MUD MOUNTAIN WATERSHED

LANDSLIDE HAZARD
ZONATION PROJECT


Photo taken by Pat Pringle

King and Pierce Counties, Washington

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in coordination with the
Washington State Division of
Geology and Earth Resources

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Mass Wasting Assessment
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WASHINGTON STATE DEPARTMENT OF
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DISCLAIMER

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Project Summary

The Mud Mountain watershed administrative unit (WAU) drains both sides of the White River valley from Enumclaw eastward about 8 miles to the Clearwater River drainage. This analysis divided the 34,149-acre watershed into 15 mass wasting landforms that were assigned slope stability hazard ratings from low to very high. During this study, 875 landslides covering 2,932.62 acres were mapped using aerial photos and lidar (light detection and radar) imaging. Mapped landforms (summarized in Table 1) include those high hazard units defined in the Washington State Forest Practices Rules such as: inner gorges, bedrock hollows, convergent headwalls, outsides of meander bends, and toes of deep-seated landslides. Other high hazard landforms include; active deep-seated landslides, steep terrace faces (>60%), and steep hillside slopes (> 70%). Moderate to steep hillsides slopes (41% to 70%) were found to have a slope stability rating of moderate.

Landform number	Name of landform	Landform slope stability hazard rating	Slope of landform	Total area of landform in acres	**No. of delivering landslides in landform**	Comment
#1	Inner Gorges	Very High	>70%	340	45	FP rule-identified High Hazard
#2	Bedrock Hollows	High	>70%	84	7	FP rule-identified High Hazard
#3	Toes of Earthflows and Deep-seated	High	>65%	260	11	FP rule-identified High Hazard
#4	Steep Terrace Faces (>60%)	High	>60	164	15	
#7	Convergent Headwalls	High	>70%	9	1	FP rule-identified High Hazard
#8	Active Deep-seated Landslides	High	N/A	223	6	LHZ Protocol High Hazard
#9	Outside Edge of Meander Bends	High	>24	43	3	FP rule-identified High Hazard
#10	Valley & Stream Bottoms	Low	<11%	1,216	0	LHZ Protocol Low Hazard
#11	Ridge Tops & Noses	Low	<11%	619	0	LHZ Protocol Low Hazard
#12	Mud Mountain Reservoir Valley Stream Bottom	High	<11%	308	12	Unique landform to this watershed (on federal land)
#13	Mud Mountain Reservoir Steep Terrace Face (50% and greater)	High	>49%	807	144	Unique landform to this watershed (on federal land)
#14	Terrace Top (<11%)	Low	<11%	8,600	3	Unique landform to this watershed
#15	Steep Hillside Slopes (>70%)	Very High	>70%	1,679	63	Steep area near bedrock hollows and inner gorges
#16	Low Gradient Hillside Slopes and Valley Side Slopes (11 to 40%)	Low	11 to 40%	14,795	60	
#17	Moderate to Steep Hillside Slopes (41 to 70%)	Moderate	41 to 70%	5,015	91	
	Totals			34,162	461	

Table 1. Summary of the 15 landforms mapped in the Mud Mountain watershed.

2.0 Introduction

The Mud Mountain watershed covers 34,149 acres extending from the eastern side of the Puget Lowlands to the foothills of the west-central Cascade Range. The area is roughly divided in half by the White River and the river is the dividing line between King and Pierce Counties. White River headwaters begin at the Emmons and Frying Pan Glaciers on the north side of Mt. Rainier and flow for 68 miles before draining into the Puyallup River. The White River owes its name to the abundance of glacial rock flour in the water coming from the melting glaciers.

The majority of the watershed (31,846 acres) is in private and state ownership; much of it is owned and managed by Hancock Forest Management. Most of this watershed is managed as timberlands. A total of 1,545 acres comprises the Mud Mountain Dam and Reservoir, managed by the U.S. Army Corps of Engineers. The U.S. Forest Service and Clearwater Wilderness Area manage 758 acres along the southern tip of the watershed. The western edge of the watershed includes portions of the towns of Buckley and Enumclaw. All areas and ownerships in the watershed have been included in this study for a comprehensive view of landslide assessments.

Within the western portion of the watershed, the lower White River occupies a broad, flat-floored valley that freely passes moist air while the upper tributaries have more narrowly constricted valleys that force air to rise and produce precipitation. The average annual precipitation at the Mud Mountain Dam is approximately 60 inches (Western Regional Climate Center). Annual precipitation data on the DNRGIS indicates that precipitation ranges from 45 to 90 inches.

Every year winter storms trigger landslides within the Mud Mountain watershed. The White River gauging station near Buckley measures stream flow peaks that usually occur in late fall to late spring. The timing of peak flows at Buckley is due to stream flow regulation by Mud Mountain Dam to prevent flooding in the Puyallup valley. Stream flow data is shown in Appendix F, Figure 2. Landsliding along terrace faces upstream from the dam is attributed to hydrologic fluctuations affecting pore pressure. Rain-on-snow events usually occur on slopes between 1,500 to 3,500 feet. Rain-on-snow events have triggered widespread slope failures in many watersheds within the Cascade foothills (Sidle, 1985). The highest recorded precipitation occurred during the winter of 1996-1997 (Appendix F, Figure 1) and produced many landslides. Other related historic information regarding climate can be found in Appendix F.

3.0 Topography

Elevation in the Mud Mountain watershed ranges from approximately 620 ft along the western boundary adjacent to the White River floodplain to 5,050 ft at the top of The Three Sisters mountains at the southern tip of the watershed (Figure 1). The western side of the watershed is part of the Puget Lowland and is a relatively flat plain. To the east are small bedrock hills and remnant glacial terraces covered by lahar deposits. The White River flows along the south side of a broad, mature valley at the front of the Cascade Range referred to as Scatter Creek Flat. The flat extends southward as a finger toward the White River, which the flat constricts. The southernmost part of the constriction is named Mud Mountain where bedrock is exposed; the remainder of Mud Mountain contains Pleistocene sediments (Anderson, 1954). Steeper terrain surrounds the tributaries to the north and south of the White River. These include Grass Mountain to the north and The Three Sisters to the south. These steeper areas have been molded by erosion, by alpine glaciers, and mass wasting, creating the current topography.

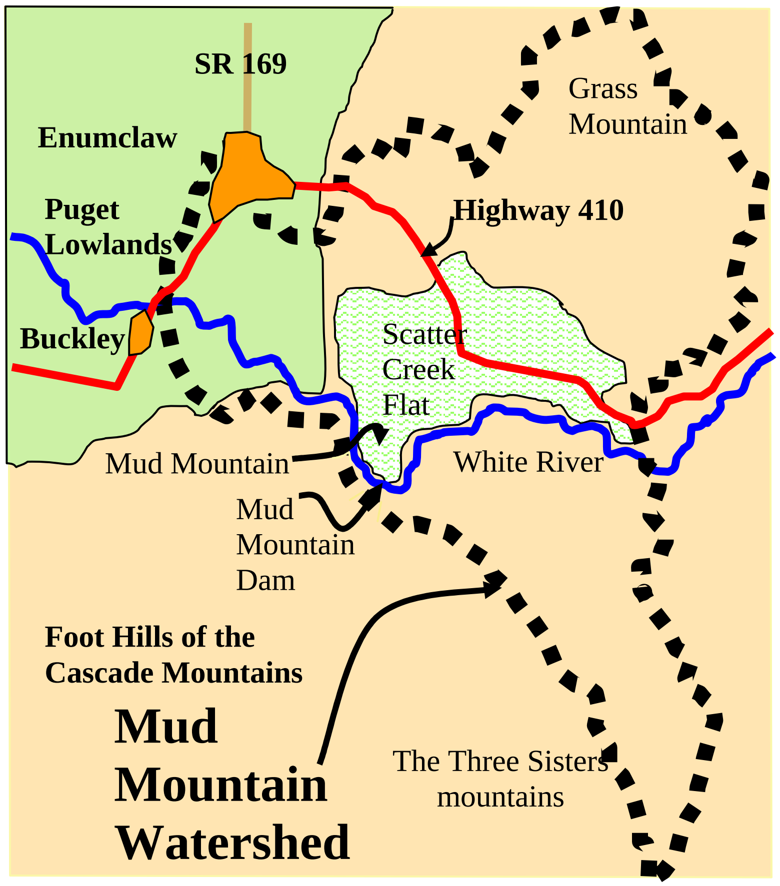

Figure 1. Sketch map of the Mud Mountain Watershed shown as a dashed line. The western portion of the watershed is in the Puget Lowlands; the rest is in the foothills of the Cascade Mountains. The watershed is divided by the White River. The lahar-covered glacial terrace of the Scatter Creek Flat is in the middle of the watershed.

The White River flows from east to west through the center of the watershed. The northern tributaries include Red Creek, Boise Creek, and Scatter Creek. The southern tributaries include Cascade Creek, Upper Cascade Creek, Old Pond Creek, and Canyon Creek. The Canyon Creek headwaters drain from Cedar Lake in the Clearwater Wilderness Area.

The steepest slopes and highest elevations are found in the northeastern and southern portions of the watershed. Slopes are near vertical in the southern portion of the WAU near Cedar Lake where glacial cirque headwalls stand and in the northern portion of the watershed on the southwest side of Boise Ridge where continental ice eroded a steep feature. Slopes that range from 0 to 10 % are found along the flat terrace tops and along the White River floodplain. The majority of the watershed is made up of Low Gradient Hillside Slopes that range from 11 to 40% (Figure 2).

Figure 2. Photo of low gradient hill slopes adjacent to gravel road. Note railroad trestles still standing.

4.0 Geology

4.1 Regional Geology

The Mud Mountain WAU lies within the western foothills of the Cascade Range, a mountain belt that extends over 700 miles from California to British Columbia. Mountain building and crustal uplift within this belt are the result of subduction of the Juan de Fuca plate beneath the western edge of North America, a process that has been underway for the past 36 Ma. Continental and alpine glaciation modified much of the current topography during the Pleistocene (<1.8 Ma).

4.2 Local Geology

Bedrock geology of the Mud Mountain WAU consists of pyroclastic rocks and lava flows all of which are products of subduction-related Cascade Arc volcanism. The oldest rocks, which are found only in the northeast corner of the WAU, belong to the Ohanapecosh Formation and are of Oligocene age (36-27 Ma). The Ohanapecosh Formation consists of multicolored intermediate composition tuffs and breccias, volcaniclastic sedimentary rocks, and basaltic to andesitic lava flows (Frizzell and others, 1984; Tabor and others, 2000). The most widespread bedrock unit is the Miocene age Fifes Peak Formation (23-20 Ma) which unconformably overlies the Ohanapecosh Formation. The Fifes Peak consists of mafic lava flows and breccias with less abundant volcaniclastic sedimentary rocks and tuffs (Tabor and others, 2000). The Basalt of Canyon Creek, dated at less than 700 ka, flows from The Three Sisters into Canyon Creek and consists of light gray basalt flows and lesser basaltic tuff and breccia. It is the youngest bedrock unit in the WAU (Fischer, 1970; Hammond, 1980; Tabor and others, 2000).

Evidence of continental and alpine glaciation is found throughout the Mud Mountain WAU. Cordilleran ice sheet glaciation progressed southward, filling the Puget Lowland and moving up onto the lower western slopes of the Cascade Range. The Puget Lobe blocked the mouths of river valleys flowing from the Cascade Mountains. Ice-contact recessional outwash deposits located on the southwest side of Boise Ridge consist of stratified water-laid sediments ranging in grain size from gravel to clay accompanied by minor till. Abrupt grain-size changes and collapse features indicate these sediments were deposited adjacent to active or stagnant ice (Tabor and others, 2000). Vashon Drift, the term for a variety of glacial deposits associated with the last ice sheet advancement, occurs on the south side of the White River and underlies lahar deposits on the north side of the river (Tabor and others, 2000; field observations). In general, glacial sediments tend to be well drained and relatively stable except where over-steepened by road cuts or undercut by stream action, creating opportunity for shallow landsliding. However, in places glacial deposits may contain till and clay layers that can be nearly impermeable. These layers commonly perch water that may create saturated conditions and/or be emitted from seeps and springs along the edges of the terraces. Alpine glacial deposits are found in the north central portion of the WAU, bordered to the north by Boise Creek and south of Scatter Creek.

Volcanic rocks also play a part in the local geology. The Fifes Peak Formation (tuffs and brecciated volcaniclastics which commonly weather to clay) underlies the glacial deposits and is susceptible to the formation of earthflows. Mt. Rainier to the southeast of the WAU has erupted at least 11 times in the past 10,000 years (Hoblitt and others, 1998). Pyroclastic flows similar to those of Mt. St. Helens may be forthcoming. Other potential depositional events include glacial outburst floods (mentioned above), lahars (landslide or mudflow composed of pyroclastic material from the flank of a volcano), and debris flows. In the past 10,000 years there have been more than 60 lahars that have originated on Mt. Rainier (Hoblitt and others, 1998). These lahars formed when volcanic rocks weakened by weathering and hydrothermal alteration formed clay and collapsed.

There are several lahar deposits mapped in the WAU. The largest and most notable is the Osceola Mudflow. The Osceola Mudflow originated as a collapse of the northeastern side of Mt. Rainier approximately 5,700 years ago (Crandell, 1971; Scott and others, 1992). The mudflow extended into Puget Sound forming the ancient deltas at Puyallup and Auburn (Dragovich and others, 1994). These deposits range in depth from a few feet on top of till drumlins to 75 feet thick in other locations (Crandell, 1971). Dragovich and others (1994) have determined that the Osceola thicknesses vary due to buried topographic features. In ancient river valleys deposit depths have been measured at 10 to 100 feet. Those authors have also tripled Crandell's (1971) volume calculation of 0.12 mi^3 to 0.89 mi^3. The lahar deposits create a resistant and relatively impermeable cap on the terraces which perches surface runoff. These terrace caps are prone to shallow soil slips. The erosional resistance of lahar deposits on glacial terraces allows the terrace face to steepen for a time while it is undercut by adjacent streams. At some point, the edge of the terrace becomes too steep and fails as shallow and deep-seated landslides.

The White River Fault runs through the northern portion of the Mud Mountain WAU. The White River Fault is a northwest-southeast trending high angle structure along which rocks on the southwest side have been down-dropped (Walsh and others, 1987; Tabor and others, 2000). There is no evidence that the fault has offset Quaternary alpine glacial sediments. This implies that the fault has not been active in the last 10,000 years. The White River Fault is also known as the Grass Mountain Fault (U.S. Army Corps of Engineers, 1983). To the northeast of the fault the Ohanapecosh Formation is exposed and to the southwest of the fault the Fifes Peak Formation is exposed. Alpine glacial deposits overlie areas of the Fifes Peak Formation. Deep-seated landslides near the White River Fault may be related to weathering of the fractured bedrock in the vicinity of the structure.

4.3 Geologic Interpretations

Based on field observations and aerial photo interpretation some lithologies within the Mud Mountain watershed have a greater frequency of landslides. It appears that some deep-seated landslides move on layers of decomposed clay from hydrothermally altered volcaniclastics and tuffs such as seen within the Fifes Peak and Ohanapecosh Formations. Some of the glacial deposits contain seeps and springs due to water perched above till and clay layers, which appear to initiate shallow and deep-seated landslide activity along terrace faces. Additionally, earthflows at very low angles (18-24%) may develop secondary landslides when disturbed by road construction (see gps point locations and field observations in Appendix E). The secondary landslides on earthflows exhibit many seeps and springs.

5.0 Previous Investigations

Watershed analysis mass wasting assessments were done for the basins to the north, west, and east of the Mud Mountain Watershed. The Clearwater/Middle White Watershed Analysis Mass Wasting Assessment was prepared by Jeffrey Clark for the Weyerhaeuser Company in 1996 and Patrick Reynolds and Kari Paulson prepared the Howard Hanson and Smay Creek Watersheds in 1999 for the Muckleshoot Indian Tribe Fisheries Department. Investigators for the Landslide Hazard Zonation (LHZ) Project reviewed and modified these two watershed analyses. In 2003 Karl Wegmann reviewed and modified the Howard Hanson and Smay Creek analysis while Lorraine Powell reviewed and modified the Clearwater and Middle White analysis. South Prairie Creek Watershed assessment was prepared in 2004 by William Lingley for the Landslide Hazard Zonation Project. These studies are available on the Department of Natural Resources Forest Practices website:
www.dnr.wa.gov/forestpractices/lhzproject/completed/

The Mud Mountain watershed is well known for its flood control dam along the White River. A 1978 U.S. Geological Survey study quantified sediment transported into the Mud Mountain Dam reservoir (Nelson, 1978). Calculations made during the first years of the study, between July 1974 and June 1976, estimated that the river transported 430,000 tons of sediment into the reservoir the first year and an additional 1,400,000 tons during the second year. The study also found that 55% of the sediment was transported in only seven days during this study, which is attributed to short periods of high stream flow due to storm events. This time period also corresponds with the highest precipitation recorded at the time

(Appendix F, Figure 1). Flood control practices have adversely impacted water quality due to high sediment and turbidity loads (Kerwin, 1999).

The watershed has experienced past and present timber harvest practices that have contributed sediment from roads and landslides (Figures 3 and 4).

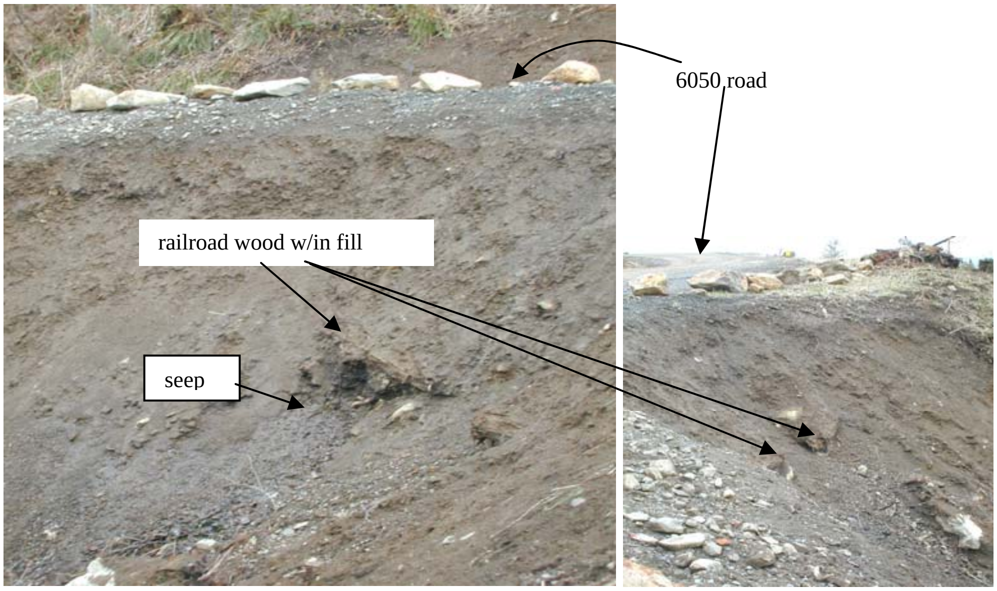

Figure 3. Slope stability problems related to past harvest-related activities have impacted the watershed. Old railroad grades commonly included buried organic matter in the road fill prism. Rotting wood acts as a conduit for water seepage that can destabilize slopes and initiate road failures, 2006.

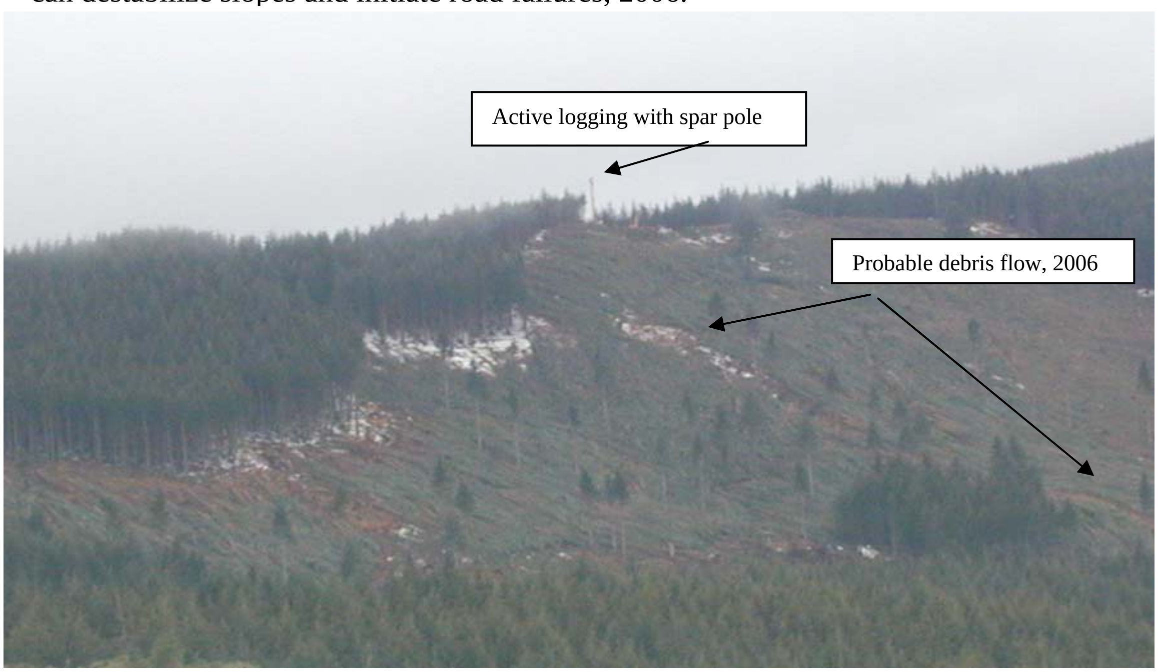

Figure 4. Probable landslide and associated debris flow in active logging operation in southern area of the watershed, 2006.

6.0 Summary of Landslide Inventory

During this review, a representative sample of 875 mass-wasting features were inventoried from air photo and field investigations (Form A-1). Additional landforms and landslide features not listed in the inventory are described in Appendix E and are shown as GPS points on Maps A-1 and A-2. Of the landslides identified during this mass wasting assessment, 50% were mapped as shallow undifferentiated failures, 9% were debris flows, 31% were debris slides and topples, and 10% were deep-seated landslides (Table 2). The resulting mass wasting coverage is displayed as Map A-1. Pertinent attributes of individual features were recorded on data sheets (Form A-1).

Based on landslide mapping and attempts to determine land use associated with the landslides, it was found that over 60% of the mass wasting features identified were located in sub-mature timber (15-50 years old). Land use was determined for each feature (Appendix B).

Mass Wasting Type	Number of Mass Wasting Features Mapped	Area (acres) of Mass Wasting Features	Percentage of Total Landslides
Shallow undifferentiated landslides	441	84.73	50%
Debris flows	81	18.46	9%
Debris slide/avalanche	265	137.96	31%
Rock topple/fall	2	1.22	0%
Deep-seated landslides	86	2,690.25	10%
Total	875	2,932.62	100%

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

7.0 Landforms

The distribution of the 15 landform units identified in the Mud Mountain watershed study area are shown on Map A-2 and are described in Forms A-2, Appendix C. These units have been delineated to depict areas having similar mass wasting potential, potential to deliver to public resources, and/or potential to impact public safety. Mass wasting potential is based primarily on landslide process, failure density, lithology, geomorphology, hydrogeology, and topography. The following sections briefly describe the characteristics of each landform with additional information provided in Appendix C. Landform numbers are identical to landforms identified in the Landslide Inventory: Form A-1 (Appendix A). Rule-identified landforms have been given a standardized numbering system as part of the DGER's implementation of the Landslide Hazard Zonation (LHZ) Protocol. Not all rule-identified landforms occur in a given watershed and therefore the identifying numbers of landforms in any given watershed may not be listed as consecutive. Landslide hazard ratings have been summarized on Form A-4 (Appendix D).

7.1 LANDFORM #1: Inner Gorges - Rule-identified high mass wasting potential and high delivery potential. These features are present as both asymmetrical and symmetrical inner gorges. Slopes are generally greater than 70%, although failing gorge walls have been observed on slopes of 65%. Shallow and deep-seated landslides are commonly located along the gorge walls. Debris-filled channel bottoms yield useful evidence for approximate age determination of slide activity. Some inner gorges have multiple failures that develop along the original gorge wall. Inner gorges are sensitive to both roads and harvest. Steep slopes (>70%) in the Ohanapecosh and Fifes Peak Formations have an abundance of inner gorges.

7.2 LANDFORM #2: Bedrock Hollows - Rule-identified high mass wasting and high delivery potential. Hollows are long, pointed ellipse or round, inverted spoon-shaped features. These features are primarily found on convergent slopes but can also be found on planar slopes. They are often found up gradient from inner gorges and on steep slopes (>70%) in the Ohanapecosh and Fifes Peak Formations. Field-observed bedrock hollow failures can occur on ~60% slopes. Multiple hollows and gorges adjacent to Canyon Creek have evacuated as small debris flows as observed in the field.

7.3 LANDFORM #3: Toes of Earthflows and Deep-seated Landslides – Rule-identified high mass wasting and high delivery potential. Landslide toes generally fail at >65% due to unconsolidated landslide material and possible undercutting by streams or road construction. Streams cut some deep-seated landslides bodies, and the landform was thus drawn around a portion of these streams or the entire body.

7.4 LANDFORM # 4: Steep Terrace Faces (>60%) - High mass wasting and high delivery potential features consisting of unconsolidated material (glacial and lahar deposits). The terrace faces have been cut by the White River, (downstream of the Mud Mountain Dam), which has caused oversteepening of the banks creating unstable slopes. The terrace edges have few shallow landslides.

7.5 LANDFORM #7: Convergent Headwalls – Rule identified high mass wasting and high delivery potential. These features are steep (>70%) and occur in the Ohanapecosh Formation in the northeast portion of the watershed. Cirque headwalls located in the southern most portion of the watershed near Cedar Lake resemble Landform 7.

7.6 LANDFORM #8: Active Deep-seated Landslides - High mass wasting and high delivery potential. This landform encompasses the entire area of some active deep-seated landslides due to the number of streams cutting through the features. There is a high potential for additional secondary landsliding within this landform.

7.7 LANDFORM #9: Outside Edges of Meander Bends – Rule-identified and high mass wasting and high delivery potential. Due to the high erodibility of the glacial and lahar terraces, the outer edges of the meander bends are failing directly into the White River as numerous shallow and deep-seated landslides.

7.8 LANDFORM #10: Valley and Stream Bottoms - Low mass wasting and delivery potential. Low gradient (0-10%) glacially-carved valley and stream bottoms are generally composed of alluvium, colluvium, soil, glacial, and landslide deposits. Mass wasting on these naturally stable slopes is unlikely but possible due to improper routing of surface waters.

7.9 LANDFORM #11: Ridge Tops and Noses – Low mass wasting and delivery potential. Low gradient (0-10%) areas along the tops of the ridges and along the noses of ridges have been mapped. Some low gradient ridge tops have landslides directly below the flats but these failures have low delivery potential.

7.10 LANDFORM #12: Mud Mountain Reservoir Valley Stream Bottom – High mass wasting and delivery potential. This is a unique landform due to the repeated fluctuation in water retention every year behind the dam. Constant wetting and de-watering of unconsolidated glacial and lahar deposits creates unstable conditions by hydrostatic liquefaction on relatively flat (0-10%) ground when pore water pressures in the geologic materials rise. This landform is located within federal land jurisdiction and lies outside Forest Practices LHZ Protocol.

7.11 LANDFORM #13: Mud Mountain Reservoir Steep (50% and greater) Terrace Faces – High mass wasting and delivery potential. This is landform is uniquely hazardous due to the repeated fluctuations of reservoir filling and floodwater release many times within a given year. Storm events that fill the reservoir multiple times during a single year increase hydrostatic liquefaction caused by pore water pressure of the unconsolidated glacial and lahar deposits. This fluctuation in pore water pressure causes material to become loose from the terrace faces, which destabilizes the slopes. Mass wasting occurs by slope undercutting when the reservoir fills and empties.

7.12 LANDFORM #14: Terrace Top (<11%) – Low mass wasting and delivery potential. This unique landform is relatively flat and consists of glacial deposits overlain by lahar deposits.

7.13 LANDFORM # 15: Steep Hillside Slopes (>70%) - High mass wasting hazard and delivery potential. Computer generated digital elevation model (DEM) slopes were used to draw this landform and as they commonly underestimate actual slope gradients in the field by 10% or more, the landform was drawn with > 60% DEM. This landform is found throughout the watershed as convergent and planar slopes and often adjoins inner gorges and bedrock hollows. Slope failures occur primarily as shallow landslides such as debris slides and debris flows, or as deep-seated landslides. This landform is especially prevalent along Canyon Creek (Fifes Peak Formation) where there is a high incidence of inner gorges.

7.14 LANDFORM # 16: Low Gradient Hill Slopes and Valley Side Slopes (11 to 40%) - Low mass wasting and delivery potential. These landforms occur mainly in the Fifes Peak and Ohanapecosh Formations and in glacial material. The Fifes Peak and Ohanapecosh Formations are deeply weathered and commonly host deep-seated landslides when disturbed by slope toe undercutting and/or during high precipitation storm events. Earthflows found in glacial material around the Scatter Creek drainage, have been found to fail on slopes as gentle as 20% when undercut by road construction.

7.15 LANDFORM # 17: Moderate to Steep Hillside Slopes (41 to 70%)- Moderate mass wasting and delivery potential. Computer generated DEM slopes were used to draw this landform and as they commonly underestimate actual slope gradients in the field by 10% or more, the landforms were drawn with 41% to 60% DEM. Shallow landslides, debris slides, debris flows, and deep-seated landslide have occurred within this landform.

8.0 Summary of Methods

Landslide inventory - The procedures described below follow the Landslide Hazard Zonation Protocol version 2.0 http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf, with minor modification. Four sets of 1:12,000 aerial photographs from 1978 to 1996, and one set of 1:60,000 photos from 1965 were analyzed with a mirror stereoscope with 3x magnification (Table 1). Other photo flight years were available from DNR's collection in Olympia, however these sets were missing many key photos and were therefore not used as complete reviews.

Year	**Scale**	**Image**	**Flight Line Number**	**Reference Ownership**	**Comment**
1978	1:12,000	Black & White	NW-78 71B-23 to 81B-15	DNR	Complete coverage
1985	1:12,000	Black & White	SP-85 26-070-093 to 32-080-120	DNR	Partial coverage
1989	1:12,000	Black & White	SP89 8 71-242 to 25 78-101	DNR	Partial coverage
1996	1:12,000	Color	SPP-C-96 1-1-1 to 5-7-12	DNR	Complete coverage
2003	3 ft pixel	Color Orthophotos		DNR	Partial coverage of corporate geo-database
1965	1:60,000	Black & White	WFPA-65 36-10to14; 37-9to14;38-3to7	DNR	Complete coverage

Table 3. Aerial photographs used in this study.

Cadastral and archival topographic maps produced between 1881 and 1913 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 a portion of the Mud Mountain WAU 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 1902 USGS Forest Service Map of Washington Showing Classification of Lands and the 1913 1:250,000 USGS topographic map. These historical maps were scanned and entered into ArcGIS and geo-referenced in a methodology adapted from Collins and others 2003.

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 (Washington Forest Practices Board, 1995); all remaining landslides are classified as shallow landslides. The mass wasting feature types include shallow-undifferentiated landslides, debris flows, debris slides and avalanches, rock topples and falls, snow avalanches, 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, over-steepened 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 could not be identified with the same level of certainty 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 that were identified in the field were not evident on the photos, mostly in areas of heavy canopy or postdate the most recent photo set.

Following stereo air photo analysis, all observed landslides were hand drawn on 1:12,000 plastic map sheets. Transfer of mapped features to a digital database was accomplished by tracing the landslides onto a GIS map with layers that included streams, roads, townships, geology, and a USGS 10-meter DEM with DEM-derived contours, slope gradients, hillshades, and lidar. The landslides mapped in the Mud Mountain WAU are presented on Map A-1 and itemized on Appendix A Landslide Inventory.

Lidar was available only for the northern portion of the Mud Mountain WAU. Without lidar in the southern portion of the watershed the maximum resolution of the map base there 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 for the sake of expeditiousness to estimate the gradients of landslides. It should be emphasized that all slope gradient estimates presented in this report are likely minimum approximations.

Lidar from the DNR GIS corporate geo-database was originally derived and modified from http://pugetsoundlidar.ess.washington.edu/. The lidar available for the northern portion of the Mud Mountain WAU was used to generate 10 ft contours and as shaded relief maps. After locating landslides on aerial photos, lidar was then utilized to confirm locations and delineate landslides more accurately.

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 (Bilderback, 2006).

Mass wasting map units - The aerial photo survey was also used to determine land use and to map rule-identified landforms (inner gorges, bedrock hollows, etc.). The 10 m 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, lithology, and slope convergence. A combination of slope gradient and elevation data (derived from the 10 m DEM), slope convergence data (derived from the DNR SLPSTAB model (Shaw and Johnson, 1995)), geologic data (from USGS 1:100,000 geologic maps), and rain-on-snow data aided in the designation of these landforms. The landforms are intended to predict areas within the WAU that pose hazards for mass wasting. The landforms mapped in the Mud Mountain WAU are presented on Map A-2 and described in Appendix C. Each landform was assigned a landslide frequency rate (LFR), a landslide area rate for delivery (LAR), and an overall hazard rating (low, moderate, or high) as called for by the LHZ Protocol [www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2_final.pdf].

9.0 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 landslide is used instead of the area of delivering landslides. Deep-seated landslides were not included in the calculations for Form A-4. 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 4: Qualitative rating system for the LFR and LAR.

10.0 Confidence in Work Products

The confidence in this mass wasting assessment is high. This rating is based on the Landslide Hazard Zonation Project design to provide a watershed administrative unit 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 heavy canopy forested areas.

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, 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. Keep in mind that this is only a reconnaissance study, and some landslides have been accidentally omitted and some benign features may be improperly mapped as landslides herein.

In addition, there are several sources of systematic error that reduce the confidence in the work products of this analysis, those being omission, misinterpretation, 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 (Brardinoni and others, 2003). The scarcity of mass wasting features identified under mature canopy, steep, and north-slope aspect shadow conditions is not necessarily an indication of the relative stability of these slopes.

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 WAU 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 very few 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.

11.0 Use of Report

The purpose of this mass wasting assessment is to identify all private and state lands within the Mud Mountain watershed administrative unit (WAU) that have a risk of landsliding due to both natural phenomena and to the effects of forest practice activities (logging, roading, thinning, yarding, etc.). All areas and ownerships in the watershed have been included in this study for a comprehensive view of landslide assessments. All lands within the WAU have been divided into designated mass wasting hazard landforms[1]. Maps of these landforms are designed for use by landowners in determining the areas likely to create landslide hazard and by Department of Natural Resources (DNR) 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. Thus, the landslide inventory presented in this report (Map A1 and Form A1) is intended to be a representative but not an exhaustive inventory. For these reasons, it is possible 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.

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, these studies 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 dense canopy on air photos (Brardinoni and others, 2003).

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

- A generalized characterization of mass wasting processes that are active in the WAU;
- 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] Landforms as defined herein can be more inclusive than the small-scale unstable landforms commonly defined in rule (Chapter 222-16-050 WAC), referred to as “rule-identified landforms”. Rule-identified landforms in the Mud Mountain WAU include inner gorges, bedrock hollows, convergent headwalls, and active deep-seated landslides.

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Appendix B - Form A-3: Mass Wasting Summary Table
Mud Mountain Landforms

Mass Wasting Summary: Totals

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	18	13	8	29	1	69
2 = young stands (timber 5-15 yrs)	18	6	11	6	0	41
3 = submature timber (15-50 yrs)	143	23	125	48	1	340
4 = mature timber (>50 years)	0	0	2	0	0	2
5 = road	16	18	8	0	0	42
6 = partial cut	0	0	0	0	0	0
7 = yarding	0	0	0	0	0	0
8 = alpine	0	0	0	0	0	0
9 = other-e.g., housing, agric	34	6	13	0	0	53
Totals	229	66	167	83	2	547

Mass Wasting Summary: Landform 1 - Inner Gorges						
Activity	**Shallow Landslides**	**Debris Flows**	**Debris Avalanches/ Slides**	**Deep-Seated Landslides**	**Earthflows**	**Total**
1 = clearcut (timber 0-5 yrs)	2					2
2 = young stands (timber 5-15 yrs)	2	2	1			5
3 = submature timber (15-50 yrs)	14	3	11	1		29
4 = mature timber (>50 years)						0
5 = road	4	6				10
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	22	11	12	1	0	46

Mass Wasting Summary: Landform 2 - Bedrock Hollows						
Activity	**Shallow Landslides**	**Debris Flows**	**Debris Avalanches/ Slides**	**Deep-Seated Landslides**	**Earthflows**	**Total**
1 = clearcut (timber 0-5 yrs)		1				1
2 = young stands (timber 5-15 yrs)	1			1		2
3 = submature timber (15-50 yrs)			2			2
4 = mature timber (>50 years)						0
5 = road	2	1				3
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	3	2	2	1	0	8

Mass Wasting Summary: Landform 3 - Toes of Earthflows and Deep-seated

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)				1		1
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)	9			4		13
4 = mature timber (>50 years)						0
5 = road			1			1
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric	1					1
Landform Totals	10	0	1	5	0	16

Mass Wasting Summary: Landform 4 - Steep Terrace Faces (>60%)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)	6	1	3	9		19
4 = mature timber (>50 years)						0
5 = road	1		2			3
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric	3					3
Landform Totals	10	1	5	9	0	25

Mass Wasting Summary: Landform 7 - Convergent Headwalls

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)						0
4 = mature timber (>50 years)						0
5 = road	1					1
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	1	0	0	0	0	1

Mass Wasting Summary: Landform 8 - Active Deep-seated Landslides

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)			1			1
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)		1	4			5
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	0	1	5	0	0	6

Mass Wasting Summary: Landform 9 - Outside Edge of Meander Bends

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)	1		1	1		3
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric	1					1
Landform Totals	2	0	1	1	0	4

Mass Wasting Summary: Landform 10 - Valley & Stream Bottoms

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)						0
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	0	0	0	0	0	0

Mass Wasting Summary: Landform 11 - Ridge Tops & Noses

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)						0
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	0	0	0	0	0	0

Mass Wasting Summary: Landform 12 - Mud Mountain Reservoir Valley Stream Bottom

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)						0
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)	5	1				6
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric	5		1			6
Landform Totals	10	1	1	0	0	12

Mass Wasting Summary: Landform 13 - Mud Mountain Steep Terrace Faces (50% and greater)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	2	3	2	1		8
2 = young stands (timber 5-15 yrs)	2		4			6
3 = submature timber (15-50 yrs)	31	4	54	5		94
4 = mature timber (>50 years)						0
5 = road			1			1
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric	24	5	12	1		42
Landform Totals	59	12	73	7	0	151

Mass Wasting Summary: Landform 14 - Terrace Tops (<11%)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	1					1
2 = young stands (timber 5-15 yrs)						0
3 = submature timber (15-50 yrs)	2					2
4 = mature timber (>50 years)						0
5 = road						0
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	3	0	0	0	0	3

Mass Wasting Summary: Landform 15 - Steep Hillside Slopes (>70%)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	2	2	3	5		12
2 = young stands (timber 5-15 yrs)	1	2	1	4		8
3 = submature timber (15-50 yrs)	23	3	17	16		59
4 = mature timber (>50 years)			2			2
5 = road	3	2	1			6
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric		1				1
Landform Totals	29	10	24	25	0	88

Mass Wasting Summary: Landform 16 - Low Gradient Hillside Slopes and Valley Side Slopes (11-40%)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	3	4		11	1	19
2 = young stands (timber 5-15 yrs)	4					4
3 = submature timber (15-50 yrs)	29	4	14	3	1	51
4 = mature timber (>50 years)						0
5 = road	1	1				2
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	37	9	14	14	2	76

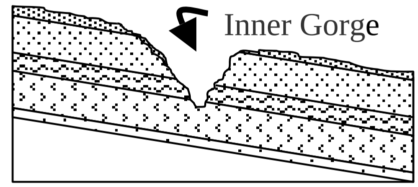
Mass Wasting Summary: Landform 17 - Moderate to Steep Hillside Slopes (41-70%)

Activity	Shallow Landslides	Debris Flows	Debris Avalanches/ Slides	Deep-Seated Landslides	Earthflows	Total
1 = clearcut (timber 0-5 yrs)	8	3	2	11		24
2 = young stands (timber 5-15 yrs)	8	2	5	1		16
3 = submature timber (15-50 yrs)	23	6	19	9		57
4 = mature timber (>50 years)						0
5 = road	4	8	3			15
6 = partial cut						0
7 = yarding						0
8 = alpine						0
9 = other-e.g., housing, agric						0
Landform Totals	43	19	29	21	0	112

Appendix C Landform Descriptions - Mud Mountain Watershed: Form A-2

Landform #1 - Inner Gorges – High Hazard

Description of Mass Wasting Unit: Inner gorges are steep (>70%) walled canyons or gullies eroded by stream action with evidence of mass wasting along their sidewalls. Inner gorges may be either symmetrical or asymmetrical in profile and are commonly intermittent in lateral extent. They are occasionally scoured by debris flows during storm events. A 10° break in slope usually separates the upper margin of the inner gorge feature from the surrounding slope forms. Inner gorge scarp slopes revegetate rapidly which can mask their appearance on aerial photos. Inner gorges are present in of a wide range of other landforms including deep-seated landslides. Often buried wood is observed in the channels from previous mass wasting events.



Slopes:	> 70%
Slope Shape:	Convergent
Material:	Soil, colluvium, alluvium, landslide & glacial deposits, and volcanics (primarily Fifes Peak and Ohanapecosh Formations)
Elevation:	1,000 ft to 4,900 ft
Total Area:	340 acres

Mass Wasting Processes: Inner gorges are canyons created by a combination of the downcutting action of a stream and mass movement on the slope walls; they commonly show evidence of recent movement, such as obvious landslides, or vertical tracks of disturbance in vegetation. The over steepened wall(s) of the gorge (or gully) fails as slope ravel, debris slides or small rotational failures sometimes initiating debris flows.

Forest Practice Sensitivity and Trigger Mechanisms: Root strength within and adjacent to inner gorges has been found to be a factor in increasing rates of mass wasting (Krogstad, 1995) therefore trees adjacent to the inner gorge can have roots extending into the slopes of the gully providing slope stability. Since slope failures can increase due to declining root strength, timber harvest can have a significant impact on slope stability within this landform. Roads and landings can destabilize slopes in inner gorges by undercutting and oversteepening slopes. Side cast and road (or landing) fill can also oversteepen slopes and can add weight; roads and landings can also capture runoff water or shallow groundwater, channeling it to point locations that saturate road or landing fill and/or soils draping bedrock, triggering landslides. There are multiple inner gorge failures in the northeast portion of the watershed within the Ohanapecosh Formation, within the Fifes Peak Formation in the southern portion of the watershed, and within the area adjacent to Canyon Creek south of the White River. Old roads constructed across inner gorges in the northeast area are actively failing due to channelized water and slopes loaded with fill material. Some of these roads are directly on top of fractured bedrock that has high failure potential.

Mass Wasting Potential: **Very High** for road construction and timber harvest based on 45 "delivering" failures with a total failed area of 15.5 acres in an area of 340 acres. This landform has a Landslide Frequency Rating of 4,727 with roads and 3,676 without roads.

Delivery Potential/Criteria: **Very High.** Inner gorges are part of the drainage network and forty-five mapped landslides that occurred in inner gorges delivered to a public resource. Delivery criteria are based on historical occurrence observed on aerial photographs and confirmed during field investigations. This unit has a calculated Landslide Rate of Delivery of 1,630 with roads and 1,234 without roads.

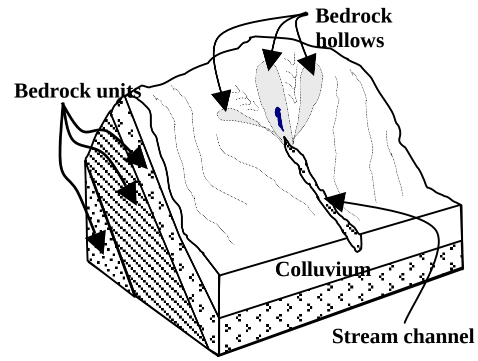
Overall Hazard Potential Rating: **Very High** for roads and harvest based on LHZ Protocol and standard Forest Practices Rules.

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

Comments: Many field-identified inner gorges are shown as GPS points on Maps A-1 and A-2 and described in Appendix E. These inner gorges have an area greater than the small circle or point shown on Map A-2, however their individual extent could not be determined on aerial photographs. Inner gorges are described in more detail in the Forest Board Manual, Section 16 (p. M16-15).

Landform # 2- Bedrock Hollows - High Hazard

Description of Mass Wasting Unit: Rule-identified bedrock hollows are steep (>70% at the steepest point), shallow spoon- or elongate areas of convergent topography with concave profiles. Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows. These features can exist on any steep hillslope and within other landforms. They seldom contain channels but commonly drain directly into inner gorges or other channels downslope. Colluvial debris that accumulates in these steep convergent areas is prone to saturation by shallow ground water making bedrock hollows highly susceptible to slope failures. Over time, bedrock hollows re-vegetate and refill with soil, which can mask their presence on air photos and on the ground.



Slopes: > 70%
Slope Shape: Primarily convergent
Material: Colluvium, alluvium, landslide & glacial deposits, and volcanics (primarily Fifes Peak and Ohanapecosh Formations)
Elevation: 1,250 ft to 4,900 ft
Total Area: 84 acres

Mass Wasting Processes: Soil saturation, loss of root strength, and/or oversteepening of slopes in hollows can trigger evacuations as debris slides, debris flows, or other shallow landslides. When located at the top of steep inner gorge slopes, hollows often feed directly into streams, and evolve into debris flows that scour channels and flow into inner gorges.

Forest Practice Sensitivity and Trigger Mechanisms: Root strength within bedrock hollows have been found to be a factor in increasing rates of mass wasting, therefore, harvest can have a significant impact on slope stability within this landform. Roads and landings can destabilize slopes of bedrock hollows by undercutting and oversteepening slopes. Sidecast and road (or landing) fill can oversteepen and add weight to slopes; roads and landings can also capture runoff water or shallow groundwater and channel it to point locations that saturate road or landing fill and/or soils draping bedrock, triggering landslides. Multiple failures were initiated in bedrock hollows in the northeast portion of the watershed within the Ohanapecosh Formation and within the Fifes Peak Formation, within the southern portion of the watershed, and within the area along Canyon Creek south of the White River. Active road failures within the Fifes Peak Formation were due to rotting railroad trestles within road fill material (See Figure 2).

Mass Wasting Potential: **Very High** for road construction and timber harvest based on 7 "delivering" landslides with a total failed area of 1.4 acres in an area of 84 acres. This landform has a Landslide Frequency Rating of 2,976 with roads and 1,700 without roads.

Delivery Potential/Criteria: **High.** Delivery criteria are based on historical occurrence observed on aerial photographs and confirmed during field investigations. Bedrock Hollows are part of the drainage network and occur adjacent to or at the head of streams. In this mass wasting map unit 7 mapped landslides delivered to a public resource. This unit has a calculated Landslide Rate of Delivery of 600 with roads and 230 without roads.

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

Confidence: High based on the excellent photo quality, partial lidar coverage, and field observations.

Comments: The southern areas of this watershed contain multiple failures that began in bedrock hollows on steep convergent slopes. Most of the bedrock hollows are mapped in the Ohanapecosh Formation and the Fifes Peak Formation. Hollows within steep headwalls tend to be shallow and elongated (long ellipses or round in shape) and are difficult to delineate from shallow landslides on photographs. Areas steeper that 65% may contain unmapped bedrock hollows and should be field-reviewed. Bedrock hollows are fully described in the Forest Board Manual, Section 16 (p. M16-10).

Landform #3 – Toes of Earthflows and Deep Seated Landslides - High Hazard

Description of Mass Wasting Unit: Landform #3 consists of the toes of deep-seated landslides (including earthflows). Rule identified deep-seated landslide toes have slopes >65%, however, the toes of a few earthflows within the watershed were observed failing at slopes as low as 20%. These toes consist of the lower portion of deep-seated landslides that are commonly undercut and oversteepened by stream erosion. They have a hummocky or irregular topography that may show indications of past shallow or small reactivated deep-seated landslide activity. Springs and seeps (sapping), small wetlands areas, and sag ponds are also common. Adjacent to some earthflowfailures, extensive sapping was noted along road cuts. If the toe is active, jackstrawed trees, cracks, fresh scarps, and/ or areas of unvegetated soil may be observed.

Slopes:	Toes of deep-seated landslides with slopes > 65% (earthflow toe slopes fail at gradients as low as 20%)
Slope Shape:	Convergent
Material:	Glacial, lahar deposits (mainly Osceola Mudflow), and Volcanics (Fifes Peak Formation and Ohanapecosh Formations)
Elevation:	800 ft to 3,950 ft
Total Area:	260 acres

Mass Wasting Processes: This landform is prone to shallow rapid landslides (slope ravel, soil slips, debris slides, debris flows and debris avalanches) due to oversteepening caused by stream undercutting and road construction. Some of these secondary landslides occur at exceptionally low angles (20-30%) as observed on the toes of earthflows that are being actively undercut by Scatter Creek and road cuts that remove resisting forces or the buttressing effects of earthen material on a slope. Oversteepened slopes and the sheared broken nature of material in the toes of deep-seated landslides promote the formation of smaller deep-seated landslides within this landform. These conditions are observed in deep-seated landslide toes along Canyon Creek located in the southern portion of the watershed.

Forest Practice Sensitivity and Trigger Mechanisms: Past forest management activities within the watershed have reactivated the toes of deep-seated landslides resulting in numerous shallow and small deep-seated slope failures in this landform. These failures occurred as a result of soil saturation, loss of root strength, undercutting or oversteepening of slopes, and loading of slopes with sidecast or fill materials. Soil saturation usually occurs as a combination of natural storm events and human activities that alter hydrologic conditions. This includes harvest related loss of evapotranspiration and canopy interception, rain-on-snow effects, and road related water channeling, concentration discharge and/or ponding. Near Scatter Creek in the northeastern corner of the watershed, roads have been cut into the toes of deep-seated landslides and low gradient earthflows triggering small rotational landslides sometimes at very low slope angles (20-30%). Additional harvesting in these areas may cause additional failures due to diminishing root strength and roads may undercut stable slope configurations.

Mass Wasting Potential: **Very High** for road construction and timber harvest**.** Toes of deep-seated landslides over 65% are rule-identified high hazard features. Toes of earthflows in this watershed can have a high mass wasting potential on slopes as low as 20%. This landform has 11 “delivering” slope failures with a total failed area of 1.1 acres in an area of 262 acres. This landform has a Landslide Frequency Rating of 1,499 with roads and 1,363 without roads.

Delivery Potential/Criteria: **High** for road construction and timber harvest and **Moderate** for areas without roads. Shallow landslides have been observed to directly fail into creeks and rivers throughout the watershed. The unit has a calculated Landslide Area Rate of Delivery of 151 with roads and 108 without roads.

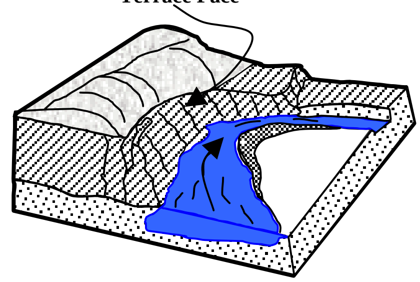
Overall Hazard Potential Rating: **Very High** for roads and timber harvest based on LHZ Protocol and Standard Forest Practices Rules.

Confidence: High based on the number of landslides located in this landform, excellent photo quality and coverage, partial lidar coverage, and field observation. Toes of deep-seated landslides are more fully described in the Forest Board Manual, Section 16 (p. M16-20).

Comments:

Landform # 4 - Steep Terrace Faces (>60%) - High Hazard

Description of Mass Wasting Unit: The White River has cut into glacial sediment deposits and volcanic mudflows and formed terraces that commonly have steep (>60%) unstable edges or faces. Terrace Faces located on the west side of the Mud Mountain watershed along the White River contain many shallow & deep-seated landslides.



Slopes:	60% and greater
Slope Shape:	Convergent to planar
Material:	Flood plain, glacial outwash, soil, colluvium, alluvium, Osceola Mudflow (lahar deposit), and Fifes Peak Formation
Elevation:	750 ft to 1,500 ft
Total Area:	164 acres

Mass Wasting Processes: The White River has undercut adjacent upland slopes and caused mass wasting along oversteepened slopes in the form of ravel, soil slides, debris slides, and deep-seated landslides. Landslides are concentrated on the outside of the meander bends along the White River, however, they occur all along this terrace face.

Forest Practice Sensitivity and Triggering Mechanisms: Stream bank and terrace face erosion from the White River undercutting this landform making it prone to mass wasting even under mature forested conditions, therefore, any disturbance resulting from timber harvest or road construction can further destabilize these slopes. Loss of root strength, changes in slope gradient, and changes in hydrology from forest management activities on or near the terrace edge can destabilize these slopes especially during major rain-on-snow storms or intense precipitation events. Roads and landings can cause instability by undercutting and oversteepening slopes. Sidecast and road (or landing) fill can oversteepen and add weight to terrace faces; roads and landings can capture runoff water or shallow groundwater and channel it to point locations causing soil saturation. Nineteen of the 25 mapped landslides that delivered to streams in this landform occurred after the typical root strength loss time from clearcutting.

Mass Wasting Potential: **<u>Very High</u>** for road construction and timber harvest based on 15 "delivering" failures with a total failed area of 6.61 acres in an area of 164 acres. This landform has a <u>Landslide Frequency Rating</u> of 3,267 with roads and 2,831 without roads.

Delivery Potential/Criteria: **<u>Very High.</u>** The landform is stream adjacent which greatly increases the likelihood of delivery. The unit has a calculated <u>Landslide Area Rate of Delivery</u> of 1,439 with roads and 1,344 without roads.

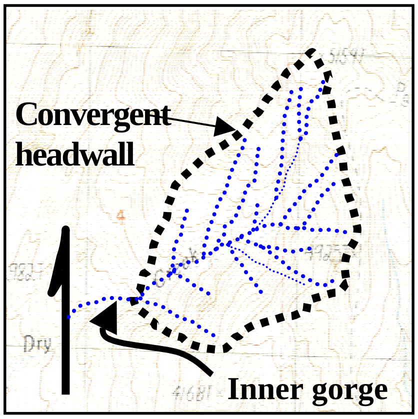
Overall Hazard Potential Rating: **<u>Very High</u>** for roads and timber harvest based on LHZ Protocol.

Confidence: <u>High</u> for the entire unit based on observed direct delivery to typed waters, excellent photo coverage, partial lidar coverage, and field verification.

Comments: Surface disturbances related to homes and associated roads create gullies, ravel and slope instability visible on aerial photos. Many of the landslides in this landform are also mapped within Landform #9 Outside Meander Bends.

L**andform #7** – Convergent Headwalls - High Hazard

Description of Mass Wasting Unit: This Forest Practices rule identified landform consists of steep (>70%), headwall basins located in the upper end of drainage systems. The arrangement of bedrock hollows and first-order channels in a convergent headwater drainage area causes this landform to be a unique mass-wasting feature. Convergent headwalls are broadly convergent and contain bedrock hollows and inner gorges usually separated by steep ridges. Channels draining the convergent headwalls have the potential for debris flows forming incised streams within inner gorges that often initiate in bedrock hollows.



Slopes:	>70%
Slope Shape:	Convergent
Material:	Colluvium and colluvial soils overlaying volcanic bedrock (volcaniclasitics of the Ohanapecosh Formation)
Elevation:	1,470 ft to 3,850 ft
Total Area:	9 acres

Mass Wasting Processes: The highly convergent shape of these slopes, coupled with thin soils (due to frequent slides), allows rapid onset of surficial and subsurface stormwater flow. The mass-wasting response of these areas to storms and forest practices activities is much greater than is observed on other steep hillslopes in the same geologic units. Channel gradients are extremely steep within convergent headwalls, and generally remain so for long distances downstream. Landslides that evolve into debris flows in convergent headwalls typically deliver debris to larger channels below. Convergent headwalls are prone to surface erosion, soil slips, debris slides, and debris flows. Channels that exit the bottoms of convergent headwalls have been formed by repeated debris flows. Convergent headwalls commonly have debris fans at the base of their slopes.

Forest Practice Sensitivity and Triggering Mechanisms: Timber harvest, road construction and/or landing construction on steep convergent slopes in poorly consolidated colluvium and deeply weathered bedrock can increase slope instability. Loss of root strength can increase rates of mass wasting as can roads and landings that undercut or load or change the hydrology of these steep slopes. Failures tend to occur during major rain-on-snow storms or intense precipitation events.

Mass Wasting Potential: **Very High** for road construction and timber harvest based on 1 "delivering" failure with a total failed area of 0.19 acres in an area of 9 acres. This landform has a Landslide Frequency Rating of 3,968 with roads and zero without roads

Delivery Potential/Criteria: **High**. This unit has a calculated Landslide Area Rate of Delivery for delivery of 754 with roads and zero without roads.

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

Confidence: High based on excellent photo quality and coverage, partial lidar coverage, and field observation.

Comments: Although there is only one convergent headwall mapped, there are multiple areas nearby in the Ohanapecosh Formation as well as the Fifes Peak Formation in the southern portion of the watershed that have inner gorges and adjacent steep convergent slopes (See Landforms #1 and #15) and should be reviewed for potential problems relating to road construction and timber harvest. Convergent headwalls are more fully described in the Forest Board Manual, Section 16 (p. M16-13).

Landform #8 – Active Deep-Seated Landslide - High Hazard

Description of Mass Wasting Unit: This landform encompasses the entire area of active deep-seated landslide features, including toes (<65%). The toes often contain multiple landslides (shallow undifferentiated and small deep-seated) nested within larger features. The landslides within this landform display evidence of recent movement such as fresh head scarps; oversteepened toes; crevassed ground; stepped and hummocky ground; undrained sag areas; bowed, jackstrawed or split trees; recent shallow landsliding; and distinct lateral boundaries (side scarps). Active deep-seated landslides within this landform are commonly dissected by multiple creeks that can be deranged or displaced in peculiar ways.

Slopes: 35% and greater
Slope Shape: Irregular topography
Material: Glacial, lahar deposits (mainly Osceola Mudflow), and
Volcanics (Fifes Peak Formation and Ohanapecosh Formations)
Elevation: 775 ft to 3,800 ft
Total Area: 223 acres

Mass Wasting Processes: Although the entire landslide mass may be moving, more often movement is localized as debris slides or smaller deep-seated landslides within the larger feature. Active deep-seated landslides are composed of unconsolidated material (fractured and deeply weathered bedrock) that can absorb large quantities of water which increases their susceptibility to continued failure. These landslides were observed failing at slopes as low as 35%, however the majority of slopes fail at 50-60%.

Forest Practice Sensitivity and Triggering Mechanisms: Increased water run-off on deep-seated landslides has been found to be a factor for increased activity of secondary landsliding within the original feature or reactivation of the deep-seated landslide. Loss of root strength, especially in unconsolidated material and deeply weathered bedrock, has been observed to increase shallow landslide activity on parts of larger features. Future harvests could initiate increased deep-seated activity and shallow landsliding within this landform. Water management should be carefully executed to prevent reactivation of failures. Groundwater recharge areas of glacial deep-seated landslides and earthflows must be carefully reviewed prior to harvesting.

Mass Wasting Potential: High. This landform is composed of active deep-seated landslides therefore by definition they are at a higher risk for failure and potential for reactivation of slide activity. This landform has 6 "delivering" landslides with a total failed area of 1.82 acres in an area of 223 acres. This landform has a Landslide Frequency Rating of 961 with or without roads.

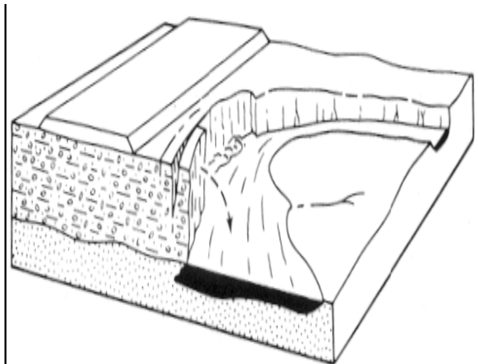
Delivery Potential/Criteria: High. Shallow slides failures occur and have high potential for delivery to streams that are within this landform. Failures on the bodies of these deep-seated landslides, especially where angles are high, have a high chance of delivering as well. This landform has a Landslide Area Rate of Delivery of 291 with or without roads.

Overall Hazard Potential Rating: High based on LHZ Protocol

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

Comments: The mouth of Scatter Creek is impacted by water retention of the Mud Mountain Reservoir during flood events when water is retained for flood prevention. There are multiple small deep-seated landslides along the portion of Scatter Creek from the mouth to an area upstream of Highway 410. See locations of GPS points on Maps A-1 and A-2 and Appendix E for descriptions of these features.

Landform #9 - Outside of Meander Bends - High Hazard



Drawing of an outer edge of a meander bend (Forest Board Manual).

Description of Mass Wasting Unit: Alluvium and lahar terrace faces located on both sides of the White River directly adjacent to meander bends and on the outside of meander bends downstream of the Mud Mountain Dam stretching to the western edge of the watershed. Inner gorges and bedrock hollows can occur within this unit.

Slopes: >25%
Slope Shape: Convergent to planar
Material: Alluvium, glacial and lahar deposits (Osceola Mudflow and others)
Elevation: 650 ft to 1,100 ft
Total Area: 43 acres

Mass Wasting Processes: The White River downstream of Mud Mountain Dam has created unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces. The outer edges of meander bends are susceptible to shallow landsliding including debris slides, debris avalanching, small-scale slumping, and deep-seated landsliding.

Forest Practice Sensitivity and Trigger Mechanisms: Any disturbance of root strength, concentration of waters, or disturbance of the ground within this feature increases slope instability. Water concentration, sidecast, and loading from landings can cause instability by adding weight or oversteepening the outside of meander bends. Sediment delivery to the White River from slope failures on this landform is imminent.

Mass Wasting Potential: **Very High.** Meander Bends are rule-identified in the Forest Practices Rules and listed as high hazard in the LHZ Protocol. These features can be associated with active deep-seated and shallow landslides. This landform has 3 "delivering" failures with a total failed area of 1.5 acres in an area of 43 acres. This landform has a Landslide Frequency Rating of 2,492 with or without roads.

Delivery Potential/Criteria: **Very High** due to proximity of the White River. The unit has a calculated Landslide Area Rate of Delivery of 1,262 with roads and without roads.

Overall Hazard Potential Rating: **Very High** 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, partial lidar coverage, and field observation.

Comments: The outsides of Meander Bends are more fully described in the Forest Board Manual, Section 16 (p. M16-21). Some landslides in this landform are also shown in Landform #4 Steep Terrace Faces.

Landform # 10 - Valley & Stream Bottoms - Low Hazard

Description of Mass Wasting Unit: This map unit includes all slope forms and gradients less than 11% located in the valley bottoms, flat terraces, prairies, some portions of deep-seated landslide bodies that appear to be stable, and major stream flood plains, excluding Landform #12, that exhibit a low landslide potential, and/or are not likely to deliver sediment to a stream, impact public safety or impact a public resource. (Caution: Unmapped inner gorges, bedrock hollows, and other high-hazard landforms may have been erroneously included in landform #10 through mapping errors.)

Slopes:	Variable 0 to 10% (DEM-measured). Field-measured slopes are commonly steeper than those determined from the DEM.
Slope Shape:	Planar
Material:	Colluvium, alluvium, landslide & glacial deposits, lahar deposits (mainly Osceola Mudflow), and volcanics (Fifes Peak and Ohanapecosh Formations and Canyon Creek basalt)
Elevation:	800 ft to 4,925 ft
Total Area:	1,216 acres

Mass Wasting Processes: Shallow landslides may occur but are not common and generally do not have the potential to deliver to waters of the state or impact public safety or resources. The most common mass wasting process observed on aerial photographs was stream erosion through the toes of deep-seated landslides and was located away from public resources.

Forest Practice Sensitivity and Triggering Mechanisms: Mass wasting on these naturally stable slopes is unlikely, but possible if caused by human activities. Forest harvest related activities that could contribute to landslides developing on this landform would generally be the result of poor management practices and would likely be a violation of forest practices rules. These activities might include damming streams with road fill or as the result of blocked culverts, diverting streams from their channels, creating large undrained areas that could saturate fill material or hillslopes, sidecasting excessive amounts of uncompacted material, or channeling runoff excessive distances in drainage ditches. This type of mass wasting event can be engineered on any type of landform with any type of slope gradient even if the landform is stable. Where deep-seated landslide bodies are mapped on this landform in glacial material, there is a potential for glacial recharge areas and may require further investigation prior to harvest.

Mass Wasting Potential: **Low** for road construction and timber harvest. This landform has no "delivering" failures in an area of 1,216 acres. This landform has a Landslide Frequency Rate of zero with roads and without roads.

Delivery Potential/Criteria: **Low**. The delivery rate for this unit is 0. No mass wasting features were noted within this landform that delivered. Delivery is unlikely as lack of channel access precludes transport. Road and landing failures do not travel great distances. Distance from stream channels and topography inhibits transport of landslide debris deposited onto this landform from upper elevation sources and does not impact public safety. Any landslide in this landform would be caused by above average precipitation. The Landslide Delivery Rate for this unit is 0.

Overall Hazard Potential Rating: **Low** for the entire unit.

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

Comments: Very little failure activity noted. Some valley bottoms with portions of lakes in the south end of the watershed were mapped to be consistent with low gradient slopes and low failure possibility. There are a few areas mapped within the body of deep-seated landslides, which have little or no potential delivery to resources.

Landform # 11 - Ridge Tops & Noses – Low Hazard

Description of Mass Wasting Unit: This map unit includes ridge tops and noses of ridges with mostly planar slopes that have gradients between 0 % and 11 %, exhibit a low landslide potential, and/or are not likely to deliver sediment to a stream, impact public safety or impact a public resource. (Caution: Unmapped inner gorges, bedrock hollows, and other high-hazard landforms may have been erroneously included in landform #11 through mapping errors.)

Slopes:	Variable 0 to 11% (DEM-measured). Field-measured slopes are commonly steeper than those determined from the DEM.
Slope Shape:	Divergent to planar
Material:	Colluvium, alluvium, landslide and glacial deposits, lahar deposits (mainly Osceola Mudflow), and volcanics (Fifes Peak and Ohanapecosh Formations and Canyon Creek basalt)
Elevation:	900 ft to 4,900 ft
Total Area:	619 acres

Mass Wasting Processes: Shallow landslides may occur but are not common within this landform.

Forest Practice Sensitivity and Triggering Mechanisms: Poor forest management practices on this landform could cause mass wasting on slopes below rid tops and noses on other landforms.

Mass Wasting Potential: **Low** for road construction and timber harvest. This landform has no "delivering" failures in an area of 619 acres. This landform has a Landslide Frequency Rate of zero with roads and without roads.

Delivery Potential/Criteria: **Low**. The delivery rate for this unit is 0. No mass wasting features were noted within this landform that delivered. Delivery is unlikely as lack of channel access precludes transport. Road and landing failures do not travel great distances. Distance from stream channels and topography inhibits transport of landslide debris deposited onto this landform from upper elevation sources and does not impact public safety. The Landslide Delivery Rate for this unit is 0.

Overall Hazard Potential Rating: **Low** for the entire unit.

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

Comments: Very little failure activity noted. Some ridge tops with low angles have landslides directly below flats. Few have potential for delivery in the south area of the watershed.

Landform Number: #12 – Mud Mountain Reservoir Valley Stream Bottom (Unique) – High Hazard

Description of Mass Wasting Unit: This map unit includes primarily planar slopes and gradients less than 11% located along the valley bottom of the White River within the reservoir area behind Mud Mountain Dam.

Slopes: Variable 0 to 10%
Slope Shape: Planar
Material: Alluvium, glacial outwash, and lahar deposits (mainly Osceola Mudflow)
Elevation: 950 ft to 1,200 ft
Total Area: 308 acres

Mass Wasting Processes: Primarily shallow undifferentiated landslides occur on relatively flat ground and deliver to the White River. Typically, valley stream bottoms have low landslide potential but due to the repeated fluctuations in water retention in the reservoir every year, the hydrostatic liquefaction in pore water pressure of geologic materials are constantly being wetted and de-watered creating unstable conditions on relatively flat ground.

Forest Practice Sensitivity and Triggering Mechanisms: Forest practice activities are limited due to the fluctuation of water retention in the Mud Mountain Reservoir. Water storage after storms is used as flood prevention for down river activities. Mass wasting triggering mechanism is directly related to the retention of water and the changes in pore water pressure.

Mass Wasting Potential: **Very High.** This rating is based on 12 “delivering” failures with a total failed are of 0.99 acres in an area of 308 acres. This landform has a Landslide Frequency Rate of 1,391 with roads and without roads.

Delivery Potential/Criteria: **Moderate**. This rating is based the Landslide Delivery Rate for this unit is 115 with roads and without roads.

Overall Hazard Potential Rating: **High** for the entire unit.

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

Comments: Additional landslides in this landform may not have been mapped due to water retention in reservoir during some years of air photos.

Landform #13 – Mud Mountain Reservoir Steep Terrace Face of (50% and greater) (Unique) – High Hazard

Description of Mass Wasting Unit: Located on the east side of the Mud Mountain Dam to the eastern side of the watershed along the White River are steep (50% and greater) slopes and highly failing terrace faces. These terrace faces contain numerous shallow and deep-seated landslides (See report cover page).

Slopes:	50% and greater
Slope Shape:	Convergent to planar
Material:	Alluvium, glacial outwash, and lahar deposits (Osceola Mudflow and others)
Elevation:	950 ft to 1,600 ft
Total Area:	807 acres

Mass Wasting Processes: The White River undercuts adjacent upland slopes causing shallow undifferentiated landslides, debris slides as well as debris flows and deep-seated landslides on the terrace face along the White River Reservoir. The majority of the terrace face has high landslide potential due to the undercutting of and adjacent river and upslope area of reservoir water. This terrace face has a greater susceptibility to failure due to repeated fluctuations in water retention in the reservoir every year. Geologic materials are constantly being wetted and de-watered which causes hydrostatic changes in pore water pressure creating higher than typical unstable conditions along the terrace face.

Forest Practice Sensitivity and Triggering Mechanisms: Stream bank and terrace face erosion from the White River undercutting this landform making it prone to mass wasting even under mature forested conditions, therefore, any disturbance resulting from timber harvest or road construction can further destabilize these slopes. Loss of root strength, changes in slope gradient, and changes in hydrology from forest management activities on or near the terrace edge can destabilize these slopes especially during major rain-on-snow storms or intense precipitation events. Roads and landings can cause instability by undercutting and oversteepening slopes. Sidecast and road (or landing) fill can oversteepen and add weight to terrace faces; roads and landings can capture runoff water or shallow groundwater and channel it to point locations causing soil saturation.

Mass Wasting Potential: **Very High** for road construction and timber harvest based on 144 “delivering” failures with a total failed area of 70.87 acres in an area of 807 acres. This landform has a Landslide Frequency Rating of 6,373 with roads and 6,329 without roads.

Delivery Potential/Criteria: **Very High.** Any disturbance delivers directly to the river and/or reservoir. The unit has a calculated Landslide Area Rate of Delivery of 3,136 with roads and 3,132 without roads.

Overall Hazard Potential Rating: **Very High** for the entire unit.

Confidence: High for the entire unit based on observed direct delivery to typed waters, excellent photo quality and coverage, partial lidar coverage, and field verification.

Comments: Additional landslides in this landform may not have been mapped due to water retention in reservoir during some years of air photos.

Landform #14 – Terrace Top (<11%) (Unique) – Low Hazard

Description of Mass Wasting Unit: This landform consists of a flat terrace surface that was covered by the lahar deposits of the Osceola Mudflow. This terrace is underlain by the continental ice-contact recessional outwash (Tabor and others, 2000). (Caution: Unmapped inner gorges, bedrock hollows, and other high-hazard landforms could have been erroneously included in landform #16 through mapping errors.)

Slopes: 0 to 10% (DEM-measured). Field-measured slopes are commonly steeper than those determined from the DEM.
Slope Shape: Includes all slope shapes
Material: Lahar deposits of the Osceola Mudflow
Elevation: 620 ft to 1,700 ft
Total Area: 8,600 acres

Mass Wasting Processes: Shallow undifferentiated landslides are uncommon and generally do not have the potential to deliver to waters of the state or impact public safety or resources.

Forest Practice Sensitivity and Triggering Mechanisms: Mass wasting is uncommon in this landform and Forest practice activities have very little impact on slope stability.

Mass Wasting Potential: **Low** for road construction and timber harvest. This landform has 3 “delivering” failures with a total failed area of 0.13 acres in an area of 8,585 acres. This landform has a Landslide Frequency Rate of 12.48 with or without roads.

Delivery Potential/Criteria: **Low** for road construction and timber harvest. The unit has a calculated Landslide Area Rate of Delivery of 0.54 with or without roads

Overall Hazard Potential Rating: **Low** for the entire unit.

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

Comments:

Landform # 15 – Steep Hillside Slopes (>70%) - Very High Hazard

Description of Mass Wasting Unit: These slopes are convergent to divergent in shape. They may contain isolated areas of cliffs and steeper (>70%) slopes. This landform may include head scarps of deep-seated landslides that are not likely to deliver. The landslides in this landform were mapped from aerial photographs and given the inaccuracy of DEM slope determinations, many of the mapped features within this landform could actually be other unmapped high hazard landform (e.g., inner gorges, or bedrock hollows).

Slopes:	Variable but >70% (DEM-measured). DEM-measured slopes commonly underestimate actual slope gradients in the field by 10% or more, therefore, landforms were drawn with >60% DEM.
Slope Shape:	Variable from convergent to divergent
Material:	Glacial, lahar deposits (mainly Osceola Mudflow), and Volcanics (Fifes Peak and Ohanapecosh Formations and Canyon Creek Basalt)
Elevation:	755 ft to 4,967 ft
Total Area:	1,679 acres

Mass Wasting Processes: Soil saturation, loss of root strength, and/or over steepening of slopes in this landform can trigger debris slides, debris flows or small deep-seated landslides. This landform is commonly located between mapped inner gorges in the volcaniclastic formations and along the continental ice-contact terrace (east of Baldy Hill).

Forest Practice Sensitivity and Trigger Mechanisms: Timber harvest on these steep (>70%) slopes may result in the loss of root strength as well as road construction and/or landing construction are major factors of slope instability. Side cast and road (or landing) fill can cause instability by undercutting, oversteepening, and loading slopes. Roads and landings can also capture runoff water or shallow groundwater and channel it to point locations that saturate road or landing fill and/or deeply weathered bedrock, triggering slope failures. The loss of root strength, changes in slope gradient, and changes in hydrology caused by timber harvesting and road or landing construction has destabilized similar slopes that have failed during major storms or intense precipitation events. The majority of the landslides in this landform that deliver to streams occurred in clearcut areas that were older than 15 years which is beyond the time when roots can still hold soils in place on steep ground. Therefore it is assumed that a loss of root strength adversely influenced slope stability on this landform.

Mass Wasting Potential: **Very High** for road construction and timber harvest based on 63 "delivering" failures with a total failed area of 24.5 acres in an area of 1,679 acres. This landform has a Landslide Frequency Rating of 1,340 with roads and 1,212 without roads.

Delivery Potential/Criteria: **High** for road construction and timber. This landform has been assigned a high delivery potential because the unit has a calculated Landslide Area Rate of Delivery of 522 with roads and 486 without roads.

Overall Hazard Potential Rating: **Very High** for this landform unit.

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

Comments: The majority of Landform #15 is mapped within Fifes Peak and Ohanapecosh Formations. The majority of area within this landform is located adjacent to inner gorges.

Landform # 16 - Low Gradient Hill Slopes and Valley Side Slopes (11 to 40%) - Low Hazard

Description of Mass Wasting Unit: This map unit includes all hill slope forms and gradients between 11% and 40% that exhibit a low landslide potential, and/or are not likely to deliver sediment to a stream, impact public safety or impact a public resource. (Caution: Unmapped inner gorges, bedrock hollows, and other high-hazard landforms could have been erroneously included in landform #16 through mapping errors.)

Slopes:	Variable 11% and 40% (DEM-measured). DEM-measured slopes commonly underestimate actual slope gradients in the field by 10% or more.
Slope Shape:	Variable from convergent to divergent
Material:	Alluvium, glacial and lahar deposits (mainly Osceola Mudflow), and Volcanics (Fifes Peak and Ohanapecosh Formations and Canyon Creek Basalt) and soils
Elevation:	650 ft to 5,050 ft
Total Area:	14,795 acres

Mass Wasting Processes: Shallow undifferentiated landslides, debris slides, as well as debris flows, and deep-seated landslides with varying slope shapes occur within this landform fail at gradients between 11% to 40%. These landslides are rare, usually only occurring during storm events commonly associated with historic forest practices techniques.

Forest Practice Sensitivity and Trigger Mechanisms: Clearcut areas, in which root strength loss occurs, appear to be the most significant triggering mechanisms for landsliding within this landform. Undersized culverts may lead to road fill failures and may not deliver to streams. Roads and landings can cause instability by undercutting and oversteepening slopes. Side cast and road (or landing) fill can oversteepen and add weight to slopes; roads and landings can also capture runoff water or shallow groundwater and channel it to point locations that saturate road or landing fill and/or deeply weathered bedrock or glacial deposits, and trigger slope failures. The loss of root strength changes in slope gradient, and changes in hydrology caused by timber harvesting and road or landing construction have the potential to initiate slope failure.

Mass Wasting Potential: **<u>Moderate</u>** for roads construction and timber harvest based on 60 "delivering" failures with a total failed area of 8.4 acres in an area of 14,795 acres. This landform has a <u>Landslide Frequency Rating</u> of 145 with roads and 140 without roads.

Delivery Potential/Criteria: **<u>Low</u>** for roads construction and timber harvest. This landform has been assigned a low delivery potential because the unit has a calculated <u>Landslide Area Rate of Delivery</u> of 20 with roads and without roads.

Overall Hazard Potential Rating: **<u>Low</u>** for entire unit.

Confidence: <u>High</u> based on the number of landslides located in this landform, excellent photo quality and coverage, partial lidar coverage, and field observation.

Comments: These low angle earthflows occurring in glacial deposits located in the Scatter Creek drainage have small, deep-seated landslides along their toes and were located as GPS points on Maps A-1 and A-2 and Appendix E describes features. Earthflows have not been completely mapped in this landform and careful field review is necessary. There are multiple failures within this landform that do not appear to impact public safety or deliver due to sufficient distances from stream channels and topography, which inhibit transport of landslide debris. Additionally, there are dormant distinct and dormant indistinct deep-seated landslides that have the potential to deliver to streams if reactivated, therefore careful field review is necessary for those landslides shown on the Map A1.

Landform # 17 – Moderate to Steep Hillside Slopes (41 to 70%) - Moderate Hazard

Description of Mass Wasting Unit: These slopes are varied in shape (with the majority being convergent and planar) and have a gradient between 41% and 70%. This landform often includes head scarps of deep-seated landslides as well as other landslide processes. (Caution: Unmapped inner gorges, bedrock hollows, and other high-hazard landforms could have been erroneously included in landform #17 through mapping errors.)

Slopes:	Variable 41% to 70% (DEM-measured). DEM-measured slopes commonly underestimate actual slope gradients in the field by 10% or more, therefore, landforms were drawn with <70% DEM.
Slope Shape:	Variable from convergent to divergent
Material:	Glacial, lahar deposits (mainly Osceola Mudflow), and Volcanics (Fifes Peak and Ohanapecosh Formations and Canyon Creek Basalt) and soils
Elevation:	750 ft to 4,975 ft
Total Area:	5,015 acres

Mass Wasting Processes: Shallow undifferentiated landslides, debris slides, as well as debris flows, and deep-seated landslides occur within this map unit. The majority of the landslides in this landform that deliver to streams occurred in clearcut areas that were older than 15 years which is beyond the time when roots can still hold soils in place on steep ground. Therefore it is assumed that a loss of root strength adversely influenced slope stability on this landform.

Forest Practice Sensitivity and Trigger Mechanisms: Timber harvest, road construction and/or landing construction on slopes between 41 and 70% in poorly consolidated colluvium and deeply weathered bedrock can increase slope instability. Loss of root strength can increase rates of mass wasting as can roads and landings that undercut or load or change the hydrology of these steep slopes. Side cast and landings can cause instability by oversteepening slopes, loading and undercutting them. Roads and landings can also capture runoff water or shallow groundwater and channel it to point locations that saturate fill and/or deeply weathered bedrock, triggering slope failures. Loss of root strength, changes in slope gradient, and changes in hydrology caused by timber harvesting and road or landing construction have destabilized slopes during storms or intense precipitation events.

Mass Wasting Potential: **High** for roads construction and timber harvest based on 91 "delivering" features with a total failed area of 22.4 acres in an area of 5,015 acres. This landform has a Landslide Frequency Rating of 648 with roads and 541 without roads.

Delivery Potential/Criteria: **High** for road construction and timber harvest and **Moderate** for areas without roads. The unit has a calculated Landslide Area Rate of Delivery of 159 with roads and 131 without roads.

Overall Hazard Potential Rating: **Moderate** for entire unit.

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

Comments: Some moderate to steep hillsides contain several cut bank failures adjacent to roads that were not mapped as landslides.

Appendix D – Landform Hazard Rating Table: Form A-4

Mud Mountain WAU

Landforms	Landform 1	Landform 2	Landform 3	Landform 4	Landform 7	Landform 8	Landform 9	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Total WAU
Years	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
Landform Area	340	84	262	164	9	223	43	1216	619	308	807	8585	1679	14795	5015	34149
Number of 'Delivering' Landslides	45	7	11	15	1	6	3	0	0	12	144	3	63	60	91	461
Area of 'Delivering' Landslides (acres)	15.52	1.41	1.11	6.61	0.19	1.82	1.52	0	0	0.99	70.87	0.13	24.52	8.43	22.37	155.49
Landslide Frequency Rate (Number of slides/Landform Area/Years) x 10^6	4726.89	2976.19	1499.45	3266.55	3968.25	960.92	2491.69	0	0	1391.47	6372.81	12.48	1340.08	144.84	648.06	482.13
Landslide Area Rate for Delivery (Delivering Landslide Area/Landform Area/Years) x 10^6	1630.25	599.49	151.31	1439.46	753.97	291.48	1262.46	0	0	114.8	3136.4	0.54	521.57	20.35	159.31	162.62
Overall Rating	Very High	Very High	Very High	Very High	Very High	High	Very High	Low	Low	High	Very High	Low	Very High	Low	High	High

Without Roads

Landforms	Landform 1	Landform 2	Landform 3	Landform 4	Landform 7	Landform 8	Landform 9	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Landform 1	Total WAU
Years	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
Landform Area	340	84	262	164	9	223	43	1216	619	308	807	8585	1679	14795	5015	34149
Number of 'Delivering' Landslides	35	4	10	13	0	6	3	0	0	12	143	3	57	58	76	381
Area of 'Delivering' Landslides (acres)	11.75	0.54	0.79	6.17	0	1.82	1.52	0	0	0.99	70.78	0.13	22.83	8.25	18.33	131.61
Landslide Frequency Rate (Number of slides/Landform Area/Years) x 10^6	3676.47	1700.68	1363.14	2831.01	0	960.92	2491.69	0	0	1391.47	6328.55	12.48	1212.46	140.01	541.23	398.46
Landslide Area Rate for Delivery (Delivering Landslide Area/Landform Area/Years) x 10^6	1234.24	229.59	107.69	1343.64	0	291.48	1262.46	0	0	114.8	3132.41	0.54	485.62	19.92	130.54	137.64
Overall Rating	Very High	Very High	High	Very High	Moderate	High	High	Low	Low	High	Very High	Low	Very High	Low	Moderate	Moderate

APPENDIX E - MUD MOUNTAIN GPS DATA:

The GPS points described in this appendix have been used to aid, describe and delineate the data, and are not part of the inventory of landslides or landforms already described in this report. The following field notes are transcribed as taken in the field. These maps provide references on the ground for the field identified landslides within the Mud Mountain watershed.

<u>25 August 2005</u>
Mud Mtn WAU
Scatter Creek
cfs (Carol F. Serdar), Jack Powell

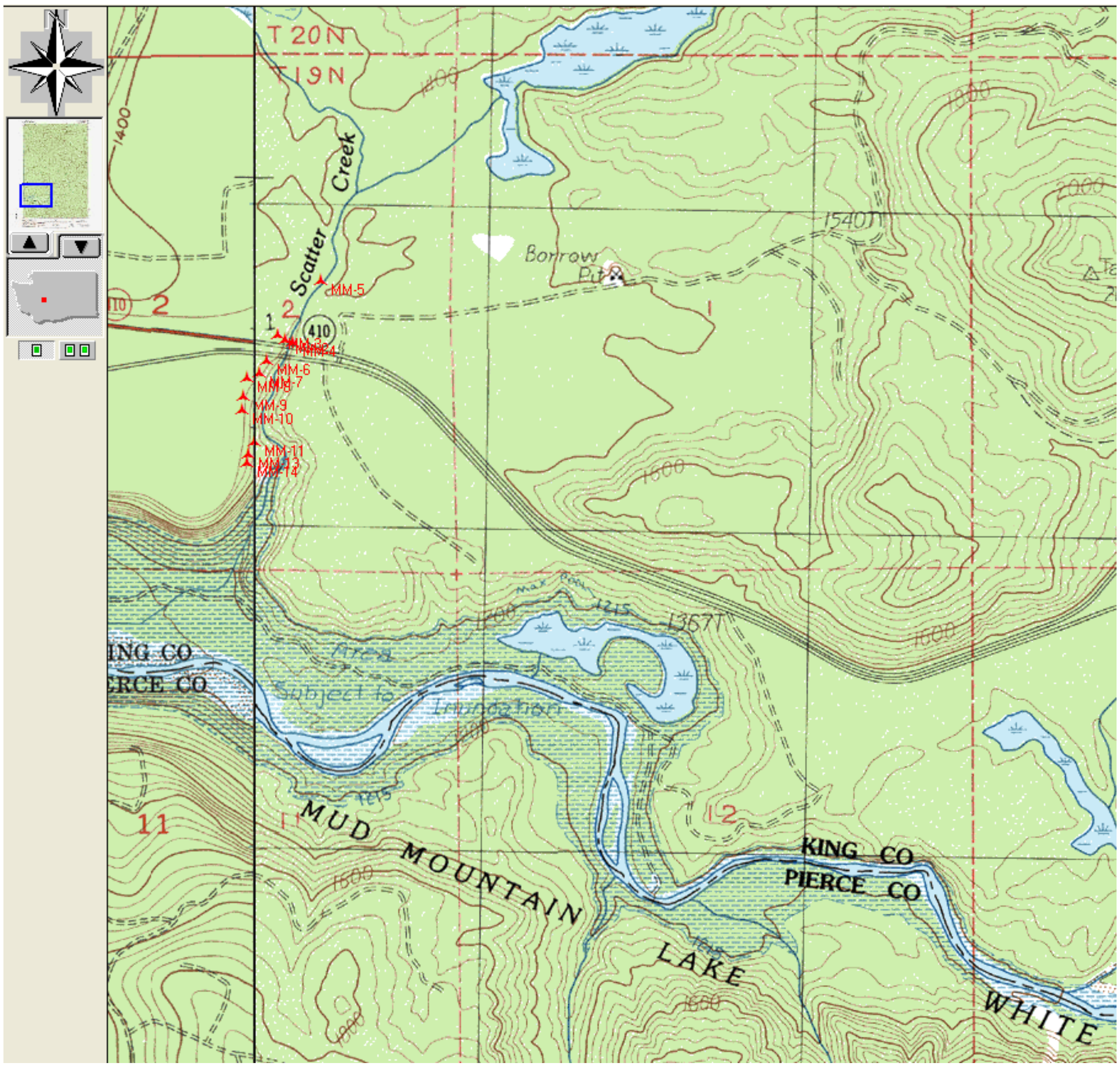


Figure 1. – Map of GPS points

MM-2 (+/- 20)
100' north side of HWY410, right bank Scatter Creek. **Shallow ls** (landslide) on edge of inner gorge. Ls based on trees appears to be +/-20 yrs w/some activation in recent times. 80% across surface of ls. Slope that failed was 70% or greater. Ls appears to be caused by stream undercutting. FP issues: loss of root strength due to cutting, loading of slope w/rd building, undercutting and oversteepening due to rd building. 50'wide x 50' long. Actively failing. *ls w/in inner gorge. Very shallow deep seated, slightly below rooting strength of trees w/some bedrock material. Delivered to stream.

MM-3 (+/- 23)
Ditch 5' deep at head of scarp of **deep-seated landslide**, perhaps rdway runoff? Undercut bank cause of ls, contributing factor by drainage ditch draining onto slopes of inner gorge. 2nd ditch + 150' from last one. 160' to other edge of ls where tree age changes. Old growth slumps on slope. Sweeps in conifers (bow then straightening out but still tilted – "punctuated motion" or jack strawed) . Delivered to stream.

MM-4 (+/- 22)
Next **landslide**, lahar deposit. Old growth stumps, 60 yr conifer along scarp, large downed tree w/root wad adj to stream. 50'w x 100'l, 50% across surface of ls w/vertical headscarp. Delivered to stream.

MM-5 (+/- 30)
End of **inner gorge**, farthest upstream

(MM-6 through MM-14 located on south side of HWY410 still along right bank of Scatter Creek down stream towards White River.)

MM-6 (+/- 41)
Top of 40' high scarp. 70% overall slope. 90-100% scarp and body slope (scarp vertical). Lahar deposit, 75'w x 100' l, 5-10yr old ls, horsetails apparent spring below scarp, undercutting of toe and perhaps some contributing factor is ditch adj to haul rd, **deep-seated landslide**, no old growth stumps on body, (root strength important w/small body). Delivered to stream.

MM-7 (+/- 25)
Top of scarp. 30 yr old maple on body of ls, appears to have pushed the creek over to opposite side. Deep-seated landslide, lahar deposit, 70% scarp and body, 150'w x 60'l, prefailure slope 75-80%. Trees on body aiding in stabilization of this **shallow deep-seated ls**. Delivered to stream.

MM-8 (+/- 23)
Top of **landslide** scarp. Skidding trail up ls, vine leaf maple on body, ls 30 yrs old w/10 yr ago reactivation, minor scarps w/sword fern. 70-90% original slope, deep seated, 150'w x 200+'l. Delivered to stream.

MM-9 (+/- 24)

Top of scarp. Pre-failure slope = 100%+. Within inner gorge. 30-40’w x 150’l. **Shallow deep-seated ls**. Delivered to stream.

MM-10 (+/- 22)
Top of **landslide** scarp. Pre-failure slope = 100%+. Vertical scarp, landslide 2-3 years old with a lot of salmonberry. Delivered to stream.

MM-11 (+/- 25)
Top of scarp, apex between **two deep-seated ls**: 1) 15-20 year old slide = 120’w x 100’l; and 2) 5 yr old slide and surface runoff contributed to ls w/5’w x 1’ deep channel = 50’w x 200’l (downstream). Both pre-failure slope = 110%+. Undercut by river, outside of meander on inner gorge. Delivered to stream.

MM-13 (+/- 19)
Top of **deep-seated** scarp, dead maple on body. 50-60’w x 200’l. Undercut by river, questionable if influenced by of Mud Mountain Reservoir. Delivered to stream.

MM-14 (+/- 16)
Top of **deep-seated** scarp. Closest to mouth of Scatter Creek. Lahar deposit = ~15’, ashy sand (black laminated) = ~8’, foreset bedding sands = ~6’, gravels with interbedded sands = ~ 100’. **Landslide** 75’w x 200’l, small alders on lower body. 5-10 year old slide. gps elevation 1249’. Delivered to stream.

26 August 2005
Mud Mtn WAU
South side of White River
cfs, Jack Powell

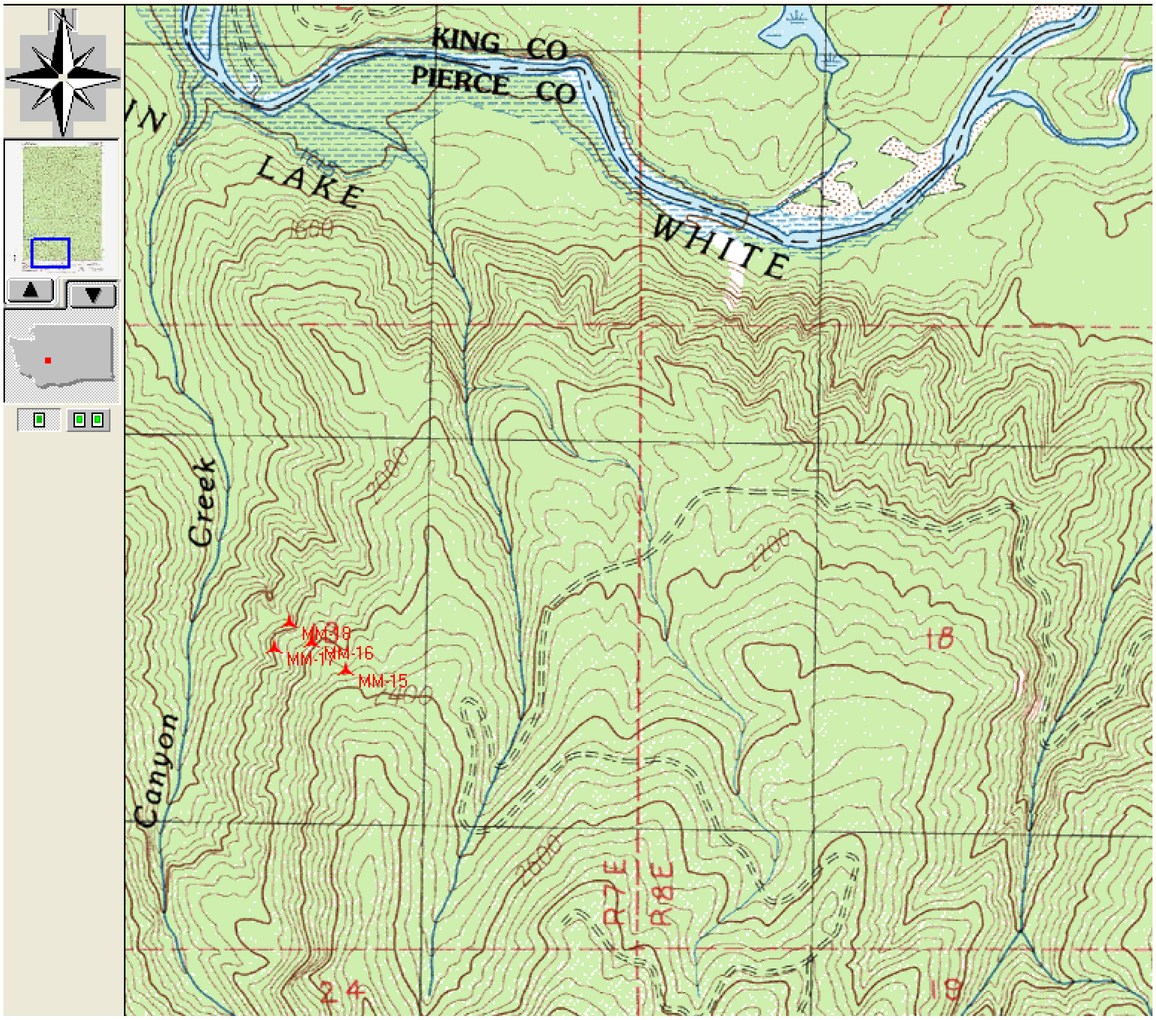


Figure 2. – Map of GPS points

Canyon Creek drainage:

MM-15 (+/-68)

Center of log rd in alignment with center of scarp. **Debris slide**-rotational, undercut by rd ("cutslope failure"). 25'w x 40'l. Convergent slope with overall hill planar. Pre-failure slope = 58%. When slide occurred, likely to have had debris covering rd, now debris side cast down slope of rd. 2-3 yrs old. No delivery to stream. Landuse = rd. gps elevation 2275'.

MM-16 (+/-38)

Bedrock hollow, 95% feature slope, adj original slope 58-65%. >50 year old forest, seep w/devils club, east of this BH is another wet feature, but slope not >70%.

Down slope = **debris flow** in not too distant past (20-25 yrs ago, alder age w/in body). Ls feature 50'w x +300'l. Original slope 75%; adj landuse >50yr forest; colluvial soils over volcanic bedrock; concave and convergent; many shallow slides; spring present. Another **BH** along E side & down slope; dry and no recent failure.

MM-17 (+/-45)
Debris flow multiple df (debris flows) thru this one. Original grade = 85-100%; (adj tree age)+/-50 yrs; definite; 70'w x 300'l; occurred 15-50 yrs; landform w/in b.h.; slope concave and planar; delivery.

MM-18 (+/-26)
Debris flow same as last (MM-17).

<u>20 September 2005</u>
Mud Mtn WAU
South side of White River
cfs, jhtepper

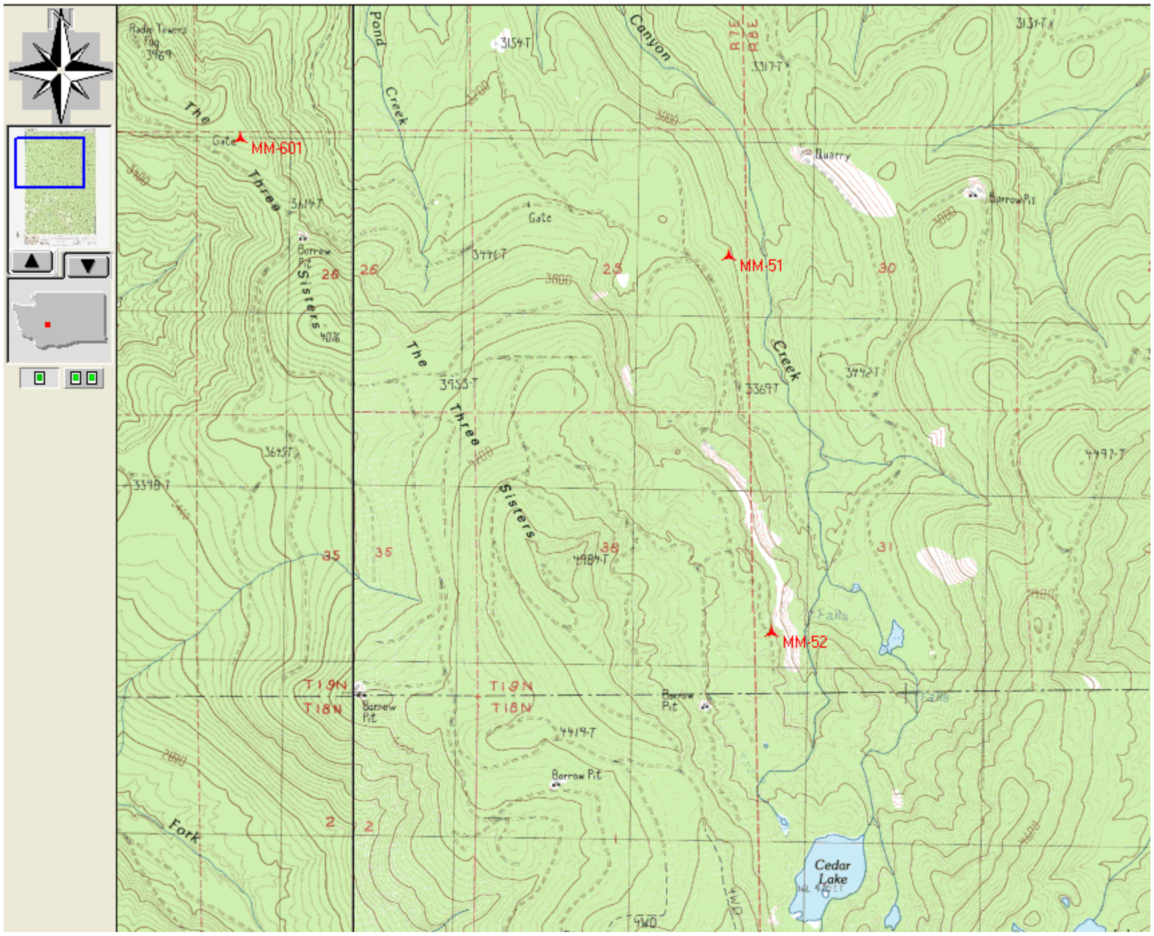


Figure 3. – Map of GPS points

<u>Southern WAU:</u>

MM-51 (+/-23)
Walked thru woods to open spaces; salmonberry, devils club, some conifers – pistol butted adj to bedrock nose; slope 50%; deranged stream. (**lsi** #364)

MM-52 (+/-18)
Edge of over hang above talus, above **lsi** #328. Rd 6065-2A5 (not the end).

25 October 2005
Mud Mtn WAU
North side of White River
cfs, lpowell

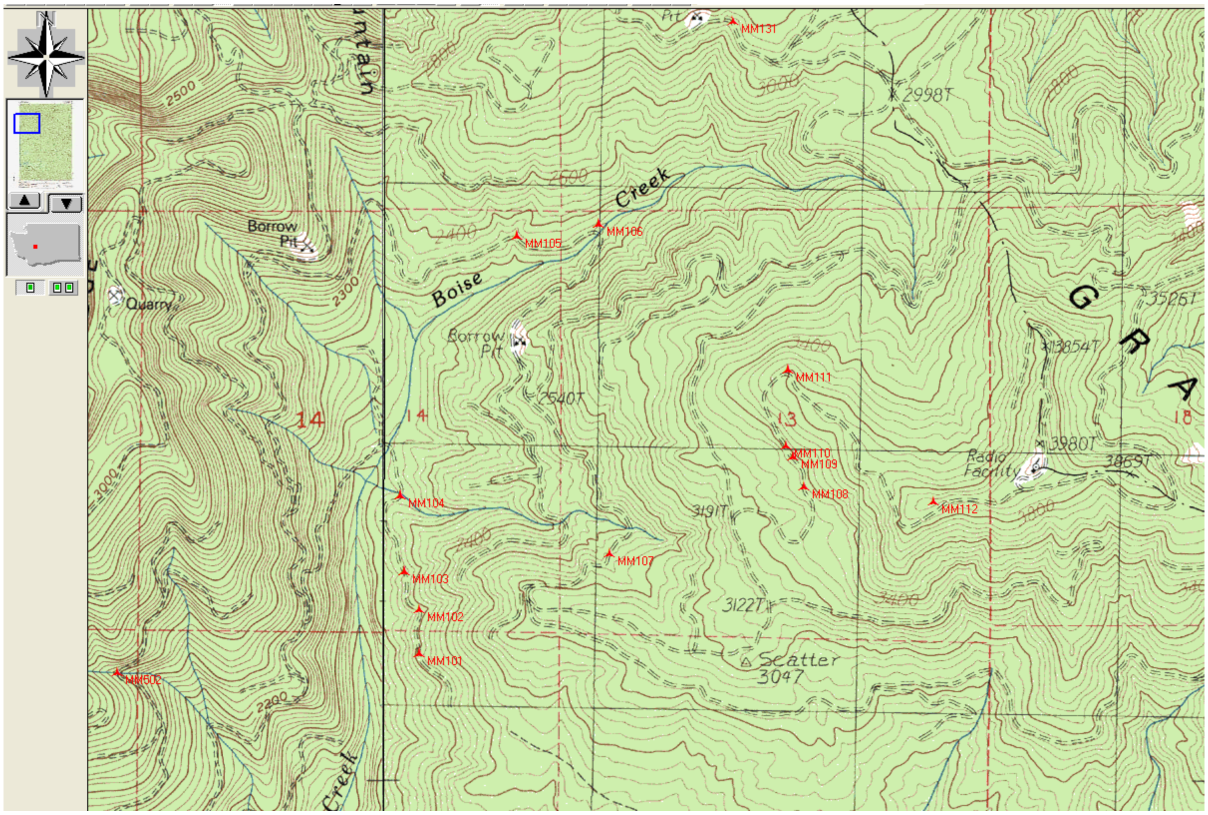


Figure 4. – Map of GPS points

Boise Creek area:

MM101 (+/-10)
Rd 5307-4 = ?? **dsls vs ig** across Boise Cr.

MM102 (+/-12)
IG under rd; just beyond pt = rd cut failure w/Andesite exposed; 72% of side slope adj to creek (good water flow); asymmetrical (steeper rt bank); sm **b.h.** partially failed & some filled again & bedrock creek; steeper below rd (down cr). Sags in rd fill. Slipped not~ completely failed. Trees holding failure back.

MM103 (+/-18)
b.h. & ig below rd. Rd at bottom of b.h. w/ig below rd); running water; not down to bedrock (partially filled).

MM104 (+/-9)
Major stream/trib to Boise Cr. Colluvium, fill along stream bed, ?**D.F.**?, not ig.; water (ponded) in ditch ~ toe of **dsls**.

MM105 (+/-23)
Older **df**, trees alder in creek >20 yrs.; 5-8' deep ~ scour line below firs adj to creek; cr completely covered w/wood & stumps; after area was cut it slid, cut marks on wood in stream.

MM106 (+/-23)
Bridge/culvert removed from Boise Cr.; cut alder = 6yrs +1 yr to germinate; flat area; toe of **dsls**.

MM107 (+/-11)
Maybe **dsls** toe

MM108 (+/-17)
Dsls body; toe below rd, colluvium, nasty rd.

MM109 (+/-17)
Cutslope failure & **fillslope failure**; deliver = no, water = no; 50'w x 4-6' cut, rd missing 100' down. Rd construction & water channeling onto ls fill areas.

MM110 (+/-8)
Rd fill failure; 30'w x 4-6'- 100' down; cutslope and fill failure; cup shaped; no delivery. Rd construction & water channeling onto ls fill areas.

MM111 (+/-9)
Across water to main line; below mainline **df** in mid slope w/delivery.

MM112 (+/-8)
Radio tower (new location not on maps).

27 October 2005
Mud Mtn WAU
Northside of White River, Scatter Creek & NE portion of WAU
cfs, lpowell

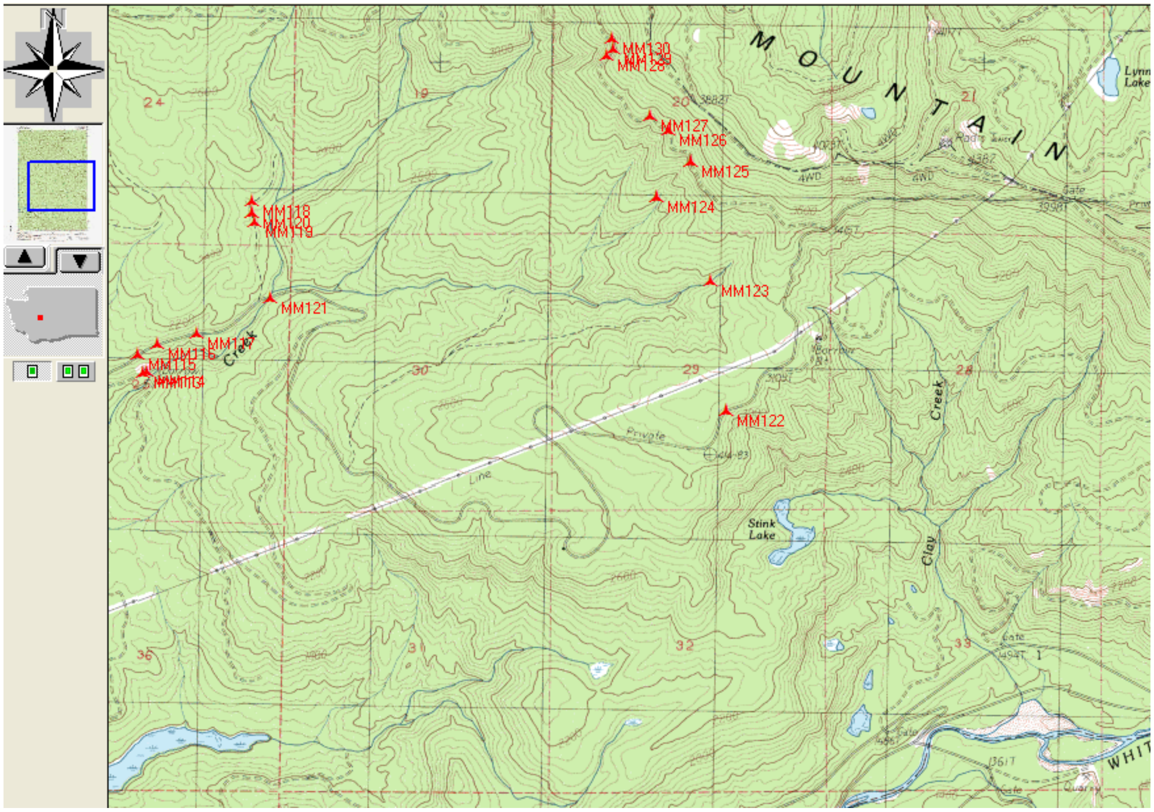


Figure 5. – Map of GPS points

Scatter Creek:

MM113 (+/-13)
So of Quarry across Rd, initiation pt of **df** into Scatter Cr.; initiation pt has been filled w/cobble, rock, tree stumps; +5 yrs based on size of alder on fill. Sweeps of 60% of trees on **dsls** toe, 40' up trees. Pulled stream crossing, 12 tiles lying out of water.

MM114 (+/-14)
Marginal stream on west side of **dsls** to east of Quarry location. Walked across toe adj to stream; toe w/seeps near stacked tiles = 65% slope of dsls toe adj to Scatter Cr.; sags/flatter areas wet and 35% slopes with devils club; east side 70% slope along dsls body; ditch adj to rd above = wet.

MM115 (+/-10)
Edge of scarp & marginal stream; top of MM114 marginal stream; scalloped top upslope side of rd; sag /failure plane @ edge of rd, water infiltration to this sag.

MM116 (+/-10)

Seeps between MM116 and MM117; cut bank due to rd= colluvium; transition area from cut to fill area; colluvium on cutbank @ nose between cup shape; seeps on upslope side & scarp below rd; shallow scarp (25') & no lateral extent due to leaf cover; concave slopes up slope from rd; sedges & reeds in ditches.

MM117 (+/-10)
Marginal stream east side of **dsls**; sweep in fir (30 yr old) all the way up; rd sited on top of body.
Cutslope failure @ "Y" w/ main rd (5200 – top of "birds head"). Buttressing toe of rd (**dsls**) seep; glacial deposit. Followed rd to end, another older **ls** deposit (hummocky ground)slicks & andesite contact with colluvium; stream gentle – no df.

MM118 (+/-8)
Marginal stream along dissected toe of **earthflow** – adj water, seeped onto rd, young trees <8 yrs old w/sweeps.
Just south of MM118 scalloped area = 22% slopes N side of scallop; 26% slope crest of scallop; 18% slope S sode pf scallop – rd adjacent.

M119 (+/-16)
Marginal stream to scallop edge.

MM120 (+/-16)
N edge of scallop of shallow **dsls** @ toe of **earthflow**. Sapping.

MM121 (+/-18)
DF. Rd/bridge blow out & replaced bridge, armored stream bank; debris adj to stream & buried.

MM122 (+/-9)
Along 5200 rd – **b.h.**; 30yr old conifers w/sweeps; measured slope in b.h. (78% on sides, 74% in center).

MM124 (+/-13)
Old, old **df** (?original harvest last one); **ig** starts out asymmetrical then goes to 81% right bank, 85% left bank w/25' to break in slope; start ig above rd 150'.

<u>Northeast side of WAU (Ohanapecosh Formation):</u>
See map above.

MM125 (+/-25)
Pt taken on 5218 rd, but measured slope below rd ballast to break in canopy 70%; **B.H.**, above slope from MM124.

MM126 (+/-13)

B.H. actively failing; rd thru b.h.; open no conifers/open canopy; no ditch upslope side; rd bed slumping.

MM127 (+/-12)
B.H.; rd fill actively failing; fill failin in bh/2 sets of tension cracks (on rd & just on downslope side of rd); break/hole in canopy; 17 yr old hemlock w/multiple sweeps; rd over bh; no ditch on upslope side; 80% slope w/in bh. (volcanic breccia sample).

MM128 (+/-12)
B.H.; w/**debris slide** & alder in flow path; >90% above rd & no ditch; >110% below rd (reading taken from rd bed which is bedrock).

MM129 (+/-17)
B.H. actively failing; alder & devils club; bedrock above rd & no ditch; slumping above rd, and rd slumping, roadbed cracked on outside; water running over rd.

MM130 (+/-15)
B.H./Debris flow actively failing; rd railing at edge (15' drop); buried wood w/in rd fill; rd channeling water into bh; no ditch upslope; tension crack 5' from rd on upslope side; hear water up slope, but none seen downslope-then can hear farther downslope; open canopy @ rd, conifers just below; no ig.

MM131 (+/-19)
B.H.; very steep upslope side of rd (east of Quarry); conifers; >70%.
See map on 25 October 2005 for this gps point location.

<u>8 February 2006</u>
Mud Mtn WAU
North side of White River, Boise Ridge
cfs, lpowell

<u>Boise Ridge:</u>
MM502 (+/-16)
Inner gorge; water present; upper zero order trib to Boise Cr; 78% of sideslope w/in inner gorge; steeper left bank.
See map on 25 October 2005 for this gps point location.

<u>29 March 2006</u>
Mud Mtn WAU
Southern tip of WAU
cfs, lvaugeois

<u>Active logging operation along The Three Sisters in southern WAU:</u>
Confirmed toe of dsls #570 and debris flow #949. #949 has dam impoundment with water near top of dam.

MM601 (+/-22)
See map above from 20 September 2005 for this gps point.
Top of harvest, north of active yarding in harvest unit where **probable landslide** (photos from 10 mile marker).

<u>23 June 2006</u>
Mud Mtn WAU
Three Sisters Mtns
cfs

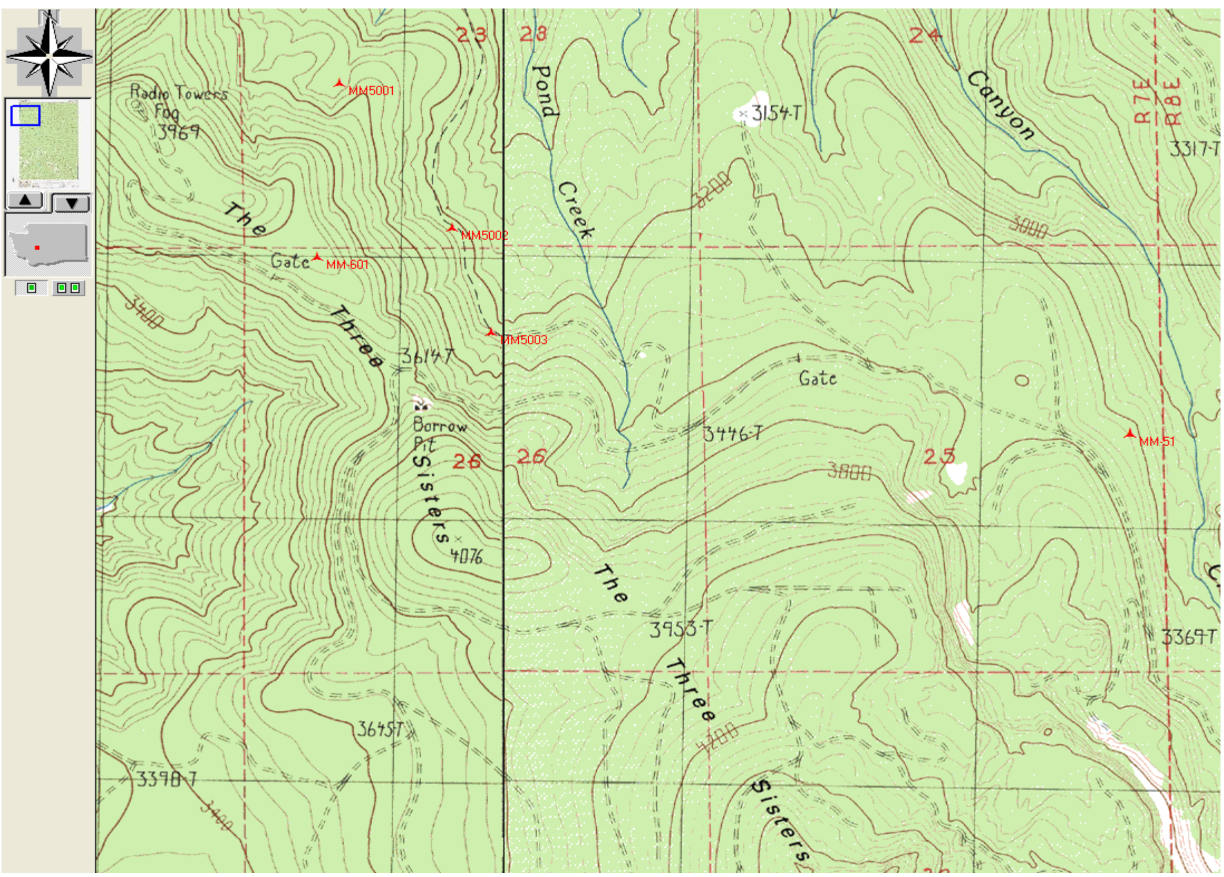


Figure 6. – Map of GPS points

The Three Sisters Area.
MM5001 (+/-22)
On rd #6062 north side/edge of clearcut at stream flowing. Photo with pink flagging.

MM5002 (+/-20)
Fill on clearcut side of rd #6062, 40'x50'+/-, photo.

MM5003 (+/-26)
15' stream cascade/fall on clearcut side of rd #6062, w/culvert almost buried on upslope side, photo.

Figure 7.

Appendix F: Land use and Historical Considerations

Additional information is provided below to better understand the contributing factors and triggering mechanisms for the landslides found in the Mud Mountain watershed inventory.

General History

A network of trails and railroads accessed the watershed for timber harvesting and some of these historical practices are shown to be contributing factors for slope failures. The Muckleshoot Native Americans (multiple tribes of Indians) made the first trails in the area. They also used the White River as a transportation route to and from Mt. Rainier and relied heavily on the river and its tributaries for the substantial salmon runs. Archeological findings date back 6,000 years shows that the natives were well established in the Puget Lowlands prior to the signing of the Medicine Creek Treaty. The European settlements began in the lowlands and moved into the higher elevations, and began with the development of trails through the mountains. In 1841, Pierre Charles led an exploration expedition through the Naches Pass, east of the Mud Mountain watershed. Highway 410 now runs east/west across Naches Pass and over the Cascade mountains. The Puget Sound region development was in part due to the Northern Pacific Railroad in the 1870's.

In 1830, Hudson's Bay trading company fur trappers built a log cabin near present day Buckley. Buckley was more substantially developed in 1884 when a spur of railroad track was built. In 1885 the founders of the town of Enumclaw, Frank and Mary Fell Stevenson, platted their homestead with King County to create the town of Enumclaw.

Forest History

Forests within the Mud Mountain watershed are predominately of western hemlock, Douglas fir, Sitka spruce, Grand fir, and western red cedar in the lower elevations and Noble fir and sub-alpine fir in higher elevations. Deciduous trees are found primarily in the lower elevations and most commonly include cottonwood, red alder, vine maple and willow. Replanting is primarily Douglas fir with western hemlock naturally re-seeding.

Historically forest fires have occurred in the Mud Mountain WAU at intervals of 300 to 350 years. Seven hundred year old Douglas fir trees show stand regeneration fires between 300-350 years (J.L. Johnson, personal communication, 2006). A 1902 map showed extensive logging in the western portion and areas in the northwest of the watershed had been burned (Gannett). During the 1970's the area around The Three Sisters was the site of an "out of control" local burn.

Logging has a long history within the Mud Mountain watershed. In the early 1900's, the Northern Pacific (Tacoma Line) and the Chicago Milwaukee and St. Paul Railroads had major lines near the western portion of the watershed. Also in the early 1900's the first mill site around the Enumclaw area was established; it is referred to as the "Upper Mill" and is still owned by the Weyerhaeuser Company. The railroads were able to distribute supplies and lumber, which led to additional railroad development in the forests. Railroad logging has had a lasting influence on slope stability in the watershed. Slope stability issues related to railroad grades include construction across inner gorges and bedrock hollows, burying organic material within the road prism, excess sidecast, large poorly drained through cuts, and road prisms built entirely on fill. Most of the undersized culverts and wooden box culverts have been replaced but were problematic in past years.

Past harvest patterns were driven by topography: lower elevation hills were logged first and then the ridges. In the early 1900's the valley bottoms were heavily timbered with red fir, red cedar, hemlock and Engelmann spruce and the hillsides grew noble fir, lovely fir, white fir, white pine, and Alaska cedar (Gannett, 1900 and Plummer, 1902). The progression of logging operations moved upslope with the progression of railroads. The railroad grades crisscross throughout the watershed and have been used as the present haul roads. Some old railroad trestles can be seen in the 1978 aerial photos used in this study. Current logging operations are harvesting third growth timber in the valleys and second growth (60-70 year old) on the ridges (J.L. Johnson, personal communication, 2006). The last of the old growth timber was harvested on the very steep (>70%), western side of Boise Ridge in the fall of 2005.

<u>Mining</u>

There are few mining claims found in the watershed. An unofficial dairy of a surveyor plots out the W. H. Gilliam Quartz-Mining Claim and was recorded on 27 September 1883. The description cites the S. F. Combs and Moses Kone claims as part of the metes and bounds for the Gilliam claim, and both were described as quartz claims. The 1956 inventory of Washington's mineral mines shows one claim on the north side of the White River in King County (Section 6, Township 19 North, Range 8 East, W.M.). This claim is listed as the White River lode gold claim found on the south side of Quartz Mountain in silicified and altered volcanic rocks associated with alunite deposits. Two adits were developed, one of which extended 300 ft. A stamp mill was built to process the ore, but was quickly abandoned (Huntting, 1956).

A memo and study from 1941 identifies hydrothermally altered portions of Miocene volcanic rocks as alunite. The study states that the alunite would be difficult to retrieve due to large amounts of overburden and dense forests (Hill and Melrose, 1941). This is similar to rock described by Fischer (1970) as altered "Enumclaw Formation" along the White River. He believed that this rock had potential for economic development (Fischer, 1970).

Currently, there are a few DNR Surface Mine Reclamation permits for sand and gravel pits and quarries. Two of these are permitted for mining silica. The White River lode gold claim mentioned above is near the currently permitted DNR Surface Mine Reclamation Permit known as the Scatter Creek Quarry, where silica is mined.

Historical Weather Events
Historical records related to storm events within Washington State were first recorded by European-American settlers in farming journals, some of which date back to the early 1850's. Major winter storms of 1906 changed the course of the White River and contributed to flooding in the Puyallup valley and tidelands in Tacoma (Stein, 2001). Several hydrologic events as well as Pierce County suing led to the necessity of building the Mud Mountain Dam, whose sole purpose is flood prevention (Lencioni, 1992).

The average annual precipitation in the watershed is approximately 60 inches (Western Regional Climate Center). The following water years had greater than 65 inches of recorded precipitation data (as recorded at the Mud Mountain gauging station): 1948, 1959, 1972, 1974, 1976, 1990, 1996, and 1997 (Figure 1). These dates of high precipitation were used in determining the appropriate aerial photos sets to be selected for this study.

Several dates listed above correspond to an increase in slope stability problems in the Mud Mountain watershed. The 1977 winter storms triggered numerous landslides as well as the 1996 storms. The impacts from the 1996 storms were widespread throughout the Pacific Northwest, causing the highest number of landslides in the watershed during the last 25 years (L. Vaugeois, personal communication, 2006). Based on air photo interpretation there is evidence of increased landslide activity after greater than average precipitation, such as the winter storms (rain-on-snow events) of 1996. Numerous debris flows and shallow landslides were initiated during these storms.

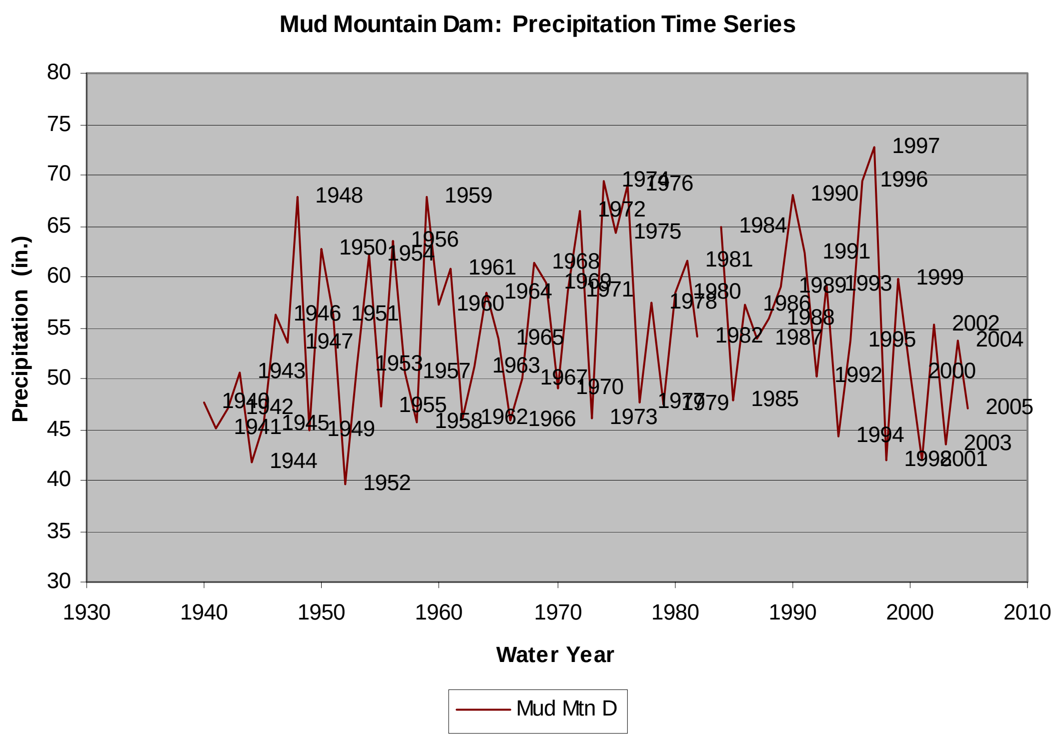


Figure 1. Annual precipitation data at the Mud Mountain gauging station (Western Regional Climate Center).

Flow monitoring records listed on the USGS Water Resources website on the White River started in 1928 (USGS, 2006). Large peak flow events since the start of hydrologic monitoring occurred on 1932*, 1933*, 1948, 1959, 1972, 1974, 1975, 1977, and 1996. During these years there was at least one event having a peak discharge greater than 3,900 cfs at the gauging station downstream of the Mud Mountain Dam near Buckley (*=prior to construction of Mud Mountain Dam).

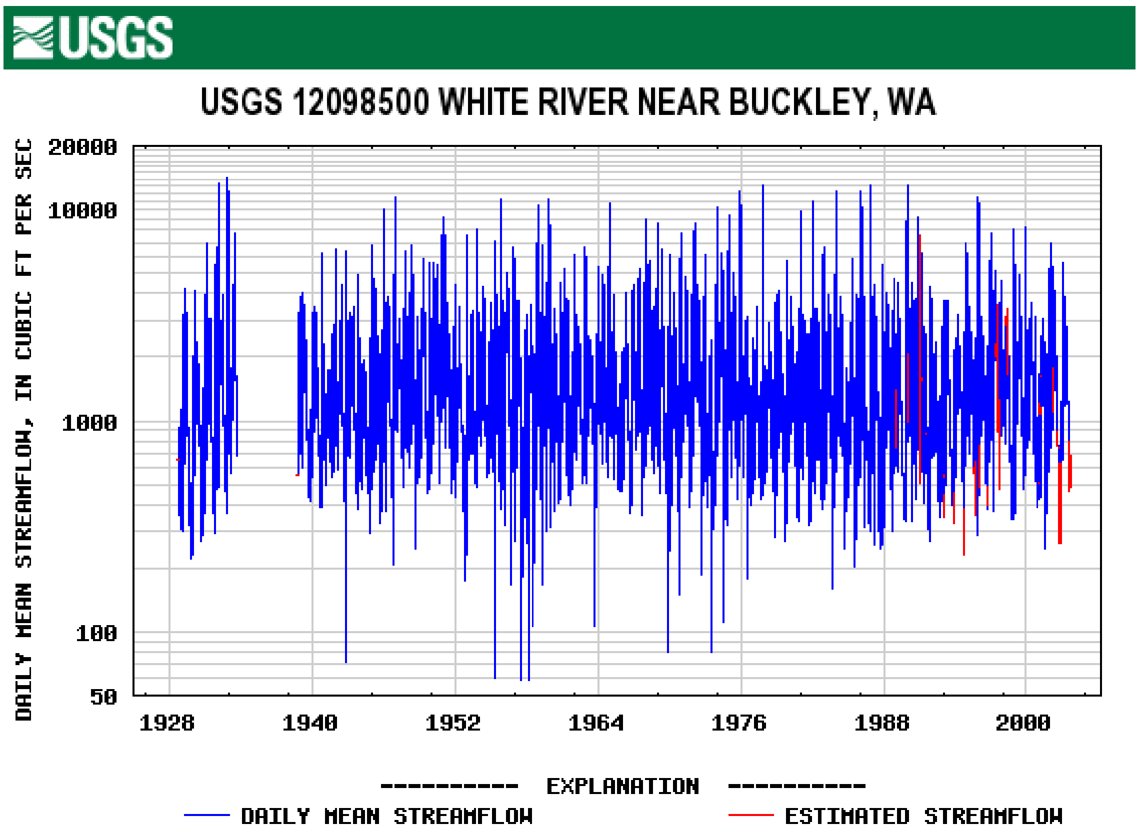


Figure 2. Daily Mean Stream flow from USGS gauging station (#12098500) near Buckley, WA – downstream of the Mud Mountain Dam.

<u>Mud Mountain Dam History</u>

The Mud Mountain Dam is located on the White River 29 miles upstream from the confluence of the Puyallup River. The majority of the dam was constructed between 1939 and 1941 and completed in 1948 for the sole purpose of flood control for the lower

Puyallup basin. Water is not retained in the reservoir for periods longer than a few months.

There have been some modifications to the earth-filled dam since its construction (Miller and others, 1995).
Currently, the dam stands 432 ft high and is 1,600 ft thick at the base. The storage reservoir is approximately 5.5 miles long and can store 106,000 acre-ft of water. The dam has a concrete-lined spillway and two concrete outlet tunnels (9-ft and 23-ft wide) located in the right bank of the gorge wall.

Mud Mountain Dam is located in a narrow gorge along the White River on the western side of the watershed. This gorge formed as a result of Pleistocene events, such as impoundment of river water when its mouth was blocked by continental ice. During interglacial times, the river entrenched into bedrock along the south side of the valley (Galster and Coombs, 1989). These steep sided and narrow bedrock gorges with wide valleys upstream are ideal locations for dams, allowing for water retention during storm events to preventing flooding downstream. Unfortunately, the bedrock through this area is faulted and of poor quality (Galster, 1989).

Landslides have occurred in the vicinity of the dam. A prehistoric slide occurred about 1,800 years ago just upstream (0.5 mi.) on the right bank and another slide just below the dam on the left bank. These two slides have had more recent failures on the scarps (See Map A-1). In 1974 a large landslide occurred in Upper Cascade Creek (See Map A-1 #466) that sent 70,000 cy of material into the reservoir resulting in a 12-ft wave that splashed against the dam (Galster, 1989).