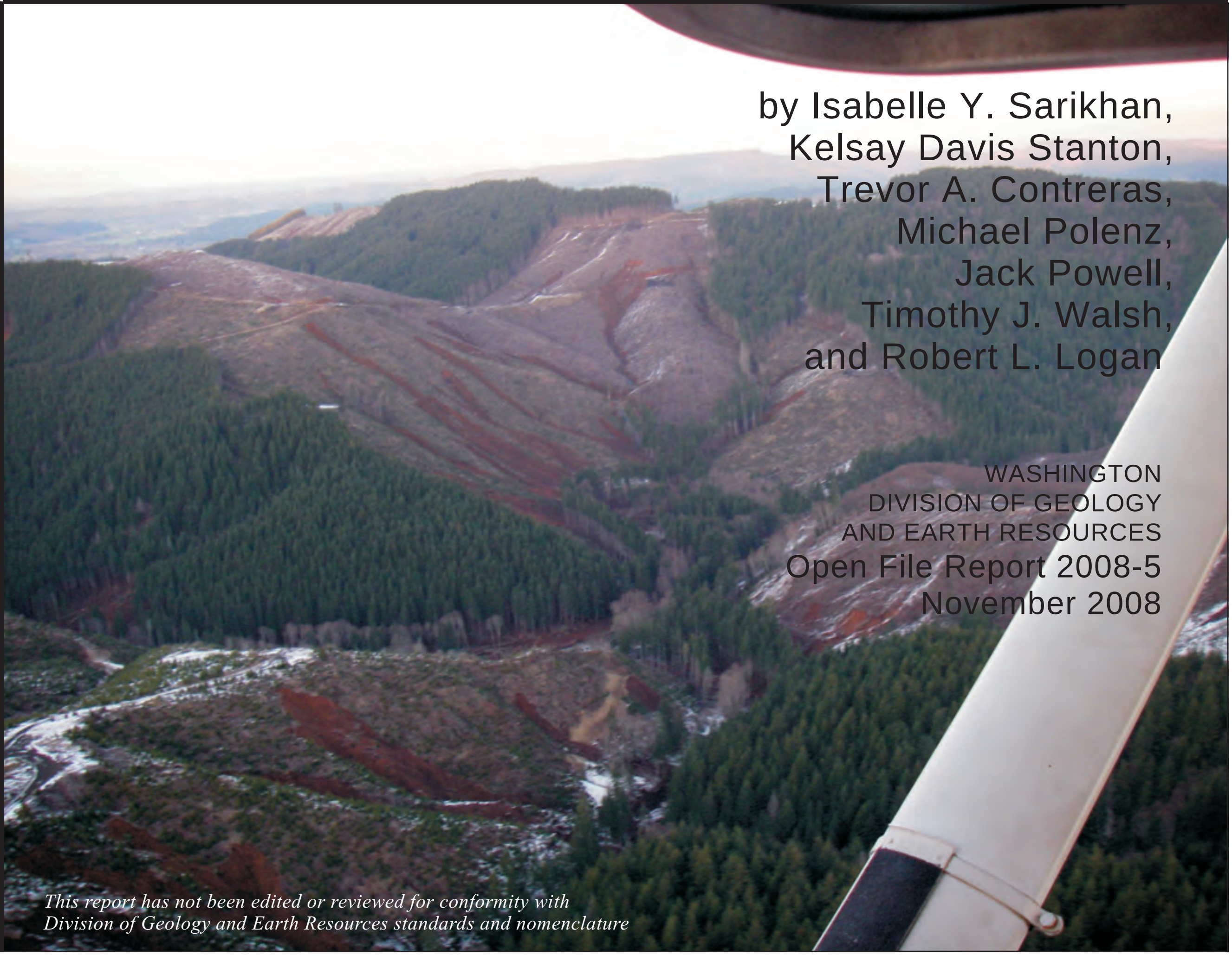
NATURAL RESOURCES

Landslide Reconnaissance Following the Storm Event of December 1–3, 2007, in Western Washington



by Isabelle Y. Sarikhan,
Kelsay Davis Stanton,
Trevor A. Contreras,
Michael Polenz,
Jack Powell,
Timothy J. Walsh,
and Robert L. Logan

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES
Open File Report 2008-5
November 2008

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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WASHINGTON DEPARTMENT OF NATURAL RESOURCES

Doug Sutherland—*Commissioner of Public Lands*

DIVISION OF GEOLOGY AND EARTH RESOURCES

David K. Norman—*Acting State Geologist*
John P. Bromley—*Assistant State Geologist*

Washington Department of Natural Resources
Division of Geology and Earth Resources

Mailing Address:
PO Box 47007
Olympia, WA 98504-7007

Street Address:
1111 Washington St SE
Natural Resources Bldg, Rm 148
Olympia, WA 98501

Phone: 360-902-1450
Fax: 360-902-1785
E-mail: geology@dnr.wa.gov
Website: http://www.dnr.wa.gov/AboutDNR/Divisions/GER/

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Cover photo: Stillman Creek drainage looking north at Little Mountain (left) and Sure Shot Mountain (right), Chehalis River headwaters, Lewis County. This area had the highest density of landslides found during this reconnaissance. Photo by Trevor Contreras.

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INTRODUCTION

During the storm event of December 1–3, 2007, heavy rains and rapid snowmelt triggered thousands of landslides throughout western Washington. Landslides blocked or damaged roads, isolating communities in the height of the storm and delaying emergency response. At least one person died as a consequence of the storm.

As population expands into once sparsely developed rural forests and agricultural lands, and climatic changes result in more frequent and intense storm events (IEG, 2007; Christensen and others, 2007), the need for mapping geologic hazards, such as landslides, becomes increasingly urgent. Hazards mapping is the basis for good growth management planning that can greatly reduce impacts to infrastructure and loss of life and property. Anecdotal evidence indicates that in Washington State, landslides account for at least several tens to hundreds of millions of dollars in economic losses per year. In 1998, the Aldercrest–Banyon landslide in Kelso, Washington, alone damaged or destroyed 138 homes and accounted for $30 to $40 million in losses (Wegmann, 2006). Nationally, landslides account for more than $2 billion in losses annually and result in an estimated 25 to 50 deaths a year (Spiker and Gori, 2003; Schuster and Highland, 2001; Schuster, 1996).

In order to mitigate such losses during future catastrophic landslide events, it is crucial to understand where and why slope failures and flooding occur. The time to accomplish such documentation is as soon after the event as possible, because the data are perishable. Landslides are quickly removed from roads and often stabilized or otherwise modified, destroying or obscuring critical data used to analyze the triggers for slope failures. If left too long, landslides become obscured or modified by weathering, erosion, and vegetation. Data recovered from landslide studies are essential to understanding hazards and associated risks, which greatly aids in identifying susceptible communities, speeding up emergency response, and helping state, county, and city officials mitigate potential property damage and loss of life.

This report is an overview of the reconnaissance of landslides associated with the storm event of December 1–3, 2007, in western Washington. Further study is being conducted by the Upslope Processes Science Advisory Group (UPSAG), a scientific research branch of the Cooperative Monitoring Evaluation and Research Committee (CMER). They are researching and critically examining the effects of land management practices during the storm event.

The purpose of this reconnaissance is to document a sampling of landslides triggered by the December storm event and the losses associated with them. These landslides have been entered into a statewide geographic information system (GIS) landslide database and are coded with field data. The information and data in this report supplement the Quick Report available online at: http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazardsMapping/Pages/landslides_dec07storm.aspx.

The December storm landslide inventory should be considered an initial baseline for future site-specific landslide-related studies. It is not intended to be detailed enough to replace site-specific investigations by a qualified (licensed) geologist or engineering geologist.

STORM EVENT SUMMARY

The storm event of December 1–3, 2007, was a truly historic event, where snow, strong winds, and heavy rainfall battered western Washington, triggering thousands of landslides and causing major flooding on numerous rivers (Read, 2007; Reiter, 2008).

On December 1, the first part of the storm reached the Washington–Oregon border, bringing winds and heavy snow to higher elevations and lighter snow to lower elevations. Snow depths in higher elevations reached up to 14 inches, whereas lower elevations received 1 to 4 inches.

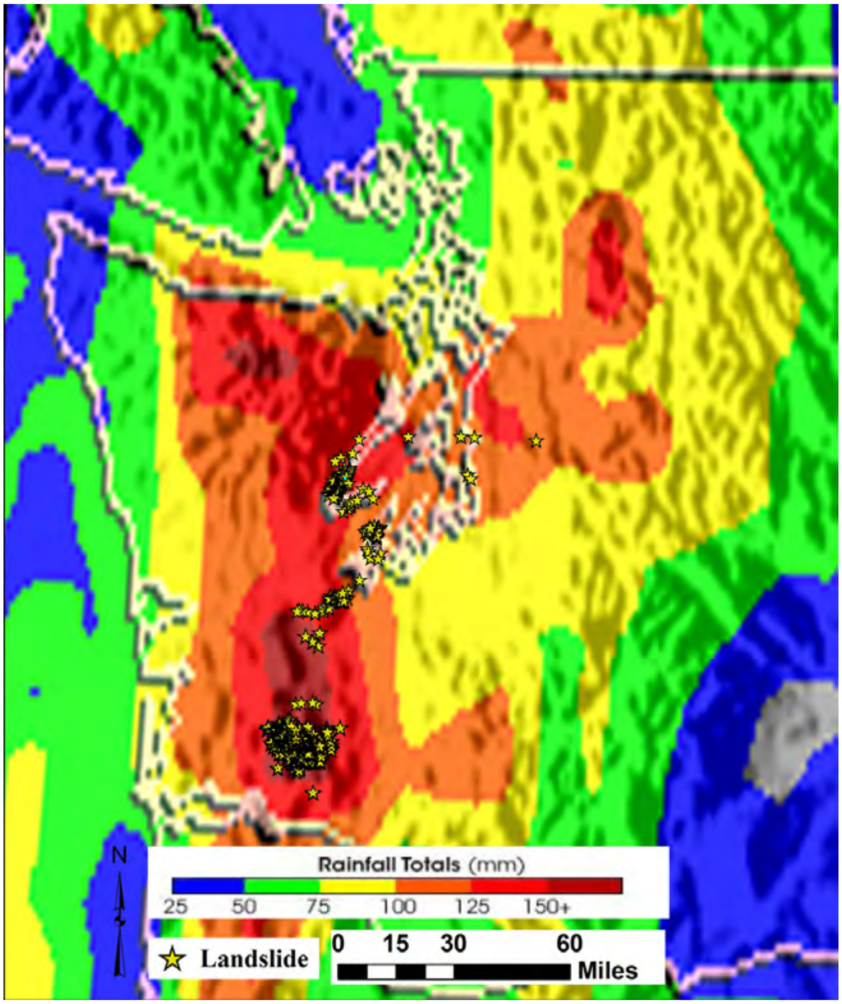

Figure 1. Modified NASA Multi-satellite Precipitation Analysis of western Washington from November 28 to December 4, 2007, overlain with landslide initiation points.

As the first storm moved away from Washington to the northeast, a second storm approached. By December 2, the cold temperatures, which had allowed snow to accumulate quickly, jumped to as high as 60°F in some areas in a matter of hours. Heavy rainfall began across western Washington, focusing on the Chehalis River headwaters area and north into the Olympic Mountains (Fig. 1). (The Chehalis River headwaters are defined as the upper drainage basin of the Chehalis River, which includes the South Fork Chehalis River, the Chehalis River, and Stillman Creek.) In the Chehalis headwaters area, nearly 20 inches of rain was recorded within a 48-hour period, most of that falling within the first 24 hours (Fig. 2). Intense flooding followed the heavy rain, primarily along the Chehalis River. Woody debris and sediment, including material from more than 1,000 landslides in the Chehalis headwaters basin, partially clogged the flood waters for a time. Debris clogged channels at bridges, creating temporary dams and causing widespread deposition of logs and debris, especially across the Boistfort valley. The flood waters reached Chehalis and Centralia on December 3, inundating Interstate Highway 5 (I-5) with as much as 10 feet of water and flooding numerous homes. The flood waters persisted and closed I-5 until December 6, when flood waters finally receded enough to reopen the interstate.

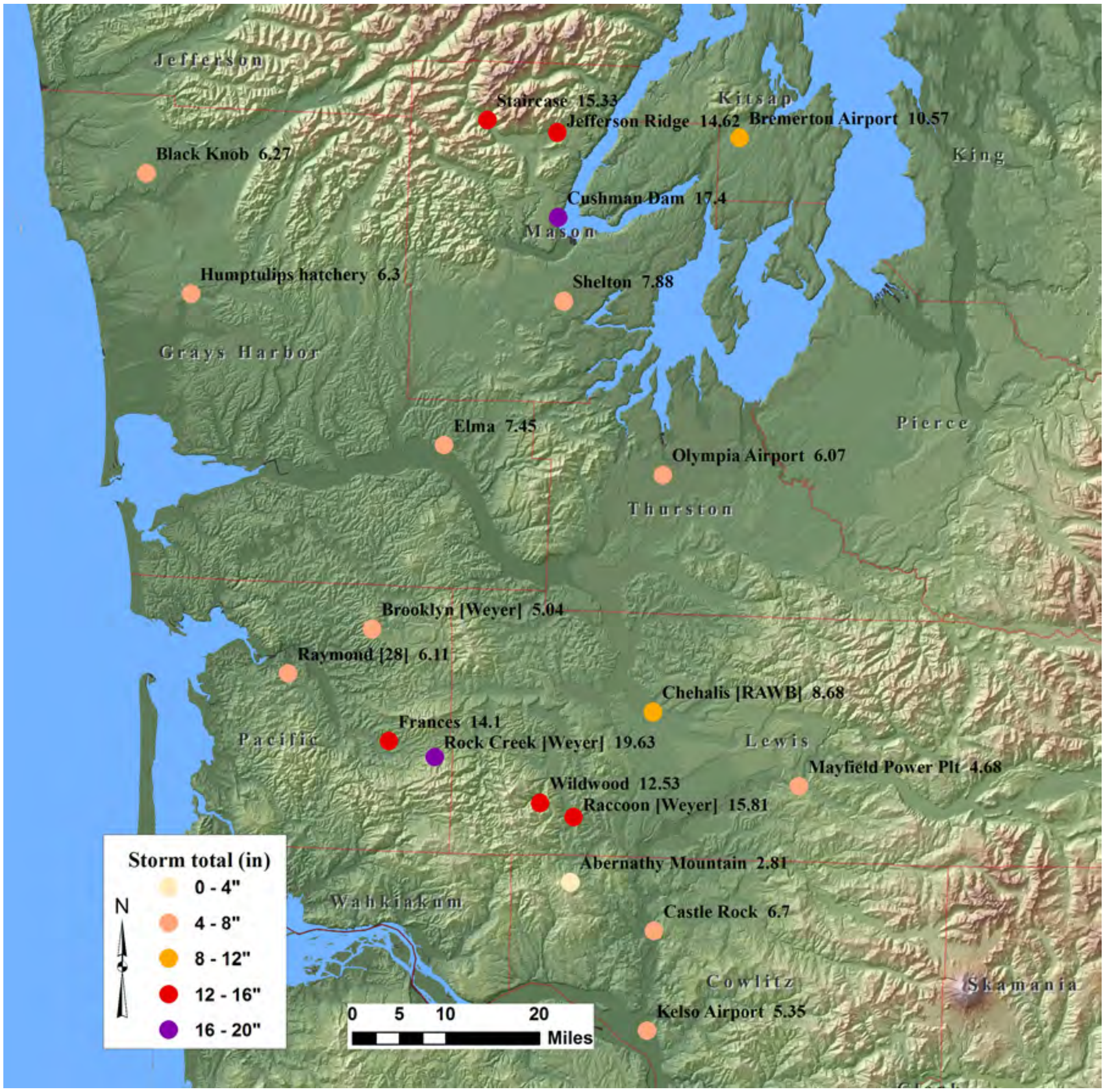

Figure 2. Rainfall totals for the December storm event from precipitation gauges in southwest Washington (modified from Reiter, 2008).

Intense winds followed the heavy rains on December 3, blowing mostly along the coastal range. Some areas experienced sustained winds of 80 miles per hour (mph) with gusts exceeding 145 mph (Washington State Dept. of Natural Resources, written commun.*, 2008). The intense winds battered the coast and the western Willapa Hills, blowing down 600 to 800 million board feet of timber and leaving more than 100,000 coastal residences without power (Reiter, 2008; Washington State Dept. of Natural Resources, written commun.*, 2008).

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* http://www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesApplications/Pages/fp_storm_damage.aspx

DEFINITION OF LANDSLIDE TYPES

‘Landslide’ is a broad term covering a wide variety of ground-movement and mass-wasting processes, including falls, topples, spreads, and flows (Cruden and Varnes, 1996). Generally, the process involves gravity-driven downslope movement of debris, soil, and (or) rock. This mass continues to move until it reaches stability, sometimes traveling a few feet and sometimes miles from the original location. The duration of these events can be instantaneous to very prolonged, lasting for years to decades. Landslides are caused by numerous natural and human-influenced factors, including intense rainfall, long-duration precipitation, rapid snowmelt, water-level changes, wave or stream erosion, earthquake shaking, volcanic eruption, water concentration, and removal of lateral support (Wieczorek, 1996).

For the purpose of this study, landslide processes were grouped in accordance with the statewide landslide database (Sarikhan and Davis, 2008). Shallow landslides are divided into shallow undifferentiated (including shallow colluvial) landslides, debris flows, debris slides (including debris avalanches and torrents), hyperconcentrated flows, and block falls and topples. Deep-seated landslides are divided into lateral spreads, undifferentiated deep-seated landslides, earthflows, translational landslides, rotational landslides, composite landslides, and megalandslides/sturzstroms.

Debris Avalanches

During this event, the majority of landslides that occurred were debris avalanches. Debris avalanches are characterized by unconsolidated rock and soil that has moved downslope along a relatively shallow failure plane. They form steep, unvegetated scars (depressions) in the head region and irregular, hummocky deposits (when present) in the toe region. Debris avalanche scars are likely to ravel and remain unvegetated for many years. These scars can be recognized by the steepness of the slope and the light bulb–shaped form left by many mid- and upper-slope failures.

Debris avalanches are most likely to occur on slopes greater than 65 percent where unconsolidated colluvium overlies a shallow soil or bedrock. The shallow slide surface is usually less than 15 feet deep. However, debris avalanches with slide surfaces in excess of 25 feet deep have been recorded in the Chehalis headwaters (Jim Ward, Weyerhaeuser, oral commun., July 2008). The probability of sliding is low where bedrock is exposed, except where weak bedding planes and extensive bedrock joints and fractures parallel the slope.

Debris Flows and Torrents

Debris flows and torrents were also common during this event, many transforming from debris avalanches as the slide material integrated water and gained momentum. Debris-flow and debris-torrent tracks are characterized by long stretches of bare, generally unstable stream channel banks that have been scoured and eroded by the extremely rapid movement of debris-laden water. They are commonly caused by debris sliding or the failure of fill materials along stream crossings in the upper part of drainages during high-intensity storms.

Debris-flow and debris-torrent tracks are formed by the failure of water-charged soil and organic material down steep stream channels, and in the case of the December storm event, by debris avalanches and road failures. They are often triggered by debris-slide movement on adjacent hill slopes and the mobilization of debris accumulated in the stream channels themselves. Debris flows and torrents commonly entrain large quantities of inorganic and organic material from the stream bed and banks. Occasionally, the channel may be scoured to bedrock. When momentum is lost, scoured debris may be deposited as a tangled mass of large organic debris in a matrix of sediment and finer organic material. Such debris may be reactivated or washed away during subsequent events. The erosion of steep, debris slide–prone stream banks below the initial failure may cause further failure downstream.

Shallow Undifferentiated Landslides

Shallow undifferentiated landslides were not as common as debris avalanches or debris flows, but occurred in small number during this event. Shallow undifferentiated landslides are characterized by very shallow failures composed mostly of soil. They are characteristically above the rooting depth of trees. These landslides can include various processes, including slump, translational, or flow processes.

RECONNAISSANCE INVESTIGATION

The reconnaissance investigation focused primarily on areas hardest hit by the storm. If landslides were deadly or caused damage to property or infrastructure, they were site-inspected and critical information was collected. Landslides that were in more isolated or forested areas were documented by aerial reconnaissance. Mason, Lewis, and Thurston Counties, which had the highest concentration of landslides, were the main targets for reconnaissance. Mason and Thurston Counties were investigated on the ground, with some aerial reconnaissance. Lewis County was mostly investigated from the air, due to lack of road accessibility, remoteness, and density of landslides. Flight paths are shown on Figure 3.

Reconnaissance Areas

MASON AND JEFFERSON COUNTIES

Ground reconnaissance in Mason County between Hoodsport and Lilliwaup, along U.S. Highway 101, was conducted in the field on December 6 and aerial investigations were completed on December 10. The aerial reconnaissance followed along Highway 101 north to the Mason–Jefferson County line and back along the eastern front of the Olympic Mountains. Numerous ground reconnaissances were conducted by boat and truck for the coastline of Mason County in conjunction with the County Shoreline Landslide Mapping project.

THURSTON AND GRAYS HARBOR COUNTIES

Thurston County field reconnaissance was conducted on December 6; the Rock Candy Mountain debris flow, the landslides at the interchange of U.S. Highway 101 and State Route 8, and the washout at Cedar Flats Road were the only sites investigated. A flight over part of Thurston County on January 16, 2008, did not reveal any additional landslides (Fig. 3). A ground reconnaissance was conducted October 20 and 23, 2008, in the Capitol State Forest area to check lower priority landslides that were reported by DNR Land Management Division, but not addressed in the original field assessment because of time constraints.

PIERCE, KING, AND SNOHOMISH COUNTIES

Aerial reconnaissance in Snohomish, King, and Pierce Counties was conducted on December 10. The flight path was between Edmonds in Snohomish County to the southern border of Pierce County, primarily along the Puget Sound shoreline. A ground reconnaissance was conducted on October 30, 2008, to various landslides reported in the media.

LEWIS, PACIFIC, WAHKIAKUM, AND COWLITZ COUNTIES (CHEHALIS RIVER HEADWATERS)

Ground reconnaissance in Lewis County was conducted on December 11 and January 14, mainly along State Route 6 and through the Boistfort valley where roads were accessible. Air reconnaissance was conducted on December 21 and January 16 and 17 throughout the Willapa Hills in Pacific, Lewis, Wahkiakum, and Cowlitz Counties (Fig. 3).

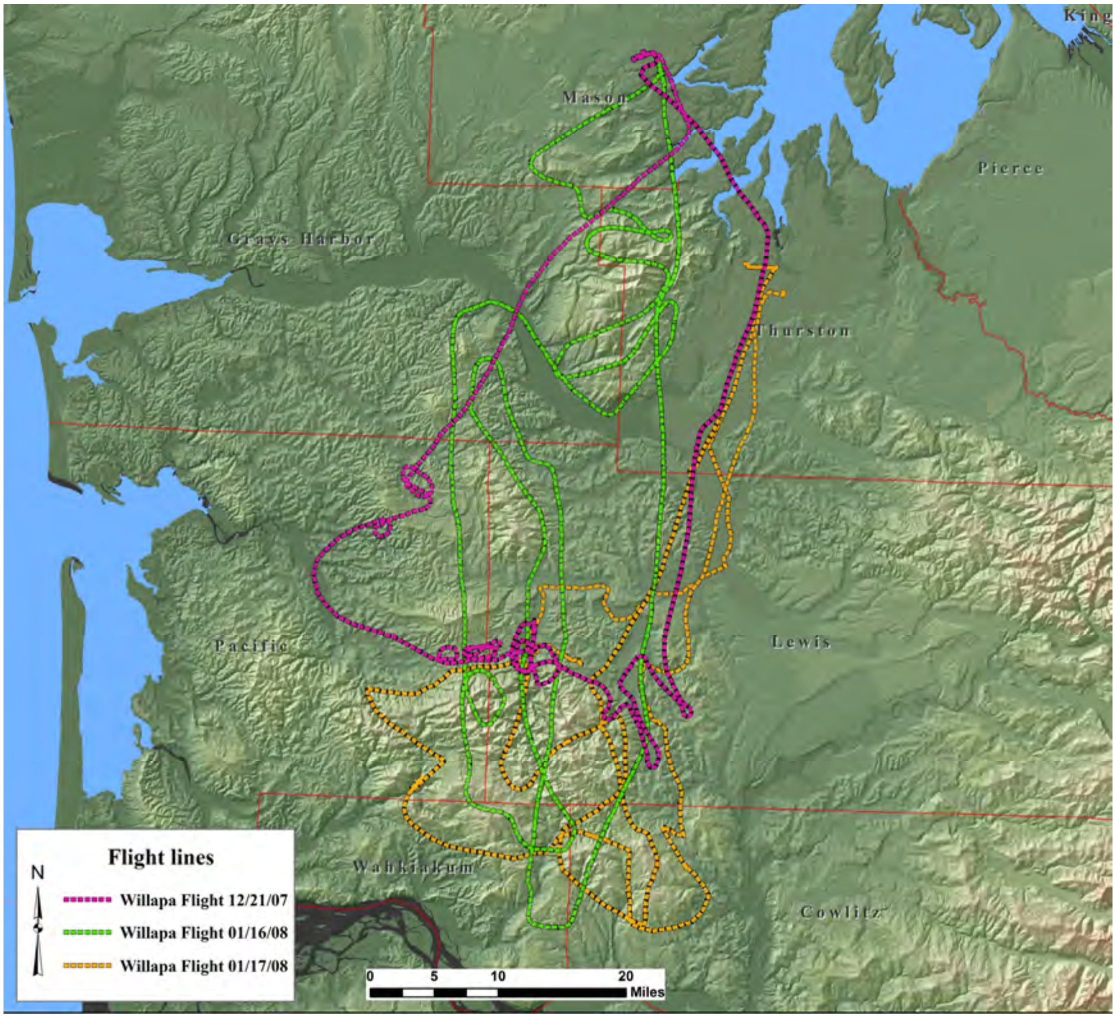

Figure 3. Paths of three flights conducted for aerial reconnaissance over the Chehalis River headwaters, southwest Washington. The December 10 flight path was not recorded by Global Position System (GPS) and therefore was omitted.

Methods

Landslide data were gathered from three sources: on-the-ground site investigations, oblique aerial photographs taken during our reconnaissance flights, and information from the Washington State Department of Natural Resources (DNR) Forest Practices, Land Management, and Geology and Earth Resources Divisions and individuals. From all of these sources, critical information regarding landslide processes, morphology, land use, and damage to property or infrastructure was collected. A global positioning system (GPS) location and photographs of key components were recorded during on-site investigations. Data collected on the ground were entered into the December storm landslide inventory as attributes to a spatial representation of the landslide. The reconnaissance areas were focused on the general storm track and areas that experienced the greatest precipitation. Areas where damage to infrastructure or structures was reported were also examined.

Aerial reconnaissance in western Washington was conducted in a fixed-wing airplane with a pilot, navigator, and two photographers, all of whom were geologists except the pilot. The navigator directed the pilot to the location, collected GPS points, and recorded azimuth (relative to the direction of the plane's flight) of landslides photographed by the photographers. A GPS device was used to track the airplane's path which, combined with the azimuth and GPS points of the photos, provided a starting point to estimate the location of each landslide. U.S. Geological Survey topographic maps were used to identify topography and roads on the oblique photos, and landslides were recorded on the topographic maps. These maps were scanned, geo-referenced, and entered into ArcGIS for an overlay on orthophotos (USDA-FSA, 2006), where landslide location was accurately determined using vegetation and other visible clues on the orthophotos. Once a reliable location was established, the landslides were digitized into the inventory and the spatial data were attributed.

Slope gradients for shallow landslides were determined by calculating the average lidar or 10-meter digital elevation model (DEM)–derived slope angle within each landslide initiation polygon. Lidar was used to determine slopes for landslides mapped in Mason, Jefferson, and Thurston Counties; however, because of sparse lidar coverage in Lewis County (and the general area of the Chehalis headwaters), the 10-meter DEM was used to calculate slopes for landslides in those areas.

REGIONAL GEOLOGY

Puget Lowland

The Puget Lowland in the areas most affected by the December storm is composed primarily of glacial material deposited during the Pleistocene. The continental ice sheet deposited advance outwash from braided streams highly laden with sediment as it moved into the Puget Lowland, glacial till as it passed over an area, and recessional outwash as it retreated. In Mason County, these events occurred repeatedly from both alpine and continental glacial advances.

Southwest Washington

The Willapa Hills province, which is part of the Southwest landslide province (Thorsen, 1989), is composed of Tertiary marine sedimentary rocks deposited over submarine and oceanic-island basalts, which have been accreted by subduction (Wells, 1981; Armentrout, 1987; Cashman and Brunengo, 2006). Near the uplifted core of volcanics, the coastal mountains expose older Paleogene to Neogene volcanic and sedimentary rocks that were deposited in the forearc. These materials, combined with uplift and crustal deformation, created a complex mountain structure. Geomorphic processes have carved this landscape over a long history of erosion by water and mass wasting (Cashman and Brunengo, 2006).

The Southwest landslide province has two features that are relevant to slope stability—steep topography and thin soils over weathered bedrock. Absence of continental and alpine glaciation has resulted in long-term weathering for most of the province, in some areas up to tens of millions of years. As part of this long-term weathering, the province has experienced a variety of weathering processes, such as extended periods of subtropical climates. This intense weathering has formed a laterite (highly weathered layer) that may have contributed to some of the larger deep-seated landslides in the area (Livingston, 1966), but may not have played a role during the December storm event. Due to this thoroughly and deeply weathered surface, the topography is in most places highly dissected. However, debris avalanches and torrents tend to occur where relatively unweathered rocks form steep slopes with smooth surfaces overlain by thin (less than 25 feet) colluvial soils. These landslides usually involve only soil and vegetation and are triggered by intense rainstorms or rain-on-snow events (Thorsen, 1989).

Eocene Crescent Formation submarine basalts are the backbone of the Willapa Hills in the Chehalis headwaters. Crescent Formation basalts form a relatively mature topography with deeply dissected canyons and steep hillsides. Much of the basalt is relatively unweathered and overlain by a thin colluvial soil cover. This combination of topography and unweathered bedrock beneath a thin colluvial soil blanket makes this area an ideal location for debris avalanches and torrents.

Uplift and erosion of the Willapa Hills began near the end of the Eocene, probably associated with the start of Cascade arc magmatism (volcanism) (Cashman and Brunengo, 2006). In the Oligocene, the region experienced marine transgression (advance of marine waters), accompanied by deposition of sandstones and siltstones containing large portions of tuffaceous materials derived from Cascade eruptions, known collectively as the Lincoln Creek Formation. In the earliest Miocene, the Willapa Hills underwent folding and faulting, which lifted much of the coastal range above sea level. Uplift in the late Pliocene and Quaternary further raised the coastal ranges into their present elevations (Cashman and Brunengo, 2006).

North–south compression and associated folding have occurred mainly within a band of mountainous territory perpendicular to the northeast–southwest direction of plate convergence. Faulting generally follows a northwest–southeast trend. Bedding planes generally dip moderately away from the volcanic core of the Willapa Hills.

RESULTS

The December storm event triggered thousands of landslides in southwest Washington, the vast majority in the Chehalis River headwaters. A sample consisting of 1,940 landslides was mapped (Table 1). In addition to landslide locations, data were collected on the geology, rainfall, age ranges of trees, and location of roads. Most landslides appeared to have started as debris avalanches and either ended downhill or transformed into debris flows. Many of the deposits created temporary dams in streams that later burst, creating debris torrents or debris flows downstream. Many of the debris torrents and debris flows, once deposited into a main channel, incorporated into the main river flow and, on some of the oblique photos, appear to have formed into hyperconcentrated flows. Table 1 summarizes the number of mass-wasting features mapped during this study. Table 2 summarizes the loss associated from mass-wasting features during this study.

Table 1. Summary of the type and number of mass-wasting features mapped in western Washington.

Feature type	Number mapped	Area (sq. ft.)
Shallow undifferentiated landslides	196	690,265
Debris flows/torrents	704	42,800,339
Debris slide/avalanche	1,027	16,798,409
Deep-seated landslide	3	371,334
Hyperconcentrated flow	10	4,601,429
Total	**1,940**	**65,261,776**

Table 2. Summary of the loss associated with mass-wasting features mapped in western Washington. No loss data were reported or recorded for Pierce or Snohomish Counties. *, reported in media but not field checked or inventoried.

County	Structures impacted	Road sections impacted	Utilities impacted	Human fatalities	Number mapped
Thurston and Grays Harbor	5	4	0	0	63
Mason and Jefferson	12	23	1	1	214
Lewis	4	6	1	0	1,655
King	0	7	0	0	8
Kitsap	0	1	0	0	0*
Total	**21**	**41**	**2**	**1**	**1,940**

Landslide Findings by Area

MASON AND JEFFERSON COUNTIES

We recorded 214 landslides: 80 shallow undifferentiated landslides, 23 debris flows, 108 debris slides, 1 deep-seated landslide, and 2 hyperconcentrated flows. Numerous other hyperconcentrated flows were observed but not recorded due to lack of damage, small size, and (or) time constraints. At least 12 houses were damaged during this event: three by debris avalanches, one by an undifferentiated landslide, and eight by hyperconcentrated flows. One death was the result of a landslide crashing into a house. At least 16 of these landslides blocked or damaged U.S. Highway 101, two blocked or damaged State Route 106 along Hood Canal, and five blocked or damaged various roads.

THURSTON AND GRAYS HARBOR COUNTIES (CAPITOL STATE FOREST)

We recorded 64 landslides: 34 shallow undifferentiated landslides, 12 debris flows, 14 debris slides, 2 deep seated landslides, and 2 hyperconcentrated flows. Numerous other hyperconcentrated flows were observed, but not recorded due to lack of damage, small size, and (or) time constraints. At least five structures were damaged or destroyed during this event. Four roads were impacted by landslides that blocked or damaged the road.

PIERCE, KING, AND SNOHOMISH COUNTIES

A reconnaissance flight was conducted between Edmonds in Snohomish County and the southern border of Pierce County, primarily along the Puget Sound shoreline. A few landslides were spotted during this flight, but could not be accurately located; however, eight landslides were documented during a ground reconnaissance on October 30, 2008. These landslides were well documented in the media and were considered low priority to field document. Loss data were recorded from field reconnaissance and various media sources, which reported five roads that were impacted by at least five landslides in King County. No loss data were reported or recorded for Pierce or Snohomish Counties.

KITSAP COUNTY

No reconnaissance was conducted in Kitsap County; however, one landslide of unknown type was reported in the media at the intersection of State Route 3 and Newberry Hill Road. The landslide is reported to have blocked a road.

LEWIS COUNTY

We recorded ten landslides, not including those in the Chehalis Headwaters area (see below): six shallow undifferentiated landslides, one debris flow, and three debris slides. At least three sections of State Route 6 were impacted by landslides that blocked or damaged the road.

CHEHALIS RIVER HEADWATERS

We recorded 1,645 landslides: 71 shallow undifferentiated landslides, 667 debris flows, 901 debris slides, and 6 hyperconcentrated flows. At least two sections of State Route 6 and one of a local road were impacted by landslides that blocked or damaged the road. Four houses were damaged or destroyed by landslides, primarily around Pe Ell, and at least one section of electrical power lines was affected.

Geology

The majority of landslide failures occurred in Crescent Formation, which contains subunits of basalt (unit Ev(c), Table 3) and coarser-grained intrusive rock (unit Eib, Table 3) in southwest Washington. (Geologic unit symbols used herein are from Washington Division of Geology and Earth Resources, 2005, based on the mapping of Logan, 1987.) In the intrusive rock of the Crescent Formation, 687 landslides initiated: 23 shallow undifferentiated landslides, 274 debris flows, and 390 debris avalanches. In the Crescent Formation basalt, 707 landslides initiated: 48 shallow undifferentiated landslides, 304 debris flows, 353 debris avalanches, and 2 deep seated landslides. In the Eocene volcanic tuffs (unit Evt, Table 3), 153 landslides initiated: 2 shallow undifferentiated landslides, 60 debris flows, and 91 debris slides. The geologic association of remaining 383 landslides (excluding hyperconcentrated flows) is presented in Table 3.

Table 3. Summary of the association of landslides (excluding hyperconcentrated flows) with geologic units mapped in western Washington. Geologic unit symbols are from Washington Division of Geology and Earth Resources (2005) based on the mapping of Logan (1987).

Geologic unit	Number of landslides	Geologic unit	Number of landslides
Intrusive in upper Crescent Formation basalt (Eib)	687	Alluvium (Qa)	6
Crescent Formation basalt (Ev(c))	707	Astoria Formation (Mm(1as))	5
Eocene volcanic tuff (Evt)	153	Pre-Frasier alpine glacial outwash (Qapo)	68
McIntosh Formation (Em(2m))	87	Mass-wasting deposit (Qls)	19
Cowlitz Formation (En(c))	26	Vashon till (Qgt)	71
Lincoln Creek Formation (OEm(lc))	17	Grande Ronde Basalt, upper flows of normal magnetic polarity (Mv(gN2))	2
Pe Ell Volcanics Member, Cowlitz Formation (Evt(pe))	12	Continental glacial outwash (Qgo)	2
Volcanic rocks of Grays River (Evb(gr))	9	Marine sedimentary rocks (Em(1))	2
Continental glacial drift (Qgp)	4	Unknown	4
Continental sedimentary deposits (Qc)	11	Advance continental glacial outwash sands (Qgas)	3
Advance continental glacial outwash (Qga)	32	Pre-Frasier glacial drift (Qgpc)	3

Managed Forest Lands

Of the 1,940 landslide processes recorded in association with this event, the vast majority (1,824 or 94%) initiated on managed forest lands (Fig. 4): 554 were in clearcuts, 659 occurred on land covered with trees (including young stands, submature timber, and mature timber) and 611 were near roads (Fig. 5). Specifically in the Chehalis headwaters, 1,614 landslides were considered to initiate off of managed forest lands: 547 in clearcuts (0–5 years), 104 in young stands (5–15 years), 403 in submature timber (15–50 years), 0 in mature timber (50+ years), and 560 near forest roads. Of the landslides that were related to forest roads, 142 occurred in clear cuts, 21 in young stands, and 397 in submature timber. In Capitol Forest, 5 were in clearcuts, 2 in young stands, 17 in submature timber, 4 in mature timber, and 33 near forest roads. Of the landslides that were related to forest roads, 2 occurred in clearcuts, 10 occurred in young stands, and 21 occurred in submature timber. In Mason County, 2 were in clearcuts, 24 in young stands, 105 in submature timber, 0 in mature timber, and 18 near forest roads. Of the landslides that were related to forest roads, 3 occurred in young stands, and 15 occurred in submature timber.

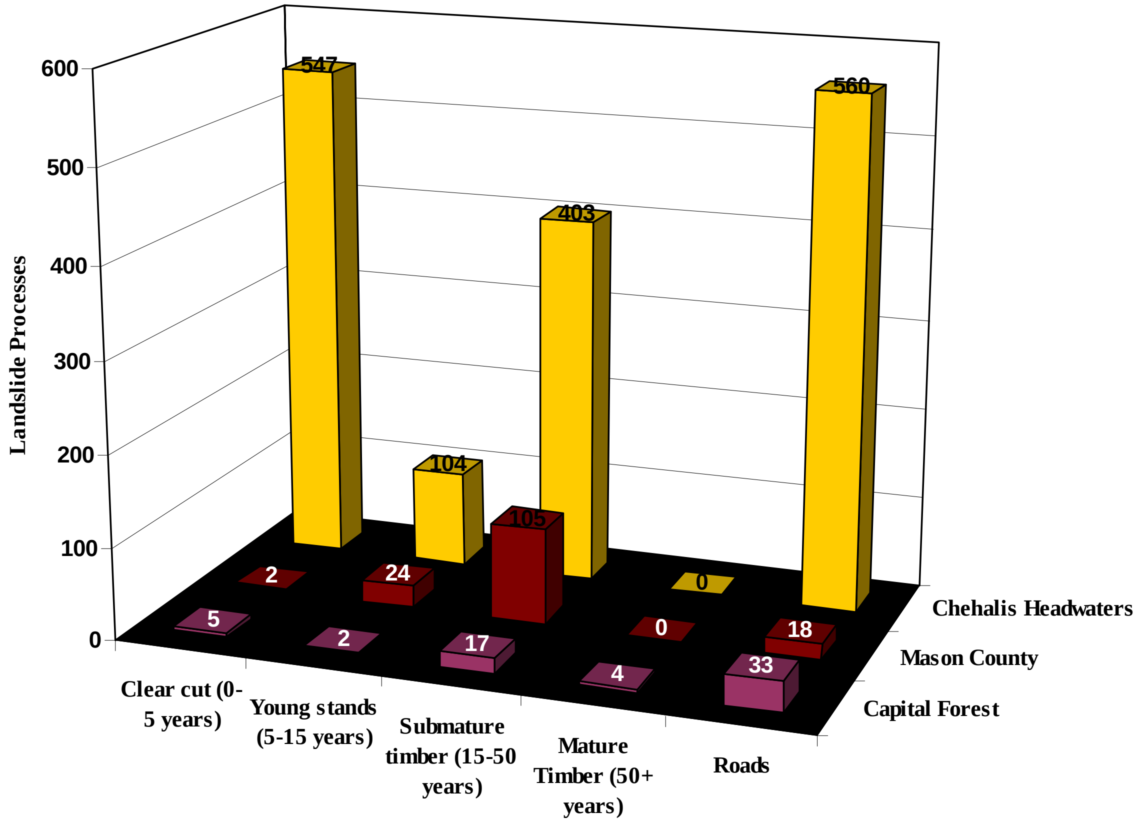

Figure 4. Graph of number of landslides initiating in managed forest land (94% of landslides recorded) versus timber age, excluding hyperconcentrated flows and urban landslides.

Debris slides were the most common landslide type recorded (see Fig. 7). Of the 898 debris slides recorded in the Chehalis headwaters, 294 initiated in clearcuts, 59 in young stands, 252 in submature timber, and 293 near roads. Of the 664 debris flows recorded, 211 initiated in clearcuts, 41 in young stands, 154 in submature timber, and 258 near roads. Of the 71 shallow undifferentiated landslides recorded, 44 initiated in clearcuts, 4 in young stands, 6 in submature timber, and 17 near roads.

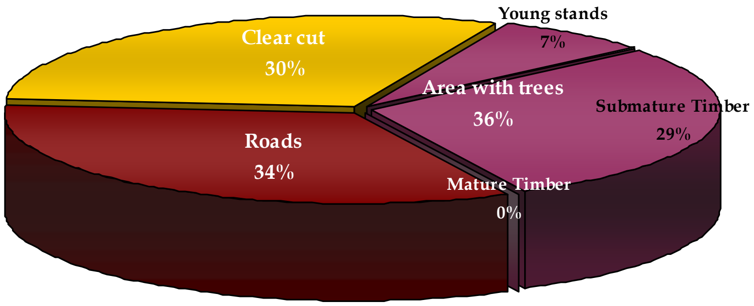

Figure 5. Graph of percentage of landslides initiating in managed forest lands: clearcuts, roads, and areas with trees (including young stands, submature timber, and mature timber).

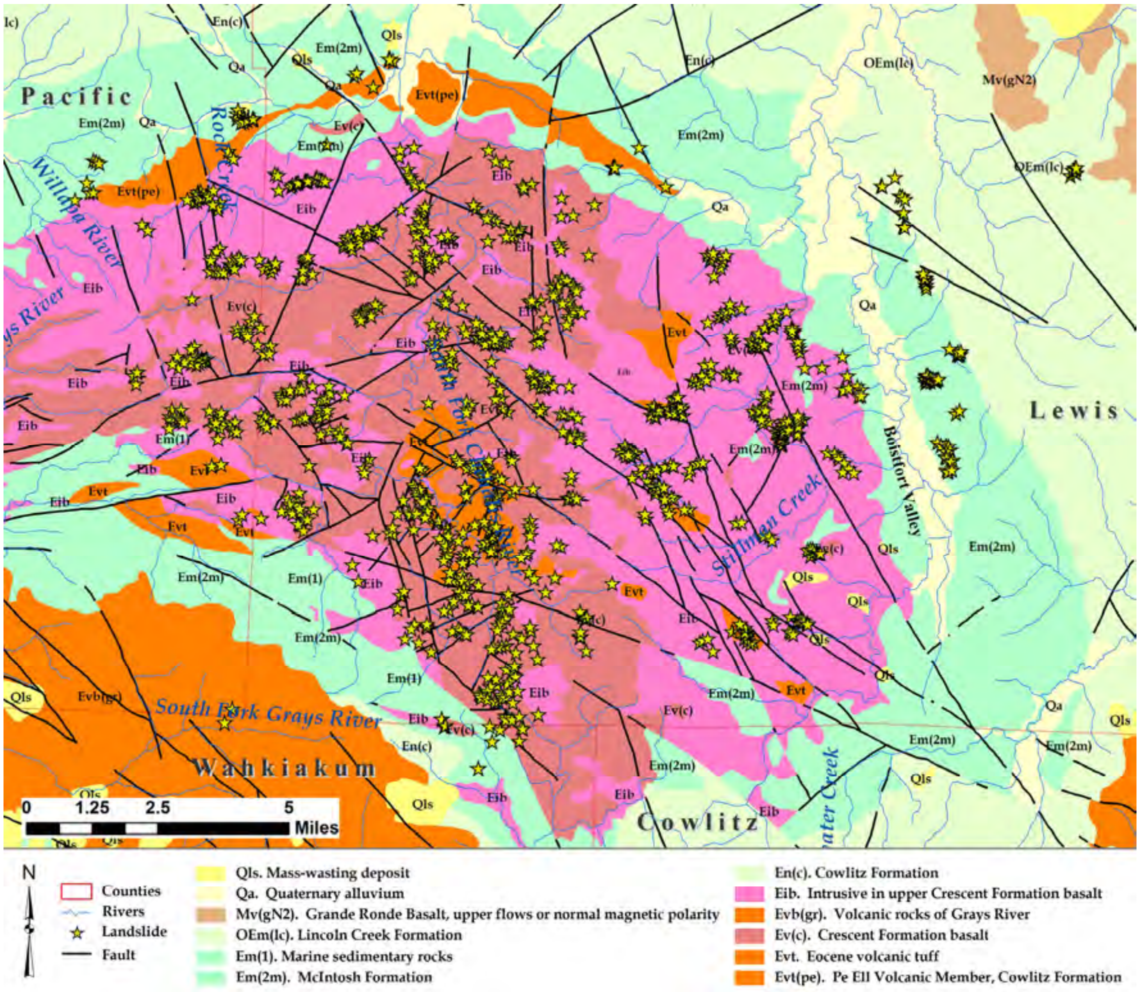

Figure 6. Landslide initiation points overlain on the 1:100,000-scale geologic map of Chehalis headwaters area (Washington Division of Geology and Earth Resources, 2005; original geologic mapping by Logan, 1987). Most of the landslides caused by the December storm event were associated with the Crescent Formation.

CONTROLS ON LANDSLIDES

Geology

Landslides generally initiated in areas where rain intensity was highest (Fig. 1). However, in the Chehalis headwaters, landslides initiated in high density within the south half of the highest rain intensity area. When overlaying the landslides on a geologic map, the initiation points appear to correlate with certain geologic units (Fig. 6). The density of landslides is highest within basalt of the Crescent Formation (Fig. 6) and is only sporadic in adjacent sedimentary rocks of the McIntosh and Cowlitz Formations (Fig. 6) with a small exception of landslides along the east side of the Boistfort valley. Most of the landslides on the east side of the Boistfort valley landslides were small and along or near roads. This could suggest that not only precipitation, but geologic conditions, were important to where landslides initiated.

Crescent Formation basalts within the Willapa Hills are characterized by deeply dissected canyons and steep hillsides. Much of the basalt is relatively unweathered, has low permeability, and is overlain by a thin (less than 25 feet) colluvial soil cover. Away from the Crescent Formation and related rocks, topography is more muted and has generally gentler slopes, resulting in fewer landslides. On many landslides viewed in the oblique aerial photos, basalt is visible within the landslide scar or debris flow track, often with shallow soils (~5–20 feet thick). This suggests that a combination of geology, thin soils, impermeable bedrock, steep topography, and heavy precipitation influenced where landslides initiated.

Managed Forest Lands

The vast majority of landslides recorded in the aftermath of this event initiated on managed forest lands. Of the 1,940 landslides recorded during this event, at least 1,840 occurred on managed forest lands. Data on timber age and proximity to roads were recorded and were used to compare timber age to landslide frequency; however, this study does not go in depth into whether harvest played a role in triggering landslides.

Most recorded landslides initiated in recent clearcuts (0–5 years) and submature timber (15–50 years) (Fig. 7), with significantly fewer recorded in young stands (5–15 years) and four recorded in mature timber (50+ years). This is possibly due to the lack of young stands and mature timber within the mapped area, or it may reflect a general trend of where landslides were triggered. We note that landslide inventories that are conducted primarily using aerial photos have been demonstrated to omit up to 85 percent of the landslides that actually exist on the ground in heavily forested areas (Brardinoni and others, 2003). Data on the distribution of stand ages versus area were not available for this report and should be considered in later studies.

The largest percentage of initiation points for landslides was associated with roads. The most vulnerable sections of roads occurred in submature timber, where over 70 percent of landslides initiated. Just over 25 percent of the landslides initiated from roads located in clear cuts.

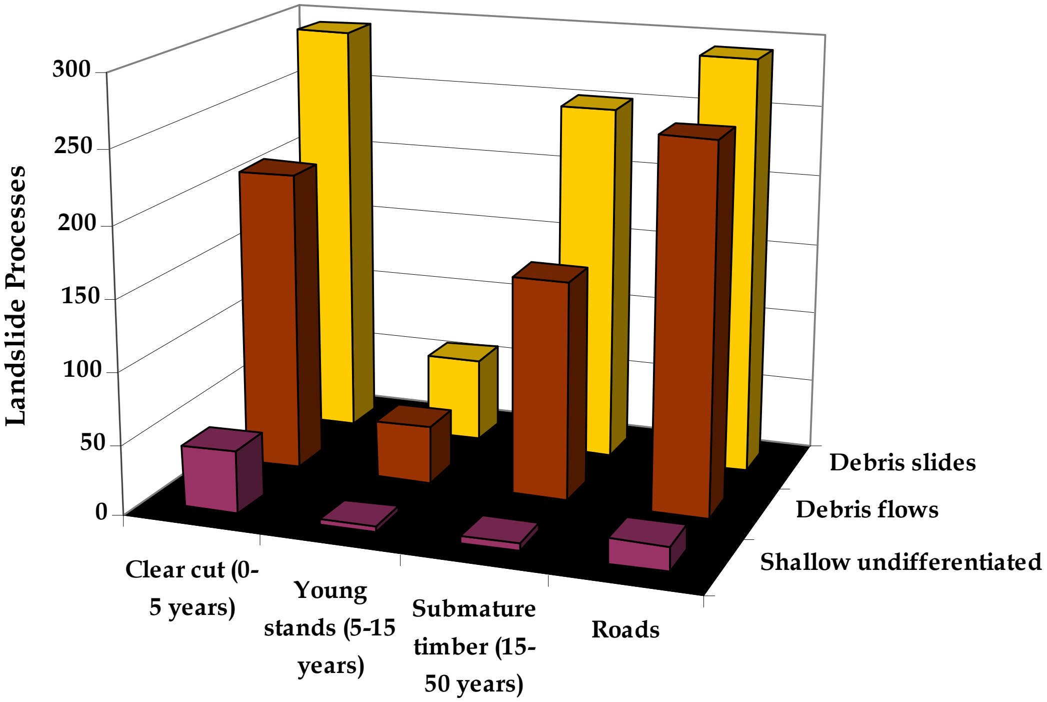

Figure 7. Graph of number of landslides initiating off of managed forest lands in the Chehalis headwaters by landslide process versus estimated timber age or proximity to roads.

Landslide Processes

Debris flows commonly transformed directly or indirectly from shallow landslides, such as debris slides and shallow undifferentiated landslides. Transformation rates between shallow landslides and debris flows on managed forest lands give insight into how land use will affect the rate of shallow landslides transforming into debris flows in a specific area. The transformation rates in the Chehalis headwaters for clearcuts (0–5 years) and submature timber (15–50 years) were about the same (60–65% transformation rate); however, the incidence of debris flows transformed from road-related debris slides or shallow undifferentiated landslides is much greater, at over 83 percent (Fig. 7). This suggests that shallow landslides initiated near or on roads are more likely to transform into debris flows. In the Chehalis headwaters, roads have been identified as a potential trigger of landslides (Laprade, 1994) and appear to trigger a greater number of debris flows.

CONCLUSION

The storm event of December 1–3, 2007, was a historical event, spawning thousands of landslides in western Washington, blocking highways and roads, destroying houses, and killing one person. Prolonged or intense precipitation is a major factor in slope instability, but during the December storm event, a combination of geology, thin soils, impermeable bedrock, age of timber stands, and topography probably controlled where landslides initiated, especially in the Chehalis headwaters. Roads also appear to be an initiation area for many landslides and suggest a higher incidence of landslides transforming into debris flows. Although lack of data prohibits us from an in-depth review of how managed forest lands respond to large storm events, a review of landslides in timber stands of various ages determined that landslides failed primarily from clear cuts (0–5 years) and submature timber (15–50 years) in the Chehalis headwaters and Capitol Forest, both of which have similar geology, but not Mason County and other areas, were geology is different.

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REFERENCES CITED

Armentrout, J. M., 1987, Cenozoic stratigraphy, unconformity-bounded sequences, and tectonic history of southwestern Washington. *In* Schuster, J. E., editor, Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 291-320.

Brardinoni, Francesco; Slaymaker, Olav; Hassan, M. A., 2003, Landslide inventory in a rugged forested watershed—A comparison between air-photo and field survey data: Geomorphology, v. 54, no. 3-4, p. 179-196.

Cashman, B. H.; Brunengo, M. J., 2006, Landslide hazard zonation project—Mass wasting assessment—Grays Bay, Pacific and Wahkiakum Counties, Washington: Washington Department of Natural Resources, Forest Practices, 50 p., 2 plates, scale 1:24,000.

Christensen, J. H.; Hewitson, B.; Busuioc, A.; Chen, A.; Gao, X.; Held, I.; Jones, R.; Kolli, R. K.; Kwon, W.-T.; Laprise, R.; Magaña Rueda, V.; Mearns, L.; Menéndez, C. G.; Räisänen, J.; Rinke, A.; Sarr, A.; Whetton, P., 2007, Regional climate projections. *In* Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K. B.; Tignor, M.; Miller, H. L., editors, Climate Change 2007—The physical science basis; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge University Press [Cambridge, United Kingdom, and New York, New York], p. 847-940.

Cruden, D. M.; Varnes, D. J., 1996, Landslide types and processes. *In* Turner, A. K.; Schuster, R. L., editors, Landslides—Investigation and mitigation: National Academy Press; National Research Council Transportation Research Board Special Report 247, p. 36-75.

IEG (Independent Evaluation Group), 2007, Development actions and the rising incidence of disasters: World Bank Evaluation Brief 4 [Washington, D.C.], 34 p. [http://www.worldbank.org/ieg/docs/developing_actions.pdf]

Laprade, W. T., 1994, Stillman Creek watershed analysis, mass wasting assessment. *In* Weyerhaeuser Timber Company, Stillman Creek watershed analysis: Weyerhaeuser Timber Company, Appendix A.

Livingston, V. E., Jr., 1966, Geology and mineral resources of the Kelso–Cathlamet area, Cowlitz and Wahkiakum Counties, Washington: Washington Division of Mines and Geology Bulletin 54, 110 p., 2 plates.

Logan, R. L., compiler, 1987, Geologic map of the Chehalis River and Westport quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-8, 16 p., 1 plate, scale 1:100,000.

Read, Wolf, compiler, 2007, The Great Coastal Gale of December 1–3, 2007. [http://www.climate.washington.edu/stormking/December2007.html]

Reiter, Maryanne, 2008, December 1–4, 2007 storm events summary: Weyerhaeuser Company, 19 p. [http://www.weyerhaeuser.com/pdfs/company/media/December2007StormEventSummary.pdf]

Sarikhan, I. Y.; Stanton, K. M. D., 2008, Washington Geological Survey GIS statewide landslide database—From design to implementation: Washington Division of Geology and Earth Resources poster, 1 sheet. [http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_Sarikhan.pdf]

Schuster, R. L., 1996, Socioeconomic significance of landslides, *In* Turner, A. K.; Schuster, R. L., editors, Landslides—Investigation and mitigation: National Academy Press; National Research Council Transportation Research Board Special Report 247, p. 12-35

Schuster, R. L.; Highland, L. M., 2001, Socioeconomic and environmental impacts of landslides in the western hemisphere: U.S. Geological Survey Open-File Report 2001-276, 47 p.

Spiker, E. C.; Gori, P. L., 2003, National landslide hazards mitigation strategy—A framework for loss reduction: U.S. Geological Survey Circular 1244, 56 p.

Thorsen, G. W., 1989, Landslide provinces in Washington. *In* Galster, R. W., chairman, Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 71-89.

USDA-FSA Aerial Photography Field Office, 2006, Orthophotos of various counties: NAIP_1-1_1n_s_wa041_2006_1 [Salt Lake City, Utah].

Washington Division of Geology and Earth Resources, 2005, Digital 1:100,000-scale geology of Washington State, version 1.0: Washington Division of Geology and Earth Resources Open File Report 2005-3, 11 ESRI shapefiles of geologic data, 3 shapefiles of nongeologic auxiliary data, 7 documentation files in Microsoft Word, Microsoft Excel and Adobe PDF formats. [http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ofr05-3.aspx]

Wegmann, K. W., 2006, Digital landslide inventory for the Cowlitz County urban corridor, Washington; version 1.0: Washington Division of Geology and Earth Resources Report of Investigations 35, 1 CD, 14 maps, scale 1:24,000. [http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ri35.aspx]

Wells, R. E., 1981, Geologic map of the eastern Willapa Hills, Cowlitz, Lewis, Pacific, and Wahkiakum Counties, Washington: U.S. Geological Survey Open-File Report 81-674, 1 sheet, scale 1:62,500.

Wieczorek, G. F., 1996, Landslide triggering mechanisms. *In* Turner, A. K.; Schuster, R. L., editors, Landslides—Investigation and mitigation: National Academy Press; National Research Council Transportation Research Board Special Report 247, p. 76-90.