Silverton Watershed
LANDSLIDE HAZARD ZONATION PROJECT
Snohomish County, Washington

By Isabelle Y. Sarikhan
Timothy J. Walsh

Forest Practices Division and Adaptive Management Program in coordination with the Washington State Division of Geology and Earth Resources

Priority 3
Mass Wasting Assessment
March 2006

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

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Washington State Department of Natural Resources

Forest Practices Division
PO Box 47012
Olympia, WA 98504-7012
Phone: 360-902-1400
Fax: 360-902-1428

Division of Geology and Earth Resources
PO Box 47007
Olympia, WA 98504-7007
360-902-1450
360-902-1785

Websites: http://www.dnr.wa.gov/forestpractices/lhzproject
http://www.dnr.wa.gov/forestpractices/adaptivemanagement
http://www.dnr.wa.gov/geology/

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1.1 Use of this report

The purpose of this mass wasting assessment is to identify non-federal, non-tribal areas within the Silverton watershed assessment unit (WAU) that have moderate or high risk of landslides due to the effects of forest management (logging, roading, thinning, yarding, etc.). All lands within the WAU have been divided into designated mass wasting hazard landforms. Maps of these landforms are designed for use by landowners in determining the areas which have high to low hazard of instability and by the Department of Natural Resources regional staff to identify sites where future forest practice applications (Chapter 222-20 WAC) may require detailed investigation prior to forest practice classification (Chapter 222-16-050 WAC).

This is a reconnaissance survey, and its relatively broad resolution must be considered when using this document and its accompanying maps. Moreover, the survey was conducted within a constrained timeline that was budgeted to produce a statewide unstable slopes screening tool as quickly as possible. For these reason, it is likely that some landslides or unstable landforms have been overlooked, some benign features have been mistakenly mapped as landslides, and some landslides have been classified improperly. Thus, the landslide inventory presented in this report (Map A1 and Form A1) is intended to be a representative but not necessarily complete inventory.

This assessment was largely conducted remotely using the best map and image-based resources available, with support from limited field visits to verify mapping results. However, we note that landslide inventories that are conducted primarily using air photos have been demonstrated to omit up to 85% of the landslides that actually exist on the ground in heavily forested areas (Brardinoni and others, 2003). Furthermore, they tend to skew the location of the majority of landslide occurrences toward recently harvested areas because they are easier to spot in these areas than under canopy on air photos (Brardinoni and others, 2003).

Information is collected and compiled in a manner that is designed to respond to the Critical Questions that are outlined in Section II of the Landslide Hazard Zonation (LHZ) protocol, and to direct attention to areas where more detailed analysis is necessary. The objective of the data collection is to generate information sufficient to establish:

- A generalized characterization of mass wasting processes active in the basin;
- Areas of landscape that share similar physical characteristics related to mass-wasting behavior;
- The relative potential for mass wasting to occur among the various landform units.

1.2 Previous Investigations

The Stillaguamish watershed, of which the Silverton WAU is a small part, has long been known to have non-point source pollution, such as high sediment yield caused from erosion and mass movement (SIRC, 2004). The Department of Ecology implemented the Stillaguamish Watershed Action Plan in 1990 (WDOE, 1990), bringing with it an extensive amount of research into the watershed, including studies pertaining to landslides. Three major landslide studies, some which have been funded through the Stillaguamish Watershed Action Plan, have been found to intersect with the DNR LHZ project lands and are summarized below (SIRC, 2004).

A Forest Resources masters thesis analyzing the hydrologic cumulative effects in the Stillaguamish watershed was completed in 1991 by Steven Toth. This study examined historical aerial photographs, climate data, and stream flow records to determine hydrologic cumulative effects within the South Fork of the Stillaguamish River. A total of 53 landslides were inventoried within this study, however, no landslides recorded in this study fall within DNR managed lands (Toth, 1991).

The Department of Ecology, in conjunction with the Stillaguamish Tribe of Indians, conducted an orphaned road inventory for the Stillaguamish River Watershed in 1993, funded by the Stillaguamish Watershed Action Plan. This report focused on inventorying road systems of all classifications (active, inactive, abandoned and orphaned) and to determine their susceptibility to mass wasting and erosion. Methods for road improvements, such as road drainage restoration and erosion control, are also mentioned within the report (Zander, 1993).

The most recent comprehensive landslide study in the Stillaguamish watershed was conducted by Daniel Miller for the Stillaguamish Tribe of Indians in 2004. This study used 2001 aerial photos to create a landslide inventory to correlate landslides to quantified landscapes, to determine slopes susceptible to mass wasting. 152 Landslides were categorized into landscapes. Of these landslides, 35 occurred within glacial landscapes and 117 in bedrock landscapes. No detailed landslide inventory map was included within the publication (Miller, 2004).

1.3 Summary of Methods

This assessment follows the Landslide Hazard Inventory Protocol dated July 13, 2005 (http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf), with minor modification.

Cadastral and archival topographic maps between 1884 to 1902 were used to determine pre-aerial photography logging activities, transportation routes, and areas affected by forest fires. The early General Land Office plat maps are the earliest map sources for the Silverton Watershed and are used as a basis for pre-settlement historical landscape. However, most of the logging activities, transportation routes, and areas affected by forest fires came from the 1899 1:250,000 USGS topographic map and the 1902 USGS Forest Service Map of Washington Showing Classification of Lands. These historical maps were scanned and entered into ArcGIS and georeferenced, in a methodology adapted from Collins and others 2003.

Five sets of aerial photographs acquired between 1958 through 2001 were viewed with a mirrored stereoscope with 3x magnification (Table 1). Unfortunately, some aerial photos were missing from DNR's collection in Olympia, resulting in incomplete flightlines. The 1958 aerial photos were taken during a time when thick snow blanketed the mountains. Because of the snow, shallow landslides were difficult to determine. Snow avalanches, however, were readily identified. 1998 color ortho-photographs coverage and 2003, 1-foot pixel color ortho-photos were used as a layer during GIS analysis and mapping. LIDAR was not available for this area.

Table 1. Photographic surveys used in this study.

Year	Scale	Image	Flight Number
1958	1:12,000	black and white	WSF-S8 17 to 28B
1971	1:60:000	black and white	NW-H-71 13B to 16A
1978	1:12,000	black and white	NW78 85A to 94D
1983	1:12:000	color	NWC83 20 to 27
1994	1:12,000	ortho-photographs	NWH94
2001	1:12,000	color	NWC01 41-73 to 53-82
2003	1:12,000	ortho-photographs	NWH03

Slope failures observed on the stereo photos were classified and catalogued according to the mass wasting feature type. For the purposes of this analysis, landslides that failed below rooting depth are categorized as deep-seated landslides (per the Forest Practices Board Manual); all remaining slides are classified as shallow landslides. The mass wasting feature types include shallow-undifferentiated landslides, debris flows, debris slides and avalanches, rock topple and fall, snow avalanche, and deep-seated landslides (including earthflows).

The mapped landslides were ranked according to their relative level of certainty as questionable, probable, or definite. Features with some combination of distinct head scarps, lateral margins, scoured run-outs, oversteepened toes, obvious deposits with hummocky topography, or vegetation patterns that indicate landslide disturbance were considered to be definite landslides. Features that were more subdued or concealed by vegetation than those mentioned above made identification of them as landslides less than certain, and were thus considered to be probable landslides. Features that resemble degraded landslides but could have been formed by non-mass wasting processes were considered questionable landslides (following Wieczorek, 1984). Most landslides were mapped from air photos; however several were identified in the field that were not evident on the photos, mostly in areas of heavy canopy or landslides that postdate the most recent photo set.

Following stereo air photo analysis, all observed landslides were mapped directly into GIS. Transfer of mapped features to a digital database was accomplished by "heads-up" digitization of landslides into a GIS map with layers that included streams, roads, townships, geology, and a USGS 10-meter digital elevation model (DEM) with DEM-derived contours, slope gradients, and hillshades.

Because LIDAR was not yet available for this area, the maximum resolution of this map base is about 10 meters (33 feet). Slope gradients and elevations of small failures that were identified on high-resolution air photos are not accurately estimated by the 10 m DEM due to raster data smoothing. Typically, DEM-derived slope gradients are underestimated by at least 10% relative to field-measured gradients (Dragovich and others, 1993), and more so on smaller features that are smoothed over by the DEM's coarse resolution. However, despite these limitations, the 10 m DEM was used in place of field measurements to estimate the gradients of landslides. It should be emphasized that all slope gradient estimates presented in this report are likely minimum approximations.

Slope gradients for shallow landslides were determined by calculating the maximum DEM-derived slope angle within each landslide initiation polygon. For deep-seated landslides, the average slope angle over the entire landslide polygon was calculated. We found that using the average slope gradient for deep-seated landslides provides the quickest and most reasonable representation of the pre-failure slope surface compared to other GIS slope measurement methods.

The air photo survey was also used to determine land use and to map rule-identified landforms (inner gorges, bedrock hollows, etc.). The 10m DEM and other GIS products were used to map low-hazard flat areas, low-gradient hillslopes, and ridgetops, according to the LHZ Protocol. The remaining land in the WAU was divided into analyst-described landforms. These landforms were identified from primary driving forces of mass wasting based on physical attributes of the landscape such as slope gradient, elevation, annual precipitation, lithology, and slope convergence. A combination of slope gradient and elevation data (derived from the 10m DEM), slope convergence data (derived from the DNR SLPSTAB model) (Shaw and Johnson, 1995), geologic data (from USGS 1:100,000 geologic maps), and precipitation and rain-on-snow data aided in the designation of these landforms. These landforms are intended to predict areas within the WAU that are at a particularly high hazard of mass wasting. Each landform was assigned a landslide frequency rate (LFR), a landslide area rate for delivery (LAR), and an overall hazard rating as called for by the LHZ Protocol.

2.0 Physical Setting Pertinent to Mass-Wasting Interpretations

2.1 Introduction

The Silverton watershed covers 46,387 acres in the Cascades, from the confluence of Wiley Creek and the South Fork of the Stillaguamish River in Snohomish County (Map A1) to the headwaters of the South Fork of the Stillaguamish River. The study area, however, only covers 3,746 acres of the watershed, or all land exclusive of U.S. Forest Service ownership. Numerous landslides crossed the U.S. Forest Service boundary and were included in map A-1 to improve the robustness of the hazard assessment on LHZ project lands within the watershed.

The watershed ranges in elevation from 1,200 feet at the confluence of Wiley Creek and the South Fork of the Stillaguamish River to 6,610 feet on the summit of Del Campo Peak.

Precipitation within the study area is high, averaging 70 inches of rain a year near Wiley Creek to over 160 inches a year near Del Campo Peak. 75% of the precipitation within the watershed occurs between October and March. Stream flows peak in late fall-to-winter. Rain-on-snow events most likely occur between 1,500 feet to 2,700 feet.

Rain-on-snow events have triggered widespread slope failures in many watersheds within the Cascade foothills (Sidle, 1985).

2.2 Topography

The South Fork of the Stillaguamish River drains the Silverton watershed from its headwaters in Eldridge Basin to Wiley Creek. Two major creeks, Boardman Creek and Mallardy Creek drain the northern Pilchuck Natural Resource Conservation Area (NRCA), from Bald Mountain to the South Fork of the Stillaguamish River. The Morning Star NRCA is drained by the South Fork of the Stillaguamish River and Wirtz Creek, a small tributary of the South Fork of the Stillaguamish River. Numerous lakes dot the Pilchuck NRCA, formed by alpine glaciation and mountain sagging (creating sag ponds).

Hillslope gradients range from flat (0%-10%) along the South Fork of the Stillaguamish River to sheer cliffs in the NRCA lands and the Hoodoo Patented Property. Alpine terrain and glacially carved valleys dominate the lands outside of the river valley.

Picture 1: The Hoodoo mine in Hoodoo Gulch. Picture by Bryce Parker.

2.3 Land use and Historical Considerations

General History

The Silverton Watershed is most commonly known today for its historical tale of failed mining towns and the ill-fated Everett and Monte Cristo Railroad. Access was first established from Silver Creek, as Joe Pearsall discovered a gleaming cliff of silver rich galena in the Monte Cristo area, east of the Silverton Watershed by about 6 miles. His discovery lead many other prospectors into this basin, not explored previously by European-American prospectors. In the summer of 1891, Abe Gordon and Fred Harrington located a ledge of pyritic ore, with significant amounts of gold and silver in Hoodoo Gulch, located between Big Four Mountain and Halls peak. They filed the first mining claim in the watershed, calling it the Hoodoo Mining Claim. Their discovery quickly led to a small rush of miners and prospectors into the area, eventually establishing the town of Silverton (previously known as Camp Independence) on August 26,1891. The name was quickly changed when the postal service refused to deliver mail to the area, fearing confusion with Independence, Oregon. By 1897, the town was exploding with growth and boasted, among other things, two lumberyards. Other major logging operations were also in the area around this time, such as the Gold Basin lumber mill, but are located on Forest Service lands. As the Everett and Monte Cristo Railroad was repeatedly washed out, the glory days of this mining town waned. Logging picked up once again when a road was established into the area in 1938, primarily on Forest Service lands (Northwest Underground Explorations (NWUE), 1997).

Hoodoo and .45 Patented Mining Properties

The Hoodoo patented property makes up 168 acres, and is one of the largest timbered lands outside of the DNR NRCA lands. This property is a combination of seven mineral claims and six millsites, which claims Hoodoo Creek, from its confluence with the Stillaguamish River to its headwaters between Big Four Mountain and Hoodoo Peak. The largest mine within the mining claim, the Hoodoo mine, is located in Hoodoo Gulch and accessed through a blasted out walkway in the cliff. The topography within the property is rugged. Hoodoo Gulch is incised into the bedrock, creating steep-to-vertical valley walls, in places more than 60 feet high. The lowlands consist primarily of outwash terraces and cliff topography. Shallow landslides are common on streams flowing down steep channels entrenched within the cliffs, but generally end on the flat benches.

Picture 2: Blasted out rock cut to access the Hoodoo Mine. Stillaguamish River in background. Picture by Bryce Parker.

The property changed hands many times, first under ownership, after the discovery by Abe Gordon and Fred Harrington, was the Sultan and Stillaguamish Mining Company. This land was eventually sold to Mr. Borque, whom he and his son aided in logging the property in the late 1960's and early 1970's. As Mr. Borque was running lines for the loggers, he suffered a heart attack and died. After his death, his widow sold the property to Mr. McCardy, who at the time owned the .45-patented mining claim.
Mountain Ram LLC of Enumclaw now owns this property. No further logging has been attempted on this land (Personal Communication, Daryl Jacobson, NWUE 2005; Hodges, 1897). The .45-patented mining property intersects the Silverton Watershed with 28 acres. The two intersecting properties are along the high ridgeline separating Williamson creek sub-basin with the headwaters of Marble and Silver creek. These high elevation lands contain little to no marketable timber. Little mining or timber harvest development has occurred on these properties (Lee, 1903; Pinkham, 1964; Huntting, 1956). Mountain Ram LLC of Enumclaw currently owns this land.

Boardman Creek Property

This property is located to the east of Boardman Creek and makes up 165 acres of the Silverton WAU. This property is largely wooded and has been logged twice, once in the late 1950's to early 1960's and in the late 1980's to early 1990's. This property transferred ownership in 2001, when the Trillium Corporation sold the property to IP

Forestry LLC. The Mountain Loop Highway passes through this property and landslides have to potential to deliver onto the highway.

Other Major Private Property along Stillaguamish River

Private property is located on or near the South Fork of the Stillaguamish River. Private property, from Wiley Creek to Boardman creek (excluding the Boardman Creek Property) is generally flat with little to no landsliding, except for small failures on terrace faces triggered by undercutting by the South Fork of the Stillaguamish River.

The property at the confluence of Gordon Creek and the South Fork of the Stillaguamish River is generally flat, but intersects the corner of the Gordon Ridge deep-seated landslide (see geology section).

The property is located on the flanks of Long Mountain, east of Martin Creek, and is a mixture of private owners and Triangle Recreational Camp Inc. It is flat near the South Fork of the Stillaguamish River, but quickly gains in steepness on the flanks of Long Mountain. Debris flows from above this property have traveled through the property to the South Fork of the Stillaguamish River.

Picture 3: Slot canyon 'inner gorge' within the Morning Star NRCA, tilting about 30 degrees. Picture by Isabelle Sarikhan

The town of Silverton lies on flat ground with little to no landsliding, except for small terrace-face failures triggered by undercutting on the South Fork of the Stillaguamish River (see appendix D).

Natural Resources Conservation Area Property

In 1987, the Natural Resources Conservation Area (NRCA) Act was passed, leading the way for much of DNR's land in the Silverton watershed to be categorized as a conservation area. Two major areas were identified, the Morning Star NRCA and Mount Pilchuck NRCA. Morning Star and Mount Pilchuck NRCAs make up 10,003 acres; however, only 3,065 acres are located within the Silverton Watershed (Washington Department of Natural Resources, 1992).

Mount Pilchuck NRCA

The Mount Pilchuck NRCA includes the lower southwest corner of the Silverton WAU and covers the land north of Bald Mountain. It encompasses subalpine terrain, including tarns, huckleberry-heather- rich meadows, and old growth Douglas fir and hemlock forests. This land remains undisturbed from mining and timber harvest and is an ideal location to understand natural landslide rates without human influence. Debris flows, debris avalanches and shallow landslides dot the landscape.

Morning Star NRCA

The northwest section of the Morning Star NRCA is located in the southeast part of the Silverton Watershed. The two main basins, Wirtz Basin and Eldridge Basin, comprise most of the timbered land within the NRCA. Wirtz Basin is well known for its Sunrise Trail to Headlee Pass, just shy of the Sunrise mine. Eldridge Basin is named after the Eldridge mine, located on the lower flanks of the Morning Star Peak to Del Campo Peak, to the south. These basins are predominantly glacially carved valleys with steep valley walls. Rock topples, debris avalanches, debris flows, and snow avalanches are common along the basin walls. Areas indicated as inner gorges and bedrock hollows are usually within bedrock, as the thin soils within this area apparently taking hold or quickly fail once formed. Inner gorges are unique within this area as they are formed more like slot canyons and the canyon walls are not always vertical, but can be angled (see picture 3).

Picture 4: Eldridge Basin, looking upstream towards Del Campo Peak. Picture by Isabelle Sarikhan

Forest History

Forests within the Silverton Watershed are predominantly western hemlock, Douglas fir, Sitka spruce, and western red cedar in the lower elevations and Pacific silver fir and subalpine fir in higher elevations. Deciduous trees can be found primarily in the lower elevations, most commonly red alder, vine maple and willow.

Forest fires occur in the Silverton WAU at intervals of 200 to 300 years. The last major fire in the area occurred 1508, where a large fire stretched from Canyon Creek up to the Silverton WAU (SIRC, 2004). Forest fires were observed early on as a potential problem in flooding and snowmelt. In Forest reserves: U.S. Geological Survey Annual Report, an excellent explanation on the effects of fires on snow melt and flooding was observed. 'The Stilaguamish [Stillaguamish] heads in somewhat higher mountains and has a recently burnt forest (burned in 1894) of about 15 square miles. To attribute the while flood on the Stilaguamish [Stillaguamish] to the burning of these 15 square miles of its forest would be erroneous, but, whether mere coincidence or cause and effect, the floods since the fire have been greater than those known before. It seems reasonable that fires should have such effects, for at moderate temperatures in higher altitudes it was found that on the wooded areas more of the snow was melted as it fell than in the openings. The covering of the trees seemed to keep the earth under them warmer. The water from this melted snow had filtered away gradually. The accumulated snow in the opening awaited a warm rain, or "chinook," which would melt it rapidly, and then the waters from both the rain and the snow would run off at the same time. At lower temperatures snow ceases to melt as it falls in the woods, and in spring the shading woods greatly retard the melting of snow. In the unburnt woods, too, the moss and litter is usually a foot deep and forms a great absorbent, acting as a sponge or reservoir and regulating the flow of the water. Fires destroy this sponge, as well as the trees, and the water from rain falling or snow melting on the bare surface has nothing to retard it.' (Gannet, 1900)

Logging has a long history within the Silverton WAU, beginning with numerous shake mills logging old-growth cedar throughout the watershed in the early 1900's to modern logging currently. Splash dams were abundantly used in the early 1900s along the South Fork of the Stillaguamish River, mostly to move shingle bolts. Logging has been sparse on lands managed by DNR. The Boardman Creek property was logged in the late 1950's to-early-1960's and recently, in the late 1980's-to-early-1990's. The Hoodoo Patented property was logged in 1970. No logging was found in the NRCA lands.

Historical Access and Transportation

The only major town to form within the Silverton WAU was the town of Silverton in 1891. A small pack trail was established prior to the railroad, but was difficult to navigate and stifled growth within the city. Major access into the area was established by the completion of the Everett and Monte Cristo railroad line in 1892, which greatly benefited the town of Silverton. Several major mines within the area, such as the .45 mine, the Hoodoo Mine and the Independence Mine, created a boom within Silverton, as prospectors and workers flocked to the city seeking riches. Miners working at the .45 mine accessed the Sultan Basin through Marble Pass, located to the south of the town of Silverton (Lee, 1903; Pinkham, 1964).

Severe storm systems and inadequate engineering plagued the Everett and Monte Cristo Railroad, repeatedly washing out the tracks in 1892 and 1897. The railroad was removed in 1936, when an automobile road was established up to the Big Four Inn, at the flank of Big Four Mountain. The road construction continued up to the town of Monte Cristo, and was completed in 1938. This remains the main access into the basin (Woodhouse and Wood, 1979; Northwest Underground Explorations, 1997). This road eventually became known as the Mountain Loop Highway.

Historical Weather Events

Historical records on storm events within Washington State were first recorded by European-American settlers in farming journals, dating back to the early 1850's. The major winter storms of 1860, 1861-1862, 1875, and 1880 most likely caused extensive flooding and mass movement, but no records exist for these storms within the Silverton WAU.

The first major recorded storm in the Silverton WAU rolled through the area in 1892, destroying some of the right-of-way being constructed on the Everett and Monte Cristo Railroad. An excerpt from The Everett and Monte Cristo Railway book has an excellent description of this storm:

"The lofty peaks around Silverton were already covered with fresh snow in November 1892, and the snowpack was growing each night. But, on November 16, Mother Nature's mood changed. The temperature rose rapidly, the wind began to blow out of the southwest, and for several days a fierce rainstorm raged. Both the Great Northern and Everett and Monte Cristo lines in the Snohomish Valley were under water in places. The Snohomish River ran 20 feet above the low-water mark – the highest it had been since 1872. The entire lower half of Snohomish City was flooded. The Great

Northern bridge at Snohomish was threatened, and every wagon bridge on the Everett and Monte Cristo tote road between Granite Falls and Silverton was washed away. In the canyon, water ran through tunnel #6, filling it with logs and debris. Cribbing and ballasting were washed away almost the entire length of the roadbed. One man drowned – a fellow named George Meader.

The *Engineer News* of October 5, 1893, said that in 1892 “great boulders were carried down and tossed about the canyon, striking against one another and the sides of the canyon grinding, grating, and clashing with a noise almost deafening.” (Woodhouse and others, 2000)

The storms of 1896 witnessed two storm events, one in November, and the other in December. An excerpt from The Everett and Monte Cristo Railway book has a detailed description of the storm event. “By November, snow was 6 to 10 feet deep and rains in the lowlands began to swell the rivers.

Downstream residents began preparing for floods, and ranchers started moving livestock to higher ground. But few, if any, residence expected the two days of warm Chinook winds that quickly melted the vast snowfields, turning the rivers and creeks into foaming torrents. On November 14, the Snohomish River was at the highest level ever recorded. In only a few hours, the river burst over its banks and turned the rich Snohomish Valley into an enormous lake. The lake rose so fast that much livestock was lost. Homes were flooded, and some were carried down the valley. Rail service and all nonfloating transportation came to a complete standstill. The next day, the river was 18 feet above normal.

Old-timers said it was much worse than the big flood of 1860, which had held the record. On November 16, temperatures began to drop, giving needed relief to the flood-ravaged lowlands and bringing snow to the mountains.”(Woodhouse and others, 2000)

In Forest reserves: U.S. Geological Survey Annual Report the November of 1897 storm was stated as a storm “greater than any known in the tradition of the Indians – flooding farms, drowning cattle, washing out roads and railroads and endangering lives. The losses approximated $10,000,000.” (Gannet, 1900)

The description continues: “Heavy, warm rains began the night of the [November] 16th and continued until noon of the 18th. At 10.00 a. m. on the 17th the Pilchuck was nearly full bank, and on the 18th, at noon, was considered unusually high. But before this the Stilaguamish [South Fork of the Stillaguamish] had rendered the Everett and Monte Cristo Railway impassable, with water 30 feet above its usual height in the canyon [Robe Canyon], running in fierce torrents through the tunnels and over the tracks. Punctuating the roar of the water, the boom of large bowlders [boulders] being rolled down the bed of the river could be heard and felt, while the angry, leaping torrent demonstrated its power to the eye by tearing out stone-filled cribbing, bending steel rails, and tossing heavy logs, even whole trees, in its muddy course. But the destruction caused was not very great.” (Gannet, 1900)

Another severe storm system triggered a large flood event during the winter of 1902, once again destroying tracks along the Everett and Monte Cristo railway, mostly from landsliding. The largest flooding was recorded on February 26, 1932, most likely a rain-on-snow event. A severe storm system swept through during the winter of 1943-1944 and caused severe flooding (Carithers and Guard, 1945). Another severe storm system swept through on February 9, 1951 and was most likely a rain-on-snow event.

The storm systems in November of 1990 and February of 1996 caused extensive flooding and slope failures within the WAU. Numerous debris flows and shallow landslides, mostly outside DNR regulated lands, were triggered by these storms.

Flow monitoring records listed on the USGS Water Resources website on the Stillaguamish River did not start until 1928 (USGS, 2005). Large peak flow events since the start of hydrologic monitoring occurred on February 26, 1932, February 9, 1951, Nov. 24, 1990, and Nov. 29, 1995. Canopy coverage and age deterred good aerial photo coverage for analysis of storm related slope failures.

2.4 Geology

<u>Regional Geology</u>

Regional bedrock that includes the Silverton watershed belongs to the Western Mélange Belt, part of the Western and Eastern Mélange Belts (WEMB) terrain. The WEMB includes Mesozoic (late Jurassic to early Cretaceous) marine sedimentary rocks, along with lenses of Paleozoic limestone, Mesozoic intrusives, and other rock types in fault-bounded bodies that were tectonically juxtaposed (Tabor et al, 1993). The WEMB rocks underwent high pressure, low temperature metamorphism in the late Cretaceous orogeny at about the time they were juxtaposed against the Northwest Cascade System terrain to the North.

Numerous faults trend northwest to southeast throughout the watershed. One major fault, the Darrington-Devil's Mountain Fault runs through the headwaters of the South Fork of the Stillaguamish River. Numerous landslides occur within the fault zone, potentially from bedrock that has been fractured due to fault movement.

<u>Local Geology</u>

Bedrock in the Silverton watershed is mainly composed of the Western and Eastern Mélange Belt (Phipps and others, 2003; Dragovich and others, 2002; Tabor and others, 1993). The oldest units in this watershed are derived from the Stillaguamish Ophiolite suite. Sedimentary rocks were deposited during the late Jurassic to early Cretaceous (170 to 100 million years ago) periods (Carithers and Guard, 1945). The older sedimentary rock formed from thick silt and mud deposited in a marine setting. This unit appears to have had subsequent submarine landslides, resulting in chaotic bedding called mélange (Tabor and others, 1993; Cowan, 1985). Most of the units in the Silverton WAU have been metamorphosed so such features are locally difficult to discern. Younger, continentally derived sediments, composed of mostly sand and gravel, of the late Cretaceous and early Paleocene lay unconformably on the older rocks (Hedderly-Smith, 1975). Peridotite (dark green to black plutonic rock) intruded around this time into the older marine sedimentary rocks. These rocks were then exposed to regional metamorphism (exposed to heat and pressure). The metamorphism changed the marine sediments into primarily argillite (metamorphosed siltstone), phyllite (metamorphosed mudstone) and chert (white to gray rock) (Yeats, 1964). Sedimentary continental rocks changed primarily into argillite, quartzitic sandstone and meta-conglomerates. Peridotite has metamorphosed into serpentinite (light green to dark green and black dense rock with waxy luster) and talc.

This unit was imbricated (thrust as slivers) into the North American plate by an accretionary wedge (Wells and Heller, 1988; Jett, 1986). The timing for this event is not well known, but is constrained to somewhere between early Cretaceous to the early Eocene (Tabor and others, 1993; Frizzell and others, 1987). This was primarily done by faults, many of the faults responsible for this imbrication can still be seen trending northwesterly within the WAU, where they form saddles and linear drainages. Most or all of these faults are no longer active. Severe folding also occurred during emplacement and tightly folded and truncated anticlines and synclines can be found throughout the WAU.

The Bald Mountain pluton is composed of granodiorite (light gray granitic rock) intruded into the area in the early to mid-Eocene (55 to 49 Ma). Contact metamorphism can be seen near the edges of the pluton and marine metamorphic rock, resulting in gneissic margins (light gray large grained metamorphic rock) (Dungan, 1974; Carithers and Guard, 1945).

Oligocene batholiths (Vesper Peak stock and the Index batholith) intruded into the Stillaguamish Ophiolitic suite (Tabor and others, 2002; Tabor and others, 1993). These intrusions are primarily composed of tonalite (light gray granitic rock). The Index batholith caused widespread hydrothermal alteration and metamorphism throughout the ophiolitic units in the Silverton WAU (Baum, 1968).

As the batholiths cooled, metalliferous solutions and meteoric waters flowed into the metamorphic sedimentary rocks, following cracks from the intruding batholiths, shear zones and faults. As these solutions lost pressure and temperature, they precipitated ore minerals in veins (Carithers and Guard, 1945). Due to the long history within the WAU of faulting, shearing and intrusion, no common structure exists for these veins to follow.

From Bald Mountain to the north, along the sub-alpine meadows from the Cutthroat Lakes to the Ashland Lakes, sackungen (mountain splitting) appear to be occurring. Steep linear scarps with linear lakes (sag ponds) indicate potential large-scale movement in a north-northwest direction, also the main direction of foliation among the bedrock (Thorsen, 1989).

Poorly-Consolidated Surficial Units

Surficial units in the Silverton WAU consist of continental glacial drift, alpine glacial drift, alluvium and talus. About 14,000 years ago, the Puget Lobe of the Cordilleran ice sheet, which represents the most recent advance of continental ice sheet, flowed into surrounding valleys. The deposits of this glaciation are called the ‘Vashon Drift’ locally. Tongues of the Vashon glacier dammed valleys that were tributaries to the Puget Lowlands, creating large ice dammed lakes. Continental glaciers advanced up the Stillaguamish River system and the Pilchuck valley, but failed to enter into the Silverton WAU. Continental glaciers blocked the paleo-Stillaguamish river, creating a large impounded lake, leaving valley filled deposits of fluvial (river) and lacustrine (lake) deposits. Alpine glaciation, however, was very active within the Silverton WAU, carving valleys and depositing layers of alpine till (Tabor and others, 2002; Booth, 1990).

As the glaciers retreated, the South Fork of the Stillaguamish re-established its channel as it cut into the fluvial and lacustrine deposits. Some of the largest landslides (such as the ones west and east of Wiley Creek) within the watershed were triggered by this sharp incision by the river.

Lacustrine deposits interfingering with glacial outwash are present from Wiley Creek to Martin Creek. Large deep-seated landslides are present throughout this material throughout the valley, from Wiley Creek to Martin Creek. Shallow landslides are common, especially where springs, streams, or where water is concentrated. Shallow landslides, especially near springs, can fail in gradients as low as 20%. Landslides, typically, fail at a much higher gradient within this area. (Sarikhan and Walsh, 2005). Boardman Creek has cut into the toes of two deep-seated landslides, creating numerous shallow landslides, debris avalanches and terrace failures.

Stability Issues

The Gordon Ridge deep-seated landslide, on the south flank of Gordon Ridge, stretch from Eldred Creek nearly to Martin Creek. This landslide is predominantly in glacial outwash, but Gordon Ridge is composed of eastern mélange belt meta-sedimentary rocks and intrusive meta-gabbro. The body of this landslide is more than 400 feet high. This landslide, due to the size and lack of impoundment, would suggest a very old age. However, the USGS 1899 Stillaguamish topography map fails to show this landslide.

Geologic units within this area have affected general slope stability. The marine metasedimentary units, present predominantly in the southwest section of the WAU in the Pilchuck NRCA, have beds striking around N20W with a variety of dipping beds (due to tightly folded and truncated anticlines and synclines). This unit has been observed in field and aerial photo interpretation to correlate with increased landslide activity, specifically when bedding is near vertical (Sarikhan and Pringle, 2005; Sarikhan and Walsh, 2005). Historical aerial photos show hundreds of debris flows that have occurred in areas where these geology factors are present. Meta-sedimentary beds within the Pilchuck NRCA are vertical in areas, specifically east of Bald Mountain, spawning large debris flows into the alpine meadows. Bedding that is dipping into the mountain or at angles that are not vertical has not been shown to produce intensive landsliding, but field verification should be considered in areas where this geology is present (Sarikhan and Pringle, 2005; Sarikhan and Walsh, 2005).

Continental metamorphic units observed within the watershed have high levels of failures in the convergent headwall basins in the Morning Star NRCA. These rocks trend along the peaks and ridges along the southeastern section of the watershed, from Gothic Peak and Headlee Pass to Del Campo Peak. The beds strike N15W to N20W and dip from vertical at Headlee Pass (Carithers and Guard, 1945).

Altered ultramafic rocks (peridotite and serpentinite), although it has not locally been shown within this study to cause slope instability, has created major slope stability issues in other areas (for example, Blewett Pass). Ultramafic rock can occur in pockets throughout the watershed (Tabor et al, 1993).

Tonalite (light gray granitic rock) from the Index Batholith and Vesper Peak Stock have caused major rock topples to occur within the watershed. A prominent feature present within the rock is three strong joint planes. These planes can aid in rocks breaking into rectangular blocks or wedges, as large as 15 feet on each side (Carithers and Guard, 1945). Most rock topples recorded within the watershed were independent of harvest or road construction and are generated by erosion of the basin. One major deep-seated rock avalanche was located on the flanks of Morning Star peak. Two major deep-seated rock avalanches that were located in the Sultan Basin have led to the belief that these deep-seated rock avalanches have been seismically triggered. Large regional earthquakes could generate major rock topples within the Silverton watershed in the future (Sarikhan and Walsh, 2005).

3.0 Summary of Landslide Inventory

Most of the landslides were recorded from a review of 1958 to 2003 aerial photo and field investigations (Form A-1). The landslides were rated as ‘questionable’ to ‘definite’, depending on their size and the amount of canopy coverage. The aerial photos were also used to determine the land-use and delivery, as well as the landform features. All landslides were recorded into a GIS coverage to aid in identifying their delivery potential, slope shapes, gradient and elevation. The information from these landslides, once inventoried and mapped, was used in the creation of the landform map (Form A-2).

Mass Wasting Feature Type	Number of Mass Wasting Features Mapped	Area (acres) of Mass Wasting Features
Shallow undifferentiated landslides	86	7.8
Debris flows	118	68.6
Debris slide/avalanche	9	1.6
Rock topple/fall	10	36.9
Snow Avalanche	0	0.0
Deep-seated landslides	13	1722.9
Total	236	1837.8

Table 2. Summary of the type and number of LHZ Protocol-specified mass-wasting features mapped in the Silverton WAU.

This assessment found that 12% of the mass wasting features identified were located in *landuse type*, including harvest and road failures. Land use was determined for each feature (Appendix B). The majority of landslides, 88%, occurred in alpine conditions, in areas with little to no harvest or road construction.

For the purposes of this study, most landslides that failed below rooting depth are categorized as deep-seated, consistent with the Forest Practices Board Manual. Those deep-seated landslides that moved rapidly and clearly deliver sediment are included in the analyses of sediment delivery.

In reviewing the Silverton WAU, a representative sample of 236 landslides was recorded in DNR regulated lands. Of these landslides recorded on LHZ Project lands, 213 were shallow landslides, 13 deep-seated landslides, and 10 rock topples. Snow avalanches were present within both the NRCA project lands and some of the higher elevation properties. Hundreds of these snow avalanches were recorded for just one flight year. Due to time considerations, it was determined that it would be easier to block out lands that experience high concentrations of snow avalanches. 213 of these landslides were interpreted to have delivered sediment and were used in construction of the overall hazard ratings (Form A-4). 207 of these landslides were not road related and were used to construct hazard ratings for harvest and other related forest practice uses. No deep-seated landslides were included in these calculations, but their locations and statistics are presented within this report. These deep-seated features should be evaluated during field visits. A quick review of Form A-1 should determine whether the deep-seated landslides were identified as 'definite', 'probable', or 'questionable' and their activity level. Deep-seated landslides can range in age from about 14,000 years (glacial related deep-seated landslides) to presently active. Toes and scarps should also be carefully evaluated even in dormant and extinct landslides in case of reactivation. Active deep-seated landslides are predominantly in glacial material, from fine-grained lakebeds and are located on Boardman Creek. The one active bedrock deep-seated landslide occurs near the Darrington-Devils Mountain fault zone, in material consisting phyllite and argillite. Dormant to relict glacial deep-seated landslides are located in glacial material, consisting of fine-grained lakebeds, ice-contact deposits and recessional outwash deposits. These landslides are located in or near the valley floor of the South Fork of the Stillaguamish River. Dormant to relict bedrock deep-seated landslides occur in material consisting predominantly of marine meta-sediments, primarily argillite and phyllite.

High densities of snow avalanches were observed in the Pilchuck and Morning Star NRCA lands, as well as the Hoodoo property at its higher levels. Slopes most ideal for avalanches to be triggered are between 25 and 60 degrees, with 38 degrees being the peak triggering angle. Slopes most common for avalanches are planar and convex slopes, but convergent slopes can fail as well.

The most active and potentially dangerous landforms in this watershed are glacial lakebeds, bedrock hollows, and inner gorges. These features have spawned numerous deep seated landslides, debris avalanches, shallow rapid landslides and debris flows, most of which delivered to major rivers or creeks that flowed directly into the South Fork of the Stillaguamish River. Major storm events have been shown to cause severe instability and deliver a large amount of sediment. Caution should be used in road construction and harvest anywhere near these features. Water concentration on glacial lakebeds has caused numerous failures and should be avoided at all cost.

One of the landforms present within this watershed, landform 7, has been continued into this watershed from the Spada Lake LHZ assessment (Sarikhan and Walsh, 2005). Review of the Spada Lake WAU report and maps will be extremely useful in delineating hazard in these areas.

4.0 Landforms

The Silverton WAU has been delineated into 11 landforms that characterize areas having similar features and identified through the Landslide Hazard Zonation Project Protocol. Landforms are based on a number of characteristics, such as geology, hydrology, geomorphology, topography, and landslide characteristics. The first landforms to be delineated were low slope areas with no evidence of mass wasting. These landforms have been split into flats (0% to 10%), low gradient hills (10% to 40%), and ridgetops (0% to 10%). Four named landforms (also known as rule-identified landforms), inner gorges, bedrock hollows, convergent headwalls, and toes of deep-seated landslides were delineated by slope and convergence. The remainder of the area was then delineated by lithology, delivery potential, and slope gradient and forms. These include high gradient hills (40% and greater), bodies of active deep-seated landslides, scarps of active deep-seated landslides, and glacial lakebeds.

One of these landforms, glacial lakebed deposits, is also present within the Spada Lake WAU and has similar hazards and conditions (Sarikhan and Walsh, 2005). The following section presents the results of this investigation (4.2 landform description), which has been split into low and high-hazard potential landforms. High-hazard landforms will require careful review and field investigation.

A note should be added regarding the Pilchuck NRCA land. From the flanks of Bald Mountain and its ridges to Boardman Creek, this area has experienced 'mountain sagging', sometimes referred to as sackungen. This area (see figure 1) has many features that can be mistaken for other features, such as scarps of deep-seated landslides and sag ponds. Many of these scarps experience slow creep and trees may reflect this with bent trunks. Review of sackungen before placing timber harvest or road construction would be useful. (for further reading: Clague and Evans, 1994; Thorsen, 1989; Anderson and others, 1980; Dohrenwend and others, 1978; Tabor, 1971)

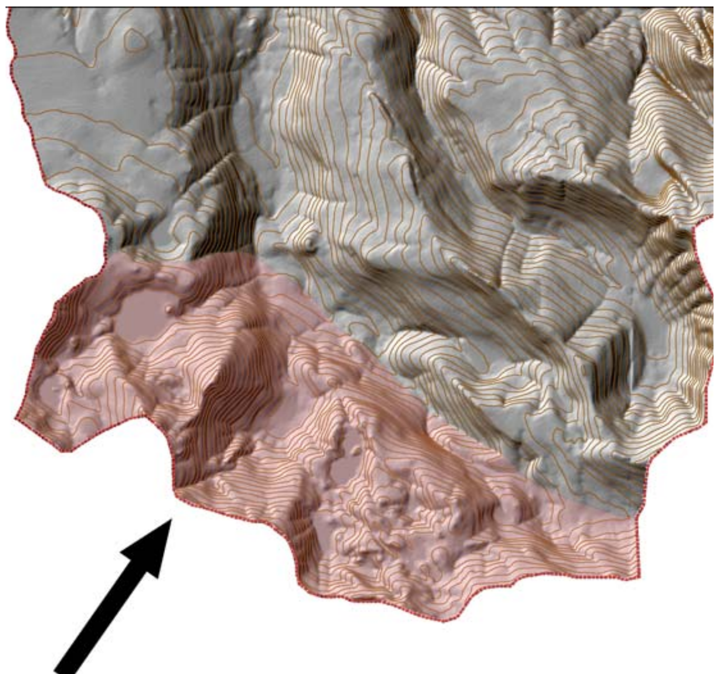

Figure 1: The area highlighted in red is the area currently experiencing mountain sagging. The arrow indicates the general direction of this movement.

4.2 Landform Descriptions
Low Hazard Descriptions (Landforms 1 through 3)

LANDFORM NUMBER:	**1**
LANDFORM NAME:	**Flats**
OVERALL HAZARD:	**Low**

Description:

Landform 1 (Alluvial Plains) consists of level (0-10%) slopes of recent alluvium of the South Fork of the Stillaguamish River (Geologic Unit: Qa), glacial outwash (Geologic Unit: Qgo), glacial till (Geologic Unit: Qgt), and glacial lakebeds (Geologic Unit: Qgl). Small, non-delivering landslides were found on small terraces, but present little danger to harvest or road construction. Landslide Rate Delivery is low. Confidence is high.

LANDFORM NUMBER:	**2, 3**
LANDFORM NAME:	**Ridge Tops, Ridge Noses and Low Gradient Hills**
OVERALL HAZARD:	**Low to moderate**

Description:

Landform 2 (Ridge Tops and Ridge Noses) and 3 (Low Gradient Hills) comprise low hill slopes (10-40%) as well as ridge tops and noses of glacially carved hills. Some minor landslides have occurred along these hills but do not constitute a danger to harvest practices. Confidence is high.

Moderate to High Hazard Descriptions (Landforms 4 through 13)

4 – High Gradient Hills

Description of Mass Wasting Unit: Landform 4 consists of high gradient hillslopes above the valley floors (over 40% gradient) to the rugged vertical alpine cliffs. Much of this area has experienced alpine glaciation, creating steep valley walls and alpine lakes.

Slopes: Greater than or equal to 40%
Slope Shape: Convergent (Predominantly) and Planar
Material: High gradient hills occur in all rock types in this watershed
Elevation: 1,500 to 6,000 feet
Total Area: 1,678acres

Mass Wasting Process: Shallow landslides occur owing to saturated soils and high gradient hills. Shallow landslides have been observed to initiate debris flows that can flow into the valley floor, carrying rocks and woody debris. Deep-seated landslides occurred in the area and at least one active deep-seated landslide has been observed in this landform. Numerous rock topples and snow avalanches have been recorded in this landform. Landslides start at 50% slopes and increase in density at higher slope gradients.

Forest Practice Sensitivity: Many of the shallow landslides occurred in clear cuts at gradients from 50% to greater than 70%. Hill slopes above 70% did not appear to be harvested and were considered failing due to steepness and thin alpine soils. Landslides will continue in these areas, especially in the higher gradients, regardless of harvest.

Mass Wasting Potential: Very High regardless of forest practices activities
Based on 57 shallow landslides within a total failed area of 9 acres, this landform has a very high rate of failure with shallow landslides. Disturbance could reactivate relict deep-seated landslides as well as initiate new shallow landslides, especially at higher elevations where there is little soil depth. This landform has a Landslide Frequency Rate of 1,258 with or without roads.

Delivery Potential/Criteria: High. Failures that occur within this landform deliver to tributary streams and into the main channel of the South Fork of the Stillaguamish River. This landform has a Landslide Area Rate of Delivery of 200 with or without roads.

Hazard Potential Rating: Very High for roads and **Very High** for harvest based on LHZ Protocol and standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with field foresters, and field observations. There was limited field verification of landslides within this landform.

5 – Body of Deep Seated Landslide (Active)

Description of Mass Wasting Unit: Landform 5 consists of the bodies of active deep-seated landslides, primarily in glacial lakebed material. The majority of deep-seated landslide activity is located east of Wiley Creek in fine to coarse grained glacial material. One active deep-seated landslide is located on the upper flanks of the Hoodoo Property.

Slopes: 50% to 90+%
Slope Shape: Convergent to Planar
Material: Predominantly fine grained glacial lakebeds
Elevation: 3,080 to 3,580 feet
Total Area: 8 acres

Mass Wasting Process: Deep-seated landslides located along Boardman Creek have few shallow landslides on the body of the deep-seated landslide due to the low angle. Toes of these deep-seated landslides are actively undercut by the creek with small shallow landslides failing into the creek. Rapid movement can occur with persistent erosion, partially blocking the creek.

Forest Practice Sensitivity: Increased water run-off on the deep-seated landslide has been found to be a factor in increasing activity of deep-seated landslides. Timber harvest, road construction and/or landing construction should be done with caution, for disturbance can trigger shallow and deep-seated landslides. Water should be redirected off this feature if possible.

Mass Wasting Potential: Moderate for road construction and timber harvest. Because these features are associated with active deep-seated landslides, they are at a higher risk for failure and potential for reactivation of slide activity. This landform, by calculation, has a Landslide Frequency Rating of low, however is considered moderate due to the potential hazard.

Delivery Potential/Criteria: Moderate. Shallow slide failures on the body of deep-seated landslides area have a low potential of delivery into Boardman Creek; however, toe undercutting could cause a rapid failure into the creek.

Hazard Potential Rating: Moderate for roads and harvest based on LHZ Protocol and standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with field foresters, and field observations. Careful field review will be necessary to delineate all the areas containing increased risk of failures within these features, because field investigation has located a number of features masked by canopy.

6 – Toes and Scarps of Deep Seated Landslides

Description of Mass Wasting Unit: Landform 6 consists of the toes and scarps of deep-seated landslides, predominantly in glacial material. As the slides flow into Boardman Creek, the toes are actively cut into, which can increase slope instability. This produces numerous shallow rapid landslides and debris avalanches.

Slopes: Greater than or equal to 65%
Slope Shape: Convergent and Planar
Material: Predominantly fine grained glacial lakebeds
Elevation: 2,000 to 3,800 feet
Total Area: 8 acres

Mass Wasting Process: Deep-seated landslides located along Boardman Creek have numerous shallow landslides on the toes and scarps of the deep-seated landslide due active movement and the undercutting of the toes. Rapid movement can occur with persistent erosion, partially blocking the creek.

Forest Practice Sensitivity: Increased water run-off on the deep-seated landslide has been found to be a factor for increased activity of deep-seated landslides. Timber harvest, road construction and/or landing construction should be done with some caution. Water should be redirected off this feature if possible.

Mass Wasting Potential: High for road construction and timber harvest. Toes over 65% are rule-identified in the LHZ Protocol and are high hazard. Scarps also poise a danger to failure, but are not rule-identified. No shallow landslides were recorded on these features, but small failures were observed in the field. Because these features are associated with active deep-seated landslides, they are at a higher risk for failure and/or potential for increased slide activity.

Delivery Potential/Criteria: High. Landslides on the scarps and toes of deep-seated landslides near Boardman Creek have a very high potential of delivery. Deep-seated landslides located in other areas of the watershed can occur near to tributary systems and will flow into the South Fork of the Stillaguamish River.

Hazard Potential Rating: High for roads and harvest based on LHZ Protocol and Standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with field foresters, and field observation.

7 – Glacial Lake Bed Deposits

Description of Mass Wasting Unit: Landform 7 consists of glacial lakebeds formed during the blockage of the paleo-South Fork of the Stillaguamish River by the continental ice sheets. These lakebeds can be very unstable and can potentially fail without harvest, road building, or human activity. Harvest and specifically water concentration has spawned numerous shallow and deep-seated landslides.

Slopes: Greater than or equal to 50% (failures where water is concentrated can fail in as little as 20% slopes)
Slope Shape: Convergent and Planar
Material: Predominantly fine grained glacial lakebeds
Elevation: 1,200 to 1,500 feet
Total Area: 162 acres

Mass Wasting Process: This landform is prone to deep-seated earth flows and shallow landslides, especially in areas where water concentrates, such as the valley surrounding Boardman Creek. The deep-seated earth flows cover large amounts of area near Boardman Creek. Shallow landslides were predominantly caused by water concentration, under-cutting, and roads.

Forest Practice Sensitivity: This landform is potentially unstable because of layers of weak clay and silts, formed by a large glacial lake. Surface water can greatly impact slides in this area and should be redirected off of this landform. Road construction has been observed to cause an increase in landslide failures. Harvest can increase sediment transportation, especially if harvested during the rainy season.

Mass Wasting Potential: Very High for road construction and for timber harvest. Based on 21 shallow landslides and numerous deep-seated landslides with a total amount of area failed at 5 acres, this landform has a high density of shallow landslides on roads and disturbance could reactivate or increase activity of deep-seated landslides as well as initiate new slides. The landform has a Landslide Frequency Rating of 4,800 with roads and 3,400 without roads.

Delivery Potential/Criteria: Very High. Landslides produced within this landform have caused water quality issues by delivering high amounts of sediment into the South Fork of the Stillaguamish River. Water from springs and streams within this landform have been observed to carry large loads of sediment without disturbance. Delivery criteria are also based on historical occurrences of landslides observed on aerial photographs and confirmed during field investigations. The unit has a calculated Landslide Area Rate of Delivery of 1,240 with roads and 1,180 without roads.

Hazard Potential Rating: Very High for roads and for harvest based on LHZ Protocol and Standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with field foresters, and field observations.

8 – Convergent Headwalls

Description of Mass Wasting Unit: Landform 8 consists of rule-identified convergent headwalls that are steep (>70%) concave basins. Gradual accumulation of colluvial debris over long periods and convergence of surficial and shallow ground water make bedrock hollows and other slopes within convergent headwalls highly susceptible to failure. Convergent headwall basins are located within the Morning Star NRCA and small stretches of the .45-patented mining property. These basins were formed by alpine glaciation carving the valleys followed by fluvial cutting.

Slopes: Greater than or equal to 70%
Slope Shape: Convergent and Planar
Material: Predominantly marine metasedimentary rocks and glacial drift
Elevation: 3,200 to 5,600 feet
Total Area: 337 acres

Mass Wasting Process: This landform is prone to repeated shallow rapid landslides and debris slides, both of which can transform into debris flows. Thin soils and nearly vertically foliated metamorphic rock combined with high amounts of precipitation makes this landform extremely susceptible to repeated failures, particularly during and after extreme storm events. Some of these landslides do not appear to be related to harvest or road construction, but failed due to the natural instability.

Forest Practice Sensitivity: Harvest and road construction are not present within these units, however historically in other watersheds, road construction and harvesting has increased landslides within these features.

Mass Wasting Potential: Very High regardless of forest practices activities. Based on 26 shallow landslides having a total area of 9.6 acres, this landform has active slope instability and disturbance could activate massive debris flows that can travel to the South Fork of the Stillaguamish River. All 26 landslides were naturally occurring. 26 of these landslides delivered. This landform has a Landslide Frequency Rate of 2,860 with or without roads.

Delivery Potential/Criteria: Very High. Failures that occur within this landform usually deliver to streams that directly flow into the South Fork of the Stillaguamish River. Due to the high amount of rainfall, any failure within this landform will probably deliver to a stream. This landform has a Landslide Area Rate of Delivery of 1,055 with or without roads.

Hazard Potential Rating: Very High for Roads and for harvest based on LHZ Protocol and standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with DNR field foresters, and field observations.

9 and 10 - Inner Gorges and Bedrock Hollows

Description of Mass Wasting Unit: These landforms consist of inner gorges and bedrock hollows. Bedrock hollows are steep (>70%) spoon shaped depressions or swales 75 to 200 feet across. The inner gorges are steep walled (>70%) gullies formed by a combination of stream action and mass wasting. Bedrock hollow evacuations can trigger debris flows that scour channels forming inner gorges.

Slopes: Greater than or equal to 70%
Slope Shape: Convergent
Material: Inner gorges and bedrock hollows occur in all rock types in this watershed
Elevation: 1,600 to 5,400 feet
Total Area: 251acres (landform 9) and 86 acres (landform 10)

Mass Wasting Process: These landforms are prone to repeated shallow landslides (shallow rapid landslides and debris flows). Shallow landslides within the bedrock hollow and inner gorges can initiate debris flows. These landforms can be located on deep-seated landslides, which can increase instability of these landforms.

Forest Practice Sensitivity: These landforms are naturally unstable, especially when there is a concentration of water on steep slopes. Water can greatly impact landslides in this landform and should be redirected off of this landform. Extreme storm events and prolonged rain have caused landslides to occur and will continue to fail in these conditions.

Mass Wasting Potential: Very High regardless of forest practice activity based on 72 (landform 9) and 37 (landform 10) landslides totaling 54 acres of failed material. The inner gorges (landform 9) have a Landslide Frequency Rating of 10,600 with or without. Bedrock hollows (landform 10) have a Landslide Frequency Rating of 15,900 with or without roads.

Delivery Potential/Criteria: Very High. Inner gorges and often bedrock hollows are part of the drainage network and are adjacent to or contain streams. Delivery criteria are also based on historical occurrence observed on aerial photographs and confirmed during field investigation. Inner gorges have a Landslide Area Rate of Delivery of 6,200 with or without roads. Bedrock hollows have a Landslide Area Rate of Delivery of 5,000 with or without roads.

Hazard Potential Rating: Very High for roads and harvest based on LHZ Protocol and Standard Forest Practices Rules.

Confidence: High, based on the number of landslides located in this landform, excellent photo quality and coverage, communication with field foresters, and field observation. There was limited field verification of landslides within this landform.

5.0 Hazard Ratings

Pursuant to the LHZ Protocol, hazard ratings for mass-wasting landforms were determined by the following: 1) rule-identified status (WAC 222-16-050), 2) the Landslide Frequency Rate (LFR) and Landslide Area Rate for Delivery (LAR), 3) the professional judgment of the analyst, or 4) an interpretation of deep-seated landslide hazard. The Landslide Area Rate for Delivery is the area of delivering landslides normalized for the period of study and the area of each landform. These values are then multiplied by one million for easier interpretation. Limited application suggests that Landslide Area Rates for Delivery less than 76 are low hazard, rates of 76 to 150 are moderate hazard, rates of 151 to 799 are high hazard, and rates greater than 799 are very high hazard (Lingley, 2004). Note that higher Landslide Area Rates for Delivery can be achieved by reducing the area of the Landform. While this may appear to be 'data gerrymandering', it helps limit the area of high-hazard landforms to those areas that are actually demonstrated to have high hazard. The Landslide Frequency Rate is calculated similarly, however the number of delivering landslides is used instead of the area of delivering landslides. As of the writing of this report, the qualitative rating system below is used (Table 3). Form A-4 (Appendix D) summarizes all landform hazard ratings.

Qualitative Ratings	Landslide Frequency Rate	Landslide Area Rate for Delivery
Low	< 100	<76
Moderate	100 to 199	76 to 150
High	200 to 999	151 to 799
Very High	>999	>799

Table 3: Qualitative rating system for the LFR and LAR.

6.0 Note on Confidence in Work Products

The confidence in this mass wasting assessment is <u>High</u>. This rating is based on the Landslide Hazard Zonation Project design to provide a watershed overview of slope stability in a timely manner with minimal field verification. As a consequence, fieldwork and the number of aerial photograph sets examined are held to reasonable minimums. Omissions will be present due to the limited field verification of individual features, particularly in forested areas with heavy canopy.

It is critical for the reader to understand that while these decisions are sufficient to characterize aspects of the slope failure as functions of forest management, <u>this assessment would be entirely insufficient and misleading if it is used as a stand alone document for protecting private and public resources or for land use planning.</u> Keep in mind that this is only a reconnaissance study, and <u>undoubtedly, some landslides have been omitted and some benign features may be incorrectly mapped as landslides herein</u>.

In addition, there are several sources of systematic error that reduce the confidence in the work products of this analysis, those being omission, misinterpretation, and limits to accuracy and precision. Omission occurs when mass wasting features are not identified on aerial photographs or in the field due to canopy cover, gaps in the aerial photo record, quality of aerial photos, or interpreter errors. Misinterpretation occurs when a mass-wasting feature is identified but incorrectly classified or data are transposed, and where unrecognized software/file instability occurs. Accuracy involves the degree to which the physical parameters of a mass-wasting feature are correctly measured, and precision describes how variability within an assessment can be controlled when making multiple measurements over varying time and spatial scales.

This mass wasting assessment was primarily conducted with aerial photographs, and as a result, there is a high likelihood that errors of omission occurred, primarily in areas covered by mature forest canopies, steep north facing slopes always in shadow at any given time, and those areas covered with extensive glacial deposits (Brardinoni and others, 2002). The scarcity of mass wasting features identified under mature canopy and steep north slope aspect shadow conditions is not necessarily an indication of the relative stability of slopes with mature vegetation regimes or steep north face aspects.

Because many deep-seated landslide features are quite large, remain heavily vegetated during movement, and may not have obvious scars visible through the vegetation canopy, misinterpretation is more likely. A recent detailed study in Cowlitz County, Washington, suggests that up to 25 percent of inferred deep-seated landslides identified from aerial photograph analysis are misinterpreted (Wegmann, 2003). Confidence in work products related to classification of deep-seated landslide processes in this watershed is high due to visibility and completeness of photo coverage.

Another important source of potential error in this assessment is in the accuracy and precision of measurements of mass wasting features. Because less than 50% of landslides were actually visited in the field, it is not possible to report the degree to which location and measurement error in the GIS environment compares to on-the-ground field measurements. Similarly, measurements of slope angle from digital elevation models typically misrepresent the true hill slope angle. Given these sources of error, the confidence in the precise location and accuracy of measurements of individual landslides is considered moderate.

Acknowledgments

Funding for this project was provided by a Federal Salmon Recovery grant, administered through the Washington Interagency Commission on Outdoor Recreation. Technical oversight of this project was provided by the Upslope Processes Science Advisory Group (UPSAG), a subcommittee of the Cooperative Monitoring, Evaluation and Research (CMER) group. The following people have greatly contributed to this project (and special thanks given to): Dave Parks of DNR Forest Practices for his edits of this report. Bryce Parker for his aid in the field. Jack Powell of DNR Forest Practices and Lorraine Powell of DNR Geology shared many insights about landslides, field aid and the LHZ project. Laura Vaugeois of DNR Forest Practices for her extensive knowledge on GIS, landslides, and forest practices rules. Lee Walkling of the DNR Geology Library for her help in identifying reference material. Tim Walsh of DNR for his aid in mentoring me on this project, insight in the field, much appreciated help with aerial photos and careful review and editing, which has significantly improved this manuscript. Kelly Warren of the DNR Forest Practices for her assistance in obtaining aerial photographs.

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