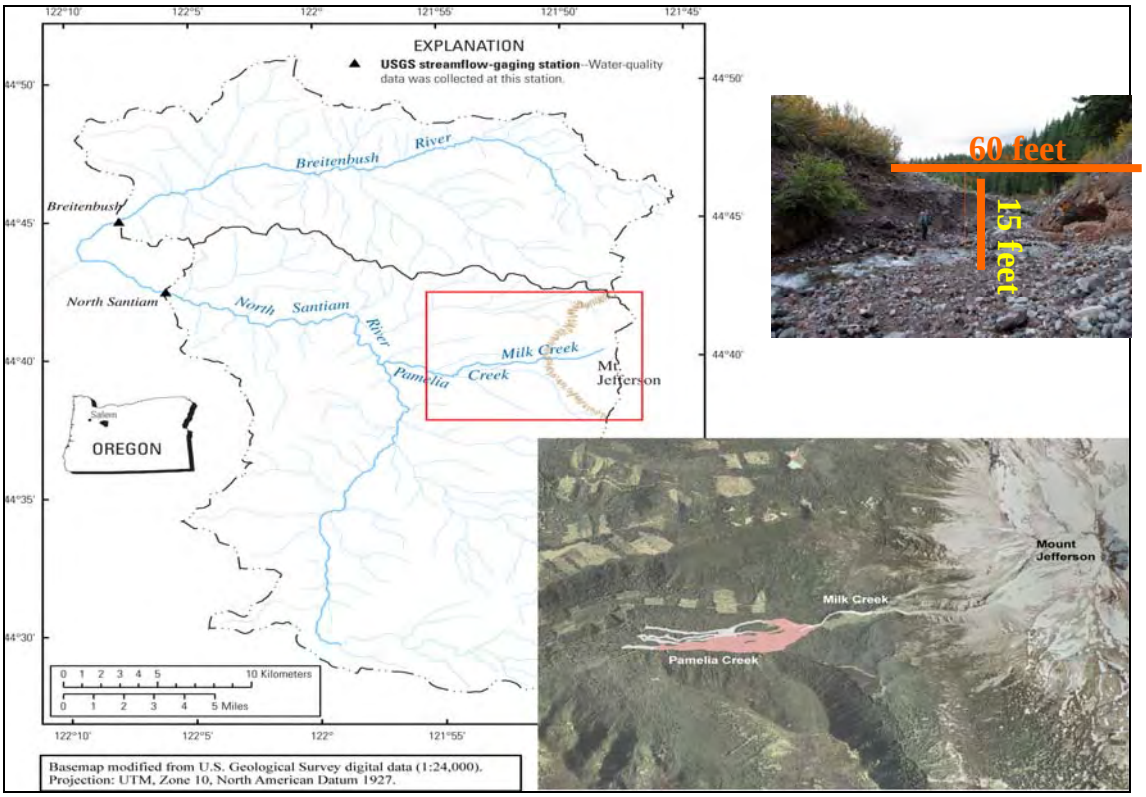

Figure 1 Map of the upper North Santiam River and Breitenbush River basins, Milk and Pamelia Creeks, and Mount Jefferson, Oregon. The mapped debris flow area and channels (shaded in pink), and photograph of surveyed Milk Creek channel taken February 22, 2010, provided by Robert Ross, Linn Benton Community College, 2009.

The combination of increased rainfall, decreased snow cover, dry soil conditions, warmer air temperatures, and melting snow contributes to conditions ideal for a debris flow initiated as a glacial and snowfield outbreak event. As the early November snowpack began to melt on Mt Jefferson, portions of the two existing Milk Creek glaciers and/or upper snowfields likely broke apart, causing a snow and rock avalanche. As the masses of snow, ice, and rock cascaded down the steep Milk Creek channels, additional rock and sediment from the channel bottoms and margins became entrained in the debris flow and were carried downslope. The flow bulldozed the larger rocks forward and cleared a wide swath through the forest, eventually casting the largest material to the side and forming lateral levees (fig. 2).

As slopes and yield strength decreased and channel roughness increased, the heavier material was further deposited along the flow boundaries. The standing trees became barriers, creating a series of temporary dams that caused large rock and debris to accumulate perpendicular to the

flow (fig. 2). The finer fluvial-sediment matrix flowed around or overtopped these obstructions and continued downslope in pulses, eventually entering the North Santiam River aided by the increase in flow from Pamelia Creek. The largest of the turbidity spikes occurred as a massive log and debris dam within Pamelia Creek at the most downstream end of flow, about 4 mi from the Mt Jefferson summit, broke loose, releasing the trapped sediment and water to the North Santiam River. All glacial and snowfield outbursts from Mt Jefferson and Pamelia Creek, as detected since 1998 at *North Santiam*, are accompanied by sharp increases in turbidity but only a small increase in streamflow (Bragg and Uhrich, in press). The November 6, 2006, debris flow on Mt Jefferson occurred a day before the most intense rain from the approaching storm, increasing daily median turbidity in the North Santiam River more than 2 orders of magnitude.

Figure 2 Lateral levees formed in the Milk Creek channel and outwash area. (Photographs taken by Mark Uhrich on September 30, 2008 (top left and right), October 13, 2008 (bottom left), and July 18, 2007 (bottom right). Survey rod is extended to 10 ft.

TURBIDITY MONITORING AT *NORTH SANTIAM*

Turbidity was measured at *North Santiam* by a continuous monitor in Formazin Nephelometric Units (FNU) (Anderson, 2005). Streamflow data also were measured at the monitoring station. Suspended-sediment samples were collected manually at *North Santiam* using an Equal-Width-Increment (EWI) method (Edwards and Glysson, 1999). An automatic pumping sampler also collected sediment samples. Turbidity sensors have limitations as to the maximum value each is designed to measure. The turbidity sensor at *North Santiam* reached its maximum value of 1,600 FNU during the November 6, 2006, debris flow from Mt Jefferson. Initially, turbidity increased for approximately 3 hr until the sensor “flatlined” (i.e., continued at the same reading) for 6 hr at

this threshold value, and then recorded values below the maximum for 1.5 hr, then increased and flatlined again at the maximum value for 7 hr (fig. 3). The automatic pumping sampler at *North Santiam* was in operation during the event and collected three samples during the initial 3-hr rise in turbidity before running out of bottles. The sampler was reset 8 hr later with new bottles, which allowed numerous samples to be collected over the remainder of the event. Three manual EWI samples also were collected through the debris flow period. Hence, the data included two periods above the sensor maximum of 6 and 7 hr, respectively, in which turbidity had to be estimated. Streamflow peak hydrographs can often be used to estimate peak turbidity, but in this instance the increase in turbidity did not accompany a significant increase in streamflow. The EWI and pumping samples provided the best data for estimating turbidity values above the maximum value of the instream sensor.

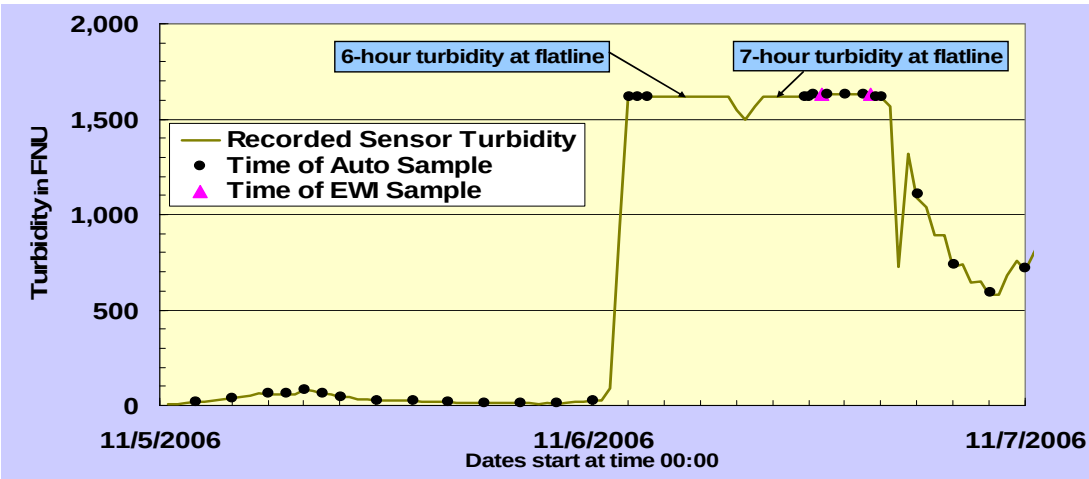

Figure 3 Turbidity values and suspended-sediment sample collection at *North Santiam*.

ESTIMATING TURBIDITY AT *NORTH SANTIAM*

Various methods can be used to estimate turbidity values that surpass a sensor maximum. Some of these methods are outlined in Bragg and others (2007). For the turbidity record on November 6, 2006, a combination of methods was used. First, all pumping and EWI samples collected were tested for turbidity in the laboratory before analysis for suspended sediment concentration (SSC). A standardized static-turbidity test was conducted in Nephelometric Turbidity Ratio Units (NTRU) (Anderson, 2005) for all samples. Regression techniques were used to convert the NTRU values of the turbidity test samples to FNU values, so that values for all the samples would have consistent units. Turbidity was then estimated for the flatline periods (Bragg and Uhrich, in press).

Ground reconnaissance of the debris flow area also revealed supplementary information as to the range and extent of turbidity and SSC at *North Santiam*. Surveys of the overflow area in the Milk Creek basin suggested that at least three surge flows occurred, each of diminishing volume, which appear as three smaller peaks for the first flatline period (fig. 4a). Stair-step banks indicating the three surge flows are shown in Figure 4b for an overflow channel and at Pamelia Creek. Also, continuous pH and specific conductance data at *North Santiam* were used to estimate the timing of each of the turbidity peaks. Normally, during a rise in turbidity, pH and

specific conductance will decrease sharply. This was a trend observed for previous Mt Jefferson events recorded at *North Santiam*. A peak turbidity of 55,000 FNU was estimated during the second flatline period using a two-point extrapolation from samples collected just prior to the peak, each with turbidities leading up to the peak of 26,500 and 30,000 FNU, respectively (fig. 4a). This extreme peak in turbidity was caused by the final release of fluvial sediment trapped by a large log and debris dam within Pamelia Creek, located at the lowest downstream point in the debris-flow area. The debris dam diverted Pamelia Creek 300 ft southward creating a new channel that increased the suspended-sediment load as the flow incised into the forest floor.

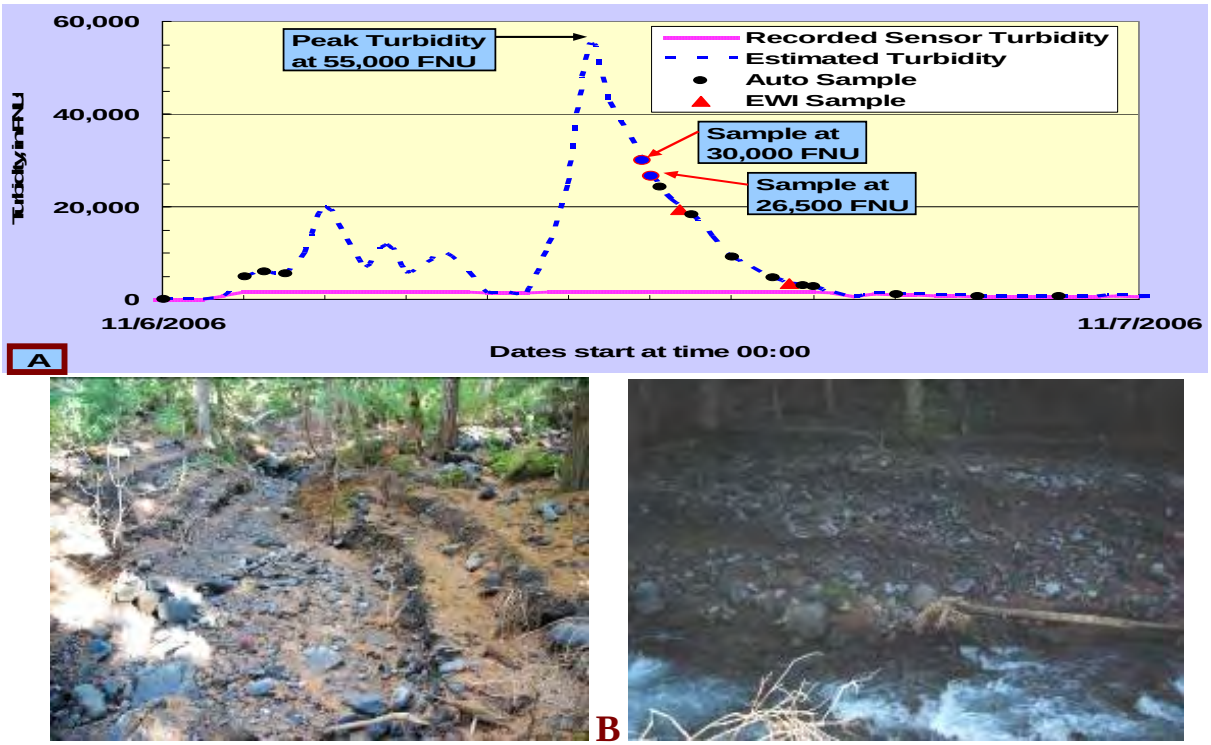

Figure 4 **(A)** Recorded sensor and estimated turbidity values at *North Santiam*. **(B)** Photographs of an overflow channel (left) and Pamelia Creek (right) showing at least three levels of surge flows. Photographs taken by Mark Uhrich, taken on November 6–7, 2007.

ESTIMATING SUSPENDED SEDIMENT CONCENTRATION AT *NORTH SANTIAM*

Since numerous suspended-sediment samples were collected during the peak debris flow period, the SSC determinations from the laboratory analyses were used directly rather than the laboratory turbidity values. This eliminated the intermediate step of converting turbidity to SSC, although for longer periods when no samples are collected, continuous turbidity below the sensor maximum could be used to estimate SSC. The estimated *North Santiam* SSC record for November 5–7, 2006, followed a similar trend as in the turbidity graph in figure 3. The peak SSC was estimated at 35,000 milligrams per liter (mg/L) using the same 2-point extrapolation method as with turbidity. The SSC corresponded directly in time with the turbidity peak. The missing 30-minute SSC values between samples were taken directly from the interpolated line for this period.

SUSPENDED-SEDIMENT LOAD CALCULATIONS

The interpolated SSCs (in milligrams per liter) and corresponding 30-min streamflow values (in cubic feet per second [ft^3/s]) are used to compute the 30-minute suspended-sediment discharge (SSQ; equation 1), reported in tons per 30 minutes:

$$\text{SSQ(tons/30 min)} = \text{SSC(mg/L)} \times Q\text{(ft3/s)} \times c \qquad (1)$$

where c is used to convert the units to tons per 30 minutes and is equal to 0.0000562. The daily SSL is calculated by summing the 48 SSQ values per day. The debris-flow suspended sediment load (SSL) was calculated by summing the 30-minute values that corresponded with the event.

ESTIMATION OF MT JEFFERSON DEBRIS FLOW SUSPENDED SEDIMENT CONCENTATION

The debris-flow SSL from *North Santiam* was used to compute the average debris-flow SSC by first estimating the water-discharge volume of the sediment slurry as it entered from Pamelia Creek. The debris flow occurred over a 22-hr period on November 6, 2006. The estimated discharge increase during this period was deduced by comparing streamflow in the North Santiam River to streamflow from the adjacent Breitenbush River basin. The streamflow at *North Santiam* normally correlates closely with streamflow at the gage on the Breitenbush River (*Breitenbush*), so a hypothetical non-event (with no debris flow) streamflow could be estimated for *North Santiam* by following the same decreasing trend at *Breitenbush* (fig. 5). The estimated non-event streamflow was subtracted from the total *North Santiam* streamflow to yield the debris flow water-discharge volume from Milk and Pamelia Creeks over the 22-hr period (fig. 5).

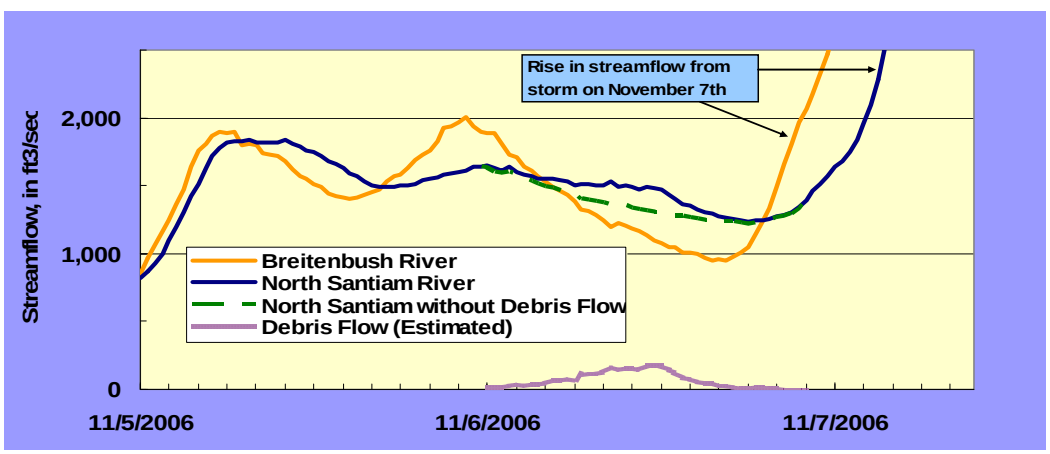

Figure 5 Recorded streamflows at *North Santiam* and at a streamflow gage in the adjacent Breitenbush River and estimated water-discharge volume attributable to the Mt. Jefferson debris flow, November 5–7, 2006.

The 22-hr period of higher streamflow corresponded to the timing of the extreme rise in turbidity at *North Santiam*. The intense precipitation of November 7, 2006, followed a few hours later, as indicated by a sharp rise in streamflow at *North Santiam* and *Breitenbush*. During November 5, just before the onset of the debris flow, turbidity in the North Santiam River upstream of the

Pamelia Creek tributary was minimal, less than 25 FNU, as recorded at *North Santiam*. Turbidity at *Breitenbush* also was at similar low levels and further decreased during November 5–6. Because of these combined low and falling turbidity levels, the North Santiam River SSL upstream of Pamelia Creek was estimated to be less than 0.2% of the daily SSL on November 6th. Therefore, all of the SSL at *North Santiam* during November 6 could be attributed to the sediment input from the debris flow, with any remaining SSL from upstream tributaries considered negligible. The average SSC from the debris flow was estimated by dividing the summed 30-min calculated SSL values for *North Santiam* by the total debris-flow discharge volume from Pamelia Creek to the North Santiam River (Q) in equation 2:

$$\text{Average Debris Flow SSC (mg/L)} = \Sigma \text{ 30-min } \textit{North Santiam} \text{ SSL (tons)} \div \text{Total Debris-Flow } Q \text{ (ft}^3\text{/s)} \times c, \quad (2)$$

where c is a conversion factor equal to 0.0000562

The estimated average SSC of Pamelia Creek over the 22-hr period was 130,000 mg/L, with a 30-minute peak near 350,000 mg/L. The average SSC was 5% sediment by volume or 12% by weight. At the peak of the SSC estimates, these increase further to 13% by volume and 29% by weight, and indicate that the sediment slurry was likely hyperconcentrationed (Pierson, 2004).

SUSPENDED SEDIMENT LOADS FROM MT JEFFERSON DEBRIS FLOWS

In addition to the November 6, 2006 event, the *North Santiam* station has recorded two other significant Mt Jefferson events from Milk Creek since 1998. The first of these events occurred on October 1, 2000, and the second on October 21, 2003. The single-day SSL value for these two events was estimated to be 420 tons and 450 tons, respectively (Bragg and others, 2007). Both events were during the characteristically low-flow, dry autumn season, when normal loads for the preceding period were less than 2 tons per day. The turbidity for both events surpassed the measuring threshold of the sensor and was estimated by using similar methods as described above (Bragg and others, 2007). The November 6, 2006, debris flow SSL estimate was 23,200 tons, approximately 1–2 orders of magnitude greater than the amounts in 2000 and 2003. The higher 2006 SSL was due primarily to a higher flow volume and larger debris-flow area.

Streamflow at *North Santiam* also was higher in 2006, although the November 6 daily mean streamflow was 80% below the WY 2007 daily mean maximum of 7,520 ft^3/s for the station. Additional sediment-slurry deposition may have occurred within the North Santiam River channel between Pamelia Creek and the monitoring station, and therefore would have reduced the SSL at *North Santiam*, but higher velocity and water volume from the mainstem kept the sediment entrained in the water column. In addition, a greater percentage of smaller, lighter-weight sediment within the slurry also remained suspended and had little opportunity to settle out, and therefore was carried past *North Santiam*. Other, less significant Mt. Jefferson events of shorter duration have occurred throughout all years of monitoring at *North Santiam*, but regardless of the magnitude, all glacial or snowfield events from the Milk Creek basin have caused a large increase in turbidity not associated with highly elevated streamflow.

GRAIN-SIZE ANALYSIS

All suspended-sediment samples were processed for concentration, with most samples also processed for a sand-silt percentage breakpoint. Some of the samples were analyzed an additional step using either a fines-only or full particle-size procedure. The fines-only procedure (Guy, 1977) partitions the sediment particles into size categories from coarse silt (equal to or less than 0.063 mm) to fine clay (equal to or less than 0.001 mm) (Vanoni, 1975). The full-size procedure documents the full range of fluvial sediments transported, which is useful during a high-flow or high-turbidity regime as particle sizes can change as streamflow or turbidity increase and then decrease over the course of a peak-flow event.

GRAIN-SIZE DISTRIBUTION DURING THE DEBRIS FLOW

During the November 2006 releases from Mt. Jefferson, the suspended sediment was almost entirely fine sediment at the *North Santiam* station. Twenty-eight suspended-sediment samples were collected at *North Santiam* by EWI and pumping during November 6–7, 2006. Of those, 10 were selected for full-size analysis (2 EWI and 8 automatic sampler), based on collection times that were at least 1 hr apart spread over the 22-hr suspended-sediment surge from Milk and Pamelia Creeks. Sample collection on November 6 began at 03:02 and ended at 20:02. After this event, rainfall from a Pacific storm increased stream levels and mobilized sediment from other sources, including additional sediments that were deposited in the channels from the debris flow. The debris flow fine-particle distribution consistently decreased as the slurry traveled past *North Santiam*. Figure 6 depicts the percent-finer-than value for five size classes between coarse silt (typically referred to as the sand-silt break) to medium clay (0.002 mm diameter) for each of the 10 samples. At the beginning of the event on November 6, the percent less than 0.063 mm was 99%, indicating the sample was nearly all fine particles smaller than sand. By the end of the event, 22 hr later, this same classification had consistently dropped to 80%. The same trend was evident in all class categories. For instance, the clay-size sediment also consistently decreased for the same set of 10 samples. The smaller than medium clay started at 24% and decreased to 12% for the same period (fig. 6).

This size distribution indicates that the larger, heavier material was deposited in the Milk Creek basin and newly created channels, now empty of any water. The fine sediment was carried downstream, with the smallest and lightest particles at the front of the slurry; the coarser sediments trailed behind and eventually were depleted. Sediment size classes larger than coarse silt were not present during the debris-flow period and therefore are not shown in figure 6.

The largest of the turbidity peaks (fig. 4) probably occurred as a massive log and debris dam within Pamelia Creek, located at the most downstream end of the flow, broke loose, releasing the trapped water and sediment. After this last sample on November 6 at 20:02, high streamflow from the storm front on November 7 again increased both turbidity and SSC, and shifted the fluvial-sediment regime to a more typical precipitation-driven mix of coarse and fine material as sediment was re-entrained from the fine-grained slurry deposit, as well as sediment from upstream subbasins. This was evident from five *North Santiam* samples (1 EWI and 4 automatic sampler) collected early on November 7 from 2:02 to 09:02, in which the percentage of fine sediment smaller than coarse silt and medium clay decreased to 50 and 7%, respectively.

In addition, there were some far-reaching lobes that overtopped the newly formed branch of Milk Creek that never entered a riverine system. These sediment lobes eventually dewatered, coming to rest before reaching Pamelia Creek. This material will settle and compact and lay dormant until the next event large enough to drive the sediment further downstream. Some of these sediment lobes did reach older overflow channels created by historic flows from Milk Creek that headed westward. The sediment deposited in these areas long ago was brought into transport, which also may have contributed to the surges in turbidity and SSC.

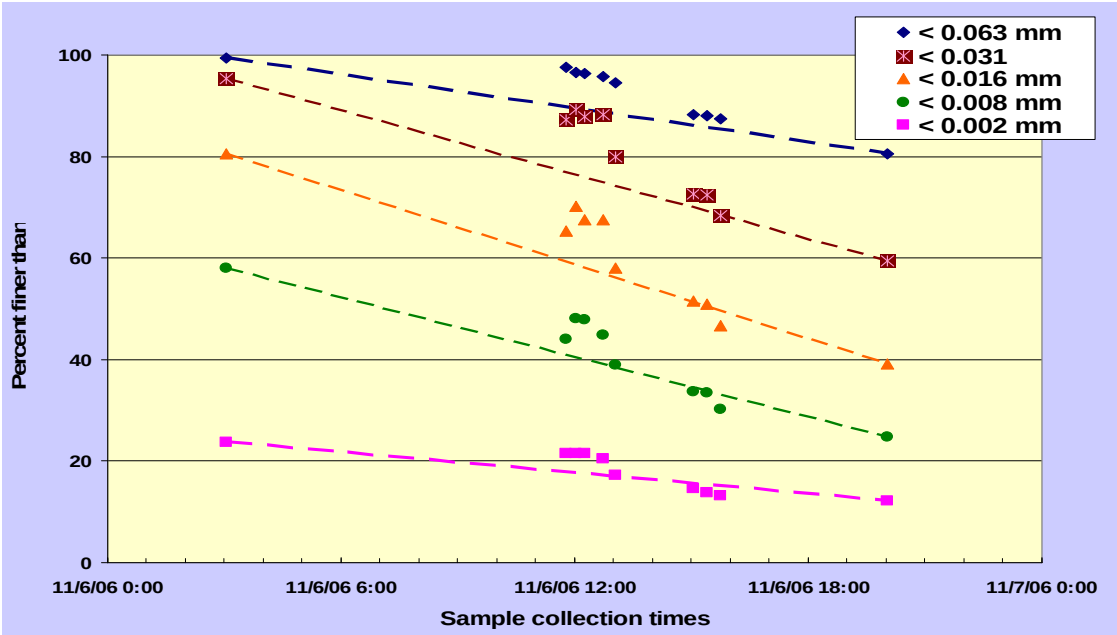

Figure 6 Grain size distributions for 5 sediment classes for each of 10 samples collected on November 6, 2006 at *North Santiam*. Straight lines are drawn between the sample start at 03:02 and sample end at 20:02.

DEBRIS FLOW PATH, DEPOSITION, AND EROSION SEQUENCE

The Mt Jefferson debris flow deposited onto the forest floor and into the Milk and Pamelia Creek channels over 2.82 million ft^3 of coarse sediment, including boulders and cobbles, and an additional 706,000 to 5.65 million ft^3 of fine material (Sobieczcyk and others, 2008). In addition to the deposited material, there was a viscous fluvial component that traveled farther downstream. Based on tree stains and scars, the flow surge was highly turbulent as it first blocked, overtopped, and diverted Milk Creek, eroding several new channels (fig. 7).

As the flow traveled farther downslope, the stain lines became smoother with less upstream velocity slope, indicating that the solid and fluid phases were beginning to separate as the debris flow transitioned to a hyperconcentrated flow (Costa, 1988). The available supply of coarse- and fine-grained sediment from the November 2006 debris flow covered an area, from where Milk Creek was first diverted, of approximately 150 acres. The fine sediment ranged in depth from 0.5 to 3 ft within the mid- to lower Milk Creek slopes and terrain.

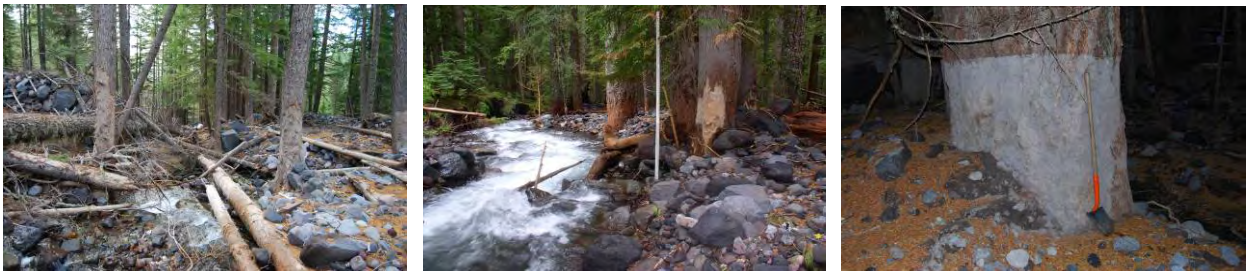

Figure 7 Photos showing tree scarring in the Milk and Pamelia Creek channels and a tree stain in the lower Milk Creek outwash area (rod [center photograph] and shovel [right] are 10 and 4 ft long, respectively). Photographs taken by Mark Uhrich on (left to right) November 7, 2007, July 18, 2007, and November 7, 2007.

Previous studies have estimated velocities of similar rubbly debris flows near Mt. Jefferson at 10 to 20 ft/s (O'Connor and others, 2001). Using these velocities and average cross-sectional area surveys of the November 2006 Milk Creek channel (fig. 1), the estimated flow volume ranged from 6,400 to 13,000 ft^3. The area and range of fine-grained sediment deposition and the estimated Milk Creek flow volume indicate that the debris-flow slurry was hyperconcentrated within the active channel, with 250 to over 5,000 times more sediment than water. The estimated flow volume entering the North Santiam River by way of Pamelia Creek was ¼ to ½ of the flow volume in Milk Creek. The downstream decrease in flow volume indicates that considerable slurry water was retained in the deposited sediment or otherwise dewatered onto the landscape and did not directly enter the North Santiam River.

The active Milk Creek channels through the debris flow were field mapped in 2007–08 and then buffered to 6 m by a GIS to estimate the percentage of fine sediment eroded since November 2006. Approximately 10% of this newly stored fine sediment had been eroded, depending on depth and location in the debris-flow area, as the stream incised into the fresh deposit.

Figure 8 Photographs showing the steep western amphitheater of Mt. Jefferson, with the north and south branches of the uppermost Milk Creek channels (left), the upper Milk Creek channel and canyon before the outwash to Pamelia Creek (middle), and close-up of the deep canyon with several waterfalls where snow accumulates down to the lower boundary (right). Photographs taken by Mark Uhrich on September 20, 2007, at the end of the summer snowmelt and before winter snowfall.

SEDIMENT SUPPLY FROM MT JEFFERSON AND RECEDING GLACIERS

The historical descriptions of Mt. Jefferson and its geologic record indicate that the two Milk Creek glaciers have long been in decline, often indiscernible and covered in scree and rubble from the western slope. Climber reports noted as early as the 1930s that no glaciers existed at all, only remnant snowfields, which at times would cover only a linear route along the lower channel boundaries of Milk Creek (Hatch, 1917; Phillips, 1938). Avalanches down the north and south couloirs of Milk Creek were frequent throughout the history of Mt. Jefferson, as the steepness of this amphitheater would suggest (fig. 8).

The recent frequency of debris flows (2000, 2003, and 2006) suggests that debris flows are likely to continue, possibly increasing in magnitude and extent, depending on environmental and weather factors. As glaciers recede, more sediment from the slopes of Mt. Jefferson will be transported into Milk Creek, ultimately filling the outwash area with sediment that could mobilize during future debris flows or prolonged precipitation. Additional studies are needed in the upper Cascades to identify trends in glacial recessions or frequency of debris flows.

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