Prepared in cooperation with the City of Salem, Oregon

Analysis of Geomorphic and Hydrologic Characteristics of Mount Jefferson Debris Flow, Oregon, November 6, 2006

Scientific Investigations Report 2008–5204

U.S. Department of the Interior
U.S. Geological Survey

Front Cover: Photograph showing view of Mount Jefferson, Oregon, with the Milk Creek channel in forefront. Debris-flow deposit visible in light gray down center channel and into forest. (Photograph by Robert Ross, Linn Benton Community College, 2007.)

Back cover: Photograph showing newly deposited material (light gray) in the Milk Creek drainage basin, Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by Robert Ross, Linn Benton Community College, 2007.)

Analysis of Geomorphic and Hydrologic Characteristics of Mount Jefferson Debris Flow, Oregon, November 6, 2006

By Steven Sobieszczyk, Mark A. Uhrich, David R. Piatt, and Heather M. Bragg

Prepared in cooperation with the City of Salem, Oregon

Scientific Investigations Report 2008–5204

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Sobieszczyk, Steven, Uhrich, M.A., Piatt, D.R., and Bragg, H.M., 2008, Analysis of geomorphic and hydrologic characteristics of Mount Jefferson debris flow, Oregon, November 6, 2006: U.S. Geological Survey Scientific Investigations Report 2008–5204, 18 p.

Contents

Figures

Figures—Continued

Tables

Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3940	inch (in.)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic meter (m^3)	1.308	cubic yard (yd^3)
kilometer (km)	0.6214	mile (m)
liter (L)	0.2642	gallon (gal)
meter (m)	3.281	foot (ft)
meter per second (m/s)	2.237	mile per hour (mph)
metric ton	1.102	Short ton [U.S.]
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

Water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends. For example, the period October 1, 2006, through September 30, 2007, is designated water year 2007.

This page intentionally left blank

Analysis of Geomorphic and Hydrologic Characteristics of Mount Jefferson Debris Flow, Oregon, November 6, 2006

By Steven Sobieszczyk, Mark A. Uhrich, David R. Piatt, and Heather M. Bragg

Abstract

On November 6, 2006, a rocky debris flow surged off the western slopes of Mount Jefferson into the drainage basins of Milk and Pamelia Creeks in Oregon. This debris flow was not a singular event, but rather a series of surges of both debris and flooding throughout the day. The event began during a severe storm that brought warm temperatures and heavy rainfall to the Pacific Northwest. Precipitation measurements near Mount Jefferson at Marion Forks and Santiam Junction showed that more than 16.1 centimeters of precipitation fell the week leading up to the event, including an additional 20.1 centimeters falling during the 2 days afterward. The flooding associated with the debris flow sent an estimated 15,500 to 21,000 metric tons, or 9,800 to 13,000 cubic meters, of suspended sediment downstream, increasing turbidity in the North Santiam River above Detroit Lake to an estimated 35,000 to 55,000 Formazin Nephelometric Units. The debris flow started small as rock and ice calved off an upper valley snowfield, but added volume as it eroded weakly consolidated deposits from previous debris flows, pyroclastic flows, and glacial moraines. Mud run-up markings on trees indicated that the flood stage of this event reached depths of at least 2.4 meters. Velocity calculations indicate that different surges of debris flow and flooding reached 3.9 meters per second. The debris flow reworked and deposited material ranging in size from sand to coarse boulders over a 0.1 square kilometer area, while flooding and scouring as much as 0.45 square kilometer. Based on cross-sectional transect measurements recreating pre-event topography and other field measurements, the total volume of the deposit ranged from 100,000 to 240,000 cubic meters.

Introduction

Every year, winter storms cause tens to hundreds of debris flows in the Pacific Northwest (Beaulieu and Olmstead, 1999; Hofmeister, 2000; National Park Service, 2007; Pirot and others, 2007; Burns and others, 2008; Scott Burns, Portland State University, oral commun., 2008). This number increases significantly during years of heavy rainfall and flooding, when thousands of debris flows may be observed. For example, during the floods of 1996 and 1997, more than 9,500 debris flows, or rapidly moving landslides, were mapped in Oregon alone (Hofmeister, 2000). Landslide activity in Oregon is so common that the Oregon Department of Forestry administers a debris flow warning system. This system issues warnings through the National Weather Service whenever conditions are deemed unsafe along or beneath certain steep hillsides, such as during heavy rainfall or after rapid snowmelt (Oregon Department of Geology and Mineral Industries, 2008). Although debris flows are dangerous, most are small, travel short distances, and occur in remote regions; however, sometimes they impact populated areas and damage infrastructure.

Although debris flows are common in Oregon and the Pacific Northwest, there is limited research investigating the relation between debris flows and downstream water-quality characteristics, such as turbidity. Where such research does exist, the discussion about turbidity usually focuses only on whether the debris flow influenced-streamflow is hyperconcentrated, not the effect the turbid water has downstream. Because of the adverse effects that turbidity can have on drinking-water operations, further investigation into the relation between landslides and turbidity is needed, especially in environments where debris flows occur proximate to reservoirs and other drinking-water sources. One such environment where landslide hazards coincide with hydrologic concerns is in the North Santiam River basin. After the flooding and landslide damage of 1996 and 1997, the U.S. Geological Survey (USGS) in cooperation with the City of Salem, established a continuous near real-time water-quality monitoring network in the basin (Uhrich and Bragg, 2003). This network allows the USGS to monitor temperature, specific conductance, pH, turbidity, and streamflow at 10 water-quality monitoring stations (U.S. Geological Survey, 2008). Using this continuous, near real-time network, the USGS and others have detected several high turbidity events and traced them to various sources, including debris flows, earthflows, and road failures (Sobieszczyk and others, 2007).

The largest recorded high-turbidity event for the North Santiam River, through December 2007, occurred November 6, 2006 (fig. 1), at the *North Santiam* water-quality monitoring station (14178000; fig. 2). After tracing the turbid water to its source tributary, Pamelia Creek, the USGS and the U.S. Forest Service (USFS) concluded that the turbid water resulted from a debris flow that mobilized off the western slope of Mount Jefferson. Debris and sediment from this event were carried down Milk Creek into Pamelia Creek and finally to the North Santiam River and Detroit Lake. In addition to the suspended sediment transported downstream, a large volume of material was reworked and deposited in the drainage basins of Milk and Pamelia Creeks. Temporary storage of this recently deposited, highly erodible material likely will increase turbidity during future high streamflow events.

Purpose and Scope

This report describes the geomorphology of the Mount Jefferson debris flow that occurred on November 6, 2006, and its effect on the downstream turbidity and suspended-sediment load in the North Santiam River. This event represents one of the few examples where water-quality data, such as turbidity, directly relates to a known sediment source, such as a debris flow (Sobieszczyk and others, 2007). Data and measurements for this event were quantified by a combination of field survey data, precipitation data, water-quality data, remote sensing data, and aerial photography. Turbidity values referenced in this report were recorded as part of the USGS North Santiam River Basin Suspended-Sediment and Turbidity Study monitoring network (http://or.water.usgs.gov/santiam/).

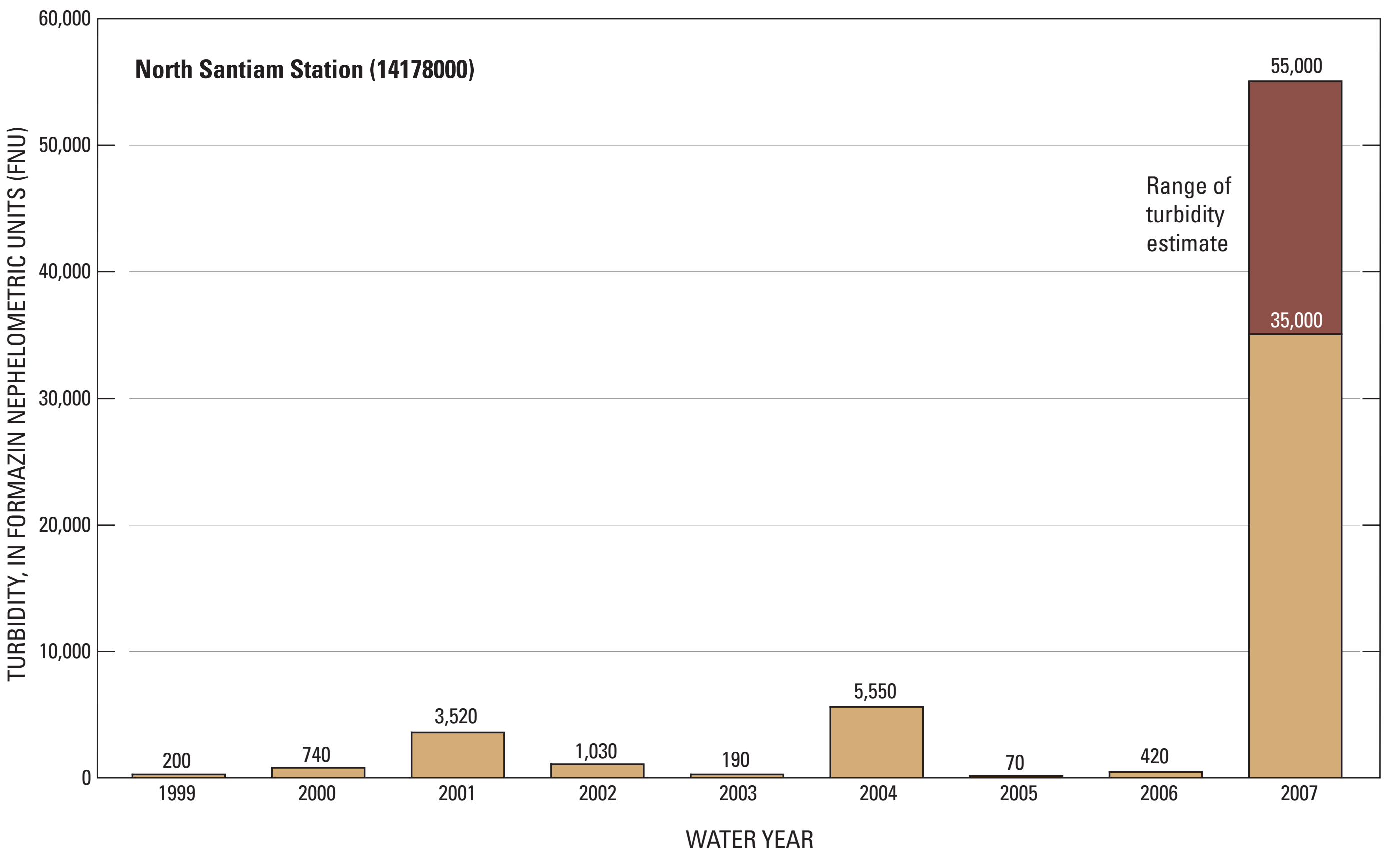
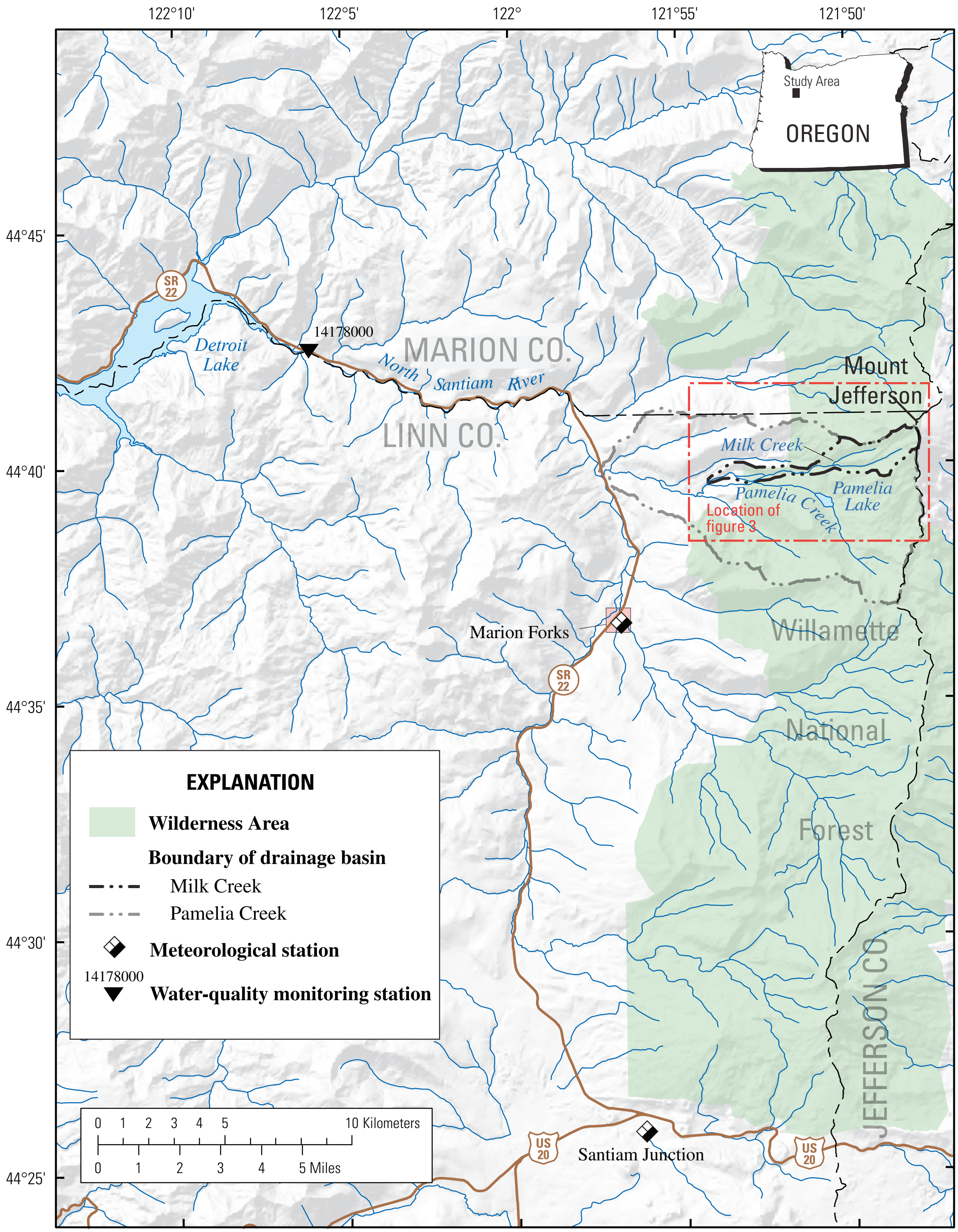


Figure 1. Peak-event turbidity values at *North Santiam* water-quality monitoring station, Oregon, water years 1999–2007.



Base map modified from U.S. Geological Survey digital data (1:24,000).
UTM projection, Zone 10
Horizontal datum: North American Datum of 1927

Figure 2. Location of Mount Jefferson and surrounding area, Oregon.

Description of Study Area

Mount Jefferson with an altitude of 3,200 m is the second tallest Western Cascade volcano in Oregon. The mountain and its accompanying wilderness area are about 100 km east of Salem, Oregon. Similar to most volcanic environments, there are multiple hazards associated with the mountain that potentially endanger people and property. Beyond the remote hazard of a large explosive volcanic eruption (last occurring more than 35,000 years ago; Walder and others, 1999) or basaltic lava flows (last occurring more than 7,600 years ago; Walder and others, 1999), other more likely hazards include landslides and snow avalanches. Although stable bedrock limits deep-seated landslides, the steep slopes and unconsolidated glacial moraine and pyroclastic flow deposits are susceptible to rock falls and debris flows. For example, at least two debris flows have mobilized from the western slopes of Mount Jefferson down the Milk and Pamelia Creek drainage basins prior to 2006 (Sobieszczyk and others, 2007). There also are accounts of debris flow activity in the Milk Creek drainage basin in the 1990s (David Halemeier, U.S. Forest Service, oral commun., 2008).

Milk and Pamelia Creek drainage basins are located on the western flank of Mount Jefferson, within the Mount Jefferson Wilderness Area (fig. 3). Pamelia Creek drains 63 km^2, conveying a large portion of the runoff from the western slope of Mount Jefferson. Milk Creek is within the Pamelia Creek drainage basin and drains 6.5 km^2, with flows originating from remnants of the Milk Creek Glacier, high-altitude valley snowfields, and ground water. Although the upper drainage basins are above treeline, the western lower altitude portions are densely vegetated with western white pine, western hemlock, Douglas-fir, silver fir, and rhododendrons in the understory (U.S. Forest Service, 2007; David Halemeier, U.S. Forest Service, oral commun., 2008). Vehicle access within the drainage basins is limited, but a large part of the Mount Jefferson Wilderness Area is accessible by trail, such as the Pamelia Lake and Pacific Crest Trails.

Mount Jefferson Debris Flow, November 6, 2006

Weather Conditions

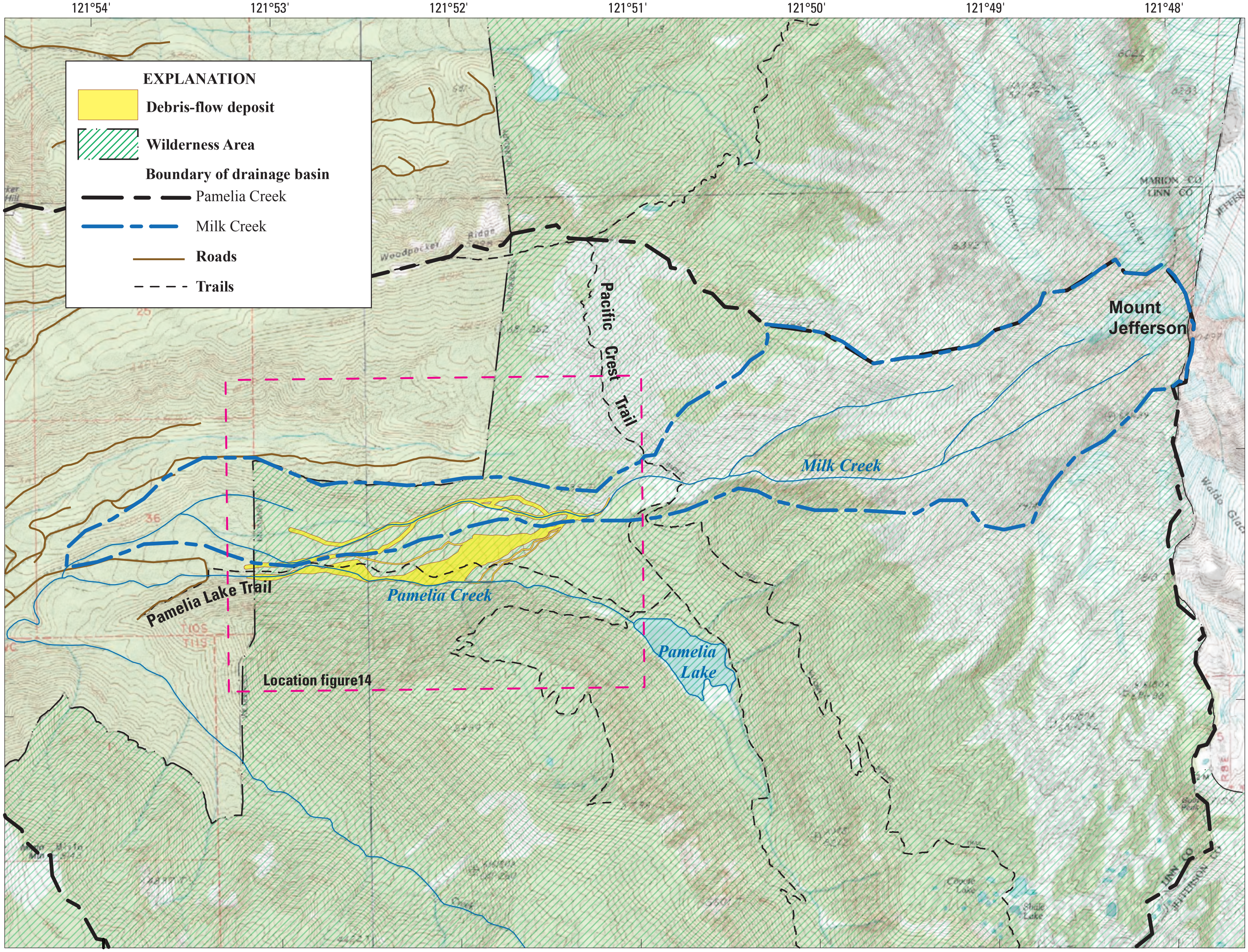
Early November 2006 was a warmer than normal period accompanied by a tropical storm which brought heavy precipitation (table 1). Air temperatures near Mount Jefferson increased quickly as the storm front moved across the Pacific Northwest. During the first week of November, maximum daily air temperatures increased 9.4°C, and minimum daily air temperatures increased 21.1°C. The warm front brought heavy precipitation to the region, peaking with a total of 12.8 cm on November 7. These weather conditions were characteristic of a “Pineapple Express,” where central Pacific tropical air streams over the Northwestern United States (National Oceanic and Atmospheric Administration, 2005). This storm was responsible for flooding and numerous landslides all over the region, such as those on Mount Rainier (National Park Service, 2007) and Mount Hood (Pirot and others, 2007). Similar conditions occurred in February 1996 and led to the worst flooding in more than 30 years for much of the Pacific Northwest.

Because the warm temperatures and rainfall occurred early in the winter, the mountain had minimal snowpack. A small amount of snow accumulated during November 1 and 2, especially at higher altitudes; however, as the warm air temperatures caused the snow level to rise, rain fell directly onto higher altitude snowfields. This “rain-on-snow” situation augmented the heavy rainfall conditions from November 3 through 6 by adding additional water to the hydrologic system.

Table 1. Air temperature and precipitation data collected from meteorological stations at Marion Forks and Santiam Junction near Mount Jefferson, Oregon, November 1–8, 2006.

[Temperature and precipitation data from Oregon Climate Service (2007). Shading indicates period of debris flow. Maximum values are in ***bold italics***. **Abbreviations:** °C, degrees Celsius; cm, centimeter]

Date	Maximum daily air temperature (°C)	Minimum daily air temperature (°C)	Precipitation (cm)
11/01/2006	5.0	-11.1	0
11/02/2006	5.6	-1.7	0.2–0.3
11/03/2006	7.8	1.1	2.6–4.9
11/04/2006	8.3	5.6	3.4–3.5
11/05/2006	11.7	7.8	6.4–7.4
11/06/2006	***14.4***	***10.0***	2.0–3.2
11/07/2006	12.2	-1.1	***6.1–12.8***
11/08/2006	3.3	-1.1	5.7–7.3



Base map modified from U.S. Geological Survey digital data (1:24,000).
UTM projection, Zone 10
Horizontal datum: North American Datum of 1927

Figure 3. Location of the Milk Creek and Pamelia Creek drainage basins, and Mount Jefferson debris-flow deposit, Oregon.

First Detection

During the storm, streamflow increased and became more turbid in most streams in the North Santiam River basin. Unlike other streams, however, the turbidity peaked on the North Santiam River at the *North Santiam* station on November 6, a full day before the peak rainfall and streamflow occurred elsewhere (table 2, fig. 4). The timing, magnitude, and location of the high turbidity event were immediately recognized as a possible debris flow or glacial outwash event, similar to major turbidity events from previous years (Sobieszczyk and others, 2007). Because turbidity was so high, it exceeded the maximum detection capability of the instream water-quality instrumentation; however, estimates from samples collected (fig. 5) during the event indicate that turbidity in the North Santiam River ranged from 35,000 to 55,000 FNU (Heather Bragg, U.S. Geological Survey, written commun., 2008).

Table 2. Measurements of mud run-up heights on trees and calculations of indirect debris-flow velocity for Mount Jefferson debris flow, Oregon, November 6, 2006.

[**Indirect debris flow velocity:** Velocity was determined by an equation proposed by Chow (1959). Shading indicates values used in indirect velocity equation. Altitude is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929). Abbreviations: m, meter; m/s, meter per second; –, no data]

Tree and index No. for mud run-up measurements (see fig. 14)	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (m)	Flow depth (m)	Tree diameter (m)	Change in height of mud run-up (m)	Indirect debris-flow velocity (m/s)	Geomorphic location
1	44.659	-121.872	1,094	0.2	0.5	0.0	0.0	valley floor
2	44.659	-121.872	1,092	0.1	0.3	0.1	1.2	valley floor
3	44.659	-121.871	1,091	0.5	0.6	0.1	1.3	valley floor
4	44.660	-121.866	1,124	0.2	0.0	0.1	1.3	valley floor
5	44.660	-121.871	1,092	0.4	0.4	0.2	1.7	valley floor
6	44.659	-121.872	1,092	0.5	0.6	0.2	1.7	valley floor
7	44.659	-121.868	1,108	1.2	0.0	0.2	1.7	confined channel
8	44.659	-121.870	1,074	0.9	0.8	0.2	1.7	confined channel
9	44.659	-121.871	1,096	1.1	0.6	0.2	2.1	valley floor
10	44.660	-121.869	1,102	0.6	0.4	0.3	2.4	valley floor
11	44.660	-121.868	1,113	1.2	0.3	0.3	2.4	valley floor
12	44.659	-121.871	1,092	0.6	0.6	0.3	2.4	valley floor
13	44.660	-121.864	1,138	1.4	1.1	0.3	2.4	confined channel
14	44.660	-121.866	1,131	2.4	0.8	0.6	3.5	confined channel
15	44.659	-121.879	–	1.5	0.9	0.6	3.5	valley floor
16	44.659	-121.877	–	1.7	0.6	0.6	3.5	valley floor
17	44.661	-121.865	1,138	1.8	1.1	0.7	3.7	confined channel
18	44.661	-121.865	1,178	1.8	0.6	0.7	3.7	confined channel
19	44.661	-121.861	1,170	2.4	0.5	0.8	3.9	confined channel
20	44.661	-121.862	1,180	2.4	0.5	0.8	3.9	confined channel
21	44.660	-121.865	1,138	2.4	0.8	0.8	3.9	confined channel
22	44.659	-121.869	1,106	1.1	0.9	0.8	3.9	valley floor

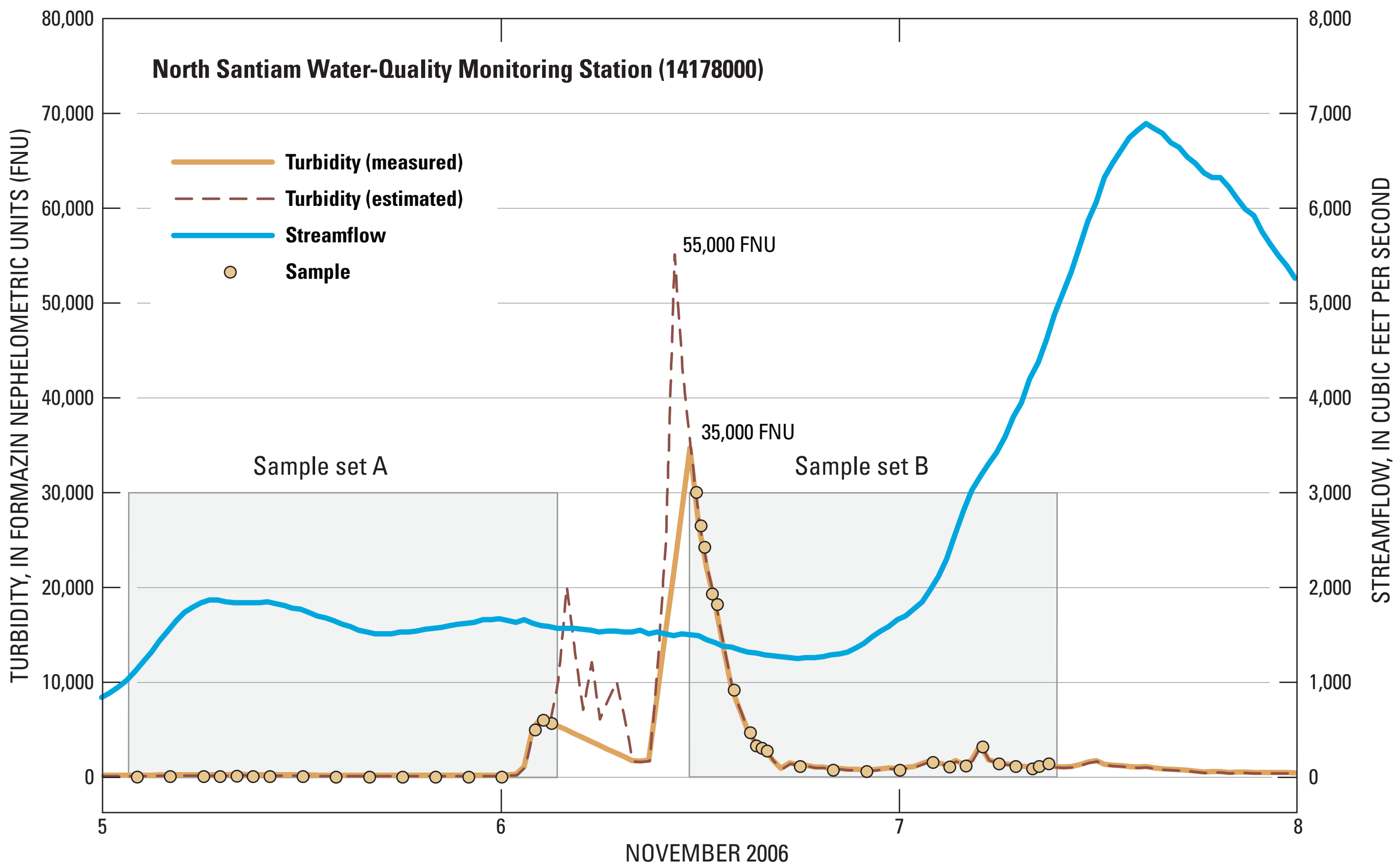


Figure 4. Streamflow and measured and estimated turbidity from samples collected at the *North Santiam* water-quality monitoring station, Oregon, November 6, 2006. Sample sets A and B correspond to water-quality samples collected by automatic pumping sampler (see figure 5).

Turbidity values for this event were based on a series of samples collected by an ISCO automatic pumping sampler. The first set of 1-L sample bottles (sample set A) were filled during the start of the event and replaced with a second set of bottles (sample set B) that captured the latter part of the high turbidity (fig. 5). Laboratory measurements from these samples supplied a conservative turbidity value for the event, whereas the peak turbidity was estimated between the sets based on trends in other water-quality parameters, such as pH and conductivity, collected from the *North Santiam* monitoring station.

Tracing the source of turbid water in the North Santiam River was facilitated by the fact that the tributary Pamelia Creek, about 10 mi upstream of the monitoring station, was visibly turbid (fig. 6). USGS and USFS personnel investigating Pamelia Creek discovered that a debris flow had mobilized down the Milk Creek drainage basin, supplying debris and sediment to both Milk and Pamelia Creeks and beyond. Streamflow at Milk and Pamelia Creeks remained extremely turbid for 12 to 18 hours during the debris flow event-period on November 6.

Figure 5. Automatic pumping samples collected at *North Santiam* water-quality monitoring station during the Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by Heather Bragg, U.S. Geological Survey, 2007.) Gap between sample sets A and B occurred during bottle replacement.

Figure 6. Streamflow from Pamelia Creek entering the North Santiam River, Oregon, November 6, 2006. (Photograph by David Klug, U.S. Forest Service, November 6, 2006.)

Geomorphic and Hydrologic Characteristics

Source Area

Historic and prehistoric debris-flow deposits have been found on all Cascade Range volcanoes, where unconsolidated volcaniclastic and glacial moraine deposits are washed away from the steep slopes (Scott and others, 1995). These unstable volcaniclastic and glacial deposits can be mobilized by any number of causes including an increase in seasonal melt-water discharge or saturation by autumn or spring rainfall. Other less common mechanisms for Cascade debris flows include dam-break floods, volcanic eruptions, or possibly earthquakes; however, these are much more low-frequency, high-consequence type mechanisms. The debris flow on November 6, 2006, appeared to be caused by a combination of mechanisms. Although rainfall influenced the debris flow, noticeable changes in high altitude Milk Creek snowfields, as observed by USFS and USGS, indicated that the debris flow likely mobilized after the collapse of part of a talus-covered stagnant valley snowfield (fig. 7). This type of proglacial collapse and flooding occurred during previous times and at other Cascade volcanoes (for example, Scott and others, 1995; Walder and others, 1999; O'Connor and others, 2001). Although the rainfall may not have initiated the debris flow, it did increase melting of surficial snow, amplified runoff, saturated sediments, and augmented subsnowfield streamflow. Snowfield calving and sediment unloading likely started relatively small, but continued to accumulate and erode more material as it progressed downstream (fig. 8). Because of the presence of older debris flow deposits in the area, much of the loose, previously deposited material was easily remobilized by this recent event.

Figure 7. View of debris covered snowfield in the Milk Creek channel, some of which collapsed and melted, supplying material for the Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by William Myers, Oregon State University, 2007.)

Figure 8. Channel incision along Milk Creek, where debris flow gained volume during the Mount Jefferson debris flow, Oregon, November 6, 2006. Note people for scale. (Photograph by Mark Uhrich, U.S. Geological Survey, 2007.)

Streamflow and Flooding

The fluvial component of the debris flow that formed down the Milk Creek drainage basin was characteristic of a hyperconcentrated flow, or mud slurry. However, streamflow from Pamelia Creek likely diluted much of the mud slurry prior to its entering the North Santiam River. Analyses of water samples collected at the *North Santiam* monitoring station correlated with estimates of streamflow from Milk and Pamelia Creeks indicate that 3 to 6 percent of the flow volume consisted of entrained sediments (Mark Uhrich, U.S. Geological Survey, written commun., 2008). Streamflow is considered to be hyperconcentrated when 5 percent of the flow volume consists of entrained sediments (Pierson, 2005). Evidence of mud run-up on trees (fig. 9) indicated that the flood stage of this flow reached depths of at least 2.4 m in the confined, high altitude channels (table 2). As the flow spread across the valley floor, tree markings displayed a reduction in stage height to 1 m or less. High flows associated with flooding remobilized boulders and debris along Milk and Pamelia Creeks, as well as deposited sand and silt across the forest floor. Flooding and high flows eroded portions of the initial debris-flow deposit and other older deposits, reworking much of the landscape. As velocities decreased, greater volumes of fine-grained sediment were deposited within distributary channels along the Milk and Pamelia Creek drainage basins. After the debris flow slowed and deposited its coarse material, the sediment-laden streamflow continued to the North Santiam River and Detroit Lake. This type of debris-flow-induced flood surge was consistent with previous events on other Cascade volcanoes (see, for example, Scott and others, 1995; Pierson, 2005; National Park Service, 2007).

Figure 9. Mud run-up markings on trees created by flooding associated with the Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by Mark Uhrich, U.S. Geological Survey, 2007.)

Velocity

The Mount Jefferson debris flow in November 2006 was not a single flow event, but rather a series of at least three or more surges of debris and flooding (David Halemeier, U.S. Forest Service, written commun., 2008). Evidence of damming and redirection of flow, channel terracing, and deposition then scouring of material all support this hypothesis. Because this event comprised multiple flows, calculating one specific velocity was impossible. Instead, using field measurements of change in height of mud run-up on trees (fig. 10) and observations of material type, an indirect velocity equation (Jakob, 2005) was used to calculate a range of values for this event. For this study, mud run-up markings for 22 trees were measured at different locations in the depositional area (table 2). The deposit material type was initially coarse and boulder-sized before thinning to a mud slurry. Based on these observations, velocity was determined by an equation for "rocky"-type debris flows proposed by Chow (1959). The equation describes debris flow velocity in relation to the change in run-up height multiplied by a multiple of the gravitational constant (Chow, 1959, eq. 1). Two known limitations for this equation are (1) it only applies to impacted objects perpendicular to the flow direction, and (2) it assumes all kinetic energy was converted to potential energy (Jakob, 2005). Theoretical run-up equations, such as equation 1 in Chow (1959), also yield velocities as much as 30 percent lower than large-scale flume experiments (Jakob, 2005). However, given the data available, these velocity calculations offered tangible values for discussion and comparison.

$$v = (2g\Delta h)^{0.5}, \tag{1}$$

where

v is velocity,

g is the gravitational mass acceleration constant 9.8 m/s^2, and

Δh is the change in run-up height, in meters.

Velocities calculated using this equation reached 3.9 m/s for the different surges of debris and flooding (table 2).

Figure 10. Change in height of mud run-up markings created by debris flow and flooding impacting tree (left to right) during the Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by Mark Uhrich, U.S. Geological Survey, 2007.)

Depositional Extent

The debris-flow depositional extent was determined based on field indicators, such as distal flow levees, log jams and boulder clusters, mud coatings on trees and boulders, organic debris accumulations, and tree scars (fig. 11; O'Connor and others, 2001; Pierson, 2005). Mapping the depositional extent of the Mount Jefferson debris flow in November 2006 was completed between July 2007 and July 2008. A Global Positioning System (GPS) handheld device was used to record coordinates for the outermost edge of the coarse debris flow boundary, and the coordinates were cross-referenced against aerial photography to verify accuracy.

The debris flow deposited a predominantly rocky debris fan, including large boulders greater than 0.4 m diameter, over a 0.1 km^2 area in the drainage basins of Milk and Pamelia Creeks (fig. 12). The material dammed Milk Creek and redirected its flow south to a newly formed channel referred by the USFS as "2 percent Milk Creek." Most of the coarse material from the debris flow in November 2006 was deposited along 2 percent Milk Creek (fig. 13). As material was deposited, multiple dams and levees were formed, continuously altering the direction and velocity of the debris flow. Surges of debris and flooding further altered the landscape in the drainage basins of Milk and Pamelia Creeks by reworking and depositing fine to coarse-grained material along an additional 0.35 km^2 area (fig. 14). High flows in Pamelia Creek also contributed to the damage caused by the debris flow. Increased streamflow and flooding during this period forced Pamelia Creek about 100 m south to an abandon section of its original channel. The combined 0.45-km^2 area represented the depositional extent, including subsequent flooding and deposition of fine-grained material along a number of other channels. All coarse material settled out before the original confluence of Milk and Pamelia Creeks, leaving only the mud slurry to pass downstream into the North Santiam River.

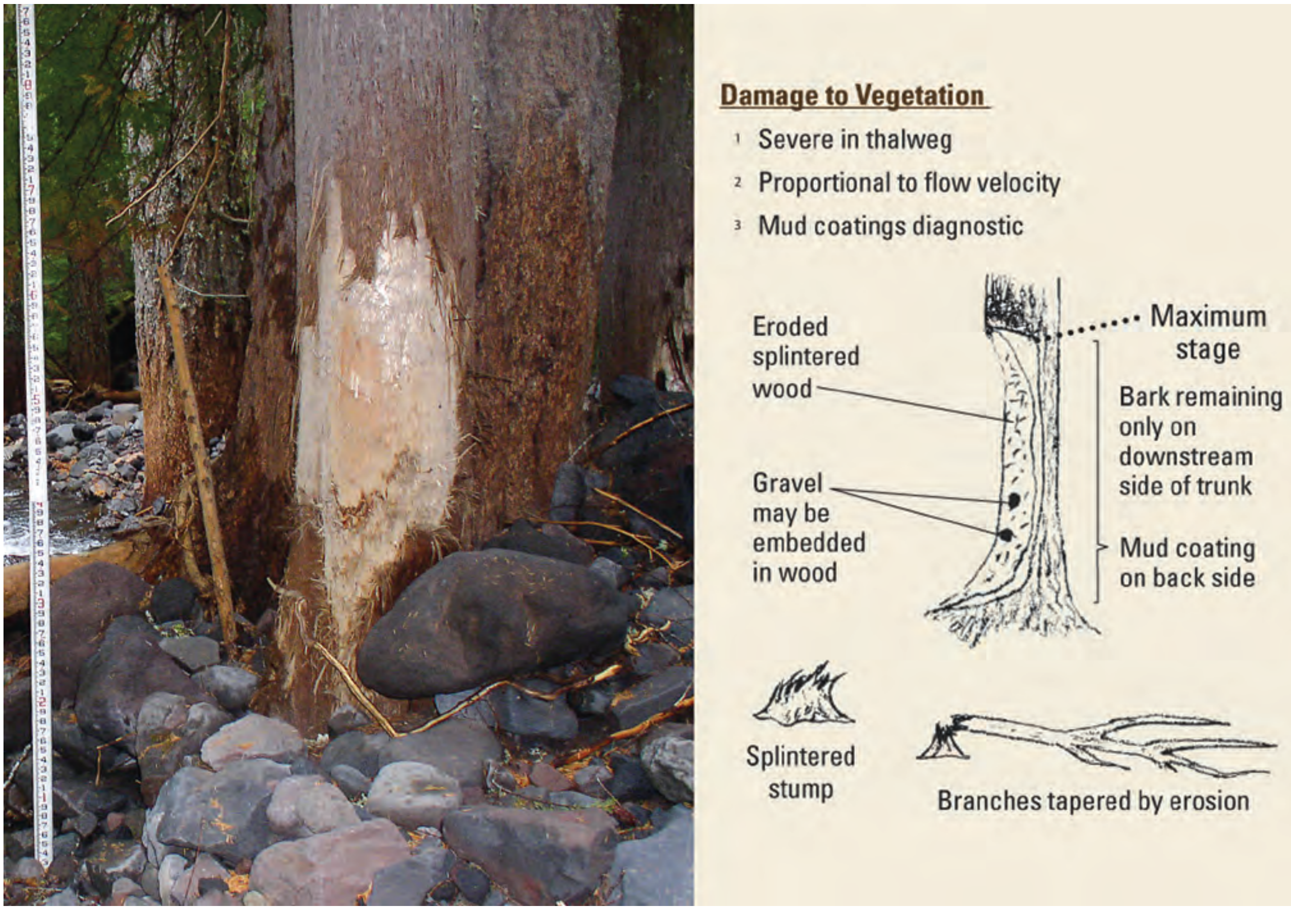


Figure 11. Tree damage caused by the Mount Jefferson debris flow, Oregon, November 6, 2006. (Photograph by Mark Uhrich, U.S. Geological Survey, 2007.) Diagram shows example of indicators of damage to vegetation during a debris flow (Pierson, 2005).

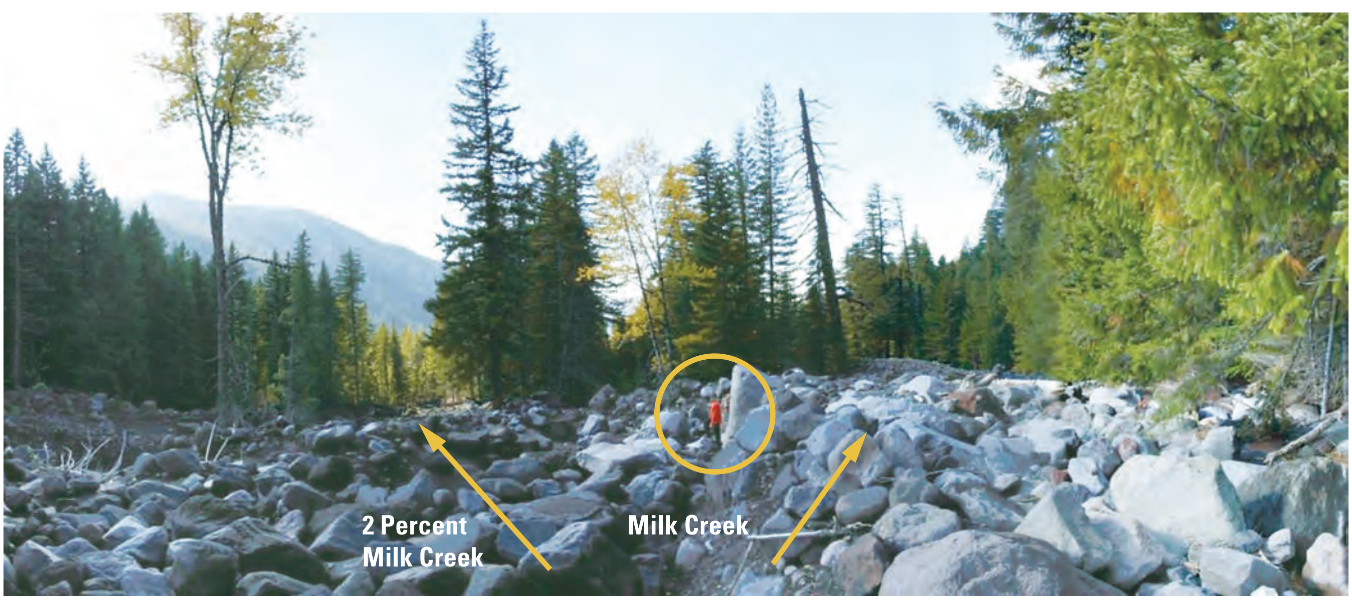


Figure 12. Downstream view of boulder-sized debris blocking the divergence between Milk Creek (right) and 2 percent Milk Creek (left), Oregon. Note person for scale. (Photograph by Chris Ricker, Portland State University, 2007.)

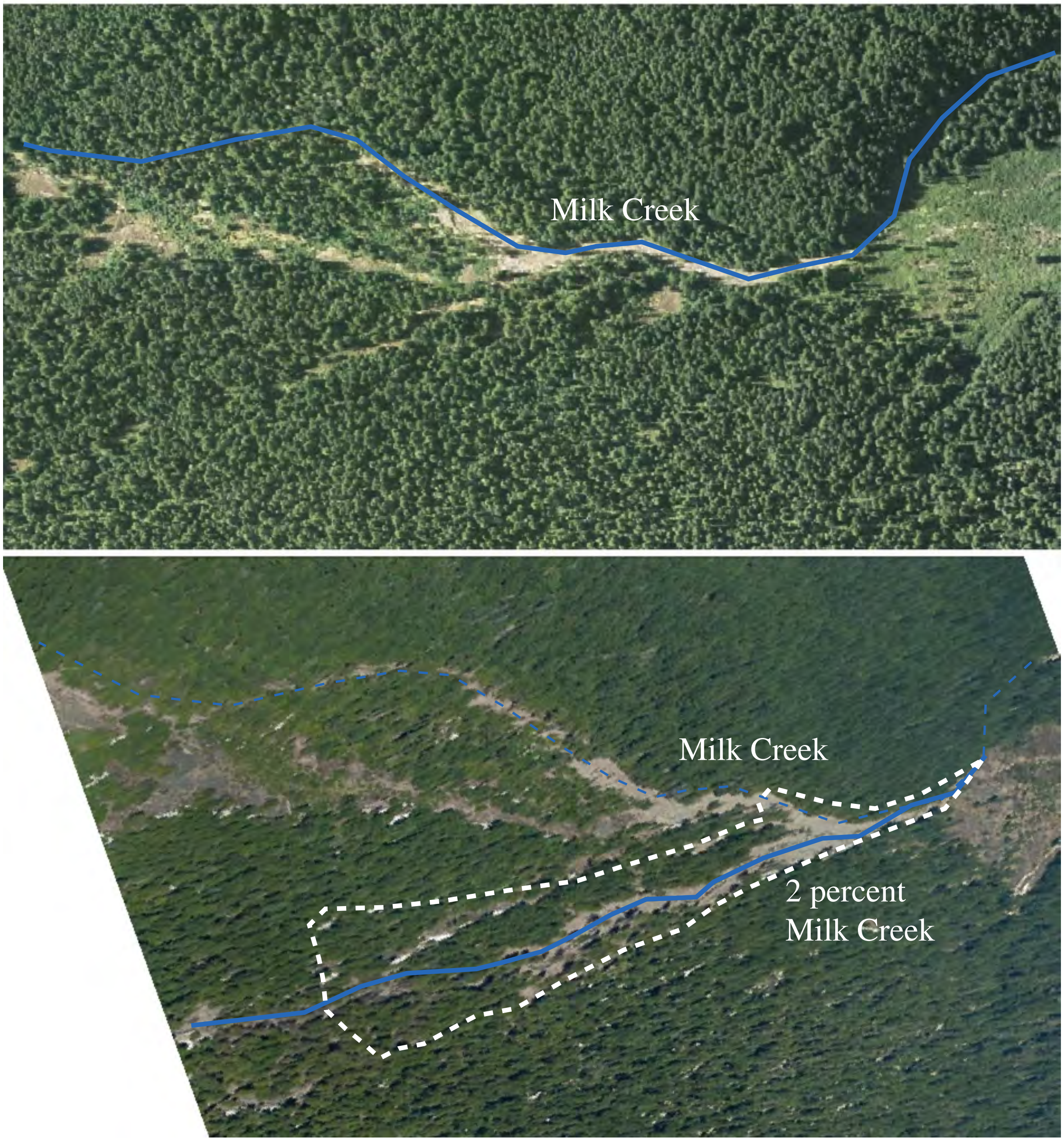
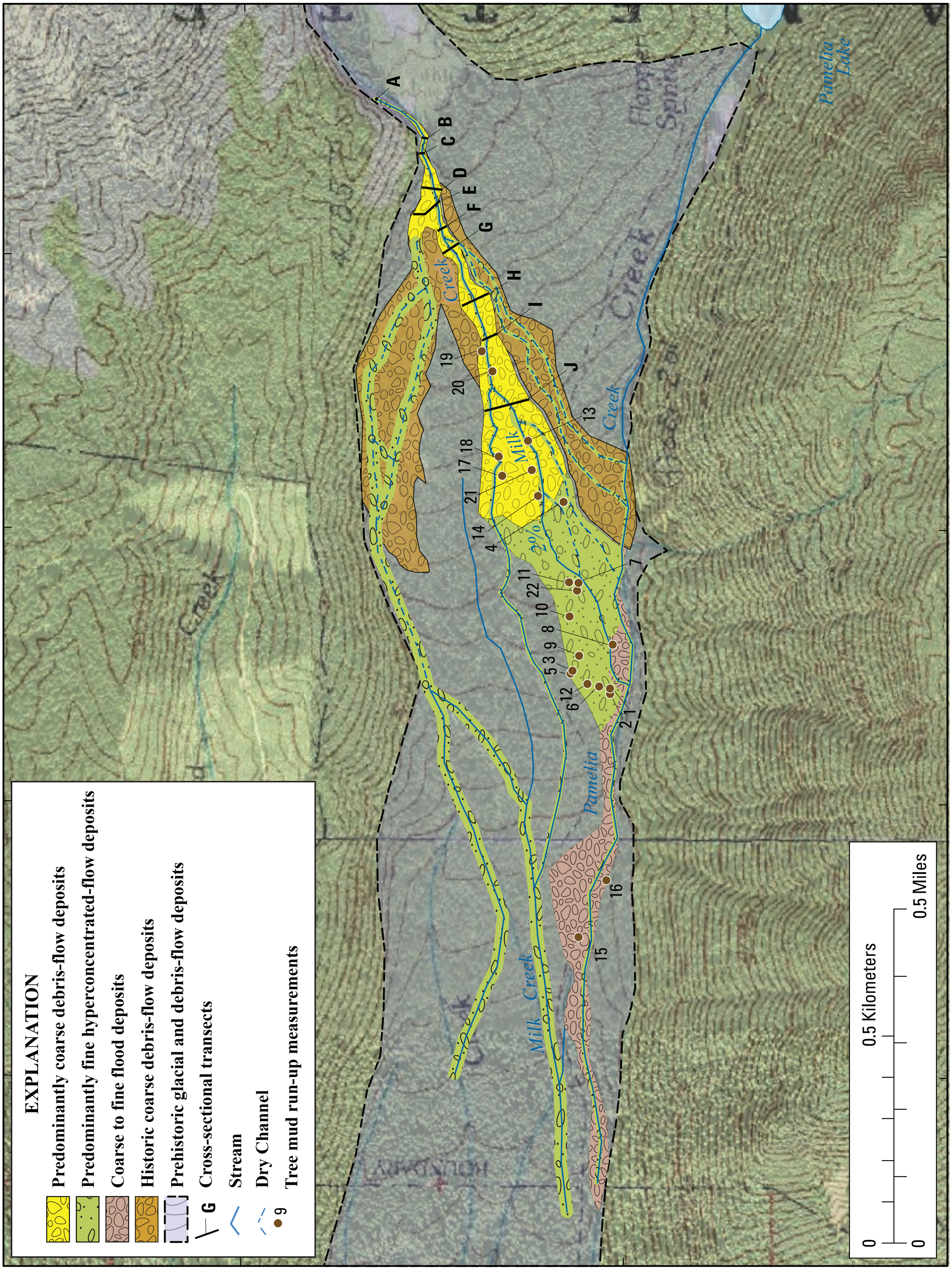


Figure 13. Comparison of aerial photographs from 2005 (top) and 2007 (bottom) of Mount Jefferson debris flow, Oregon, November 6, 2006. 2005 aerial photograph from Oregon State University (2008); 2007 aerial photograph by Robert Ross, Linn Benton Community College (2007). Note that the new deposit (light gray) extends from center-right toward bottom left along newly formed 2 percent Milk Creek.



Base map modified from U.S. Geological Survey digital data (1:24,000).
Projection: UTM, Zone 10, North American Datum 1927.

Figure 14. Depositional extent of the Mount Jefferson debris flow, Oregon, November 6, 2006.

Depositional Volume

The depositional volume of the Mount Jefferson debris flow in November 2006 was estimated using cross-sectional transect measurements (table 3; fig. 14). For this study, cross-sectional areas were surveyed using a laser distance meter and survey staff, and angles and leveling were obtained using a Brunton compass. Using 10 transects (table 3) surveyed along the length of the predominantly coarse debris deposit, deposit values were extrapolated between cross-sectional areas to produce a generalized volume. Because each transect consisted of deposit and scour, volume measurements were based on the net deposit (total deposit – scour = net deposit). Results indicated that at least 80,000 m^3 of coarse material was freshly deposited during the November 2006 debris flow. Field measurements of fine-grained sediment deposits extrapolated over the debris-flow area indicate that the hyperconcentrated flow and floodwaters contributed an additional 20,000 to 160,000 m^3 of sediment, increasing the total depositional volume to 240,000 m^3, not including the suspended sediment that was carried downstream. For comparison, nearly 100 Olympic-sized swimming pools could have been filled with boulders, debris, and sediment from this debris-flow event.

Suspended-Sediment Load

Although water quality was not monitored on Milk or Pamelia Creeks, automatic pumping samples collected at the *North Santiam* monitoring station were analyzed for turbidity and suspended-sediment concentrations. Using these samples, suspended-sediment load values were calculated for the debris flow and subsequent flooding. Estimates were based on techniques developed by Uhrich and Bragg (2003) and Bragg and others (2007). During the 24-hour period on November 6, 2006, about 15,500 to 21,000 metric tons of suspended sediment traveled downstream past the *North Santiam* monitoring station. If the dry weight per volume of the suspended sediment was assumed to be sand-sized or less, then the total volume for the suspended-sediment load portion of the debris flow was 9,800 to 13,000 m^3. Even though other sources may have contributed minor amounts of sediment, most of the suspended-sediment load was attributed to the Mount Jefferson debris flow. This event was responsible for one of the largest single-day suspended-sediment loads of any major turbidity event in the North Santiam River basin since 1998 (Sobieszczyk and others, 2007).

Table 3. Estimated depositional volumes using cross-sectional transect measurements along depositional extent of the Mount Jefferson debris flow, Oregon, November 6, 2006.

[Location of cross-sectional transect profiles are shown in figure 14. Ab**breviations:** m, meter; m^2, square meter; m^3, cubic meter]

Transect index letter	Mean height (deposit) (m)	Mean depth (scour) (m)	Net deposit (deposit – scour) (m)	Transect area (m^2)	Transect depositional volume (net deposit × area) (m^3)
A	0.0	3.0	-3.0	2,000	-6,000
B	3.0	2.0	1.0	1,000	1,000
C	2.0	3.0	-1.0	2,000	-2,000
D	2.0	2.0	0.0	3,000	0
E	3.0	2.0	1.0	5,000	5,000
F	4.0	2.0	2.0	2,000	4,000
G	4.0	2.0	2.0	6,000	12,000
H	3.0	2.0	1.0	6,000	6,000
I	2.0	1.0	1.0	10,000	10,000
J	2.0	1.0	1.0	50,000	50,000
				Coarse deposits	80,000
				Fine deposits	20,000–160,000
				Total	***100,000–240,000***

Summary and Conclusions

Each winter, landslides mobilize from slopes throughout the Pacific Northwest. If winter storms produce above average rainfall, the threat for rapidly moving landslides increases substantially. As landslides enter streams, they greatly affect downstream water quality by causing large and sudden increases in turbidity. This study analyzes one such example where turbidity data exist for a known rapidly moving landslide, or debris flow.

On November 6, 2006, a rocky debris flow surged down the western flank of Mount Jefferson in the Oregon Cascades. Although coarse, boulder-sized material settled near the base of the mountain, high flows and flooding continued through parts of the drainage basins of Milk and Pamelia Creeks, sending a mud slurry into the North Santiam River. Investigation into the source of the event suggested that warmer than normal air temperatures and heavy precipitation caused a portion of a debris-covered, stagnant snowfield to collapse in the upper Milk Creek valley. As boulders, ice, and water flowed downslope, additional material was aggregated from previous debris flows, pyroclastic flows, and glacial moraine deposits. Mud run-up markings on trees indicated that the confined channel flood stage was greater than 2.4 meters deep, while flows outside the channel gradually thinned out atop the open valley floor. Fine-grained sediments entrained in floodwaters were transported through the North Santiam River into Detroit Lake. Future high flows will continue to erode the fine-grained material remaining on boulders, logs, and the valley floor.

Velocity calculations for the debris-flow event suggest that the multiple waves of debris and water that surged throughout the day reached 3.9 meters per second. Analyses of water-quality samples collected during the event indicated that an estimated 9,800 to 13,000 cubic meters of fine-grained sediment was transported downstream to the North Santiam River. A follow-up investigation of the debris flow indicated that debris and flood deposits covered about 0.45 square kilometers, depositing between 100,000 and 240,000 cubic meters of material. The debris flow altered the landscape by diverting streamflow from its original channel south to a new channel that was carved into the forest floor. This debris flow supplied enough suspended sediment to increase turbidity values in the North Santiam River above Detroit Lake to an estimated 35,000 and 55,000 Formazin Nephelometric Units. These turbidity values rank among the highest recorded (or estimated) in the North Santiam River basin since the inception of the USGS North Santiam River Basin Suspended-Sediment and Turbidity Study monitoring network in 1998.

Acknowledgments

The authors would like to thank the City of Salem for cooperative funding. In addition, we thank Carolyn Driedger, Kevin Schmidt, Jim O'Connor, Richard Iverson, Joseph Rinella, and John Williams of the U.S. Geological Survey for their comments and review. We also would like to thank Scott Burns, Bethany Jackson, and Chris Ricker of Portland State University for their help during the inception of this research. Lastly, we could not have completed this report without the help of Robert Ross of Linn Benton Community College, William Myer of Oregon State University, and David Halemeier and David Klug of the U.S. Forest Service. Their guidance and support were invaluable.

References Cited

Beaulieu, J.D., and Olmstead, D.L., 1999, Mitigating geologic hazards in Oregon—A technical reference manual: Oregon Department of Geology and Mineral Industries Special Paper 31, 60 p.

Bragg, H.M., Sobieszczyk, Steven, Uhrich, M.A., and Piatt, D.R., 2007, Suspended-sediment loads and yields in the North Santiam River Basin, Oregon, water years 1999–2004: U.S. Geological Survey Scientific Investigations Report 2007–5187, 26 p.

Burns, Bill, Hinkle, Jason, and Hay, Stephen, 2008, The Woodson debris flow, Woodson, Oregon: Association of Environmental & Engineering Geologists News, v. 51, no. 1, p. 21–24.

Chow, V.T., 1959, Open channel hydraulics: New York, McGraw Hill, 680 p.

Hofmeister, R.J., 2000, Slope failures in Oregon, GIS inventory for three 1996/97 storm events: Oregon Department of Geology and Mineral Industries Special Paper 34, 20 p., 1 compact disc.

Jakob, Matthias, 2005, Debris-flow hazard analysis, Chapter 17, *in*, Jakob, Matthias., and Hungr, Oldrich., eds., Debris-flow hazards and related phenomena: New York, Springer-Praxis Books in Geophysical Sciences, p. 411-443.

National Oceanic and Atmospheric Administration, 2005, NOAA catches a culprit behind western storms: accessed November 2007, at http://www.noaanews.noaa.gov/stories2005/s2367.htm.

National Park Service, 2007, November 2006 Flooding: accessed July 2008, at http://www.nps.gov/mora/parknews/november-2006-flooding.htm

O'Connor, J.E., Hardison, J.H., and Costa, J.E., 2001, Debris flows from failures of Neoglacial-age moraine dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon: U.S. Geological Survey Professional Paper 1606, 93 p., 2 pls.

Oregon Climate Service, 2007, Climate data: Zone 4/Temperature: Daily/Santiam Junction and Zone 4/Precipitation: Daily/Santiam Junction, Marion Forks Fish Hatchery, and Detroit Dam—Climate data archives: accessed November 2007, at http://www.ocs.oregonstate.edu/index.html

Oregon Department of Geology and Mineral Industries, 2008, Debris flow warnings—Oregon's debris flow warning system and how it works: accessed August 2008, at http://www.oregongeology.com/sub/Landslide/debrisflow.htm

Oregon State University, 2008, Oregon imagery explorer: accessed June 2008, at http://oregonexplorer.info/imagery

Pierson, T.C., 2005, Distinguishing between debris flows and floods from field evidence in small watersheds: U.S. Geological Survey Fact Sheet 2004–3142, 4 p.

Pirot, Rachel, Burns, Scott, and Deroo, Thomas, 2007, Massive debris flow generation on Mount Hood, Oregon, November 2006: Geological Society of America, Abstracts with Programs, v. 39, no. 6, p. 363.

Scott, K.M., Vallance, J.W., and Pringle, P.T., 1995, Sedimentology, behavior, and hazards of debris flows at Mount Rainer, Washington: U.S. Geological Survey Professional Paper 1547, 56 p.

Sobieszczyk, Steven, Uhrich, M.A., and Bragg, H.M., 2007, Major turbidity events in the North Santiam River Basin, Oregon, water years 1999–2004: U.S. Geological Survey Scientific Investigations Report 2007–5178, 50 p.

Uhrich, M.A., and Bragg, H.M., 2003, Monitoring instream turbidity to estimate continuous suspended-sediment loads and clay-water volumes in the upper North Santiam River Basin, Oregon, 1998–2000: U.S. Geological Survey Water-Resources Investigations Report 03–4098, 43 p.

U.S. Forest Service, 2007, Mt. Jefferson Wilderness: accessed November 2007, at http://www.fs.fed.us/r6/willamette/recreation/tripplanning/wilderness/mtjefferson.html

U.S. Geological Survey, 2008, North Santiam River Basin suspended-sediment and turbidity study—Near real-time data for sites in the North Santiam River Basin: accessed June 1998, at http://or.water.usgs.gov/santiam/datapage.html

Walder, J.S., Gardner, C.A., Conrey, R.M., Fisher, B.J., and Schilling, S.P., 1999, Volcano hazards in the Mount Jefferson region, Oregon: U.S. Geological Survey Open-File Report 99–24, 14 p.

Manuscript approved for publication, October 22, 2008

Prepared by the USGS Publishing Network

Bill Gibbs
Linda Rogers
Luis Menoyo
Sharon Wahlstrom

For more information concerning the research in this report, contact the

Director, Oregon Water Science Center
U.S. Geological Survey
2130 SW 5th Avenue
Portland, Oregon 98402
http://or.water.usgs.gov

Sobieszczyk and others—**Geomorphic and Hydrologic Characteristics of Mount Jefferson Debris Flow, Oregon, November 6, 2006**—Scientific Investigations Report 2008–5204