APPENDIX A

Upper North Fork Newaukum and Upper South Fork Newaukum Watershed Analysis Mass Wasting Assessment

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This assessment was performed in accordance with the Standard Methodology for Conducting Watershed Analysis, Chapter 222-22 WAC, Version 4.0. Washington Forest Practices Board Manual, November 1997.

Certified Analyst 8/6/98
Date

Certified Analyst 8/10/98
Date

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SUMMARY OF FINDINGS

A summary of the mass wasting assessment is given below. The summary is presented as a response to the critical questions asked in the mass wasting module documentation (Washington Forest Practices Board [WFPB] 1997). Details and additional supporting data can be found in the main body of the document or in other module documents.

Critical Questions

<u>What are the potential sediment sources in the basin?</u>
Primary sediment sources in the Upper North Fork and Upper South Fork Newaukum watershed administrative units (WAUs) include mass wasting, surface erosion from roads (see Appendix B, Surface Erosion Module), and remobilization of alluvial sediment in channels (see Appendix E, Channel Module).

<u>Is there evidence of, or potential for, mass wasting in the watershed?</u>
Yes. 687 landslides were identified on aerial photos from flights in 1959, 1964/65/66, 1974, 1984, 1993, 1997, and during field work in 1998.

<u>What mass wasting processes are active?</u>
Shallow-rapid landslides, debris flows, small sporadic deep-seated landslides, large, persistent deep-seated landslides, and dam-break floods are the current landslide types (p.4).

<u>How are mass wasting features distributed throughout the landscape?</u>
Shallow-rapid landslides, debris flows, small sporadic deep-seated landslides, and large, persistent deep-seated landslides are concentrated in the Puget Group (Ec2(pg)), and the Northcraft (Eva(n)), Skookumchuck (En(sk)), and Wilkes (Mc(w)) Formations in the eastern two-thirds of the WAUs.

<u>What physical characteristics are associated with these features?</u>
In most of the watershed, shallow-rapid landslides (SR), debris flows (DF), and small sporadic deep-seated landslides (SSD) are associated with steep (>65%) stream adjacent slopes including inner gorges and toes of large persistent deep-seated landslides (LPDs) and Type 5 stream headwalls, LPD headscarps, and bedrock hollows.

<u>Do landslides deliver sediment to stream channels or other waters?</u>
Approximately 58% of shallow-rapid landslides and 92% of debris flows delivered sediment to channels. The large persistent deep-seated landslide toes impinge on streams but most move slowly (2-4 mm/yr (?)) so deliver only minute fractions of their deposits. Small sporadic deep-seated slides delivered only portions of their mobilized sediment, primarily when their toes reached streams or when they became debris flows.

<u>Do forest management activities create or contribute to instability?</u>
Yes. 53% of shallow landslides including debris flows were associated with roads (9% of these were old puncheon culvert failures) and approximately 28% were identified in 0-20-year-old stands.

<u>What areas of the landscape are susceptible to slope instability?</u>
Four mass wasting map units were delineated as having moderate to high potential for slope instability (see MWMU Map A2 and descriptions).

<u>What is the relative contribution of sediment from mass wasting compared with other sources?</u>
Mass wasting contributes the greatest relative amount of sediment from forest management-related sources. Approximately 1,587,600 metric tonnes of sediment was delivered to channels by shallow landslides and small deep-seated landslides over the period of record (1959-1998). (See Appendix B, Surface Erosion Module for comparison of all sediment sources.)

METHODS

Methods used for data collection and analysis for this module are those described in the Watershed Analysis Manual, Version 4.0 (Washington Forest Practices Board 1997). Landslide sediment production and delivery volumes were also estimated. Mass wasting map units and hazard ratings were determined as outlined in the Watershed Analysis Manual. The mass wasting report from the Lower North Watershed Analysis written by Periann Russell and Venice Goetz was used as a template for this report.

Landslides were categorized as shallow or deep-seated, and further distinguished as shallow rapid (SR), debris flows (DF), dam-break floods (DBF), small sporadic deep-seated (SSD), and large persistent deep-seated landslides (LPD). Shallow slides are rapid, translational failures usually associated with large storms (Swanson et al. 1987). Shallow landslides can vary in depth depending on their origin. Shallow landslides that occur in forest or harvest units typically do not exceed the depth of roots, while sidecast failures are many times as deep or deeper than the sidecast material. Shallow rapid landslides can develop into debris flows when their mass becomes sufficiently saturated to become a viscous flow of water, soil, rock and organic debris. Debris flows commonly form when shallow landslides move into stream channels.

Dam-break floods (DBF) were noted where old log culverts (puncheon culverts) failed in old railroad grades. These floods occurred when the old wood culverts rotted causing overlying fill to collapse, thus damming the channel. Water collected on the upstream side of the road and saturated the fill. Dam break floods resulted when the fill failed and the dam broke. Many of the channels that experienced puncheon failures have low gradients (<10%).

Deep-seated landslides are generally slow or sporadic mass movements, usually larger and deeper than shallow slides, potentially covering acres of the landscape. The depth of these slides can be in excess of 10 feet (3 m) depending on unconsolidated or weathered material depth. Movement of deep-seated landslides is usually the result of prolonged wet periods and increases in groundwater levels. These slides are generally dormant, but can be remobilized by undercutting mid-slopes and toe-slopes or by weighting upper benches or head-slopes.

Aerial photographs at a scale of 1:12,000 feet were used from flights flown in 1959, 1964/65/66, 1974, 1984, 1993, and 1997. In addition, high-altitude 1:45,000 photographs from 1974 flights were used because some of the LPDs were so large that they could not be mapped accurately on the 1:12,000 photographs. Several slides occurred during the winter of 1997/98, so were not mapped on the aerial photos but were located during field reconnaissance.

Field reconnaissance and data collection were conducted in February and March, 1998. A stratified random sample based on geology, failure type and management association (sidecast, railroad fill, in-unit) of about 10% of photo identified landslides was field visited.

Landslide sediment production and delivery volumes were estimated for shallow-rapid landslides and debris flows. Length, width, and depth of a few field sample landslides were measured to calculate volume. Deep-seated landslides were omitted from these calculations because they are the landscape and it is beyond the scope of this analysis to determine the rates and degrees of movements for these features. Additional areas of landslides not visited were taken off the GIS and volume calculations were made using an estimated depth based on average field-measured depths by slide type provided in Table A 1, below. While this method of estimating volumes has limitations, it can provide a general sediment delivery estimate (within an order of magnitude) for use in relative comparisons between background sediment, landslide sediment, and surface erosion.

Table A 1: Estimated landslide depths used to calculated landslide volumes.

Slide Type	Estimated depth in meters (based on average field values)
DBF	2.5
DF	2.1
SR	2.3
SSD	3.0
LPD	5.0 (hypothesized representative depth)

Landslides mapped on the air photos were digitized directly from the photos into GIS onto a corrected orthophoto image with 3ft^2/pixel resolution. This method was attempted for enhanced accuracy in landslide mapping and volume estimation, but is not recommended unless the analyst is also the digitizer because of the disconnectedness with the data that occurs when the analyst cannot immediately realize the spatial distribution of the landslides. Landslides are then often double-mapped or left out and there is sometimes a delay in receiving maps from the GIS person in a timely fashion. These discontinuities can cause difficulties that snowball with time. For the

Newaukum analysis, initial maps were delayed, which greatly restricted field measurements, thus reducing confidence in the quantitative analysis.

Other data sources for the analysis include geology, soil, and topographic maps. Overlays of geology and slopes were generated from the Washington Division of Geology and Earth Resources geologic map of the Centralia Quadrangle, Washington (Schasse, 1987), and the 30 m grid Digital Elevation Model (DEM), respectively. Overlays were used in analysis and construction of mass wasting map units.

GEOLOGIC AND GEOMORPHIC OVERVIEW

Regional Overview

The Upper Newaukum WAUs are located on the western flank of the Cascade Range. The andesitic volcanics, pebble conglomerates, and brackish water deposits of the Northcraft Formation (Eva(n)) form part of the crustal foundation of the ancestral Cascade Range (»43-36 million years ago (Ma)). The Northcraft Formation is interbedded with the continental deltaic stream deposits of the Puget Group (Ec2(pg)). The next youngest rocks in the basin are the sedimentary (Skookumchuck (T(sk)), and Lincoln Creek (Oem(lc)) Formations and basaltic intrusive (MOib) rocks that were deposited on a generally shallow continental margin. An early period of structural deformation about 23 Ma folded and faulted these formations producing anticlines and synclines, and lateral and normal faults.

The sedimentary rocks of the Wilkes Formation (Mc(w))were deposited 12 Ma, after the rejuvenation of the present-day Cascade Range. Alpine glaciation from the Cascades brought the 1.5 Ma Logan Hill (Qapo(lh), and the 140K Hayden Creek (Qapo(h)) Formations.

Geology of Upper Newaukum Watersheds

The volcanic deposits of the Northcraft Formation (andesitic lava flows, basal tuffs, volcaniclastic breccias, pebble conglomerates and brackish water deposits) and the sandstone, shale, and claystone, and coal of the Puget Group crop out over two thirds of the eastern end of the watersheds (Snavely et al., 1958, and Schasse, 1987)]) **(Map SA1)**. Both the Skookumchuck and the Lincoln Creek Formations are seen as wide sedimentary NW-SE trending belts through the western part of the watersheds. The Skookumchuck consists of micaceous feldspathic sandstone, siltstone, shale, carbonaceous siltstone, claystone, and thick coal seams, and is locally interbedded with tuffaceous and volcanic rocks and minor conglomerate. The Lincoln Creek Formation is mostly basaltic sandstone with interbeds of pyroclastic rocks, siltstone, sandstone. During Lincoln Creek time basaltic dikes and sills were intruded into the Skookumchuck and Lincoln Creek Formations. These are exposed in the southwestern part of the watershed.

The Wilkes Formation, crops out along the lower reaches of the upper North Fork Newaukum as a blue-grey and blue-green massive semi-consolidated siltstone and sandstone, conglomerate and water-laid tuff that contains carbonized wood and weathers to iron-stained, mottled yellow-orange to reddish orange.

The Logan Hill Formation, consists of well-weathered iron-stained outwash sand and gravel with minor silt and clay. It is exposed in the southwest part of the watershed and extensively beyond. Undifferentiated glacial drift comprises the Hayden Creek Formation. Hundreds of kilometer-sized deep-seated landslides (Qls) occurred in post-glacial times blocking channels and delivering huge quantities of sediments to streams. These failures were probably initiated by prolonged wet climatic conditions and earthquakes. More recent alluvial sediments (Qal) make up the lower reaches of the North and South Forks Newaukum valleys.

Controls on Geomorphology

The landforms of the Upper Newaukum Watersheds are the result of the strength properties of the rocks combined with the geologic history of the region. Most of the rocks are not particularly strong (resistant to erosion). The sedimentary rocks (sandstones, siltstones, shales, conglomerates, minor coal) were never deeply buried, and so have never been strongly lithified or metamorphosed. They weather relatively quickly, commonly to fine-grained soils, and ultimately to fine-grained (sand- and silt-sized) sediments. The volcanic rocks (flows, breccias, tuffs, and some intrusive bodies) typically are more coherent, and may erode into gravels, cobbles, and boulders.

Folding and faulting has further disrupted the rocks in the watershed. Because of the mechanical disturbance and consequent ground-water effects caused by faulting, enhanced erosion in the weaker materials along fault lines allows streams to be located on them or offset by them. Also, large persistent deep-seated landslides and earthflows may be associated with faults and sedimentary contacts.

All of the near-surface rocks have been exposed to a humid, subtropical to temperate climate throughout their history, fostering deep and intense weathering. The region was beyond the continental Pleistocene glacial limit, but experienced alpine glaciation from the Cascades.

MASS WASTING TYPES

Landslide Inventory

In the Upper Newaukum watersheds, 288 shallow landslides and 399 deep-seated landslides were identified from aerial photos and during field work **(Map A1)**. It is probable other landslides exist, but were not identified from photos due to canopy cover, incomplete photo sets or landslides missed because they occurred in years between photo coverage and "disappeared" due to vegetative healing. Debris flows developed from 97 shallow rapid landslides. Approximately 53% of shallow failures including debris flows and dam-break floods were associated with roads, 28% were associated with young (0-20yrs old) harvest units, 7% with mature or old growth forest. Two hundred and sixty-two of the deep-seated landslides were identified as LPDs and likely occurred during the 100-1000s of years prior to management activity. However most of the LPDs are very large deep-seated landslide complexes with several to many other deep-seated landslides nested within them and depending on methods of an individual mapper, the LPD count may be low.

Road-related landslides

One hundred eighty landslides, excluding LPDs, were associated with roads (27 are SSDs). Six general types of road-related landslides were identified based on field observation and land use history including sidecast/fill (including landings), stream crossings, cutbanks, road drainage, culvert/fill failures, and "other." Sidecast failures are, by far, the most common, followed by stream crossings (DF and DBF), cutbank failures, and road drainage **(Figure A 1)**. Culvert/fill-related landslides occurred historically as dam-break floods when puncheon culverts collapsed and dammed streams. These may be more common than mapped in this inventory because; 1) most reportedly occurred in 1974 or later (personal comm., March 1998, John Barone, Weyerhaeuser engineer) 2) air photo coverage is limited for those years, and 3) almost all known puncheon culverts have since been repaired so these old failures are not apparent in the field. Shallow rapid landslides, debris flows and dam break floods are the most common slide types associated with roads.

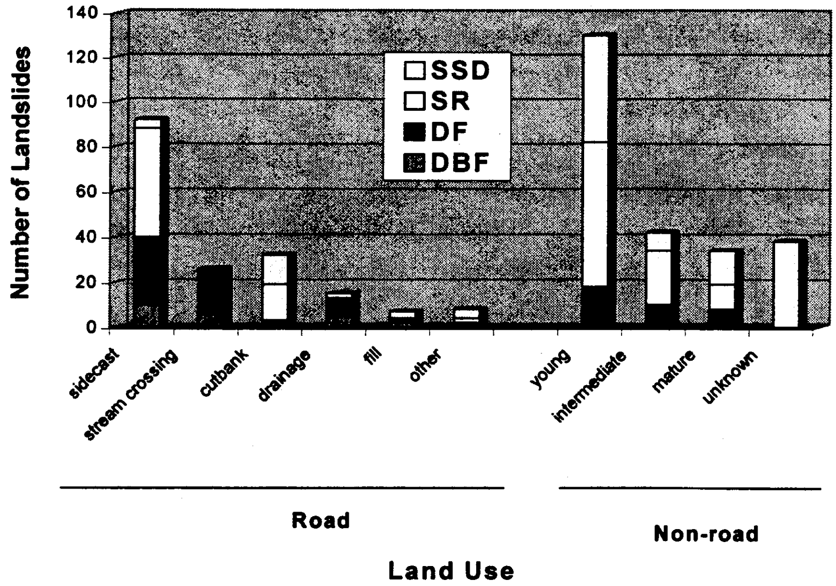

Figure A 1: Road-/non-road-related landslides and associated land use; Upper Newaukum WAUs, 1959-1998.

<u>Non-road-related landslides</u>

Two hundred forty four landslides, excluding LPDs, were not associated with roads (109 are SSDs). One hundred thirty of these slides (53%) are associated with young (0-20yrs) stands (48 are SSDs). Forty-two occurred in intermediate (20-50yrs), and 34 in mature or old growth stands (>50yrs). Thirty eight landslides are SSDs for which stand-age information at time of failure were ambiguous ("unknown" in Figure A 1).

Controls on Mass Wasting

The rocks of the Western Cascades have been eroding about as long as they have been forming. Broadleaf evergreen fossils in the Puget Group suggest a tropical climate existed in the Eocene and a humid climate more-or-less continually for tens of millions of years. Water has been the dominant erosional factor as a weathering agent, a trigger for mass wasting, and as a transporter of debris. The combination of weak rocks, topographic relief, and abundant water has contributed to high rates of mass movement. Most of the region has experienced deep-seated landsliding at one time or another, and smaller landslides occur quite frequently in some areas.

In the Upper Newaukum Watersheds, large and small deep-seated landslides and shallow failures occur due to weak, weathered rocks, sedimentary contacts, fracturing from past faulting and folding, and steep slopes. The weathered basal tuff in the Northcraft has probably devitrified to clay and is serving as a slip plane for LPDs. Other slip planes may be bedding planes and dip slopes in the Puget Group. Fractures weaken the rock, allow water penetration and rapid weathering, and act as conduits for ground water flow. Convergent topography concentrates surface and sub-surface flow more rapidly than on planar and convex slopes. All these geologic conditions can cause instability. Management activity, such as road construction and timber harvest, can contribute to an existing unstable situation.

The Northcraft and the Puget group produce both coarse and fine sediments because they are relatively resistant lithologies, and their soils tend to be shallow, clay or gravelly loams. In contrast, the Wilkes and Skookumchuck sedimentary rocks are softer and produce fine-grained material that weathers to silt loam. The rocks of the Wilkes and the Skookumchuck are fine-grained, which makes them susceptible to deep weathering and slippage along sedimentary layers.

The Wilkes Formation consists of massive, semi-consolidated, fine-grained sedimentary rocks with water-laid tuff and carbonized wood. Its semi-consolidated nature and fine grain-size makes it a likely candidate for instability. The Logan Hill glacial sediments are sliding on the Wilkes in the southwest part of the watersheds because the Wilkes has more clay and is less permeable than the Logan Hill gravels. The Wilkes clays perch the water that the Logan Hill allows to pass through and landslides probably occur in association with the clay layers. Shallow landslides also occur on the toes of deep-seated landslides in the Wilkes.

Three main situations were identified as having a dominant influence on mass wasting. Most landslides occur in association with the dominant landform in the watershed, large (ancient) deep-seated landslides (LPDs). The situations are: 1) steep stream-adjacent slopes including LPD toes and inner gorges, 2) stream headwalls and LPD scarps, and 3) active small sporadic deep-seated landslides (SSDs). The situations are described below

1. Steep stream-adjacent slopes including LPD toes and inner gorges, in the Puget Group and the Northcraft, Skookumchuck, and Wilkes Formations.

The Northcraft Formation and the rocks of the Puget Group comprise the greatest area in the watershed. These two formations are interbedded and numerous deep-seated landslides seem to indicate that their contact is naturally unstable. The Skookumchuck Formation has the next largest coverage and has experienced many deep-seated landslides as well, especially near the contact between Skookumchuck and Northcraft. The Wilkes Formation is likewise unstable near its contact with the Logan Hill glacial sediments. Deep-seated landslides occur in all of these formations. Shallow landslides and SSDs occur naturally on stream-adjacent slopes and are induced by sidecast loading or dysfunctional road drainage on LPD toes.

Deep-seated landslides almost always have their toes in streams. Landslide toes consist of geologic material that has been moved from its original location, fractured and broken in the process, and thus made unstable. When rotational landsliding oversteepens this material past its normal angle of repose, shallow landslides and SSDs commonly occur that can deliver sediment to streams adjacent to the toes.

Geologic material in deep-seated landslides has been relocated and fractured, and is inherently unstable and easily eroded. Differential movement on the landslide body creates blocks, between which channels downcut. Boundary streams mimic the deep-seated landform perimeter. Because these streams are cutting through unstable material, small slumps or shallow landslides occur on stream-adjacent slopes (commonly in excess of 65%). These slopes are sensitive to certain management practices such as road sidecast material placed on steep, concave or planar slopes, inadequate or misdirected road drainage, oversteepened cutbanks, and perched landings.

While harvesting of trees is not, in itself, a cause of landsliding, it likely contributes to slope instability and timing of landsliding in certain locations. Since these rocks are highly fractured, it is probable that root systems anchor into bedrock and contribute to slope stability. The strength of these roots systems decays over time after harvest (5-20 years), subsequently reducing slope stability. Root strength likely adds to slope stability, though it is uncertain how much, since the natural rate of shallow landsliding is high.

2. Headscarps of deep-seated landslides, steep stream headwalls, and bedrock hollows in the Northcraft, Puget Group and Skookumchuck Formations.

Headscarps are in the areas of highest elevation of deep-seated landslides and within the bodies of the larger complexes where smaller deep-seated landslides occur. Headwalls are topographically above the origination points of first order streams or the "steep, headward tip of channels" (Swanson, et al., 1987). Bedrock hollows are narrow concavities, depressions, swales, or first order basins. Shallow slope failures associated with thin soil mantles overlying weathered bedrock where gradients are greater than about 65% may occur on concave or planar headscarps, stream headwalls, and bedrock hollows. In the Upper Newaukum WAUs, these features are more susceptible to instability in Northcraft, Puget Group, and Skookumchuck Formations and are affected by loss of root strength, road sidecast material placed on steep, concave slopes, and misdirected drainage.

3. Active SSDs in the Northcraft, Puget Group, and Skookumchuck Formations.

There are a significant number of presently active SSDs occurring in the Upper Newaukum basins. Some are sliding off oversteepened, deep-seated landslide toes, and some are just in areas with a great abundance of groundwater. Slope gradients are generally not a factor in this type of landsliding. Many of these landslides are moving on slopes as gentle as 30%. Excessive groundwater, planes of weakness in the rock, and gravity are what mainly drive these features. Management activities that have and could increase slope susceptibility to these failures are road sidecast and fill that load the head of these landslides, oversteepened road cutbanks that undercut the landslide toes, and misdirected or inadequate water management from roads and landings.

LANDSLIDE SEDIMENT PRODUCTION AND DELIVERY

Landslide Frequency

The following discussion excludes large deep-seated landslides because they are not generally affected by management practices. Shallow non-road-related landslides are of interest because they usually infer root strength loss in managed terrain on certain slopes in certain geologies. Road-related landslides, on the other hand, can be caused on gentler slopes by water mismanagement. Thus it may be easier to understand and eliminate management-induced road-related failures than to prevent in-unit landslides. Although any type of landslide may be triggered by excessive water from big storms, shallow landslides occur more commonly in young (0-20-year-old) stands than in intermediate or mature stands because root strength is more tenuous in younger trees.

The frequency of shallow landslides that occurred in young stands (0-20-year-old) was high between 1964 and 1973, then much lower until the winters of 1993 to 1998 (Figure A 2). This early time period may reflect the 1972 storm event. After 1973, several high precipitation events occurred, but generally the storm (peak flow) history does not coincide with the landslide frequency until the mid-90s (Figure A 3) when the frequency of shallow landslides, as well as debris flows, and SSDs in young stands seems to coincide with large storms. For example, the February 1996 event was the largest storm on record (see Appendix C, Hydrology Module). Precipitation associated with this storm was high and probably accounts for the large increase in landsliding during the winters of 1996 and 1997.

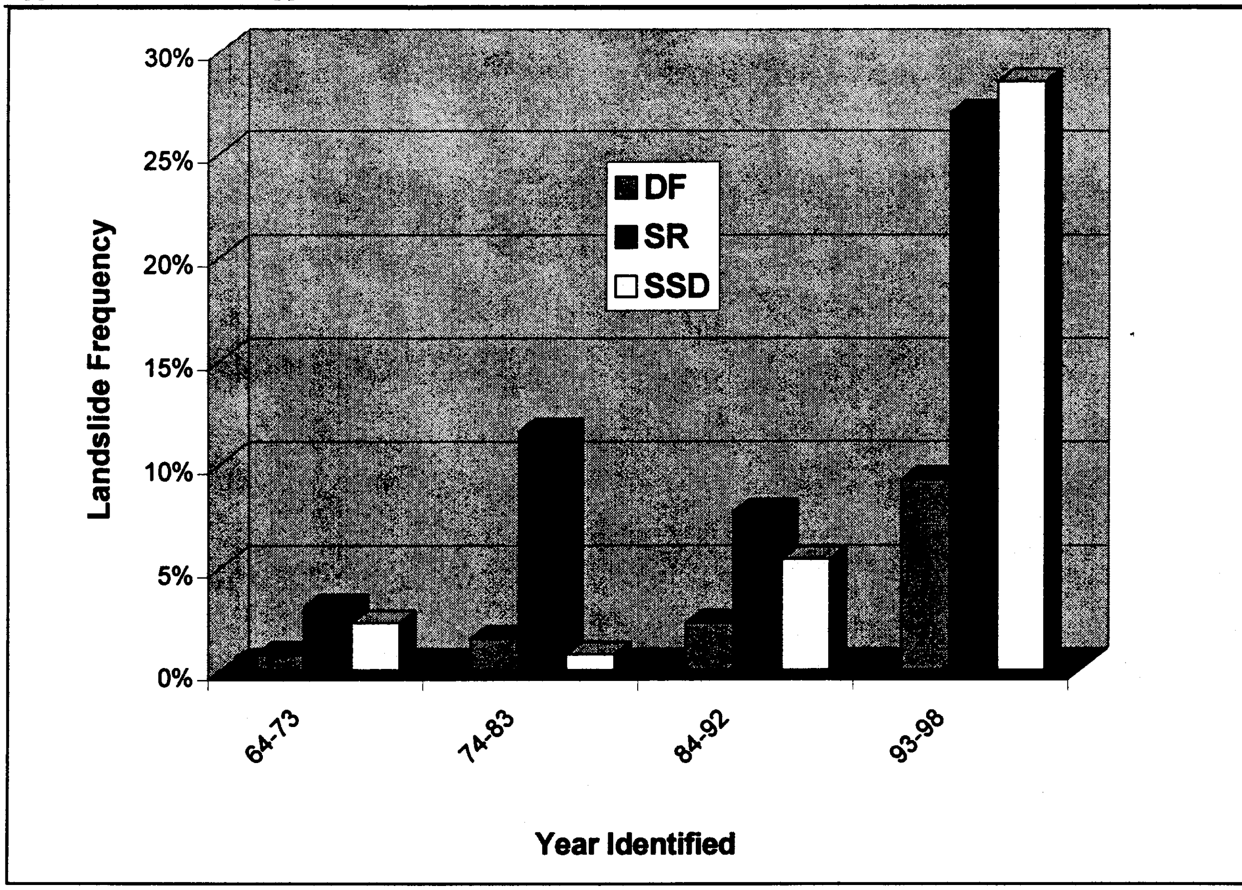

Figure A 2: Landslide frequency in young (0-20-year-old) stands

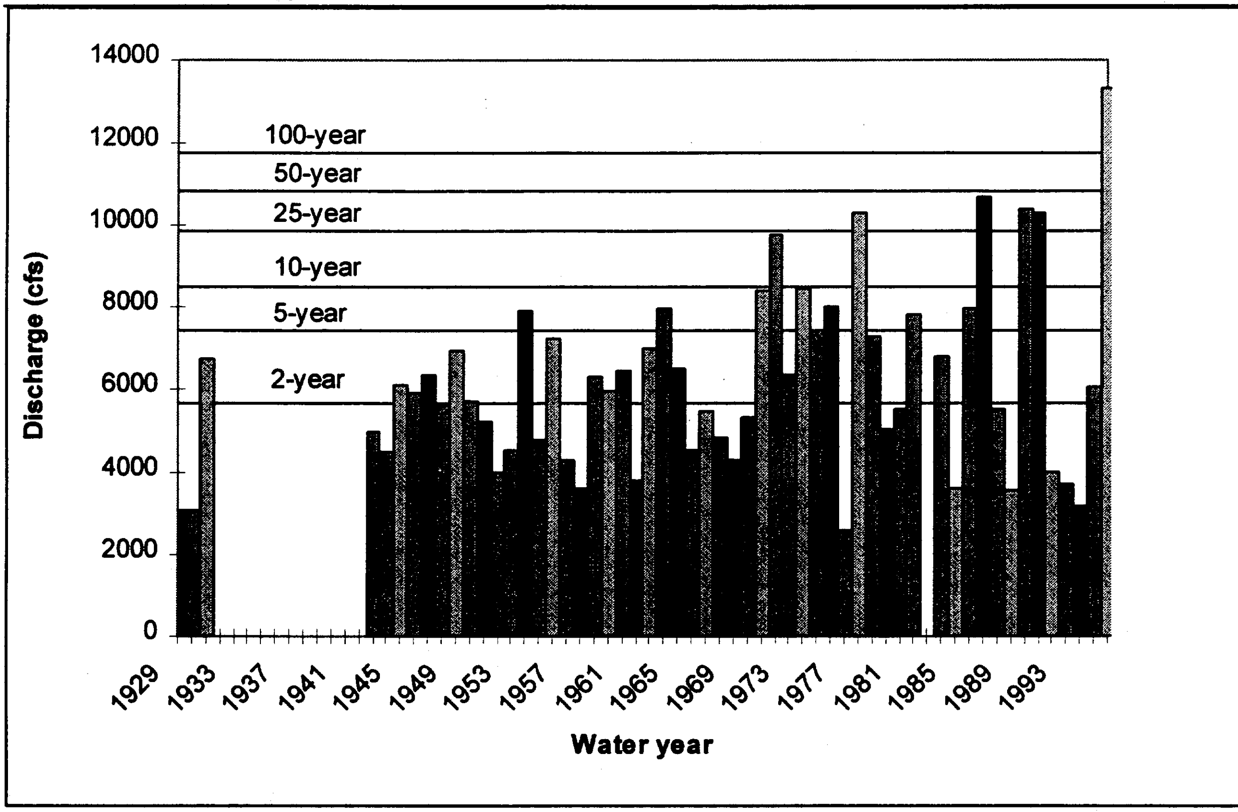

Figure A 3: Instantaneous annual peak flows (cfs) for the Newaukum River near Chehalis (USGS gaging station number 12025000). Return periods based on Williams and Pearson (1985). Water year is from October 1 to September 30.

Landslide Delivery Volume

The total estimated volume of shallow landslides (SR, DF, and DBF) and small, recent deep-seated landslide (SSD) delivery between 1959 and 1998 is 1,443,000 m^3 (7,097 m^3/km^2, or 1,587,600 metric tonnes). Large, persistent deep-seated landslide volumes are not included in this estimate because the rates of these landslides are unknown and obtaining the rates is beyond the scope of this analysis. LPDs impinge on almost every stream and advance at an unknown and very slow rate, perhaps on the order of 2-8mm/year, continuously contributing an unknown and very small annual amount of sediment. To include their delivery volumes would skew the data from other landslide types that have a larger impact on the watershed and may be related to management.

In comparison to other watershed volume estimates, the Upper Newaukums are relatively high. The geologic history of the watershed may explain the natural tendency toward instability. Again, the rocks were deposited in a wet, temperate climate. They have been deeply weathered and tectonically uplifted, rotated, and deformed and are therefore highly fractured and mechanically weak. More recently in the last 1-2 million years, the majority (over two-thirds) of the basin has been involved in ongoing, slow-moving deep-seated landsliding. The upper Newaukums are a dynamic landscape.

Road-related landslide volumes are much greater than non-road-related volumes, particularly in the photo period 1974 to 1983 **(Figure A 4)**. The high volume (but not frequency **[Figure A 2]**) during that time period coincides with a large storm event in 1974 and with the failure of puncheon culverts (DBF and DF). Volumes from landslides associated with culvert/fill failure are larger than in-unit failures, because of the size of the fill material at the time of failure. In recent years (mid-nineties) large storm events have been more frequent and the Upper Newaukum watersheds have responded with an increase in landsliding (both number and volume), in the form of DFs, SRs and SSDs.

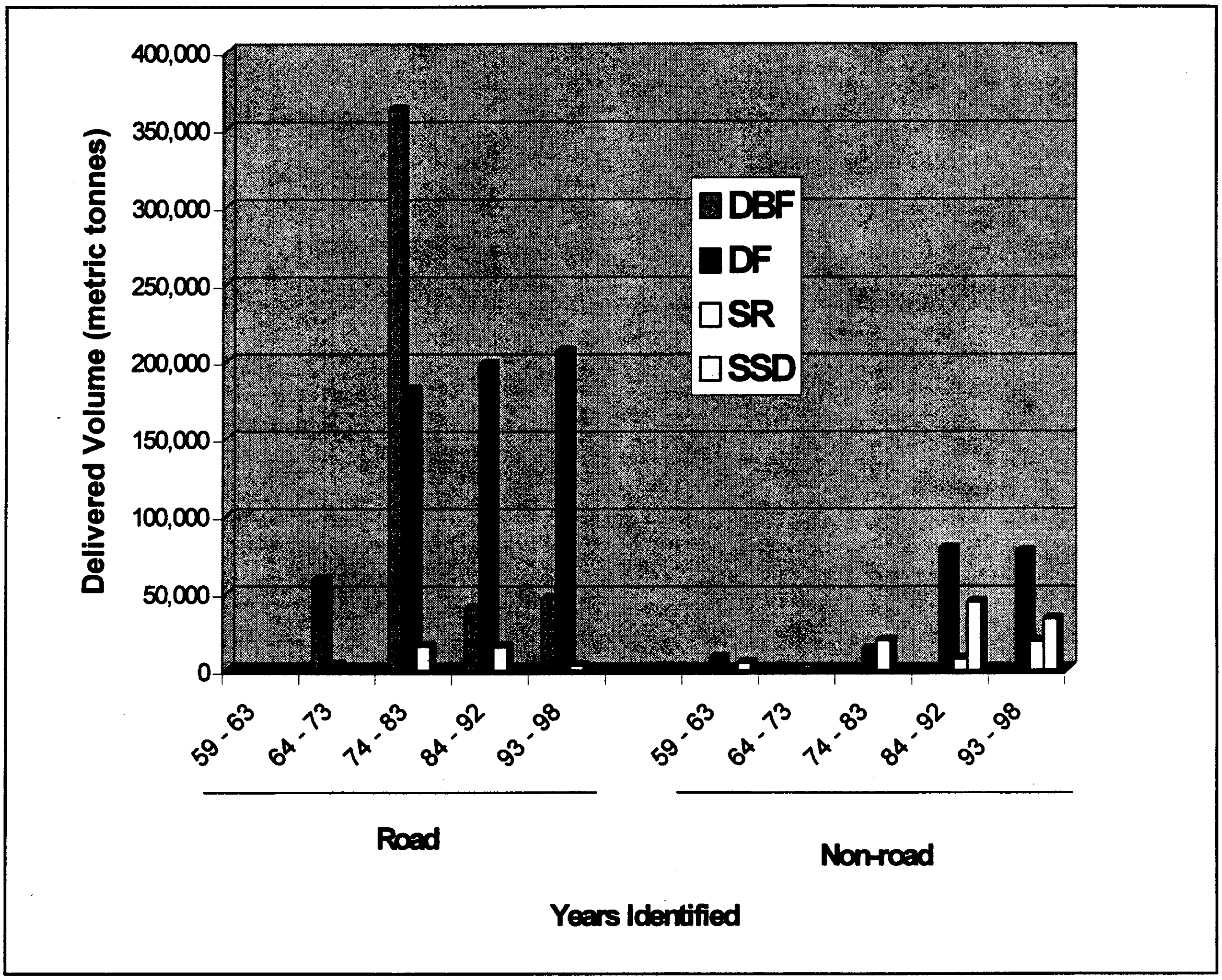

Figure A 4: Estimated road and non-road-related landslide delivered sediment volumes, Upper Newaukum WAUs, 1959-1998.

MASS WASTING MAP UNITS

The situations described above were considered along with five distinct landforms to create mass wasting map units. Mass wasting map units are illustrated and described on **Map A2** and Forms A2 and A3. The total acreage encompassed by each MWMU is listed below in **Table A 2.**

Table A 2: Areas of each Mass Wasting Map Unit.

MWMU #	Area(acres)	Area (km^2)
1	4,220.4	17.1
2	191.0	0.8
3	220.9	0.9
4	21,280.0	86.1
5	24,344.8	98.5
Total	50,257.1	203.4

Form A-2: Mass Wasting Map Unit 1 Description

MWMU number	1—Steep stream-adjacent slopes including LPD toes and inner gorges
Description	Stream-adjacent slopes including LPD toes and inner gorges in the Puget Group, the Northcraft, Skookumchuck, and Wilkes Formations. Planar, concave, and convex slopes.
Materials	Geologic materials include primarily: • Puget Group (Ec2(pg))—feldspathic sandstone and litho-feldspathic sandstone interbedded with siltstone, shale, claystone, and coal, locally interbedded with Northcraft lava flows, tuffs, volcaniclastic breccias, and pebble conglomerates. Weathers to coarse- and fine-grained sediment. • Northcraft Formation (Eva(n))—andesite lava flows, flow breccia, and sills in the upper part and matrix-supported breccia, water-laid lapilli tuff, and tuff breccia in the lower part; interbedded with the Puget Group. Weathers to coarse- and fine-grained sediment. • Skookumchuck Formation (T(sk))—micaceous feldspathic sandstone, siltstone, shale, carbonaceous siltstone, claystone, and coal; locally interbedded with tuffaceous and volcanic rocks and minor conglomerate. Weathers to fine-grained sediments. • Wilkes Formation (Mc(w))— semi-consolidated non-marine siltstone, sandstone, conglomerate, and water-laid tuff with carbonized wood.. Weathers to fine-grained sediments.
Landform	Steep concave, planar, and convex slopes adjacent to streams
Slope	Field measured slope >65%, DEM>60%. Field-measured slopes are commonly steeper than those determined from the DEM.
Elevation	345 to 3,518 feet above mean sea level (FAMSL) (DEM elevations).

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Form A-2: Mass Wasting Map Unit 1 Description, Continued

Total area	4,220.4 acres (17.1 km^2)
MW processes	SR, DF, SSD, DBF.
Non-road-related landslide density	107 non-road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 6.3 per km^2.
Road-related landslide density	98 road-related landslides (excluding LPDs) identified over the record (1959-1997), representing 5.7 per km^2.
Forest practices sensitivity	• High sensitivity to roading. • High sensitivity to harvest.
Mass wasting potential	High.
Delivery potential	High. 82% of the landslides (excluding LPDs) identified in this MWMU for the period of record delivered sediment to the fish-bearing stream system (directly or indirectly).
Delivery criteria used	Field and photo observations of proximity, visible sediment and routes of delivery.

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Form A-2: Mass Wasting Map Unit 1 Description, Continued

Hazard potential rating	High.
Triggering mechanisms	The following factors lead to the generation and delivery of sediment from landslides in MWMU 1:

Natural characteristics:

- Steep slopes, supported by relatively resistant basalts and siltstone.
- Occurrence of large storms, routing large quantities of shallow groundwater to unstable slopes.
- Fractured geologic materials displaced by LPDs
- Shallow soils formed over intensely weathered bedrock (siltstone, volcanic breccia, volcanic sediments)
- Stream undercutting.
- Mostly concave and planar slopes

Contributing management-related characteristics:

Road-related landslides (excluding LPDs)

52 of the 98 (53%) road-related failures were the result of loading sidecast material on steep slopes (including landings). While the weakness of geologic materials and slope steepness are likely the dominant influences of instability, organic debris in sidecast material and inadequate road drainage are also contributing factors. 17 failures occurred at stream crossings (17%), 13 initiated on road cutbanks (13%), and 9 were apparently triggered by road drainage alone. 3 of the landslides were initiated in culvert fill.

Non-road-related landslides (excluding LPDs)

107 non-road-related landslides occurred in this unit. 47 (44%) were identified from aerial photos and from field reconnaissance in areas with stand ages between 0–20 years old. For shallow landslides (35 of the 47 in young stands), root strength likely contributes to some slope stability since large conifer roots can anchor into fractured bedrock and help maintain soil strength. Evidence for loss of root strength as the cause for SSDs is

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Triggering mechanisms (continued)	inconclusive because SSD failure planes usually lie below the rooting depth. However, roots may be adding stability along the margins of potential failure blocks and buttressing the downslope side.
Confidence	Moderate. Sidecast/drainage failures were noted during field reconnaissance. It is difficult to observe the influence of root strength on slope stability in the field. The root strength argument is based on experience in this kind of geology and current literature.
Comments	See Map A2 for locations of MWMU 1. It is possible that some areas designated as high hazard in this unit may actually be low hazard due to the natural variation in the landscape and the inherent error associated with remotely sensed data. Therefore field checking is needed when delineating this unit on the ground.

FORM A3: MASS WASTING MAP UNIT 1

Number of landslides by landslide type and land use association in MWMU 1.

Land Use Association	Shallow Rapid (SR)	Debris Flows (DF)	Dam-Break Floods (DBF)	Large, Persistent Deep-Seated (LPD)	Small/ Recent Deep-Seated (SSD)	Total
Stand age 0-20 yrs	28	7	0	0	12	47
Stand age 20-50 yrs	21	7	0	0	4	32
Stand age >50 yrs	8	4	0	0	8	20
Sidecast/fill	23	19	6	0	0	48
Cutbank	5	2	1	0	5	13
Road drainage	0	3	4	0	2	9
Landing	2	2	0	0	0	4
Stream crossing	0	12	5	0	0	17
Culvert fill	0	1	0	0	2	3
Other	1	1	0	10	10	22
Total	**88**	**58**	**16**	**10**	**43**	**215**

Form A-2: Mass Wasting Map Unit 2 Description

MWMU number	2—Steep headwalls and LPD headscarps.
Description	Steep headwall slopes and LPD headscarps in the Puget Group, Northcraft, and Skookumchuck Formations. Concave slopes.
Materials	Geologic materials include primarily: • Puget Group (Ec2(pg))—feldspathic sandstone and litho-feldspathic sandstone interbedded with siltstone, shale, claystone, and coal, locally interbedded with Northcraft lava flows, tuffs, volcaniclastic breccias, and pebble conglomerates. Weathers to coarse- and fine-grained sediment. • Northcraft Formation (Eva(n))—andesite lava flows, flow breccia, and sills in the upper part and matrix-supported breccia, water-laid lapilli tuff, and tuff breccia in the lower part; interbedded with the Puget Group. Weathers to coarse- and fine-grained sediment. • Skookumchuck Formation (T(sk))—micaceous feldspathic sandstone, siltstone, shale, carbonaceous siltstone, claystone, and coal; locally interbedded with tuffaceous and volcanic rocks and minor conglomerate. Weathers to fine-grained sediments.
Landform	Steep headwall slopes and LPD headscarps with concave slopes in the Puget Group, Northcraft, and Skookumchuck Formations.
Slope	>65% (DEM and Map SA2). Field-measured slopes are commonly steeper than those determined from the DEM.
Elevation	557 to 3,705 FAMSL (DEM elevations).
Total area	191.0 acres (0.8 km^2)

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Form A-2: Mass Wasting Map Unit 2 Description, Continued

MW processes	SR, DF
Non-road-related landslide density	15 non-road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 19.4 per km^2.
Road-related landslide density	21 road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 27.2 per km^2.
Forest practices sensitivity	High sensitivity to roading High sensitivity to harvest
Mass wasting potential	Moderate
Delivery potential	Moderate, 58% of the landslides (excluding LPDs) identified in this MWMU for the period of record delivered sediment to the fish-bearing stream system (directly or indirectly).
Delivery criteria used	Field and photo observations of proximity, visible sediment, and routes of delivery.
Hazard potential rating	High.

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Form A-2: Mass Wasting Map Unit 2 Description, Continued

Triggering mechanisms

The following factors lead to the generation and delivery of sediment from landslides in MWMU 2:

Natural characteristics:

- Steep slopes, supported by relatively resistant basalts and siltstone.
- Occurrence of large storms, routing large quantities of shallow groundwater to unstable slopes.

Shallow soils formed over intensely weathered bedrock (siltstone, volcanic breccia, volcanic sediments)
Concave and planar slopes

Contributing management-related characteristics:
Road-related landslides (excluding LPDs)
13 of the 21 (57%) road-related failures were the result of loading sidecast material on steep slopes (including landings). While the weakness of geologic materials and slope steepness are likely the dominant influences of instability, organic debris in sidecast material and inadequate road drainage are also contributing factors. 3 failures occurred at stream crossings (14%), and 2 initiated on road cutbanks (10%). 1 (5%) was apparently triggered by road drainage alone, and 1 (5%) was initiated in culvert fill.

Non-road-related landslides (excluding LPDs)
15 non-road-related landslides occurred in this unit. 11 (73%) were identified from aerial photos and from field reconnaissance in areas with stand ages between 0–20 years old. For shallow landslides (8 of the 11 in young stands), root strength likely contributes to some slope stability since large conifer roots can anchor into fractured bedrock and help maintain soil strength. Evidence for loss of root strength as the cause for SSDs is inconclusive because SSD failure planes usually lie below the rooting depth. However, roots may be adding stability along the margins of potential failure blocks and buttressing the downslope side.

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Form A-2: Mass Wasting Map Unit 2 Description, Continued

Confidence Moderate. Sidecast/drainage failures were noted during field reconnaissance. However, it is difficult to observe the influence of root strength on slope stability in the field. The root strength argument is based on experience in this kind of geology and current literature.

Comments See Map A2 for locations of MWMU2. It is possible that some areas designated as high hazard in this unit may actually be low or moderate hazard due to the natural variation in the landscape and the inherent error associated with remotely sensed data. Therefore field checking is needed when delineating this unit on the ground.

Form A3: Mass Wasting Map Unit 2

Number of landslides by landslide type and land use association in MWMU 2.

Land Use Association	Shallow Rapid (SR)	Debris Flows (DF)	Dam-Break Floods (DBF)	Large, Persistent Deep-Seated (LPD)	Small/ Recent Deep-Seated (SSD)	Total
Stand age 0-20 yrs	6	2	0	0	3	11
Stand age 20-50 yrs	0	3	0	0	0	3
Stand age >50 yrs	0	0	0	0	0	0
Sidecast/fill	2	8	1	0	1	12
Cutbank	1	0	0	0	1	2
Road drainage	1	0	0	0	0	1
Landing	1	0	0	0	0	1
Stream crossing	0	3	0	0	0	3
Culvert fill	0	0	1	0	0	1
Other	0	1	0	1	1	3
Total	**11**	**17**	**2**	**1**	**6**	**37**

Form A-2: Mass Wasting Map Unit 3 Description

MWMU number	3—Active SSDs
Description	Presently active SSDs in the Puget Group, Northcraft, and Skookumchuck Formations. Concave or planar slopes.
Materials	Geologic materials include primarily: • Puget Group (Ec2(pg))—feldspathic sandstone and litho-feldspathic sandstone interbedded with siltstone, shale, claystone, and coal, locally interbedded with Northcraft lava flows, tuffs, volcaniclastic breccias, and pebble conglomerates. Weathers to coarse- and fine-grained sediment. • Northcraft Formation (Eva(n))—andesite lava flows, flow breccia, and sills in the upper part and matrix-supported breccia, water-laid lapilli tuff, and tuff breccia in the lower part; interbedded with the Puget Group. Weathers to coarse- and fine-grained sediment. • Skookumchuck Formation (T(sk))—micaceous feldspathic sandstone, siltstone, shale, carbonaceous siltstone, claystone, and coal; locally interbedded with tuffaceous and volcanic rocks and minor conglomerate. Weathers to fine-grained sediments.
Landform	SSDs
Slope	Field measured slope > 30%, DEM ≥????%. Field-measured slopes are commonly steeper than those determined from the DEM.
Elevation	513 to 2,059 FAMSL (DEM elevations).
Total area	220.9 acres (0.9 km^2)

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Form A-2: Mass Wasting Map Unit 3 Description, Continued

MW processes	SSD, DF.
Non-road-related landslide density	42 non-road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 47.0 per km^2.
Road-related landslide density	8 road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 8.9 per km^2.
Forest practices sensitivity	Moderate sensitivity to roading. Unknown sensitivity to harvest. (see Triggering Mechanism)
Mass wasting potential	High.
Delivery potential	Moderate. 68% of the landslides (excluding LPDs) identified in this MWMU for the period of record delivered sediment to the fish-bearing stream system (directly or indirectly).
Delivery criteria used	Field and photo observations of proximity, visible sediment, and routes of delivery.
Hazard potential rating	High.

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Form A-2: Mass Wasting Map Unit 3 Description, Continued

Triggering mechanisms

The following factors lead to the generation and delivery of sediment from landslides in MWMU 3:

Natural characteristics:

- Occurrence of large storms, routing large quantities of shallow groundwater to unstable slopes.
- Fractured geologic materials displaced by LPDs
- Stream undercutting.

Contributing management-related characteristics:

Road-related landslides (excluding LPDs)

Four of the 8 (50%) road-related failures were the result of loading sidecast material on steep slopes. While the weakness of geologic materials and slope steepness are likely the dominant influences of instability, organic debris in sidecast material and inadequate road drainage are also contributing factors. One failure occurred at a stream crossing (13%), one initiated on a road cutbank (13%), and 2 (25%) were apparently triggered by road drainage alone.

Non-road-related landslides (excluding LPDs)

42 non-road-related landslides occurred in this unit. 32 (76%) were identified from aerial photos and from field reconnaissance in areas with stand ages between 0–20 years old. For shallow landslides (17 of the 32 in young stands), root strength likely contributes to some slope stability since large conifer roots can anchor into fractured bedrock and help maintain soil strength. Evidence for loss of root strength as the cause for SSDs is inconclusive because SSD failure planes usually lie below the rooting depth. However, roots may be adding stability along the margins of potential failure blocks and buttressing the downslope side.

Confidence

Moderate. SSDs are recognizable on air photos and in the field by raw scarps or areas of hardwoods occurring midslope and they are generally known by most field workers. Triggering mechanisms of deep-seated landslides are not clearly understood.

Comments See Map A2 for locations of MWMU 3. It is possible that some areas designated as high hazard in this unit may actually be low hazard due to the natural variation in the landscape and the inherent error associated with remotely sensed data. Therefore field checking is needed when delineating this unit on the ground.

Form A3: Mass Wasting Map Unit 3

Number of landslides by landslide type and land use association in MWMU 3.

Land Use Association	Shallow Rapid (SR)	Debris Flows (DF)	Dam-Break Floods (DBF)	Large, Persistent Deep-Seated (LPD)	Small/ Recent Deep-Seated (SSD)	Total
Stand age 0-20 yrs	8	9	0	0	15	32
Stand age 20-50 yrs	0	0	0	0	2	2
Stand age >50 yrs	0	4	0	0	1	5
Sidecast/fill	3	1	0	0	0	4
Cutbank	0	0	0	0	1	1
Road drainage	0	2	0	0	0	2
Landing	0	0	0	0	0	0
Stream crossing	0	0	0	0	1	1
Culvert fill	0	0	0	0	0	0
Other	0	0	0	3	3	6
Total	**11**	**16**	**0**	**3**	**23**	**53**

Form A-2: Mass Wasting Map Unit 4 Description

MWMU number	4—LPD bodies
Description	LPD bodies including "nested" deep-seated landslides within LPD complexes. Concave, planar, and convex slopes.
Materials	Geologic materials include primarily: • Puget Group (Ec2(pg))—feldspathic sandstone and litho-feldspathic sandstone interbedded with siltstone, shale, claystone, and coal, locally interbedded with Northcraft lava flows, tuffs, volcaniclastic breccias, and pebble conglomerates. Weathers to coarse- and fine-grained sediment. • Northcraft Formation (Eva(n))—andesite lava flows, flow breccia, and sills in the upper part and matrix-supported breccia, water-laid lapilli tuff, and tuff breccia in the lower part; interbedded with the Puget Group. Weathers to coarse- and fine-grained sediment. • Skookumchuck Formation (T(sk))—micaceous feldspathic sandstone, siltstone, shale, carbonaceous siltstone, claystone, and coal; locally interbedded with tuffaceous and volcanic rocks and minor conglomerate. Weathers to fine-grained sediments.
Landform	Variable
Slope	Variable.
Elevation	299 to 3,732 FAMSL (DEM elevations).
Total area	21,280.0 acres (86.1 km^2)
MW processes	DBF, DF, SSD

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Form A-2: Mass Wasting Map Unit 4 Description, Continued

Non-road-related landslide density	59 non-road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 0.7 per km^2.
Road-related landslide density	37 road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 0.4 per km^2.
Forest practices sensitivity	Moderate sensitivity to roading. Low sensitivity to harvest.
Mass wasting potential	Low. Although road-related dam-break floods and debris flows occurred in this unit, they were initiated on gentle slopes by puncheon culvert failures. Most, if not all, puncheons have been removed and repaired. One small deep-seated failure was induced by head-loading of end haul material. This is a very rare occurrence. Therefore, mass wasting potential in this unit is presently low.
Delivery potential	Moderate. 61% of the landslides (excluding LPDs) identified in this MWMU for the period of record delivered sediment to the fish-bearing stream system (directly or indirectly).
Delivery criteria used	Field and photo observations of proximity, visible sediment, and routes of delivery.
Hazard potential rating	Low.

Form A-2: Mass Wasting Map Unit 4 Description, Continued

Triggering mechanisms

The following factors lead to the generation and delivery of sediment from landslides in MWMU4:

Natural characteristics:

- Occurrence of large storms, routing large quantities of shallow groundwater to unstable slopes.
- Fractured and displaced geologic materials
- Stream undercutting
- Concave and planar slopes.

Contributing management-related characteristics:

Road-related landslides (excluding LPDs)

13 of the 37 (35%) road-related failures were the result of loading sidecast material on steep slopes (including landings). While the weakness of geologic materials and slope steepness are likely the dominant influences of instability, organic debris in sidecast material and inadequate road drainage are also contributing factors. 4 failures occurred at stream crossings (11%), 11 initiated on road cutbanks (30%), and 2 (5%) were apparently triggered by road drainage alone. 3 of the landslides (8%) were initiated in culvert fill.

Non-road-related landslides (excluding LPDs)

59 non-road-related landslides occurred in this unit. 28 (47%) were identified from aerial photos and from field reconnaissance in areas with stand ages between 0–20 years old. For shallow landslides (13 of the 28 in young stands), root strength likely contributes to some slope stability since large conifer roots can anchor into fractured bedrock and help maintain soil strength. Evidence for loss of root strength as the cause for SSDs is inconclusive because SSD failure planes usually lie below the rooting depth. However, roots may be adding stability along the margins of potential failure blocks and buttressing the downslope side.

Confidence

High. Road-related landslides can be caused by inadequate drainage on almost any slope, but with the puncheon culverts removed, drainage problems at stream crossings happen very seldom. In one case, loading by improperly

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Form A-2: Mass Wasting Map Unit 4 Description, Continued

Confidence (continued)

placed end haul material initiated movement within the body of an LPD in this watershed. However, this was probably a rare occurrence. Undercutting of SSD toes results in cutslope failures but these usually deliver their sediment to the roads.

Comments

See Map A2 for locations of MWMU 4. It is possible that some areas designated as low hazard in this unit may actually be moderate or high hazard due to the natural variation in the landscape and the inherent error associated with remotely sensed data. Therefore field checking may be needed when delineating this unit on the ground.

Form A3: Mass Wasting Map Unit 4

Number of landslides by landslide type and land use association in MWMU 4.

Land Use Association	Shallow Rapid (SR)	Debris Flows (DF)	Dam-Break Floods (DBF)	Large, Persistent Deep-Seated (LPD)	Small/ Recent Deep-Seated (SSD)	Total
Stand age 0-20 yrs	13	0	0	0	15	28
Stand age 20-50 yrs	3	0	0	0	2	5
Stand age >50 yrs	2	0	0	0	4	6
Sidecast/fill	9	0	3	0	0	12
Cutbank	9	0	0	0	2	11
Road drainage	0	1	1	0	0	2
Landing	0	0	0	0	1	1
Stream crossing	0	3	1	0	0	4
Culvert fill	1	0	1	0	1	3
Other	1	0	0	246	23	270
Total	**38**	**4**	**6**	**246**	**48**	**342**

Form A-2: Mass Wasting Map Unit 5 Description

MWMU number	5—the rest of the watershed
Description	The rest of the watershed
Materials	All geologic formations
Landform	Variable.
Slope	Variable, but generally less than 65%.
Elevation	280 to 3,830 FAMSL (DEM elevations).
Total area	24,344.8 acres (98.5 km^2)
MW processes	LPD
Non-road-related landslide density	21 non-road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 0.2 per km^2.
Road-related landslide density	17 road-related landslides (excluding LPDs) identified over the photo record (1959-1997), representing 0.2 per km^2.

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Form A-2: Mass Wasting Map Unit 5 Description, Continued

Forest practices sensitivity	Low
Mass wasting potential	Low, except for LPDs.
Delivery potential	Variable, but 68% of the landslides (excluding LPDs) occurring in this MWMU for the period of record delivered sediment to the fish-bearing stream system (directly or indirectly).
Delivery criteria used	Field and photo observations of proximity, visible sediment and routes of delivery.
Hazard potential rating	Low
Triggering mechanisms	Variable
Confidence	High
Comments	See Map A2 for locations of MWMU 5. It is possible that some areas designated as low hazard in this unit may actually be moderate or high hazard due to the natural variation in the landscape and the inherent error associated with remotely sensed data. Therefore field checking may be needed when delineating this unit on the ground.

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Form A3: Mass Wasting Map Unit 5

Number of landslides by landslide type and land use association in MWMU 5.

Land Use Association	Shallow Rapid (SR)	Debris Flows (DF)	Dam-Break Floods (DBF)	Large, Persistent Deep-Seated (LPD)	Small/ Recent Deep-Seated (SSD)	Total
Stand age 0-20 yrs	9	0	0	0	3	12
Stand age 20-50 yrs	0	0	0	0	0	0
Stand age >50 yrs	1	0	0	0	2	3
Sidecast/fill	8	0	0	0	1	9
Cutbank	1	0	0	0	4	5
Road drainage	0	1	0	0	0	1
Landing	0	0	0	0	1	1
Stream crossing	0	1	0	0	0	1
Culvert fill	0	0	0	0	0	0
Other	0	0	0	2	6	8
Total	**19**	**2**	**0**	**2**	**17**	**40**

CONFIDENCE

Landslide Inventory

Confidence in the landslide inventory is generally high. Due to dense canopy cover in some photos, it is possible some shallow, rapid landslides were not visible through thick tree stands. Large deep-seated landslides may have been missed during mapping because they are so old and so eroded that they are not easily recognized. These problems are common to mass wasting inventories. The problems with the spreadsheet and map however, are not.

Confidence, in the spreadsheet and in map accuracy is high. Many difficulties were encountered during the digitizing phase and landslides were double-mapped or lost. Double-mapped landslides were a consequence of digitizing directly from air photos without the creation of an interim working map. Without the working map the analyst had no way of knowing what was mapped earlier and double-mapped landslides and landslides with the same number became inevitable. When these were recognized, they were deleted and discontinuous numbering in the spreadsheet resulted. Discontinuous numbering made data entry confusing and time-consuming. However, repeated checking of the inventory against the map has resulted in a present high level of confidence that what is listed in the inventory is also on the map and is representative of what is actually occurring in the watershed.

Assessment

Confidence in the overall qualitative assessment is moderate to high and confidence in the quantitative analysis is moderate. Field checking was greatly hampered by the lack of an accurate and complete working map. Thus field data is very limited. About 5% of the total number of landslides were measured in the field but these are not completely representative of all the mass wasting map units. Therefore the assessment relies heavily upon the DEM and GIS. Because the DEM averages slopes, it is known to generally produce lower gradients than those measured in the field.

Mass Wasting Map Units

Although the number of field measurements was limited, enough time was spent examining air photos and landslides in the field to make sufficient observations and evaluations of hazard potentials in the basins. There were many opportunities to observe natural landslides and the effects of forest practices. Because of this, confidence in the MWMUs is high. Unit descriptions and trigger mechanisms are well defined.

Landslide Sediment Volumes

Confidence in quantitative data, such as volume estimates, is moderate because of the sparse field data and the reliance on remotely sensed data. The natural variation in the landscape and the inherent error associated with remotely sensed data reduces confidence as well. Some estimates of volumes of puncheon culvert failures were averaged from John Barone's (Weyerhaeuser engineer, personal communication, March 1998) engineer's drawings of replaced fill and culverts. Confidence is varied in field measurements because so few were taken and they did not coincide well with GIS.

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