Landslides and Landslide Hazards in Washington State Due to February 5-9, 1996 Storm

U.S. Geological Survey Administrative Report

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Landslides and Landslide Hazards in Washington State Due to February 5-9, 1996 Storm

by

Edwin L. Harp[1]

Alan F. Chleborad[1]

Robert L. Schuster[1]

Susan H. Cannon[1]

Mark E. Reid[2]

Raymond C. Wilson[2]

[1]*U.S. Geological Survey, Geologic Hazards Team, 1711 Illinois St., Golden, CO 80401*

[2]*U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025*

Publication Layout by Margo Johnson

CONTENTS

INTRODUCTION

During the week of February 4, 1996, cumulative rainfall levels of up to 23 in. fell in areas of Oregon, Washington, and Idaho. Combined records of rainfall and water equivalent of snowmelt were as high as 39 in. for this period in the Gifford Pinchot National Forest of southern Washington (National Resources Conservation Service, Water and Climate Center, Portland, Oregon). Areas of highest rainfall intensities were centered on the Oregon-Washington border. Estimates of damage from the floods and landslides exceed $300 million (FEMA Interagency Hazard Mitigation Team, 1996) in Washington and Oregon alone. Upon receiving reports of the triggering of landslides over a widespread area, the U.S. Geological Survey sent a team of landslide specialists from offices in Golden, Colorado, and Menlo Park, California, to perform a regional reconnaissance of landslide distribution and the attendant hazards. Subsequently, the Federal Emergency Management Agency contracted with the U.S. Geological Survey to provide a documentation of the overall distribution of landslides triggered by the storms in the State of Washington and an initial assessment of specific hazards that continue to exist as a result of individual landslides that pose a threat to people and property (mission assignment # USGS-02, request/log # R-1100-23).

The state-wide reconnaissance was performed by a combination of low-level overflights in fixed-wing aircraft, ground-based field inspections, and gathering of landslide data from a variety of sources, such as federal, state, and local agencies, reports from news media, and local residents. This reconnaissance identified a pattern of overall landslide limits and distributions that conform approximately to the February 5-9 storm precipitation levels as well as to various physiographic and material susceptibility factors.

Debris flows were the most common landslide type triggered by the February 5-9 storm. Debris flows typically originate within soil overlying bedrock. As the soil becomes saturated and pore-water pressures increase such that the downslope driving forces exceed the resisting strength of the soil, failure takes place. The initial failure may appear as a spoon-shaped rotational slump, a soil slide with a rather planar failure surface, or some combination of these. Subsequent to failure, the soil mass becomes fluidized by mixing that occurs in the failure process or by intercepting water draining from the failure scarp. Once fluidized, the soil mass may move rapidly downslope similar to a slurry of wet concrete. Debris flows often destroy houses or other structures in their path.

Other types of landslides observed were rotational slumps, block slides, rock falls, soil slides, and soil falls. The largest landslide triggered by the February storm was a block slide of 100,000 to 200,000 yd^3 that became fluidized by mixing and transformed into a debris flow. This landslide is discussed in the section on the Glenoma landslide.

Plate 1 shows the approximate limits (pink shading) of landslides triggered by the February storm and attendant snowmelt. Red shading denotes areas of highest landslide concentration (>10/acre). Solid red circles denote locations of individual landslides that were noteworthy because of their impact on people and property. The red shaded area in the Blue Mountains of southeastern Washington is isolated because it is an area of highly concentrated landslides (debris flows) with little surrounding area of lower landslide concentrations. Within the area of pink shading are scattered landslides. The limit as shown on plate 1 is approximate. We are certain that some landslides were triggered outside this area by the February storm. However, we judged these limits to be the most obvious as established by our reconnaissance.

The highest concentrations of landslides due to the February storms occurred at the northwest edge of the Blue Mountains of southeastern Washington near Walla Walla (Plate 1) which is outside the landslide limits drawn for western Washington. Here, debris flows reached concentrations exceeding 100 individual failures per square mile. Sizes ranged from small flows from road cuts to long flows of several miles in length in which entire drainage channels failed from the drainage divide to the stream bottom.

Although several streambank slumps attributable to flood flow occurred as far north as Washington State Highway (SH) 20 in the North Cascades Range, slope failures of all types were sparse north of Interstate (I) 90. The northwestern limit corresponds roughly to the Kitsap Peninsula with relatively few slope failures occurring here except as debris flows along the coastal bluffs. One shallow soil slide of about 1,500-2,500 yd^3 was triggered by the February storm on river bluffs of the Skokomish River about 4.5 km west of U.S. Highway 101. Several other slumps and embankment failures were reported on the Olympic and Kitsap Peninsulas by the Washington Department of Transportation (Steve Lowell, oral commun.), but these were probably triggered by previous storms in November 1995.

South of I-90, the concentration of debris flows and other types of landslides increased markedly attaining high concentrations in the area immediately southeast of Mount St. Helens where recent deposits of volcanic ash presented extremely susceptible material for the formation of debris flows. This area also corresponds to a high-precipitation cell within the storm of the highest estimated rainfall levels shown in the radar storm imagery of February 7 of the National Weather Service (WSI Corp. Estimated Precipitation Report on World Wide Web site, February 7, 1996.)

Except in the Blue Mountains, landslide concentrations decrease sharply east of Mount St. Helens and Mount Rainier to virtually nonexistent west of Yakima. The approximate eastern boundary of landslide occurrence in western Washington extends southward to intersect the Columbia River gorge about 15 mi west of the Dalles, Oregon (Plate 1). In southwestern Washington, west of I-5 and south of Aberdeen, few landslides occurred except for a small pocket of debris flows northwest of Raymond in sparsely inhabited timberland (Plate 1). South of Raymond, landslides were sparsely concentrated except along SH-4 at the Washington border where two areas of concentrated landslides occurred. One area, approximately 8 mi west of Longview, parallels the highway for about 6 mi and consists of numerous debris flows that originated above basalt cliffs bordering the highway and flowed over the cliffs and across the road and into the Columbia River. Another area of concentrated landslides occurred about 30 mi west of Longview. This area of about 8 square miles is bisected by SH-4 and consists of primarily debris flows of up to several thousand cubic yards. A few rotational slumps also occurred within this area just west of SH-4, about 4 mi northwest of Skamakowa. The largest of these slumps is several hundred thousand cubic yards in volume and lies about 0.5 mi northwest of the K M Mountain landslide that occurred in 1990 (Steve Lowell, 1990).

The following text describes in greater detail the areas of high, moderate, and low landslide concentrations, noteworthy individual landslide sites, factors affecting landslide concentrations, and estimations of the landslide hazards that potentially still exist. Both in the text and on plate 1, significant landslides are indicated that did not occur during the week of February 5-9, 1996, because of their proximity to landslides that did form during that time period or that may be related to the rainfall during that period. Finally, it includes preliminary suggestions concerning greater documentation and analysis that may help mitigate landslide hazards in some of these areas in the future.

METEOROLOGICAL SETTING

The stage for major flooding and landslide generation was set by the combination of near-record snowfall in January followed by warm rain of unusually long duration. Until mid January, the snowpack in Washington and northern Oregon was below average. The last two weeks of January, however, saw large snowfall totals with daily totals of several feet in many locations. By the end of January, the average snowpack had risen to above 100% in many areas. An intense cold period occurred during the week of January 29. The hardest hit area was Portland where icy conditions lasted for 3 days. This was then followed by a major freezing rain episode beginning on February 3.

On February 6, a strong, subtropical jet stream reached the Oregon-Washington area which brought record rainfall amounts to the region. Although such storms are not rare, the duration of 3 to 4 days of high intensity rainfall was unusual. Also, temperatures were unusually mild during this interval, and relatively warm rain fell upon the deep snowpack even at elevations of up to 8,000 ft. This began to rapidly erode the snowpack, and streams rose quickly on the 6th and 7th reaching flood stage in many locations (George H. Taylor, Oregon State Climatologist, Unpub. information). The response of slopes to the record moisture was not far behind as the preponderance of landslide occurrences that were witnessed were reported to have occurred on the 7th and 8th.

METHODS OF RECONNAISSANCE

Approximately 4 days of aerial reconnaissance in a light fixed-wing airplane were undertaken to observe the general landslide patterns and to locate landslides posing a potential hazard to people and / or property. Approximately 3 weeks were spent examining individual landslide sites on the ground to field check aerial observations and estimations and to gather additional regional and site-specific data. Measurements and estimates relating to landslides and their distributions were gathered during these flights and ground surveys. Although we made every effort to be thorough and extensive, our reconnaissance was relatively brief. Therefore, this survey cannot be considered to be a complete inventory of all the landslides that were triggered by the storm, and there are probably some significant landslides that we failed to observe and that may pose hazards to people and property.

AREAS OF HIGH LANDSLIDE CONCENTRATION

There were several areas within the state where the concentration of landslides reached noticeably higher levels (>10 landslides/acre) than elsewhere (Plate 1).

Blue Mountains

Despite the great attention given to the flooding and landsliding in western Washington, extreme southeastern Washington had the highest landslide concentrations from the February storms. The northeastern margins of the Blue Mountains near Walla Walla contain a truly prodigious number of debris flows.

The main areas affected by the exceptional debris-flow occurrences were the Mill Creek, Blue Creek, Touchet, Tucannon, and Walla Walla drainages. Of these stream drainages, Mill Creek is the only one that has been extensively developed and populated. Some of the slopes adjacent to Mill Creek had such numerous debris flows that more than 100 individual failures could be counted within areas as small as 10 acres (Figure 1).

Debris flows were most numerous on open, grassy hillsides. The source areas of these debris flows were generally shallow, less than 3 ft thick. They had planar failure surfaces, and the resulting debris was, in most cases, spread out in an apron across the unfailed slope below the failure area. Generally, the debris from these flows did not reach adjacent downslope streams. In some cases, however, large or numerous coalescing debris flows of this type resulted in great volumes of sediment reaching drainage bottoms and covering roadbeds (Figure 2). In farmlands, debris-flow concentrations were extremely high at the edges of fields where cultivation has produced an uncompacted soil berm Powell, 1996).

Figure 1. Grassy slopes in Blue Mountains of southeastern Washington showing extremely high concentrations of debris flows that occurred along the northwestern edges of this range.

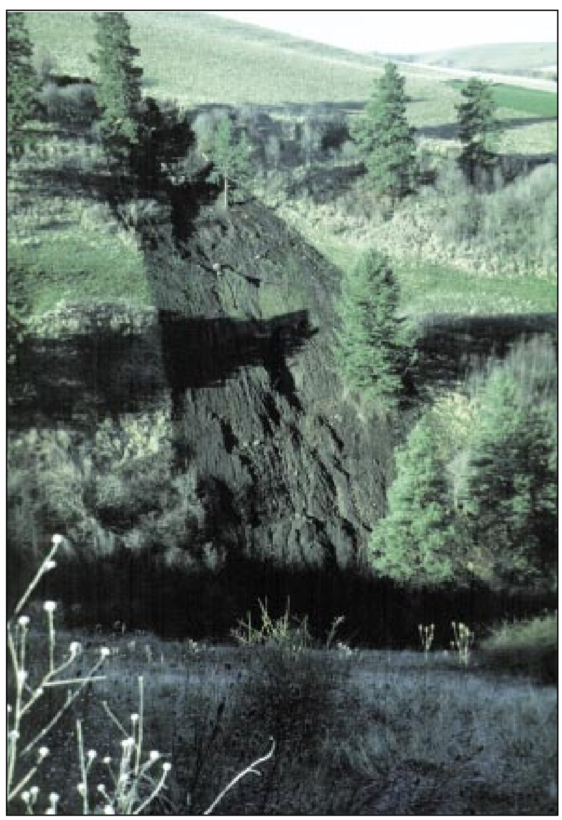

Figure 2. Large debris flow in Blue Creek drainage that, although shallow, has produced a large amount of debris. The road at the bottom of the gully was completely covered to a depth of about 4 ft.

Areas of mixed grassland and timber contained fewer debris flows; however, in these areas debris flows with lengths of up to 1 mi occurred. These debris flows incorporated trees and brush along with rock and soil and were particularly destructive to roads, houses, and other structures. The depth of failure and scour along drainage bottoms often exceeded 4 ft as it commonly removed soil and weathered rock down to the bedrock-soil interface.

Source material for the debris flows was mainly colluvial and residual soils as well as glacial loess overlying basaltic bedrock. Flow deposits originating in loess contained mostly silt and clay-sized particles. Boulders stripped from underlying weathered bedrock occurred in deposits where debris flows scoured channels down to weathered basalt.

Considerable damage to houses and vehicles was done by debris flows in the Mill Creek area (Figure 3). Seven vehicles and five houses were damaged or destroyed by debris flows emanating from side canyons to Mill Creek itself (Figure 4). Debris flows ranged in size from shallow flows less than 50 ft in length to deeply incised flows along main side drainages exceeding 1 mi in length.

There have been similar occurrences of flooding and landslides in the Blue Mountains in the past. Storms in 1931 and 1964 produced extensive flooding. According to long-time residents of Mill Creek, similar concentrations of debris flows were triggered in 1931 but were not nearly so numerous in 1964 (Rich Klicker, personal commun., 1996).

Mount St. Helens Area

A 70 mi^2-area east of Mount St. Helens including the drainages of Bean Creek, Clearwater Creek, and to a lesser extent, Smith Creek, was virtually blanketed in

Figure 3. Residence in Mill Creek located near the mouth of a side canyon. Debris flows emanating from this side canyon hit the garage shown in left center of photo, damaged two cars, and partially covered a caterpillar tractor. Remnants of the debris flow deposit can be seen in photo center.

Figure 4. Aerial oblique view of Mill Creek showing debris flows in almost every tributary canyon. Debris flows extend the entire length of all of the tributary canyons to the intersection with Mill Creek.

places by debris flows emanating from recent ash deposits erupted from Mount St. Helens (Plate 1). Individual debris flows in this area of tens of thousands of cubic yards appeared to be common (Figure 5); however, as observed from the air, most of the flows as well as their headscarps appeared to be relatively small and shallow. These debris flows represent the highest concentrations of landslides that were triggered by the February storms in western Washington.

This area of high debris-flow concentration coincides with one of the areas of peak estimated rainfall from WSI Corp. radar imagery for February 7, 1996. Figure 6 shows that, just southeast of Mount St. Helens, the maximum amount of estimated precipitation (5-6 in) for February 7 occurs in this area of high debris-flow concentration. Here we see a good correlation between the radar imagery of precipitation patterns and the landslide patterns. This is an area where the effect of high rainfall on debris-flow generation were added to by rapid snowmelt as a result of the rain on a deep snowpack.

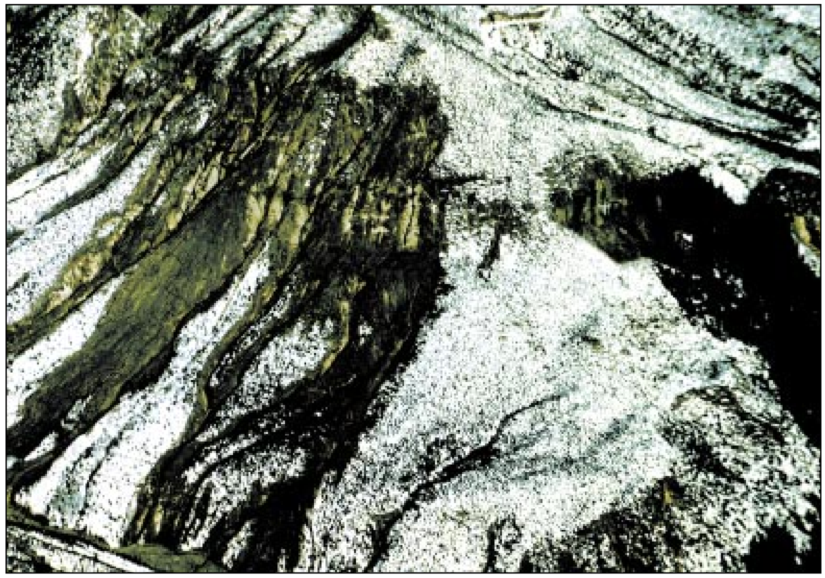

Figure 5. Large debris flows in recent volcanic ash deposits southeast of Mount St. Helens.

Ohop Creek Drainage

Northeast of Mount Rainier along the Ohop Creek drainage is an area of high landslide concentration of about 200 mi^2. The area on plate 1 is elliptical in shape parallel to Ohop Creek. Along the bluffs adjacent to Ohop Creek, abundant debris flows occurred with volumes of up to 1,000 yd^3. Most of the debris flows were much smaller averaging about 200 yd^3. Despite the small volume of most of the debris flows, a house was destroyed by a debris flow of 200 yd^3 or less that occurred on the east side of Ohop Lake (Figure 7). The debris flow originated near the top of the slope about 30 ft above the access road to the houses. It traveled across this road, knocked the house from its piers, and toppled the house on its side near the lake shoreline (#65, Table 1).

The system of county and local roads within the Ohop Creek drainage was especially hard hit. Some stretches of the Orville E. road that connects Kapowsin and SH-161, had dozens of soil slide-debris flows issuing from roadcuts and steep natural slopes per 100 yd of road length. Here, road cleanup of debris from soil slides and debris flows was still in progress in April 1996.

Willapa Bay Area

Approximately 10 mi northwest of Raymond, Washington, an area of undeveloped timberland about 10 mi^2 in area produced numerous debris flows. Most ranged from several hundred to several thousand cubic yards in volume. Logging roads were affected by both inundation by debris-flow material and by removal from slumping of the road bed and incision during the flow of debris across roads. Other than damage to logging roads, there appeared to be no impact on people or property within this small area.

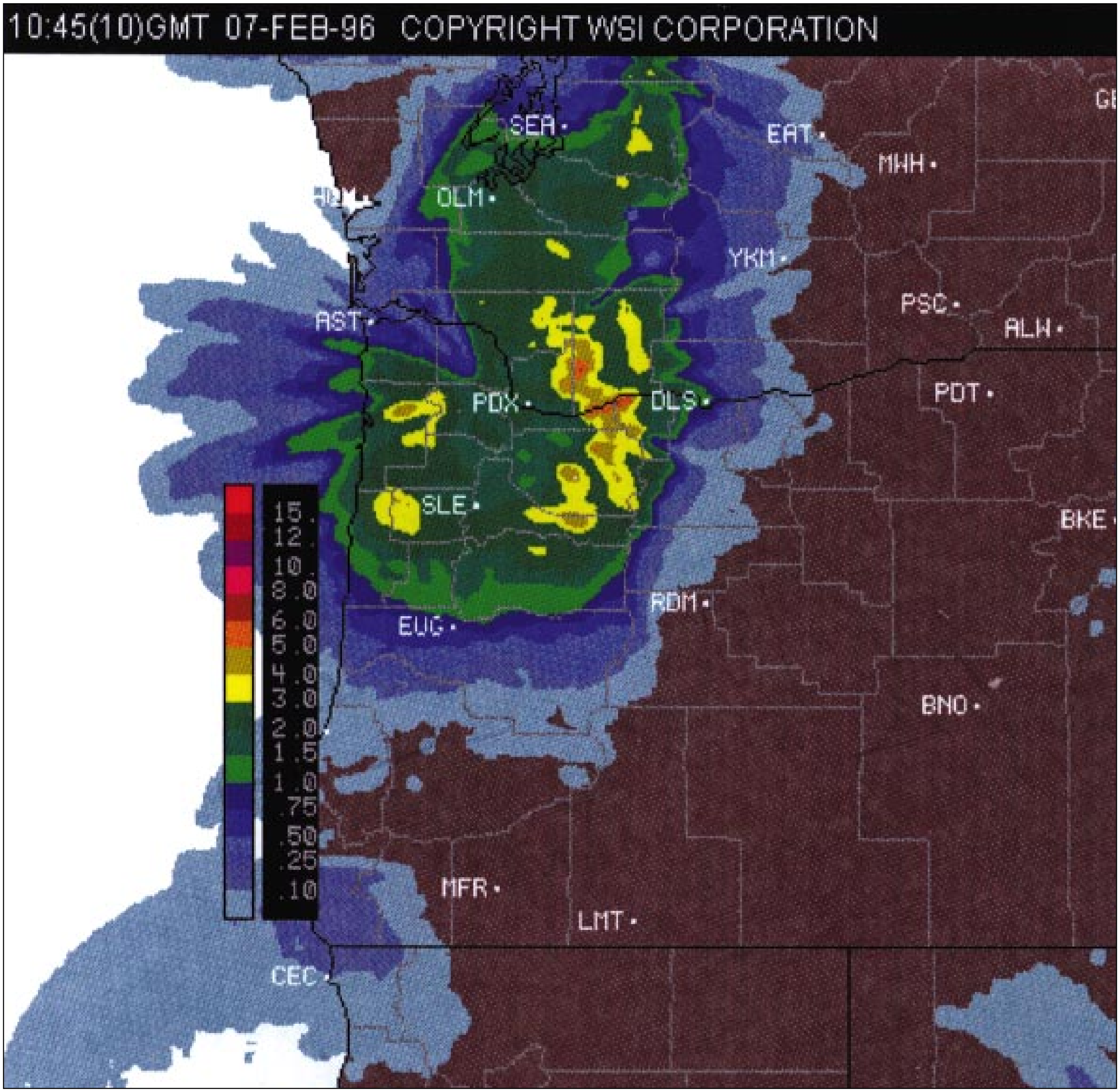

Figure 6. Radar imagery for February 7, 1996 showing high estimated-precipitation cells centered southeast of Mount St. Helens and along the Columbia River gorge near Dodson, Oregon where several large debris flows damaged houses and closed both I-84 and the Burlington Northern rail lines (Reprinted courtesy of WSI Corporation).

Skamokawa Creek Area

Another small area of about 8 mi^2 along SH-4 northwest of Stella, in the drainage of the West Fork of Skamokawa Creek was the site of numerous debris flows and several rotational slumps. The debris flows ranged in volume from several hundred cubic yards to several thousand cubic yards. These debris flows primarily damaged local and county roads. The largest of the rotational slumps was several hundred thousand cubic yards in volume (Figure 8). It is located about 0.5 mi northwest of the K M landslide of approximately 2 million yd^3 that disrupted SH-4 in 1990 Lowell, 1990). The new landslide removed a large section of trees, and its headscarp is about 10 ft below a paved previous detour of SH-4. This road may be incorporated in the landslide as retrogressive slumping takes place during future rainfall events.

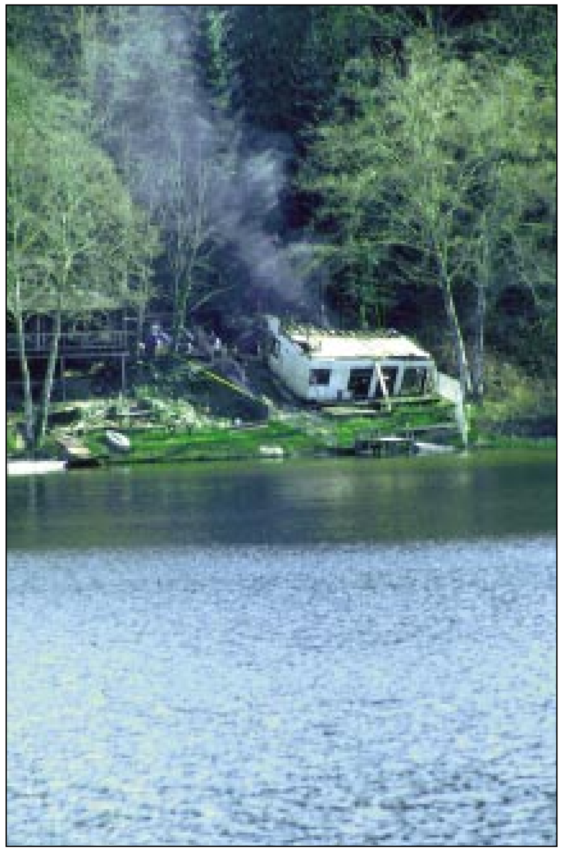

Figure 7. Cottage on east shore of Ohop Lake knocked off its footings by a small debris flow.

Columbia River West of Stella

Numerous debris flows occurred in a narrow section, about 10 mi in length, of shoreline of the Columbia River just west of Stella along SH-4. The highway was closed during the February storms in many places by debris flows that occurred in marine deposits that overlie the basalt cliffs adjacent to the highway. These debris flows ranged from several thousand cubic yards to almost 100,000 yd^3. The material from the debris flows cascaded over the basalt cliffs and buried the highway in several places. In most cases, the basalt cliffs were not involved in the failures except for a few pieces of loose basalt dislodged by the flow of the overlying material. The largest of these debris flows reached the Columbia River (Figure 9). By April 1996, all of the debris-flow material had been removed except for debris from the largest of these failures. At that time extensive excavation and slope reconstruction was still ongoing in the headscarp area (Figure 10) of this failure (#59, Plate 1).

Figure 8. Headscarp area of deep-seated slump-earth slide west of Washington SH-4 near Skamokawa Creek.

Figure 9. Large slump-debris flow located about 5 mi west of Stella, Washington on SH–4.

Figure 10. Head-scarp area of slump-debris flow shown in figure 9.

AREAS OF MODERATE LANDSLIDE CONCENTRATION

Much of the landslide-affected area from the February storms lies outside the areas of highest landslide concentration. Although lower (<10 landslides / acre) than the highest concentrations, these areas contained numerous landslides that accounted for major damage and impact.

Seattle Area

The city of Seattle recorded more than 40 different landslide incidents during the winter, about a third of which were from the November 1995 storm rather than from the February rainfall (Herb Allwine, Seattle Engineering Department, personal commun., 1996). A majority of these involve failures from steep coastal cliffs where the type of landslide varies from deep-seated rotational slumps to shallow debris flows.

Figure 11. Rock fall next to a house on Perkins Way in northern Seattle. Rock fall is a secondary failure on a larger rotational slump whose failure surface projects beneath the house and Perkins Way.

Perkins Lane Landslide

A deep-seated rotational slump developed in steep coastal cliffs below Magnolia Drive in the northwest section of Seattle (#66, Table 1). Movement of the landslide mass triggered a subsidiary rock fall from the headscarp of the rotational slump. The rockfall, containing about 1,500 yd^3 of silty conglomerate with boulders up to 4 ft in diameter came to rest at the back door of a house below on Perkins Lane (Figure 11). There appeared to be little damage to the house, although rocks had damaged part of the railing of a short walkway that led from the rear door of the house to the street.

The rock fall took place along a well developed fracture that presently forms the headscarp of the larger rotational slump at the site. To the south of the recent failure, this fracture surface forms the cliff; all rock west of the fracture having been previously removed by past episodes of failure. To the north of the present scarp, the fracture disappears behind 3-5 ft of sandy conglomerate. Additional rock may peel away from the fracture surface in future storms. Drilling done by Shannon and Wilson consultants (T.E. Kirkeland, personal commun., 1996) indicates that the failure surface of the rotational slump continues underneath the house site. The rotational slump and rockfall did not occur during the February storms. Instead its movement lagged behind the February rainfall and occurred on March 9 (T.E. Kirkeland, personal commun., 1996).

Brygger Drive Landslide

Four houses were involved in the movement of a moderate-sized slump from 4425 to 4435 Brygger Drive (#67, Table 1). Fractures that formed the head of the slump vertically offset the driveways of the houses from the street by about 4 in as of March 15, 1996. The slump upon which the houses are located moved down toward the ravine behind the houses. Only the headscarp portion of the landslide was evident at the time of observation. Although plastic has been placed over these fractures, future rains may initiate further movement of the slump.

Laurelcrest Drive Landslide

Several debris flows occurred along Laurelcrest Drive, along the shore of Lake Washington north of the University of Washington. The largest was about 300 yd^3 in volume and was the most damaging. This debris flow issued from steep cliffs behind the house at 5012 Laurelcrest Drive, missed the house by inches, but destroyed a large wooden deck, a patio, and brick barbeque structure (#69, Table 1). Its occurrence was noted by the owner as just after midnight, Thursday, February 8, 1996. As of March 15, 1996, several trees were leaning into the failure path of the debris flow as support for their roots was partially removed by the failure. Other sections of cliff adjacent to the scarp may also fail and produce small failures during future rainfall.

California Way Landslide

On the northern end of the peninsula forming West Seattle, the steep coastal bluffs above California Way failed producing a soil slide in weakly cemented sandstone of about 600-1,000 yd^3 (#70, Table 1). The slide partially mobilized into small debris flows near the toe but flowed only a short distance. Most of the failure mass remained on California Way as of March 15, 1996. Only the roadway was directly affected. Houses are located above and more than 50 ft to the south of the failure scarp and are unlikely to be involved in any reactivation or retrogression of the slide in the near future.

Tacoma Area

Several landslides that occurred in the Tacoma area caught the immediate attention of the news media because of the destruction of houses and the disruption of a major rail line as well as the derailing of a freight train.

Tacoma Narrows Landslides

A number of landslides originating in unconsolidated glacial deposits that form the steep coastal bluffs on Puget Sound destroyed two homes in Salmon Beach and damaged another (#'s 4, 5, 6; Table 1). The failures were about 1,000-5,000 yd^3 each and started as translational slides, subsequently mobilizing into debris flows that slammed into the houses, pushing them out into the Sound (Figure 12). Utility lines coming into the area were also damaged by the debris flows.

Schuster Parkway and Rustin Way Landslides

Numerous small failures from the coastal bluff were observed (#12, Table 1). Most failures occurred below Stadium High

Figure 12. Debris flow from steep coastal bluffs along Puget Sound in the community of Salmon Beach which destroyed a residence (Reprinted courtesy of the Seattle Post-Intelligencer).

School on Stadium Way and were approximately 1 m wide and <0.5 m deep, with a few up to 8 m wide. The largest failure observed left a 20-m wide swath of debris. The southbound lanes of Schuster Parkway were closed, and debris from failures overtopped the median barrier.

Marine View Drive Landslides

Many soil slip / debris flows were generated from Hylebos Bluffs onto a 2 mi length of Marine View Drive, which lies between the bluff face and Commencement Bay. The depth of scarps varied from <0.5 m to a few meters, and a few of the largest scarps were up to 10 m wide (#'s 8, 9, 10, 11; Table 1). Debris from the largest failures inundated a 50 m length of the road, collided with two houses, and travelled into Commencement Bay.

Ollala Point Landslides

Two debris flows of about 1,200 yd^3 each destroyed one house and damaged the fronts of three others (#'s 1, 2; Table 1). The house that was destroyed was hit by a debris flow that occurred at approximately 6:00 a.m. February 8, 1996. This debris flow came from the steep slope across the road from a row of houses. It traveled across the road, crushed the lower story of a two-story house and pushed it out into the Colvos Passage of Puget Sound. During the afternoon of the same day, a debris-flow pulse from this same area also crossed the road and hit a storage shed, moving it slightly off its foundation.

Carbon River Area

Numerous debris flows damaged SH-165 south of Carbonado. Volumes ranged from about 500 to 3,000 yd^3 and produced significant damage to SH-165 and to a bridge abutment across the Carbon River.

Figure 13. Debris flow undermining abutment of bridge across the Carbon River on Washington SH-165 south of Carbonado, Washington.

Carbon River Bridge Debris Flow

About 2 mi south of Carbonado on SH-165, the south abutment of the bridge crossing the river was partially removed by a debris flow of approximately 3,000 yd^3 that originated at the abutment (Figure 13; #73, Table 1). Support for part of the abutment was removed as the soil-slide moved from its source, fluidized during movement, and traveled as a debris flow into the river, a distance of about 150 ft.

Enumclaw Area

Approximately 7 mi east of Enumclaw, SH-410 was blocked by the distal end of a 1.5 mi-long debris flow that originated in the berm of a logging road (#75, Table 1). The debris-flow front consisted mainly of logs and downed timber that was pushed ahead of the leading edge of the flow. The volume of the flow is about 300,000 yd^3

and consists mainly of cobble- and boulder–sized debris with a minor amount of sandy matrix (Figure 14). The path of this flow was scoured to depths of over 4 ft along its channel.

Olympia Area

Several small slumps and debris flows occurred in the Olympia area around the state capitol campus and at the southern end of Capitol Lake. Although small, these failures had considerable impact on Capitol Lake and the City sewer system of Olympia.

Capitol Campus Landslides

Numerous small slumps and debris flows were triggered from the steep bluff north and west of the state capitol campus, which sits on this bluff about 100 ft above Capitol Lake. The largest of these is about 200 yd^3 in volume and failed from slopes just west of the Governor's mansion. Another failure of similar size originated in the slope above a steam plant located just above lake level on the shore of Capitol Lake. This debris flow hit a concrete diversion structure at the northeast corner of the plant and was deflected into Capitol Lake. Just northeast of this site, several small debris flows and slumps of several tens of cubic yards volume each covered railroad tracks and parts of an adjacent road at the bottom of the steep bluffs (Gerstel, 1996).

Capitol Lake Landslide

Immediately below Capitol Boulevard at the point where the Deschutes River enters Capitol Lake, a series of shallow coalescing debris flows severed two sewer lines. This sewer-line breakage resulted in the discharge of 6 million yd^3 of sewage into Capitol Lake.

Mineral Lake Area

Clear-cut slopes west of SH-7 near Mineral Lake produced debris flows that closed the highway for 2 days. Several debris flows originating from the outer berms of logging roads in clear cuts west of SH-7 traveled up to 200 yd before crossing the highway. One of these debris flows came within 50 yd of a home near the highway. Deposits from the flow near the home appeared to have been largely deposited by fluvial action. They were dominated by wood debris and were relatively sparse in sediment. These deposits may have been emplaced by a hyperconcentrated flow or one that is more than 50 percent water.

Figure 14. Lower portion of debris-flow path that closed Washington SH-410 east of Enumclaw. Debris flow originated in berm of logging road. Note preponderance of coarse material in debris.

State Highway 12 Area South of Mount Rainier

Much of the area adjacent to U.S. Highway 12 south of Mount Rainier is populated by scattered debris flows of moderate size (1,000-5,000 yd^3). The most notable of the landslides in this area, however, is also the largest landslide triggered by the February rainstorms.

Glenoma Landslide

At approximately 3:00 a.m., Thursday, February 8 (Elmer Day, oral commun., 1996), a block slide of about 1.5 million yd^3 was triggered from the shoulder of a partially clear-cut ridge in volcaniclastic sediments about 1 mi north of U.S. 12, 5 mi east of Glenoma and about 13 mi east of Morton (#77, Table 1). It appears that the slide moved southeast into a narrow V-shaped gully where it may have remained until overtopped by impounded water. Regardless of whether the slide mass mobilized immediately or sometime after initial failure into the gully, the slide mass eventually became extremely fluid as it traveled as a debris flow. It traveled southeast from this gully where it collided with a house and a garage (Figure 15 and 16) before stopping about 150 yd short of U.S. 12.

Figure 15. House crumpled by block slide-debris flow shown in figure 16 near U.S.-12 east of Glenoma, Washington.

Although the house was occupied at the time it was hit by the debris flow, no fatalities resulted, because the slide mass had nearly traveled its full extent before hitting the house. The house was cracked beyond repair but was not overrun or crushed by the debris. Elmer Day, who owns the house and lives in a trailer beyond the slide margins, stated that he heard and felt the debris-flow movement and could see the movement of trees as the debris flow spread out across the relatively flat field next to the dwellings.

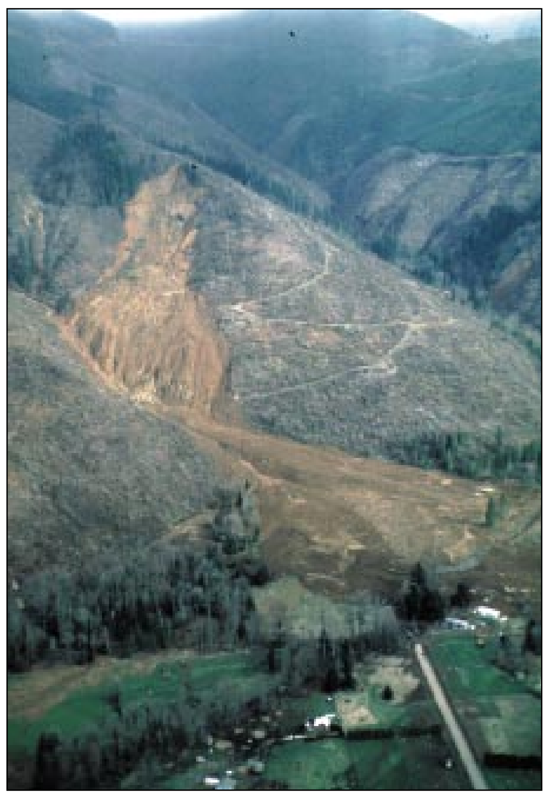

Figure 16. Block slide-debris flow that destroyed house shown in figure 15. House is at bottom right of photo. Near-vertical cliff in headscarp is about 150 ft high.

The slide headscarp, shown in figure 16 is approximately 150 ft high, with a nearly vertical headwall and a nearly 90˚ intersection of this wall with the exposed basal shear surface. The shape of the scarp suggests that the landslide's initial movement was mainly translational as a relatively coherent mass. After reaching the narrow gully, its direction of movement changed by almost 90˚ from southwest to southeast. In the first few days after the landslide, numerous small pieces of the cliff forming the headscarp fell leaving a fairly planar scarp with few remaining fractures above the present headscarp (Elmer Day, landowner, oral commun.).

Chehalis Area

Immediately east of the I-5 exit for north Chehalis is a hillside that has been cleared of trees and prepared for residential development. The devegetation and road emplacement for the development destabilized a large area of the hillside and subsequently produced several slow-moving slump-earthflow type landslides that have been active in past years (#53, Table 1). The February storms reactivated movement on these earthflows as well as triggering several debris flows from the same area (Figure 17).

Figure 17. Numerous slumps (arrows) near Chehalis, Washington, reactivated by February storm.

Kresky Avenue Landslides

Two earth slides of about 7,000 to 10,000 yd^3 each blocked Kresky Avenue in north Chehalis (#54, Table 1). The slides were about 150 ft apart and occurred in red, clay-rich sedimentary deposits. The slides crossed the street closing all lanes of traffic. Although traffic was disrupted, no damage to buildings occurred. Further rainfall may trigger renewed sliding from these slopes with similar effects. Possible hazards are repeated road closure and damage to passing vehicles and motorists.

North Fork Toutle River Area

Kid Valley Debris Flows

A group of 15 to 20 debris flows, some several hundred yards in length, occurred in Kid Valley on the south side of the North Fork of the Toutle River (#19, Table 1). These debris flows originated in soil and weathered bedrock overlying volcanic bedrock. Volumes ranged from 500 to 5,000 yd^3. Damage from the debris flows in the area was predominantly to logging roads and an improved roadway to a lumber mill.

State Highway 504 east of Kid Valley was blocked by debris flows in two places (#20, Table 1). The first of these was about 2 mi east of Kid Valley where over 200 ft of highway was buried and guard rail destroyed by a debris flow of 5,000-10,000 yd^3. Similar to those in Kid Valley, this debris flow incised a channel to the underlying volcanic bedrock. The total length of travel exceeded 600 ft and extended into the North Fork of the Toutle River.

SH-504 was also buried by a debris flow near the Hofstadt Visitors' Center near Hofstadt Creek (#21, Table 1). This debris flow was about 5,000 yd^3 in volume and buried about 90 ft of highway and destroyed the guard rail in its path. Additional debris remaining in the source areas may mobilize during future rainstorms.

Lewis River Area

Woodland Landslide

One of the largest impacts created by any individual landslide in the State of Washington was that caused by the failure of the 32,000 yd^3 landslide that blocked I-5 and the Burlington Northern-Santa Fe railroad tracks 3 mi north of Woodland (#80, Table 1). The initial landslide of about 12,000 yd^3 occurred shortly after 2:00 p.m., February 8. Its initial movement blocked only the northbound lanes of the interstate. By Friday, February 9, Washington Department of Transportation was planning to open the northbound lanes at 6:30 p.m., when, shortly after 6:00 p.m., a larger landslide mass of 20,000 yd^3 failed from the same source area and covered all lanes of I-5 as well as the rail lines adjacent to I-5 (Figure 18).

Figure 18. Slump north of Woodland, Washington that covered I-5 and the Burlington Northern-Santa Fe rail line.

Even after reopening part of the interstate on February 10, northbound traffic was commonly delayed for several hours, because only one lane was open in that direction. This situation remained until February 19. The landslide began as a rotational slump in marine sediments and remained relatively undeformed until descending a bench about 60 ft above the roadcut of I-5, which was originally about 120 ft high (Blodgett, Regional Highway Engineer, Washington Department of Transportation, oral commun., May 1996). At this point, the toe portion of the landslide became extremely disrupted and behaved much as a flow as it overran I-5 and the rail lines.

Figure 19. Small slump in northwest Vancouver that destroyed a residence located next to a steep slope bordering an old river terrace.

Lewis River Road

Along the Lewis River road (SH-503) from I-5 to its present passable extent where it is washed out, about 3 mi from the end of Swift Creek Reservoir south of Mount St. Helens, we noted 10 debris flows, 2 rock falls, and 1 slump (#'s 23-35, Table 1). All but the slump covered or partially covered SH-503 or adjacent Forest Service roads. All of these failures were 1,000 yd^3 or smaller except for one debris flow that covered Forest Road #81 near the outlet of Merrill Lake which lies about 8 mi south of Mount St. Helens.

This debris flow originated in the sides of a stream channel near the outlet of Merrill Lake and scoured the channel down to bedrock. It flowed across Road #81 and continued downslope into a campground where it spread out and deposited about 5,000 yd^3 of material.

Northwest Pacific Highway Landslide

About 0.5 mi south of Woodland, the Northwest Pacific Highway was covered by the toe of a large slump-earthflow whose source area is just below a rock quarry (#36, Table 1). The volume of the slump-earthflow is about 100,000-200,000 yd^3, and it has overrun and partially covered approximately 200 yd of the highway. This landslide predates the February storms and was moving slowly at the time of the storms. Its movement was accelerated as a result of the February rainfall.

This landslide is likely to continue its slow movement for some time unless sources of water from the area of the rock quarry can be diverted from the slide mass and some drainage measures are undertaken.

Vancouver Area

In the Vancouver Lake area, tracks of the Burlington Northern-Santa Fe Railroad were blocked by numerous slumps, debris flows, and rock debris from the shoreline bluffs adjacent to the lake. In one case, a train had to be excavated from landslide debris before being able to move (Columbian, February 7, 1996).

In the Hazel Dell area of north Vancouver at 11612 N. E. Ninth Ct., a house was broken in two when a debris flow of about 1,000 yd^3 carrying two large trees failed from a 30-foot-bluff just behind the home (Figure 19; #43, Table 1). The bluff is at the edge of an old river terrace. Most of the homes in this area are built on the terrace next to and below the low bluff that failed. In most cases, the houses are close enough to the bluff that little or no outrun onto the flat terrace is necessary for a landslide mass to hit a dwelling.

State Highway 14

State Highway 14 was closed or partially covered by debris flows in 15 different places from east of Washougal to Wishram about 80 mi to the east. These debris flows ranged in volume from about 200 to 5,000 yd^3 and consisted of colluvial and residual soils overlying bedrock.

Stevenson Landslide

In the northern part of Stevenson, west of the junction of Loop Road and Maple Hill Road, a large complex rotational slump-earthflow was reactivated in the February storms (#81, Table 1). Most of the area here is comprised of old landslide deposits with many visible old scarps and hummocky topography. Below Maple Hill Road, a zone of prominent scarps developed following the February 1996 storm with cumulative downslope displacements of 4 ft or more (Figure 20). Three houses in this area had to be removed

Figure 20. Headscarp area of deep-seated, complex rotational slump-earthflow in subdivision in Stevenson, Washington. Landslide has resulted in removal of three houses and has threatened six or seven additional residences.

from their foundations. The foundation shown in figure 21 illustrates the damage done to houses by deformation across this zone of fractures.

The fractures shown in figures 20 and 21 constitute the headscarp area of the landslide. Below this, the topography steepens due to the presence of what appears to be an old landslide scarp that produced many coalescing debris flows from its face during the February rainfall. These debris flows covered a section of Loop Road just below this old scarp and flowed across the road, plugged a culvert in the road, and filled a small basin above the road culvert.

The fractures forming the headscarp of the landslide extend for several hundred ft to the east and west of the area shown in figures 20 and 21 before they become indiscernible. The toe of the landslide near Loop Road is doming upwards from the rotation of the slide mass beneath it. This section is just below the area of the overflowage of Loop Road by the debris flows originating from the old scarp. Six to seven other houses are within the detectable slide boundaries and are beginning to experience slight deformation (David Esche, Assistant County Engineer, Skamania County, oral commun., May 1996).

Above the headscarp shown in figures 20 and 21, are other tension fractures formed by the retrogression of deformation upslope (Figure 22). These mark the spreading of displacement of the slope beyond the initial landslide boundaries. Using a crude estimate of the average landslide depth of about 50 ft, the landslide volume totals about 500,000-1,000,000 yd^3. According to residents of the area, movement continues (as of May 1996), and it is unclear how great the final extent of the landslide mass will eventually be and

Figure 21. Effects of headscarp fractures on foundation of residence on Stevenson landslide.

Figure 22. Aerial oblique view of Stevenson landslide. At center right is foundation shown in figure 21. Arrows denote additional extension fractures upslope from fractures shown in figures 20 and 21.

how many additional homes it may include.

White Salmon Area

In the city of White Salmon and along the slopes adjacent to the White Salmon River near its mouth, numerous small, shallow debris flows occurred along road cuts and grassy natural slopes. The depths of these flows as well as the vacated scarps are generally 1 ft or less, and flow distances are generally less than 20 ft. North of the mouth of the river, few debris flows are seen until reaching Phelps Creek, a distance of about 12 mi.

Unlike the surrounding terrain, the channel of Phelps Creek has been scoured by mixed debris flow and flood activity to a width of about 20 yd and for a length of at least 1 mi (#82, Table 1). Scattered trees and boulders are evident along the streambanks. State Highway 141 was covered when the box culvert was plugged, and debris-flow material flowed over the highway, burying it to a depth of about 20 ft. The debris flow mass continued over the highway and down Phelps Creek for perhaps another 200 ft (Ken Kirkland, Washington Department of Transportation, Regional Engineer, oral commun., May 1996).

LANDSLIDES IN AREAS OF LOW CONCENTRATION

There were a few isolated landslides outside the pink shaded area in plate 1 that caused significant impact to transportation routes. The two landslides discussed below affected major highways and caused closure of one of Washington State's two main interstate highways.

Ruby Creek Landslide

Approximately 12 mi north of Blewett Pass on U.S.-97, a large rock slide of several hundred thousand cubic yards was reactivated by both the November and February rainfall. Prior to November 1995, slide movement had not been reported at the site since 1960 (Steve Lowell, Washington Department of Transportation, Chief Engineering Geologist, oral commun., March 1996; #78, Table 1).

The reactivated movement in November 1995 caused extensive erosion of the highway due to the displacement of Peshastin Creek against the road fill. The slide movement almost dammed Peshastin Creek. Erosion repair cost about 2 million dollars.

Renewed activity in February resulted in almost 30 ft of additional movement on the slide and considerable renewed erosion of the newly repaired highway. Highway repair was still underway when we visited the site in April 1996. Potential for future movement remains high during storms such as those of November 1995 and February 1996. Renewed movement of the present slide mass serves to destabilize slopes that are adjacent and upslope of this slide.

Keechelus Lake Debris Flow

During the February 5-9 storm, a moderate-sized debris flow of about 5,000 yd^3 emerged from about 20 yd above I-90 and flowed across all lanes, closing the interstate for about 1 day. This debris flow occurred just east of Keechelus Dam (#79, Table 1).

FACTORS AFFECTING LANDSLIDE DISTRIBUTION

Rainfall Patterns of February Storm

As previously mentioned, the radar imagery for February 7, 1996, from the National Weather Service (Figure 6) shows cells of high intensity rainfall that correlate well with high concentrations of landslides in western Washington. The highest rainfall levels shown in figure 6 are 5-6 in. One of these cells is roughly circular and located just southeast of Mount St. Helens where the highest concentrations of landslides in western Washington occurred immediately southeast of Mount St. Helens. Although not previously discussed in this report, another area of similar rainfall level is along the Columbia Gorge near Dodson, Oregon. This area is one of elongated coalescing cells that corresponds well with the occurrence of numerous destructive debris flows that originated from the steep cliffs of the gorge that destroyed one house, damaged several others, and closed both I-84 and the Union Pacific Railroad tracks.

Although accounting for only part of the moisture delivered to slopes, the relatively warm rainfall was directly responsible for the rapid snowmelt. Thus, the spatial variation in rapid snowmelt should closely match the spatial variation in rainfall intensities from the storms.

Susceptibility of Geologic Materials

Although no thorough evaluation of the effect of the spatial variation in geology on the distribution of landslides has been attempted, a few first-order patterns are obvious. To the west of Vancouver along the Columbia River, soils and deposits of marine sediments overlying basalt cliffs proved more susceptible than the basalt or its residual soils in producing debris flows. Virtually no failures occurred within the basalts or within soils developed on them. However, the relatively soft, marine sediments that overlie the basalts have produced numerous soil slumps and debris flows.

In the Blue Mountains of southeastern Washington, the effects of glacial loess can be seen in the debris flow concentration. Because the loess is extremely susceptible to failure, debris flows in these deposits on farmlands closely spaced, and both scarps and deposits are relatively thin, generally less than 2 ft thick (Figure 23). Nowhere else in Washington did debris-flow concentrations achieve this level from the February storm. The concentrations of debris flows just southeast of Mount St. Helens were nearly as high but, as previously discussed, they were also located at one of the maxima of rainfall intensities—no accurate radar imagery was available for the Blue Mountains.

High debris-flow concentrations occurred in both loess and in the recent ash deposits of Mount St. Helens; both have low densities. Loess is formed by the settling of wind-blown silt and clay particles derived from glacial rock flour. Its low density makes it especially erodable and its interparticle structure easily collapsible upon saturation and water flow through its pore spaces.

Man-made fill in general, and road-fill embankments in particular, was especially susceptible to landsliding. The outer portions of roads on steep slopes are usually poorly compacted and, because this material has relatively low density, it is extremely susceptible to rainfall-induced instability. Many of the obvious debris flows in clear-cut areas were initiated at the outer portion of logging roads. Even improved roads and highways were susceptible to debris flows and slumps. Improved highways and roads seemed to have as numerous associated failures as the unimproved roads. Where steep road cuts existed on the uphill side of roads, materials were susceptible to landslides because of the oversteepening and removal of downslope support. Numerous small debris flows and slumps formed at and just above cut slope boundaries.

Undoubtedly, other examples of high-susceptibility deposits exist; however, more detailed investigations will be required to identify all such materials.

Figure 23. High concentration of debris flows in glacial-loess deposits on northwestern flank of Blue Mountains.

Susceptibility Affected by Vegetative Cover

The most noticeable differences in vegetative cover on slopes in western Washington are those provided by the two end members of timber harvesting: forested slopes and clear-cut slopes. There has long been controversy regarding the effects of logging and clear cutting on the stability of slopes.

Our regional aerial reconnaissance gave us the overall impression that clear cuts contained more debris flows and associated other types of landslides than similar slopes in forested areas. However, we qualify this statement with the observation that landslides were often more difficult to see on forested slopes. We certainly found numerous landslides within forested areas but had trouble seeing them clearly from the air even when we had previous knowledge of their presence. Ground-based field inspections generally allowed us to discover many more landslides in forested slopes than we were aware of from the air.

In the Blue Mountains of southeastern Washington where clear cutting is not presently done, we saw debris flows both in areas of timber and on slopes that were almost free of timber. The only major difference we saw in this area was that slopes completely free of timber tended to have high concentrations of smaller, very shallow debris flows, while slopes with mixed forest and grassland had somewhat lower concentrations of debris flows in which longer debris flows with deeper channels occurred.

From our observations, we do not feel that any conclusive statement can be made regarding the effects of logging or clear-cutting on the distribution of landslides. To accomplish this, several similar areas, both forested and deforested, will have to be studied carefully to determine if there are indeed differences in the distribution of landslides that are induced by the removal of trees.

FUTURE LANDSLIDE HAZARDS

Our regional survey highlights several areas where additional work may help to avoid future hazards to people and property. Patterns of landslide distribution discerned in our study have indicated that attendant hazards are controlled by material properties and the presence of high intensity / duration rainfall. These hazards can be predicted if detailed inventories of landslides and known geological and geotechnical data are compiled and analyzed together. Three areas where additional analysis of the February 1996 landslide event can serve to help avoid similar occurrences in the future are as follows:

(1) Large scale (1:18,000 or larger) aerial photography of the area affected by landslides in the Blue Mountains should be taken to document the distribution of debris flows in detail so that an inventory map of the debris flows could be made. Such a detailed inventory could be combined with existing geologic mapping and geotechnical data to prepare a hazard map for the area. Only one of the canyons in this area is densely developed. A hazard map could assist decisionmakers in avoiding landslide hazards in the future or to develop areas using appropriate mitigative measures to protect people and property in areas highly susceptible to landslide or debris-flow hazard.

(2) Steep coastal bluffs in the Puget Sound area were the sites of numerous debris flows and other types of landslides in the February storms, yet most of the landslides occurring there could not be seen from aerial reconnaissance. These failures were only clearly visible from fairly close quarters on the ground. We suggest that the coastal cliffs of the Puget Sound area be inspected and accurate locations be documented to the extent possible. This is an area of intense development pressure, and an accurate picture of where landslides were triggered during this storm is vital in making intelligent land use planning decisions. A consideration of existent landslide susceptibilities and potential hazards will reduce the risk to people and property both now and with future development.

(3) The Stevenson landslide may continue as an ongoing problem. Once in motion, deep-seated complex landslides such as this may continue to move for extended periods of time. Also, landslide boundaries may enlarge to include significant portions of surrounding terrain. With three houses already removed and six to seven more affected, detailed geotechnical studies and mitigative engineering measures may have to be undertaken if the area presently affected is to be stabilized and the surrounding area protected against becoming unstable.

REFERENCES CITED

FEMA Interagency Hazard Mitigation Team, 1996, February 1996 Flooding, Landslides, and Stream Erosion in the State of Oregon: Interagency Hazard Mitigation Team Report.

_____1996, State of Washington Winter Storm of 1995-1996: Interagency Hazard Mitigation Team Report.

Gerstel, W.J., 1996, Slope stability analysis of bluffs along the Washington State Capitol Campus, Olympia, Washington: Washington Division of Geology and Earth Resources, Open-File Report 96-3, 1 v.

Lowell, Steve M., 1990, The K M Mountain landslide near Skamokawa: Washington Geologic Newsletter, v. 18, no. 4, p. 3-7.

Powell, Jack, 1996, Appendix A—Mass wasting assessment, in South Fork Touchet watershed, *in* McKinney, Charles, ed., Touchet Watershed Analysis, Washington Department of Natural Resources, Olympia, Washington, 21 p.

Tacoma News Tribune, 9 February 1996.

The Columbian, 8 February 1996.

———, 7 February 1996.

Walsh, Timothy J., Korosec, Michael A., Phillips, William M., Logan, Robert L., and Schasse, Henry W., 1987, Geologic map of Washington-Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 1:250,000.

Table 1. Specific Landslide Sites

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
1,2	Soil slide-debris flow.	1,200	Granular sediments (Whidbey Fm (?) & ovelying surficial sediments.	Pushed one home into Colvos Passage & damaged fronts of three others.	Other homes threatened by adjacent unstable slopes.	Shallow failures on bluff.
3	?	?	?	?	Threatens town-houses on Lake Fenwick Rd., Kent, Wash.	Reported in Tacoma News Tribune 2/9/96 (site not visited).
4,5,6	Soil slide-debris flow.	1,000-5,000	Unconsol. glacial sand and silt.	Two Salmon Beach homes pushed into Puget Sound at Tacoma Narrows. Damaged a third house and utility lines.	Other homes along Salmon Beach threatened by possibility of more landslides during intense storms.	Several shallow failures.
7	Debris flow.	3,000	Mostly sand & silt; probably fill under paved road on steep bluff.	Collapse of about 65 ft of roadway where road intercepts drainage.	Potential for cont. failure could be diminished by improving drainage.	Inadequate culvert or broken drainpipe probable cause.
8,9,10,11	Soil slides-debris flows.	500-2,000	Glacial sand, gravel, & silt.	Two homes severely damaged; blocked road & damaged guard rail.	Future storms may cause similar failures along this stretch of Marine View Drive.	Shallow failure; some channelized.
12	Debris flow.	500-1,000	Colluvium and underlying gravel, sand, silt, and clay.	Covered part of Schuster Parkway and overtopped median barrier.	May recur during future storms.	Shallow failures on steep bluffs.
13	Slump(?)	<500	?	Collapsed 20-ft retaining wall onto three vehicles in Tacoma.	?	Reported in Tacoma News Tribune 2/9/96 (site not visited).
14	Debris flows.	<500	Granular marine sediments.	Partially covered Jovita Blvd. in Tacoma.	Likely to recur due to high susceptibility materials.	Numerous thin debris flows in previously designat-ed landslide area.
15,16	Slumps.	20,000 each?	Fill?	1.5 ft vertical displacement in shoulder of Chambers Creek Rd. about 150 ft in length.	Possible continued movement in road shoulder.	Scarps only landslide feature developed.
17	Undetermined.	?	?	Derailed train injured two crewmen and caused 3,000-gallon fuel spill.	?	Site not visited due to inaccessibility.
18	Debris flow.	1,000-1,500	Soil & weathered rock over bedrock.	Blocked road to quarry.	Possible remobili-zation with future rainfall. Hazardous to local traffic.	Shallow flow, partly channelized.

Table 1. Specific Landslide Sites—continued

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
19	Debris flow.	500-5,000	Soil & weathered rock over volcanic bedrock.	Blocked road to lumber mill on south side of North Fork of Toutle River in several places. Also some damaged logging roads higher on mountain.	Some debris flows likely to recur in intense storms.	15 debris flow—some several hundred yards in length.
20	Debris flow.	5,000-10,000	Soil & weathered rock over volcanic	Covered about 75 yd of SH-504 & flowed into N. Fork of Toutle River. Destroyed guard rail.	Possible recurrence during periods of intense rainfall.	Partly channelized shallow flow.
21	Debris flow.	5,000	Soil & weathered rock over volcanic bedrock.	Blocked SH-504 & destroyed 30 yd of guard rail.	Remaining material in source area may mobilize during intense rainfall.	Shallow failure.
22	Undetermined.	?	?	Derailed Amtrak train in Ostrander area north of Kelso.	?	Reported in Columbian 2/7/96—site not visited.
23,24	Debris flows.	<1,000 each	Mixed soil & rock over volcanic bedrock.	Partly covered SH-503.	May remobilize during intense rainfall.	Shallow failure.
25,26	Rock falls.	<1,000 each	Volcanic bedrock	Partly covered SH-503.	Additional fragments may fall during future storms.	
27	Slump.	<500	Mixed soil & rock over volcanic bedrock.	Encroached on SH-503.	None apparent.	
28	Debris flow.	<1,000	Mixed rock & soil over volcanic bedrock.	Crossed & blocked Lewis River Rd.	May reactivate during future intense rainfall.	Channelized shallow failure.
29	Debris flow.	<500	Soil & rock over volcanic bedrock.	Partly covered Forest Rd. #81.	May reactivate during future intense rainfall.	Shallow failure.
30	Debris flow.	5,000	Mixed rock & soil over volcanic bedrock.	Overran & blocked Forest Rd. #81.	May reactivate during future intense rainfall.	Channelized shallow flow.
31,32,33	Debris flows.	<1,000 each	Mixed soil & rock over bedrock.	Partly covered Forest Rd. #90.	May reactivate during future intense rainfall.	Shallow failures.
34,35	Debris flows.	<500 each	Mixed rock & soil over bedrock.	Partly covered Forest Rd. #90.	Failures may originate here in future storms.	Small, shallow debris flows.
36	Rotational slump-earthflow.	100,000-200,000	Soil & weathered rock over andesite flows.	Buried one lane of NW Pacific Highway for about 200 yd.	Earthflow mass is still wet and moving slowly. May cover both lanes of highway in heavy rainfall.	Pre-existing land slide. Movement accelerated during February storm.
37	Soil slides-debris flows.	<500	Soil & weathered rock from road cut.	Partly covered NW Pacific Highway	Continued movement & road damage likely.	Small shallow slope failures.
38	Debris flow.	1,000-2,000	Soil & Lake Missoula flood deposits.	Blocked roadway.	May block road during future intense rainfall.	

Table 1. Specific Landslide Sites—continued

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
39	Debris flow.	5,000-10,000	Fill & underlying Troutdale Fm.	Removed 50-yd section of Timmons Rd.	Likely to recur unless drainage problem is solved.	Small culvert unable to accommodate water flow, resulting in saturation of fill & underlying sediment.
40,41,42	Soil slides-debris flows.	?	?	Covered railroad tracks & part of a train.	?	Reported in Columbian, 2/7/96—site not visited.
43	Slump-debris flow.	1,000-2,000	Colluvium & alluvium.	House broken in two.	Adjacent homes might be threatened by similar failures from bluffs during future rainstorms.	Susceptible bluff above old river terrace.
44	Coalescing soil slides-debris flows.	500-2,000	Troutdale Fm. & overlying soil.	Covered & damaged NW Forest Home Rd.	Future intense rainfall would likely generate more shallow slides & debris flows.	
45,46	Debris flows.	<5,000	Pre-existing large landslide deposit.	Blocked SH-14.	Intense rainfall may trigger additional debris flows.	
47	Debris flow.	<2,000	Colluvium overlying Columbia River basalt.	Blocked SH-14.	Intense rainfall likely to trigger more debris flows.	Shallow failures.
48,49	Debris flows.	<2,000	Colluvium overlying Columbia River basalt.	Covered SH-14	Future intense rain-fall likely to trigger more debris flows.	Shallow failures.
50	Rock & earth slides.	10,000 for two slides.	Highway fill & bedrock.	Slumping of pavement on U.S.-101.	Has happened previously & is likely to recur in intense rainfall.	Two slides, about 50 yd apart began in rock slope & continued through highway fill under U.S.-101. Mainten-ance crew placed additional paving over slumped portion.
51	Soil slide-coalescing debris flows.	2,000-10,000	Old river terrace composed of gravel, sand, & silt.	Debris flowed into Skokomish River; no real damage.	Could recur during intense rainfall.	50-yd length of river terrace failed into Skokomish River.
52	Complex earth slide-earth flow.	300	Reddish, soil-like near-shore marine sediments, possibly Lincoln Creek or Cowlitz Fms.	None.	None.	Thin slide near top of logged hill in Salzer Creek drainage.
53	Debris flow.	1,000	Colluvium & marine sediments, probably Lincoln Creek Fm.	No damage on logged hillside.	Possible recurrence but not likely to reach nearest street, Kresky Ave.	Narrow debris flow down ravine above Kresky Ave., north Chehalis.

Table 1. Specific Landslide Sites—continued

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
54	Complex earth slide-earth flow.	15,000-20,000 (total for two slides)	Red, clayey sediments probably of Lincoln Creek Fm.	Both slides blocked Kresky Ave. in north Chehalis.	Could happen again in intense rainfall; if so, would block Kresky Ave., but not a hazard to nearby buildings.	Two slides about 50 yd apart crossed Kresky Ave.
55	Earth slide-debris flow.	500-1,000	Soft sedimentary rocks, probably of Lincoln Creek Fm.	Reached road at bottom of slope.	Probably not likely to trigger additional flows from source area that would reach road.	High on logged hillside above Coal Creek.
56	Debris slide.	1,000	Colluvium & residual soil.	None to logged slope.	None.	Occurred on slope above Bear Creek, tributary of Tilton River.
57	Rock slides & falls.	2,000 total.	Road cuts in andesite.	Rock had to be removed from SH-508.	Probably will recur in heavy rain.	Several small rock falls & rock slides accumulated in borrow pit & on pave-ment. Just east of SH-508 crossing of Bear Creek.
58	Rock falls, rock slides, & debris flows.	2,000 total.	Highway cuts in andesite.	Rock had to be removed from U.S.-12.	Likely to recur in heavy rain.	At least 10 small landslides (mainly rock falls, one debris flow) from short length of highway cuts on north side of U.S. 12.
59	Debris flow.	100	Red sediments above Columbia River basalt.	Blocked SH-4, 0.3 mi west of Germany Cr.	Could be reactivated by future rain.	Occurred April 26, 1996. May be a reactivation of a failure triggered in February.
60	Earth slide	200	Glacial sediments in coastal bluff.	Knocked house from foundation.	All 12 houses along this section of coastal bluff may be in danger in intense rainfall.	Occurred on April 23, 1996, due to heavy rain. Head of slide about 10 yd above house.
61	Earth slide-earth flow.	500-1,000	Glacial sediments in coastal bluff.	No damage because of absence of houses. Slide ran out onto beach.	Continuing problem with slides along bluffs in heavy rainfall.	Occurred on Feb. 8, 1996 from heavy rain. About 0.5 mi north of slide #60.
62	Debris flows.	200 total	Glacial sediments in bluff along west shore of Lake Union.	Blocked Westlake Ave. in 2300 block. Head of debris flow close to foundation of large apartment	Could easily block Westlake Ave. again. Apartment building does not appear to be in serious danger.	Two debris flows on 45° slope occurred on April 23, 1996. Both 25 yd long.

Table 1. Specific Landslide Sites—continued

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
63	Earth slide.	500	Glacial sediments in coastal bluff.	Destroyed large house on Perkins Lane.	All houses along Perkins Lane south of intersection with Rayle St. are in on-going danger during future periods of heavy rainfall.	Occurred on April 23, 1996, 0.4 mi south of Rayle St. Perkins Lane intersection. Head of slide just below Magnolia Blvd.
64	Debris slide.	1,000	Glacial sediments in coastal bluff.	Blocked Perkins Lane in section with no houses.	Entire section of bluff above Perkins Lane susceptible to failure during intense rainfall.	Occurred on April 23, 1996. About 75 yd north of south end of Perkins Lane. Separate from but related to March 8 slide at south end of Perkins Lane.
65	Debris flow.	300	Fluvial sediments in slopes above east shore of Ohop Lake.	Destroyed cottage on lakeshore.	Other small debris flows from slopes above houses suggest that other damaging flows could occur in periods of intense rainfall.	
66	Rotational slump-rock fall.	1,500-rock fall. Slump unknown but much larger.	Glacial sandy conglomerate in steep coastal bluff.	Rock fall piled up against house on Perkins Lane.	Further movement of deep-seated rotational slump beneath house will continue to deform it and possibly destroy it.	Occurred March 8, 1996. Head scarp below 1734 Magnolia Dr.
67	Rotational slump.	Not sure. Probably at least 5,000.	?	Four houses are being deformed on Brygger Dr.	Recurring movement is likely during intense rainfall unless extensive mitigation is done to slide.	
68	Debris flow.	200	Glacial sediments in coastal bluff.	Blocked Portage Bay Dr. and piled up against a garage on north side of street. Head scarp is below a house.	May have additional debris flow from head-scarp area during intense rainfall. Retrogression of head scarp may jeopardize house above scarp.	
69	Debris flow.	300	Sediments in coastal bluff.	Destroyed patio next to house on Laurelcrest Dr.	Future intense rainfall may trigger other failures from slopes that could endanger houses.	
70	Slump-debris flow.	600-1,000	Coastal bluff sediments.	Blocked California Way.	May recur in future intense storms.	
71	Debris flow.	200	Colluvium overlying Eocene continental sediments, probably Carbonado Fm.	SH-165 blocked.	Some added flow may occur from same source during high-intensity rainfall.	

Table 1. Specific Landslide Sites—continued

(Landslide numbers plotted on Plate 1)

Landslide	Type	Estimated Volume (yd^3)	Source Material	Damage	Continuing Hazard	Comments
72	Debris flow.	2,000	Colluvium overlying Carbonado Fm.	Removed downhill lane of SH-165 and covered highway.	Road is exposed to erosion during intense rainfall.	
73	Soil slide-debris flow.	3,000	Soil overlying andesite.	Head scarp undercuts bridge abutment.	Intense rainfall in future will cause head scarp to cut farther into bridge abutment.	
74	Debris flow.	2,000	Soil overlying andesite.	Blocked SH-165.	Intense rainfall could possibly initiate additional debris flows from source.	Source about 100 ft above road.
75	Debris flow.	500,000	Colluvium overlying rhyolite.	Blocked SH-410.	Additional flow may result from future intense rains, but small volumes will probably not make it all the way to the highway.	Debris flow track is about 1.5 mi long in clear-cut area.
76	Soil slump-debris flow.	100	Glacial sediments from coastal bluff.	Knocked house off wooden footings.	Intense rainfall may initiate further slope failure above houses in this area.	7970 SH-106 mile-post 8.
77	Block slide-debris flow.	1,500,000	Volcaniclastic sediments.	Knocked house off foundation & hit garage.	Little remaining hazard to residents at distal margin.	Largest failure triggered by February storm.
78	Rockslide.	200,000		Renewed erosion of U.S. 97.	Renewed movement possible in future storms with attendant deflection of creek toward highway and renewed erosion.	Slide reactivated in Nov. 1995, then in Feb. 1996.
79	Debris flow.	5,000		Closed I-90 for about 1 day.	Possible additional debris flows from retrogressive failure of soil in scarp during future storms.	
80	Rotational slump.	32,000	Marine sediments.	Blocked I-5 & Burlington Northern-Santa Fe Railroad tracks.	May pose no further hazard due to excavation of landslide mass.	
81	Complex rotational slump/earthflow	500,000-1,000,000	Reactivated landslide deposits.	Three houses removed and threatens six to seven others.	Will probably continue movement in future storms.	
82	Debris flow.	20,000-100,000	?	Covered SH-141 to a depth of 20 ft.	Small failures may occur from margins of scoured riverbank during future storms.	