WASHINGTON STATE DEPARTMENT OF
Natural Resources

Landslide Hazard Zonation Project

Mass Wasting Assessment

Jackman Creek and Corkindale Watersheds
Skagit County, Washington

Prepared by:

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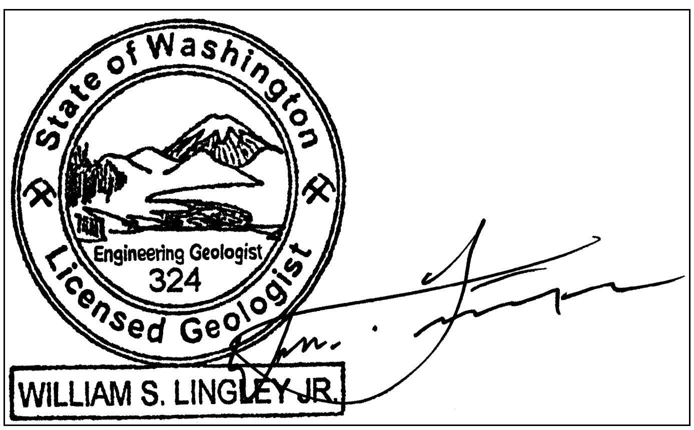
March 5, 2004
revised October 12, 2007



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1.0 Overview

The purpose of this assessment is to identify areas on non-federal and non-tribal lands within the Jackman Creek and Corkindale WAUs (here called the Jackman–Corkindale WAUs[1]) that have moderate or high risk of landslides due to natural instability and/or the effects of forest management (logging, roading, yarding, etc.). The Washington Forest Practices Board's *Standard Methodology for Conducting Watershed Analysis* (Version 4.0, 1997), used here, requires that several critical questions are answered and that mass wasting map units (MWMU) are defined, both of which help assess the risk that landslide debris could be delivered to public resources (surface waters, public roads and other infrastructure) or threaten public safety. However, this is a reconnaissance study and must not be used for assessment of risk to private property, or analysis of individual landslides or slopes. Undoubtedly, some landslides have been accidentally omitted, and some benign features may have been incorrectly mapped as landslides.

This mass wasting assessment is conducted using aerial photographs, maps, and field observations. A series of exercises have been completed, designed to respond to the critical questions or suggest areas where more detailed information is necessary to do so. The objective of these exercises is to generate information sufficient to establish:

1. A general characterization of mass wasting processes active in the basin;
2. Portions of the landscape sharing similar physical characteristics relating to mass-movement behavior;
3. The relative potential for mass wasting within each landscape unit.

1.1 Introduction to Mass Wasting Processes and Terminology

Terminology used to describe mass wasting processes in this assessment follows the classification system established by the Washington Forest Practices Board (1997) as modified by Boyd and Vaugeois (2003), which groups slope movement into nine types (shallow-rapid, debris flow, debris avalanche, undifferentiated deep-seated, shallow sporadic deep-seated, large persistent deep-seated, earth flow, rock topple/fall, and snow avalanche). Analysis is aided by designating landforms, slope shapes, land uses, and other observations associated with groups of landslides. (See Form A-1.) For the purposes of this study, most landslides that fail below rooting depth are categorized as deep-seated, consistent with the Forest Practices rules (WAC 222-16-050). However, those deep-seated landslides that moved rapidly and clearly deliver are included in the analyses of sediment delivery.

In this report, we introduce the concept of a 'delivery vulnerability factor' to help quantify the ratings for potential hazard of delivery of debris and sediment to streams by mass wasting, as outlined in Table A-2 of Washington Forest Practices Board (1997). The delivery vulnerability factor is simply the area of delivering landslides normalized for the period of study and the area of the mass wasting map unit; values are multiplied by one million to provide whole numbers. Very limited application by Karl Wegmann and the author suggest that vulnerability factors less than 100 have low delivery potential, factors of 100 to 250 are moderate, and factors greater than 250 have high potential.

[1] WAU boundaries and names were revised after this report was first prepared (2004). The Corkindale WAU (#040531) has been greatly expanded to include all the small streams draining directly to the Skagit River between Diobsud Creek and the Baker River (exclusive). Parts of what used to be the Diobsud (#040128), Illabot (#040523), and Miller (formerly #040530, now abandoned) WAUs are now included in Corkindale, as are two small tracts along the Skagit that used to be part of the Jackman Creek WAU (#040529), which is now restricted to the basin of that stream. The project area for this assessment, north of the Skagit between the towns of Marblemount and Concrete, includes all of the new Jackman WAU and more than half of the new Corkindale WAU.

2.0 Geologic and Physiographic Setting Pertinent to Mass-Wasting Interpretations

The Jackman Creek and Corkindale watersheds cover 61 mi^2 in the west-central part of the North Cascades physiographic province, including the entire drainages of Jackman and Corkindale Creeks, their tributaries, and intervening land north of the Skagit River. Jackman and Corkindale Creeks drain southwest and southeast, respectively, into the Skagit River between Concrete and Marblemount in Skagit County, Washington. Figure 1 shows some geographic features described in the text together with simplified geology of the two watersheds.

Most of the land in both watersheds is managed by the U.S. Forest Service and not included in this project. The remainder, constituting the study area, covers about 25 mi^2; it is mostly fee acreage, plus several parcels of State trust lands managed by the Department of Natural Resources, and Rockport State Park. Dense second-growth evergreen trees cover most hillslopes on Forest Service lands and some of the non-federal land, although aggressive logging and roading occurred between 1965 and the early 1990s.

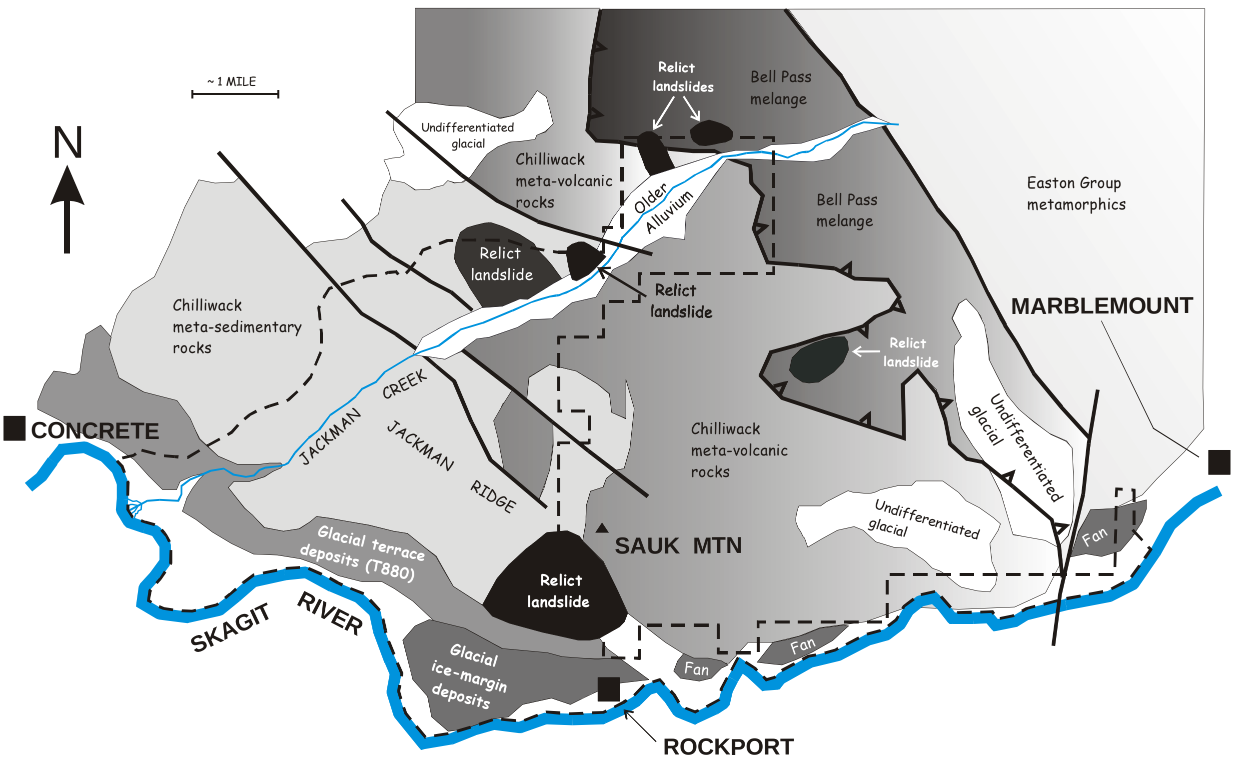

Figure 1. Map showing the simplified geology of the Jackman–Corkindale watersheds (after Tabor and others, 2002, 2003), the approximate boundary of the study area (dashed), and some geographic features referenced in the text. (Map A-1 is a more accurate depiction of the study area.) The relict landslides are from Tabor and others (2003) who mapped at the 1:100,000 scale; most of these landslides have been re-mapped at 1:12,000 scale (as described herein). The heavy and heavy barbed lines are faults.

2.1 Topography

The study area, occupying more than 16,000 acres of the 38,873-acre Jackman Creek and Corkindale watersheds, ranges in elevation from about 180 ft above mean sea level along the banks of the Skagit River; to 4,400 ft on slopes north of Jackman Creek and 3,889 ft on the summit of Jackman Ridge, which divides the watersheds.[2] Sauk Mountain, the 5,541-ft apex of the Corkindale watershed, lies north of the central study area, and several other ridges and peaks in the upper basins rise above 4,500 ft (Fig. 1). Major drainages include the Skagit River and its northern tributaries between river miles 57 and 76: Jackman, Barr, Sutter, Rocky, and Corkindale Creeks. Jackman Creek has one important tributary, Webber Creek, which enters from the southeast.

The study area can be divided into five main physiographic elements: 1) a 7.5-mi northeast-trending inner gorge, which forms the lower valley of Jackman Creek; 2) generally planar slopes forming the southwest and south sides of Sauk Mountain; 3) very steep gorges and knobs on the southeast and east sides of Sauk Mountain; 4) a highly dissected terrace (maximum elevation of about 900 ft) locally separating mountainous terrain from the valley bottom; and 5) the Skagit River floodplain. In general, slopes within the region are very steep (mostly in excess of 30%), and more characteristic of alpine than foothills topography.

The southeastern side of the Jackman Creek valley is characterized by prominent faceted spurs. The northwest end of Jackman Ridge is a typical example of such ridges, whose ends have been cut off forming planar facets parallel to the valley trend; these faceted spurs likely result from faulting parallel to the creek. Tributaries entering from the north side of the valley are characterized by linear inner gorges with deep V-profiles. A poorly-defined, northeast-trending bench at about 3,700 ft elevation separates the inner gorge of Jackman Creek from an alpine headwall along the northwestern margin of the study area.

Streams located in the Jackman Creek watershed display well-developed trellis drainage, that is, a straight main stem with tributaries entering at nearly right angles. In this case, the orientation of the drainage pattern is controlled, in part, by northwest-trending layering in the rock (metamorphic cleavage and relict bedding), northwest-trending faults, and northeast-trending faults (Tabor and others, 2003; this study). Drainages in the Corkindale watershed are generally dendritic (branching at acute angles).

Analysis of the Skagit River floodplain over a 100-yr period (U.S. Geological Survey, 1915, 1952, maps in footnote 2, and DNR aerial photography set NW-C-01) indicates that although the river scrolls rapidly across its narrow floodplain in the study area, the general configuration of meanders is controlled largely by adjacent bedrock hills. Other factors influencing meander patterns include flow regulation by upstream dams and massive sediment input from Jackman Creek. Remarkably, a delta has built out into the Skagit at the mouth of Jackman: this delta was not present in 1909, but is clearly evident since 1952.

2.2 Geology

The bedrock of the study area consists mainly of very old (248 to 417 million yr) meta-sedimentary and meta-volcanic rocks of the Chilliwack Group (Tabor and others, 2003). These include black marble, altered sandstone, and altered basalt, which are resistant to weathering; and metamorphosed claystone, which weathers more readily (i.e., may form thick soils). The Bell Pass mélange, a chaotic mixture of rock types, and black 'slate' of the Easton Group (more specifically, the Darrington Phyllite) crop out in the eastern study area (Fig. 1). These units are old, on the order to 110 to 163 million yr (Dragovich and others, 2002). Both can weather deeply and are regionally unstable.

All of the bedrock units are juxtaposed by northwest-trending faults, which control the direction of Webber Creek and the next tributary to the northeast. The linear nature of the Jackman Creek channel and the faceted spurs suggest that the location of Jackman Creek is also fault controlled. Although not documented during the field review, it is possible that mass wasting potential increases with proximity to these faults, where the bedrock is sheared and can be deeply weathered.

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[2] Based on U.S. Geological Survey topographic maps for the Marblemount (1999), Sauk Mtn (1999), Rockport (1982), Finney Peak (1982), and Lake Shannon (1989) quadrangles.

Mapped surficial units consist of sediments deposited by continental glaciers and alluvium deposited by streams. Continental ice covered the entire study area during the last advance of the Cordilleran ice sheet, as evidenced by blankets of till at the highest elevations. Till in this area is an olive-brown mixture of clay, sand, and gravel together with a few boulders, deposited directly from the base of the glacial ice. Presumably, alpine glaciers were present in parts of the watersheds although corresponding deposits have not been mapped.

The highly dissected terrace, best developed near the mouth of Jackman Creek, consists of a cap of poorly graded gravelly sand overlying blue-gray clay and silt. Interbeds of till are also mapped in adjacent parts of this terrace (Heller, 1978). It is referred to here as the 880-ft terrace because of the elevation of its tread. These sediments are interpreted as relating to glacial lake(s) that formed while continental ice sheets dammed the valley. Similar terrace deposits are present in the Sauk and Stillaguamish drainages.

Of interest is a large valley-fill sequence in the central Jackman Creek drainage mapped as older alluvium by Tabor and others (2003; see Fig. 1). This accumulation of sand, gravel, and boulders, predating human presence in the watershed, is unusual for steep mountain streams, which are normally capable of rapidly eroding and removing such deposits. Similarly, sediment accumulation in fast-flowing rivers, such as the delta in the Skagit at the mouth of Jackman Creek, is not common; the implication of this delta is that unnaturally high sediment discharge has occurred in recent decades. Both accumulations likely reflect overwhelming sediment input, although the control of Skagit discharge by up-river dams is also a factor in delta preservation.

2.3 Hydrology

Precipitation within the basin is high, ranging from 60–80 in/yr in the low elevations along the southern portions of the study area to 70–120 in/yr in the headwaters of Jackman Creek (WDNR, 1991; Oregon Climate Service, 2007[3]). Most of the annual rainfall occurs between October and May with a pronounced summer dry season. During the winter months, elevations between about 1,800 and 3,200 ft are susceptible to rain-on-snow events, which can trigger widespread mass wasting along the Cascade foothills.

Precipitation intensity and duration in the Jackman–Corkindale WAUs are important factors that likely contribute to initiation of mass wasting events (Heller, 1981; Montgomery and Dietrich, 1994). Typical 24-hr rainfall intensities in the Jackman–Corkindale WAUs range from 1.75 to 3.75 in for a 2-yr recurrence interval storm (Miller and others, 1973). Storms produced discharges greater than the peak flows expected at 10-yr recurrence intervals in the Skagit River (Concrete gauge) in 1932 (twice), 1935, 1949, 1951, 1962, 1975, 1979, 1980, 1990, 1995, and 2003 (USGS, 2007).[4]

Groundwater hydrology in the upper elevations of the watershed consists primarily of movement through forest duff or across the surface because the substrates are dominantly impermeable till and bedrock. Below the 880-ft contour, highly permeable glacial sand probably creates active groundwater recharge for glacial deep-seated landslides along terrace margins.

2.4 Summary of Previous Mass Wasting Investigations

Landslides within the Jackman–Corkindale WAUs have been mapped at two different scales, by three sets of investigators. Tabor and others (2003) identified six large deep-seated bedrock landslides while

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[3] Oregon Climate Service, PRISM Group annual precipitation maps averaged for 1971–2000; see http://mistral.oce.orst.edu/www/mapserv/.

[4] The peak flow of 166,000 cfs on October 21, 2003 was the highest since the Skagit River dams were built. Recurrence intervals are calculated for regulated flows since the 1920s; earlier high flows were estimated at >200,000 cfs.

mapping the greater Jackman–Corkindale region as part of the Mount Baker 1:100,000-scale quadrangle. Working at larger scales, Heller (1978, 1979, 1981) mapped many landslides near the mouth of Jackman Creek and along the western margin of the current study area. He concluded (1978) that groundwater perching at impermeable barriers, steep slopes, and deforestation are the most common site conditions contributing to slope failure in his study area, which also included large areas farther west. In a landslide inventory and sediment budget for ten Skagit sub-basins, Paulson (1997) mapped small shallow slides and debris flows, the kind more closely associated with forest management activities; these are now captured in the Department of Natural Resources statewide Landslide Hazard Inventory (Boyd and Vaugeois, 2003), but only the initiation point of each failure was mapped. Jackman Creek had the highest calculated sediment delivery rate of the ten basins, due chiefly to a large landslide in glacial sediment.

3.0 Summary of Methods

This assessment generally follows the Level II procedures for the mass wasting module of the *Standard Methods for Conducting Watershed Analysis* (Version 4.0; Washington Forest Practices Board, 1997). However, the data-gathering period is shorter than those of watershed analysis, and the synthesis and prescription phases have been omitted. A decision was made to limit the examination to two large-scale air-photo sets, and to sample no more than 300 newly identified/mapped landslide features.

First, a survey of readily available geologic, topographic, and hydrologic information was reviewed for the study area. Forty-six 'questionable' to 'definite' landslides[5] were located during a reconnaissance field investigation of part of the area on December 9 and 10, 2003. However, deep snow precluded examination of slopes at elevations above 1,600 ft.

Aerial photographs taken during 1965 (DNR WFPA65 1:12,000 black and white), 1978 (DNR NW-78 1:8,000 black and white), and 2001 (DNR NWC-011, 1:8,000 color) were viewed using a mirror stereoscope with 3x magnification; high altitude ortho-photographs taken in 1998 (DNR NWH-98) were also examined. Suspected landslides were identified from landforms containing headscarps, lack of vegetation along slide paths, hummocky or benched topography, ponded water bodies and marginal drainages.

The landslides were mapped directly in ArcGIS as a single Landslide-Hazard shapefile by registering the slides on the Department of Natural Resources digital raster graphic ("drg75") topographic contours. This technique results in local inconsistencies with the new DNR Hydrography layer and yields a maximum resolution of only 10 m. Maps of slope/convergence (SLPSTAB; Vaugeois, 2000) and slope-gradient (in percent), derived from USGS 10-m digital elevation models (DEM) of the watershed, aided in predicting areas of potential shallow-rapid slope failure and in assisting with the delineation of mass wasting map units (MWMUs).

The resulting landslide coverage is displayed as Map A-1. One deep-seated landslide mapped by Tabor and others (2003) has been included Map A-1, and five others were confirmed and remapped in greater detail. Several landslides mapped near the mouth of Jackman Creek by Heller (1978, 1979) were confirmed. Pertinent attributes of the features were recorded on data sheets (Form A-1). Recorded informa-

[5] *Questionable* landslides include those that cannot be mapped accurately, or that have a limited number of observed landslide characteristics; e.g., an area with a distinct arcuate headscarp but no obvious toe, hummocky ground, or deranged drainage might be mapped as a questionable landslide. *Definite* landslides include those that have been field checked, and those that have multiple slide characteristics observable on air-photos or other data. *Relict* landslides include those with rounded topographic expression or other features indicating that the slide is very old; in most cases, relict landslides appear to pre-date management activities in the forest.

tion includes: 1) the type of mass wasting process; 2) the level of certainty of the observation; 3) whether the mass wasting feature delivered sediment to surface waters or other public resources; 4) the associated land use; 5) the slope form (convergent, divergent, planar); 6) the photo-year in which the failure was initially recognized; and 7) the gradient or steepest slope increment within each landslide. The landslide process was identified where it could be done rapidly, but most failures are lumped as "shallow rapid–undifferentiated" or "deep-seated–undifferentiated" categories. The level of certainty is subjective and limited by lack of field verification.

The slope gradient was determined by exploring a DEM-derived slope map within each landslide polygon on the Landslide Hazard shapefile. Note that the steepest slope increment corresponds to the "slope at failure" (*angle of slide*; see Jackson, 1997) only for medium to large translational landslides. The slope angle cannot be reliably determined for small or narrow landslides where accuracy is limited by the 10-m resolution of the DEM. Slopes derived from DEMs are generally lower than those measured in the field, but are less subjective. Conversely, the steepest slopes on rotational failures are on the failure plane and therefore steeper than the slope of the ground just before landslide initiation. As a result, the gradient estimates presented here are approximations.

Once the locations of landslide features were mapped and evaluated, areas of similar mass-wasting potential were grouped into MWMUs, generally following the assessment procedures of watershed analysis. These are shown on Map A-2 and described in Forms A-2 (Appendix B).

4.0 Summary of Analysis and Results

During this review, a representative sample of 300 'very questionable' to 'definite, field-confirmed' landslides was identified using air-photos taken between 1965 and 2003. Inventory data are listed in Form A-1 and summarized on Form A-3 (Appendices A and C); Figures 2 through 8 characterize these features.

More than half of the landslides identified during this mass wasting assessment (51%) were mapped as shallow rapid–undifferentiated failures; 28% were debris flows, 11% deep-seated–undifferentiated, <6% small sporadic deep-seated, <3% large persistent deep-seated landslides or earth flows, and <2% debris or snow avalanches (Fig. 2). Note that 'small sporadic deep-seated landslides' as used here includes several failures in the Jackman Creek inner gorge that are on very steep ground and below rooting depth, but that moved very rapidly and were almost certainly related to forest management activities.

Landslides associated with clearcuts (0 to 5 years previous), young stands (5 to 15 yr), and sub-mature timber (15 to 50 yr) represent 26%, 25%, and 15%, respectively of the features identified (Fig. 3). Aside from those present on deep-seated landslides, road-related failures represent 9% of recorded features. Landslides in mature stands (a class that includes relict slides) and in alpine areas that have not been managed combine for 15% of observed slope failures.

Among the landform associations, secondary failures superimposed on large relict deep-seated slides are most common, followed by landslides in inner gorges and bedrock hollows (Fig. 4). More than 85% of the mapped features are smaller than 5 acres (Fig. 5), but a small number of deep-seated landslides account for most of the area affected by mass wasting (Fig. 6). Most slides have initiation/headscarp slopes of 50 to 140% (Fig. 7); there is no apparent correlation between type of failure and initiation/headscarp gradients (Fig. 8).

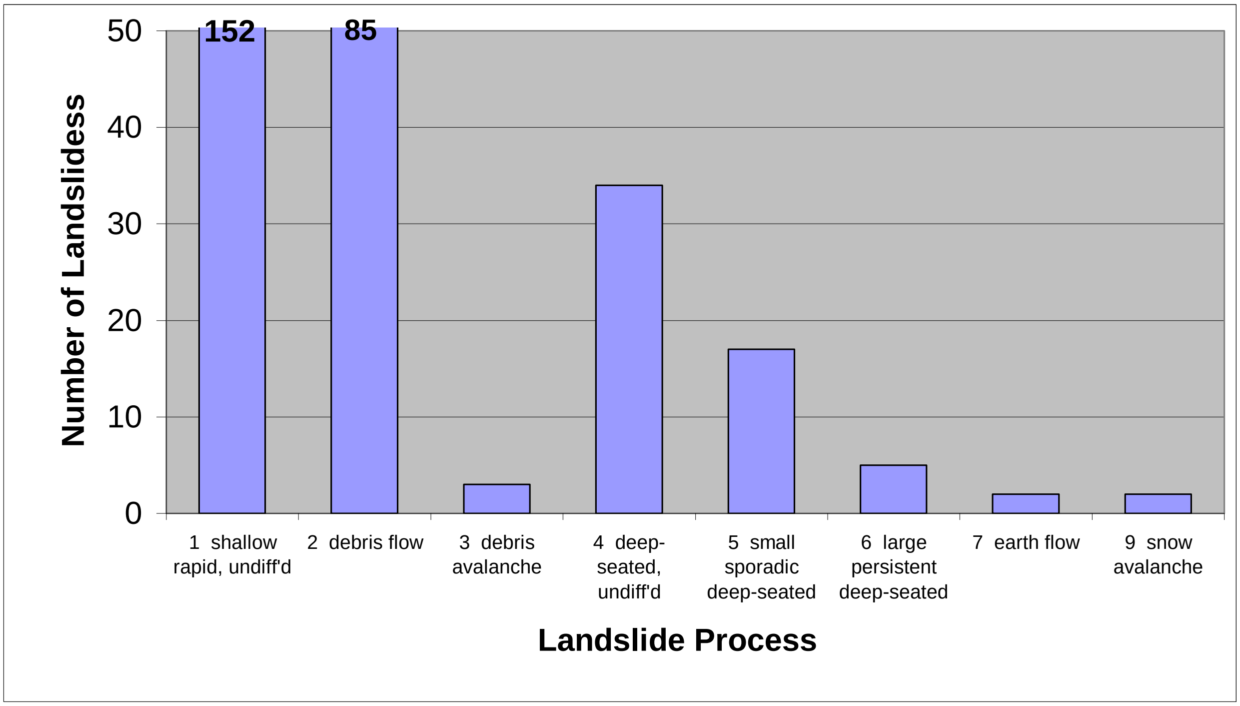

Figure 2. Number of landslides observed in the Jackman Creek and Corkindale study area by mass wasting process (category numbers as in Form A-1; no rock falls/topples were identified). In this and other graphs, number at top of a bar indicates a value beyond the range of the y-axis.

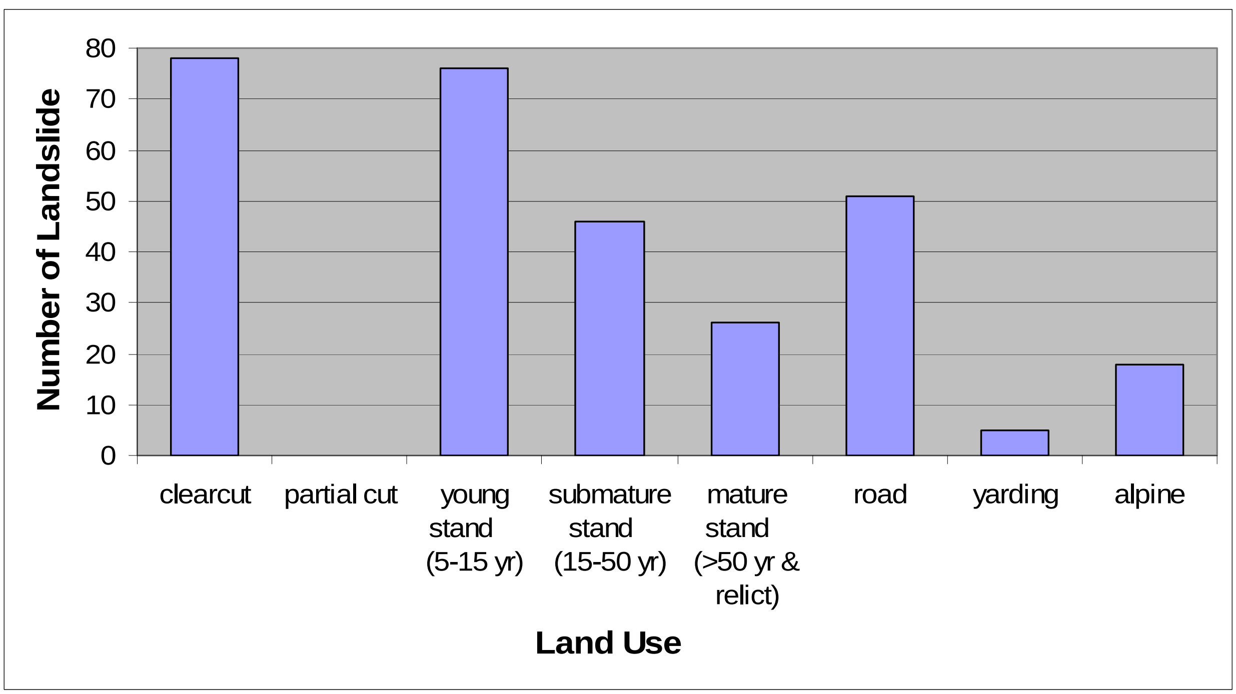

Figure 3. Number of landslides observed in the Jackman–Corkindale WAUs by land-use association.

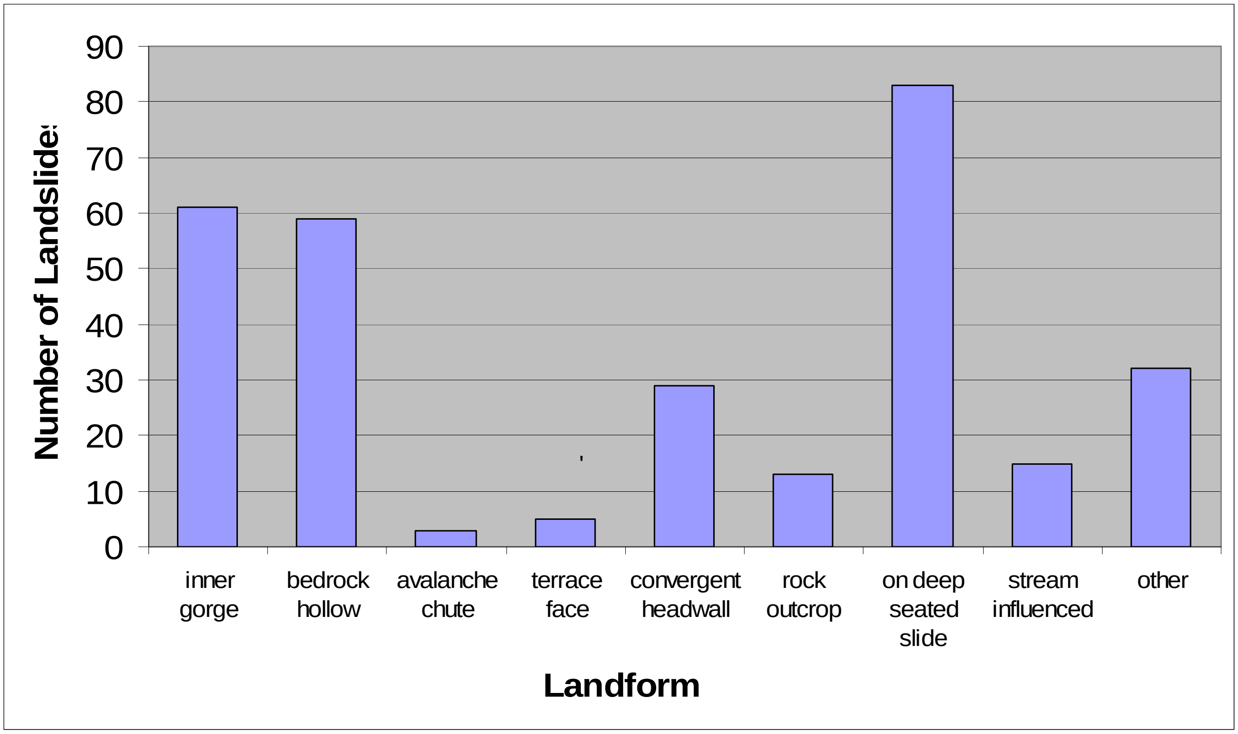

Figure 4. Number of landslides observed in the Jackman–Corkindale WAUs by landform association.

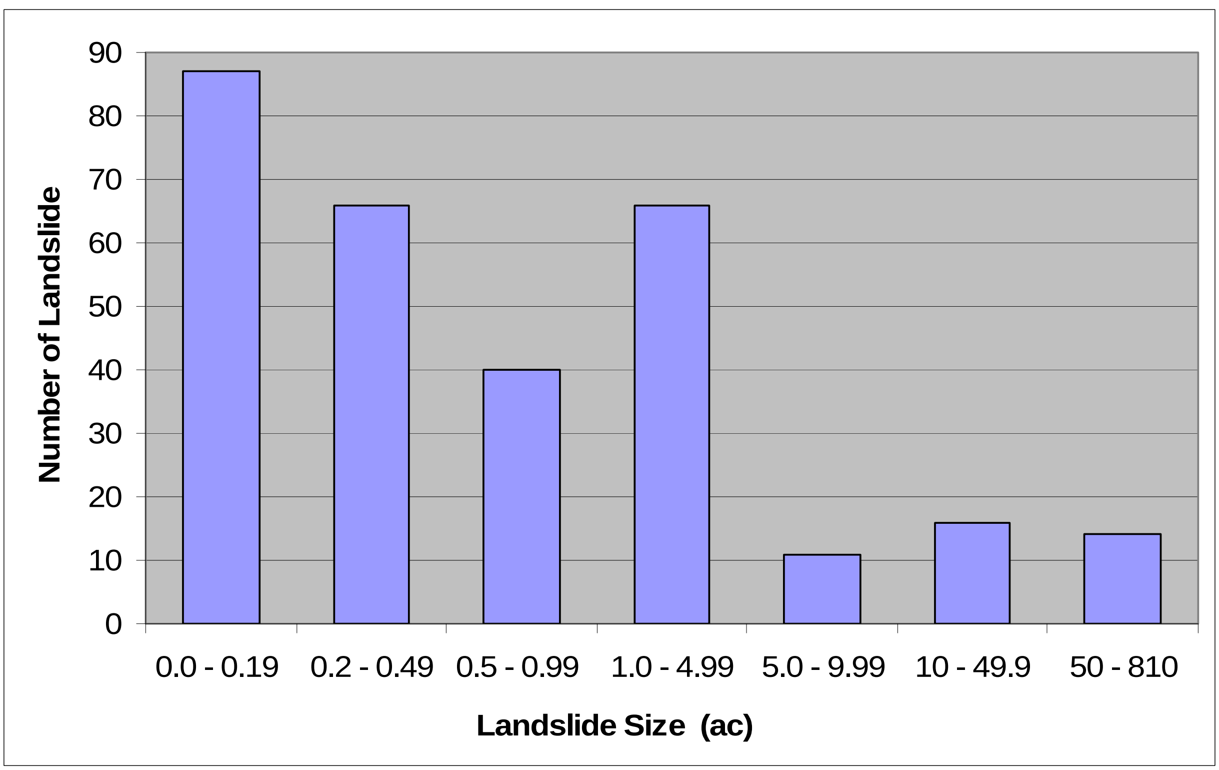

Figure 5. Size distribution of landslides in the Jackman–Corkindale WAUs.

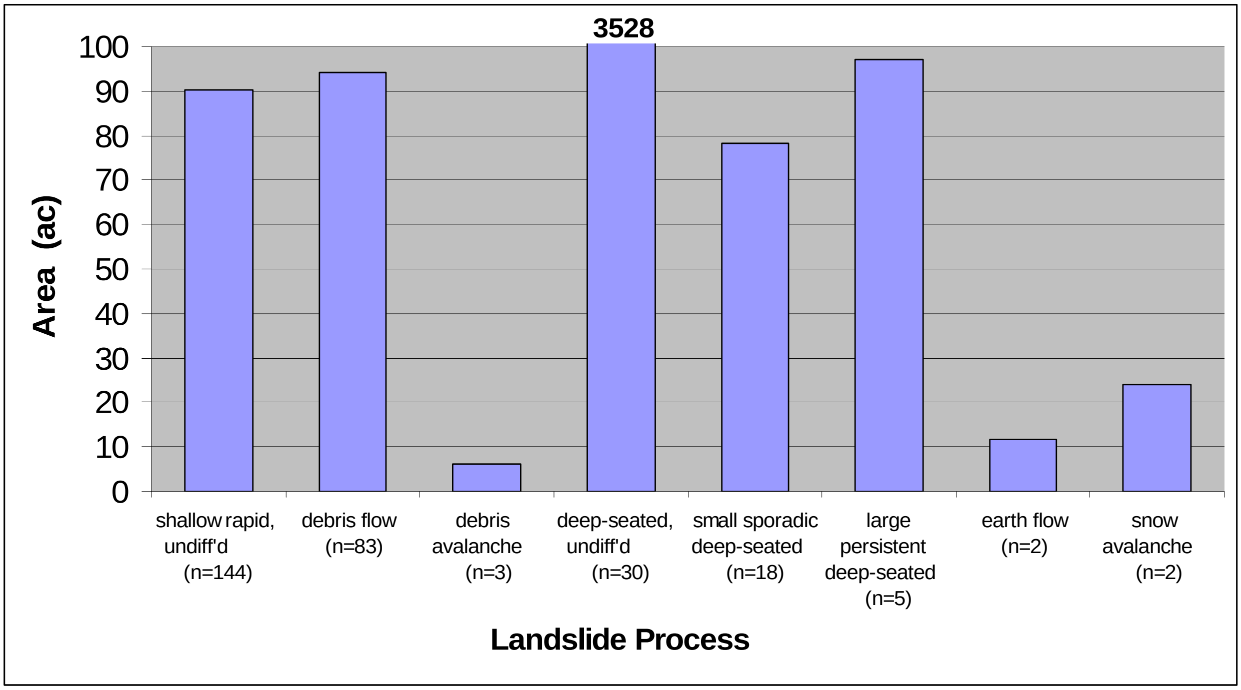

Figure 6. Total area of landslides by landslide process in the Jackman–Corkindale WAUs. Note that the deep-seated (undifferentiated) features constitute the overwhelming majority by area (3527.6 ac, off scale).

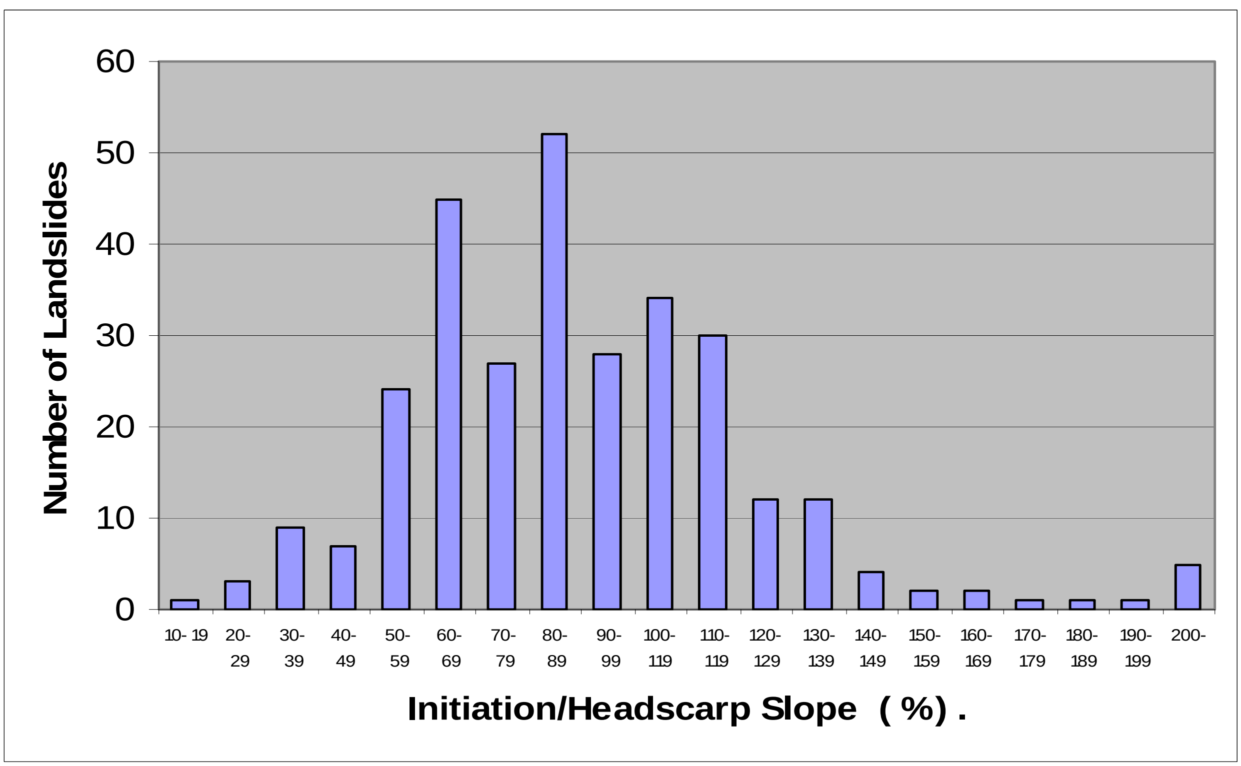

Figure 7. Distribution of landslides by slope class in the Jackman–Corkindale WAUs.

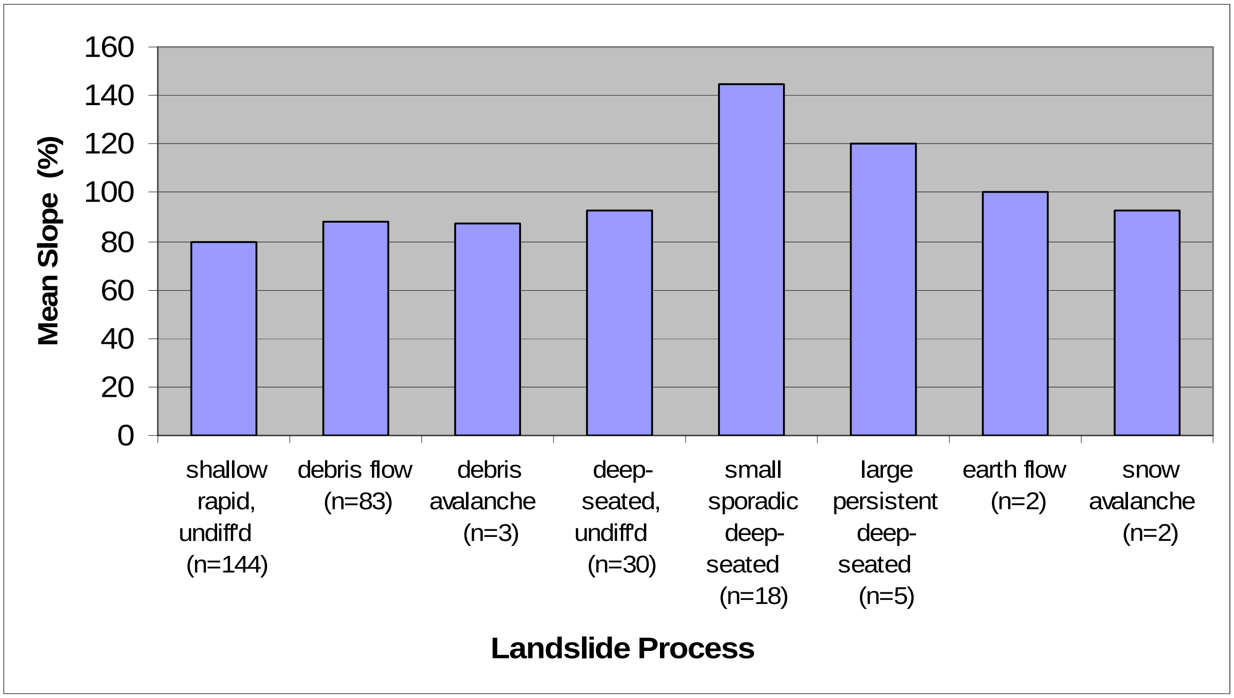

Figure 8. Mean headscarp/initiation slope for observed landslide types in the Jackman–Corkindale WAUs.

The annual rate of landsliding, normalized for the 38-yr study record and area of the two combined watersheds, is about 5 x 10^{-4} (Table 1). Recall that this assessment is based on a limited sample of 300 features, and may underestimate the slide frequency. But it is comparable to the rate estimated for the lower Finney Creek and Miller Creek area just to the southwest (Lingley, 2004); for perspective, these are both about 15 times the frequency in the Nookachamps basin, located farther west in the Skagit Valley (Wegmann, 2004).

Table 1. Landslide rates for the Jackman–Corkindale and Lower Finney–Miller WAUs

WAU	Landslides (n)	Years	Study Area Acreage	Rate (n / ac / yr)
Jackman – Corkindale	300	38	16,000	4.9 x 10^{-4}
Lower Finney – Miller	361	39	20,900	4.4 x 10^{-4}

5.0 Mass Wasting Map Units

The distribution and area of the seven mass wasting map units for the Jackman Creek and Corkindale WAUs are shown on Map A-2, Table 2, and Figure 10. These MWMUs have been delineated to depict areas having similar potential for mass wasting and delivery of sediment and debris to public resources. Mass wasting potential is based on landslide process, failure density, lithology, geomorphology, hydrogeology, and similar physical attributes. Slope thresholds for field identification were calculated based on statistics of the gradients of inventoried landslides. More detailed summaries and statistics for each unit are given in Form A-2 (Appendix B) and Form A-3 (Appendix C).

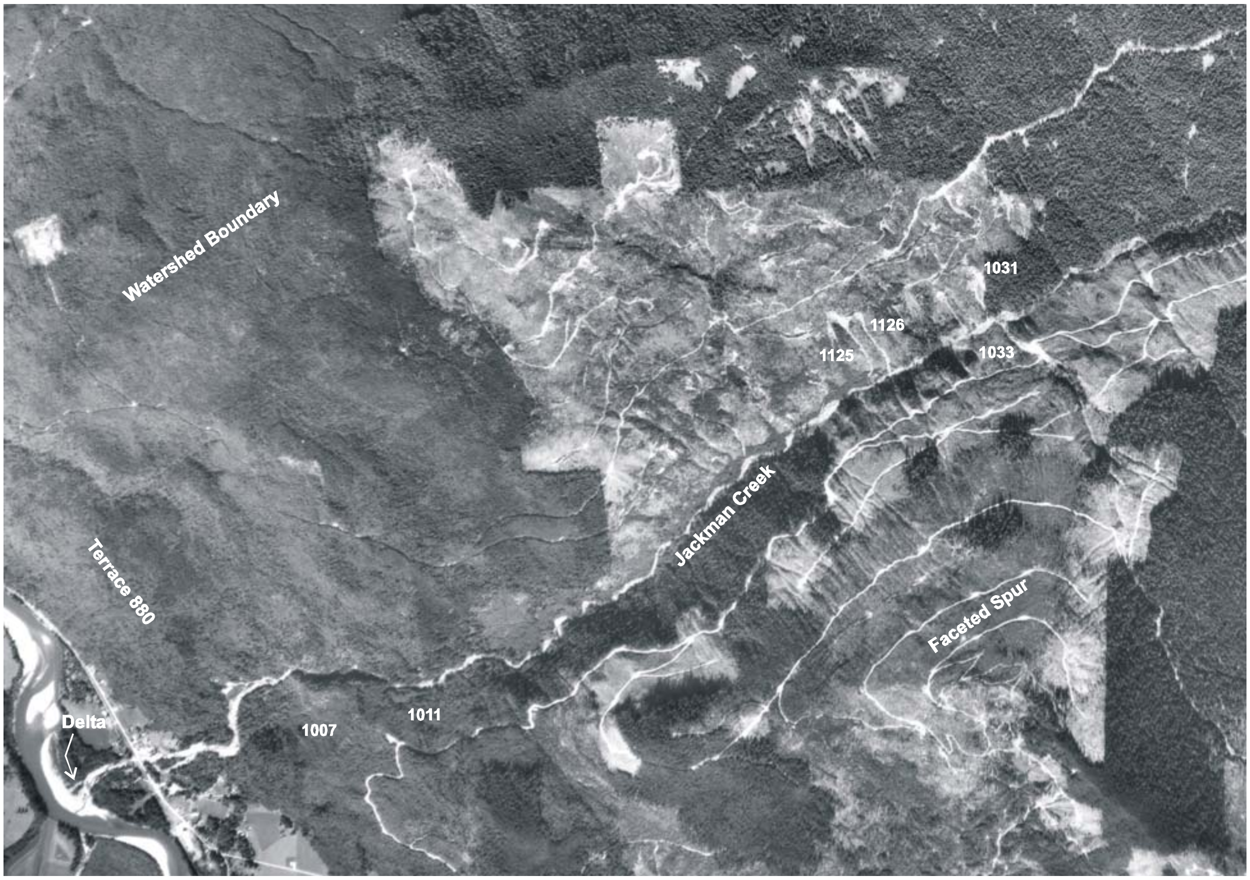

Figure 9. Part of air-photo WFPA-65 39-38 showing the lower Jackman Creek watershed, Skagit River (lower left), several landslides mentioned in the text (ID numbers), and typical landforms in the study area. Note the delta at the mouth of Jackman Creek (crossed by State Route 20) visible in the lower left. Careful examination of this photo reveals numerous landslides, many of which are related to clearcut harvesting or roading. The view is ~4 mi wide.

Table 2. Areas of landslides (in acres) by MWMU for the Jackman–Corkindale WAUs.

MWMU	Number of Landslides	Area of SR & SSD Landslides	Area of LPD & EF Landslides	Total Area of Landslides
1	17	5.3	134.7	140.1
2	7	6.9	11.6	18.5
3	105	114.8	62.5	177.3
4	63	304.2	77.1	381.3
5	48	52.7	12.9	65.6
6	13	11.7	239.2	250.9
7 & non-study area	47	20.2	2867.7	2887.9
Totals	**300**	**515.8**	**3405.7**	**3921.6**

Notes: SR & SSD refer to relatively rapid landslides (shallow rapid, debris flows, debris avalanches, snow avalanches, and some shallow sporadic deep-seated landslides), many of which appear to correlate to management activities. LPD & EF refer to all other deep-seated landslides (deep-seated–undifferentiated, large persistent deep-seated, and earth flows). Some slides on non-study area (U.S.F.S.) lands are included in this table, but not in MWMU descriptions or Table 3.

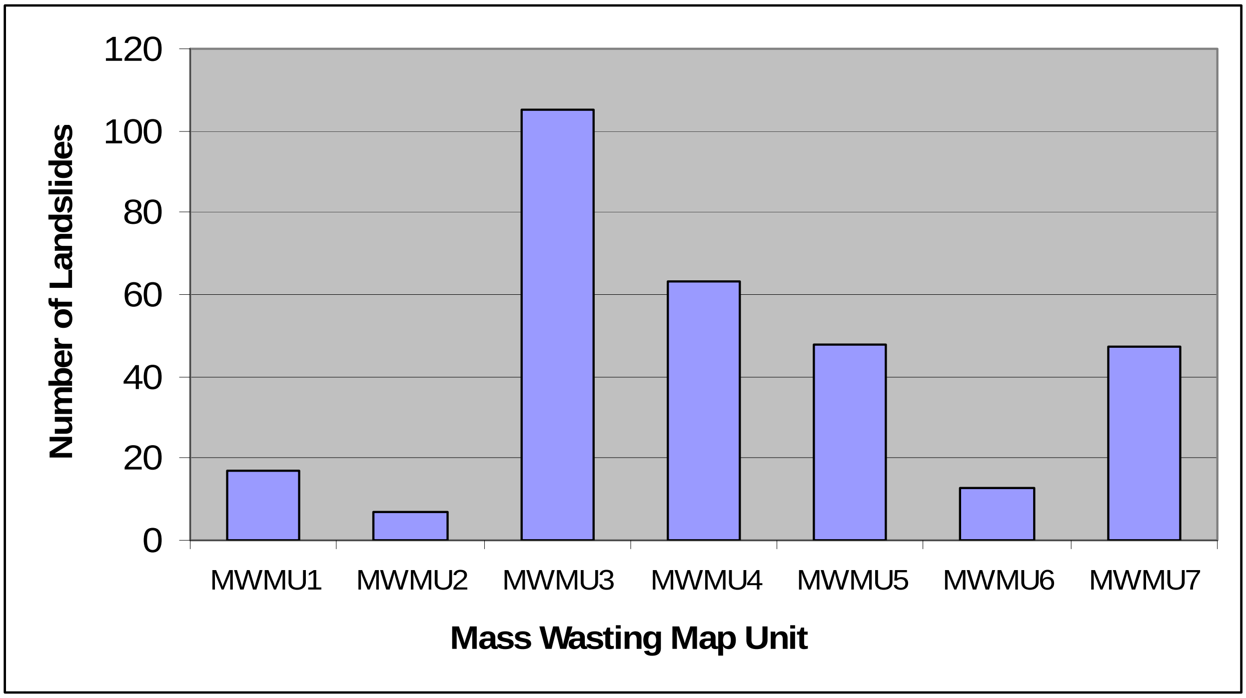

Figure 10. Distribution of landslides observed in the Jackman–Corkindale WAUs by MWMU.

For the purposes of this assessment, a method is introduced to compare the levels of slope-instability hazard among the MWMUs, using a proxy for the area of landslides likely to deliver sediment and debris to public resources. The vulnerability factor is defined as the total area of delivering slides, normalized for the area of the map unit and for the 38-yr study period (multiplied by 1 million to provide whole numbers). Table 3 lists the statistics for slide frequency and vulnerability. As a first approximation, vulnerability factors of 100 or less are usually observed in field-verified low deliverability terrain; values of 100 to 250 are associated with areas of medium delivery potential; and those in excess of 250 have high deliverability potential. These vulnerability factors do not account for the volume of material that may be mobilized, which in the case of the Jackman–Corkindale watersheds is greater than most owing to the large number of thick and rapidly moving deep-seated landslides. However, vulnerability factors appear to provide a semi-quantitative means of comparing MWMUs for the purposes of determining ratings for potential hazard of sediment delivery to streams by mass wasting, as outlined in Table A-2 of Washington Forest Practices Board (1997). They are not, however, the sole criteria used in deciding hazard ratings for the MWMUs.

Note that vulnerability factors for MWMUs 3, 4, and 5 are >1000, or more than 100 times the vulnerability factor of the low-hazard MWMU7. These are also an order of magnitude greater than high-hazard MWMUs in the Nookachamps, Clear Creek, Lime Creek, and Dan Creek watersheds, where the maximum vulnerability factors range from 119 to 650 (Karl Wegmann, WDNR, 2004 oral commun.). The Jackman–Corkindale basin-averaged frequency of delivery (306) and vulnerability (405) are also high compared to other watersheds assessed so far.

The following sections describe the characteristics of each MWMU.

Table 3. Annual rate of landslides delivering sediment/debris to public resources.

Mass Wasting Map Unit	MWMU1	MWMU2	MWMU3	MWMU4	MWMU5	MWMU6	MWMU7	Study Area
Area of MWMU (acres)	357.3	1295.6	2351.0	1696.6	1108.9	1130.2	8060.0	16000
Number of 'delivering' landslides	9	1	84	43	37	7	5	186
Frequency of delivery (no. delivering landslides / area / 38 yr) x 10^6	663	20	940	667	878	163	16	306
Area of 'delivering' landslides (acres)	0.5	0.9	108.8	75.3	48.1	9.2	3.2	245.9
Vulnerability factor (area delivering landslides / area / 38 yr) x 10^6	37	18	1218	1168	1142	214	10	405

Notes: Expressed in terms of frequency and landslide area (vulnerability factor) during the 38-yr study period (values multiplied by one million to provide whole numbers). 'Delivering landslides' include those that move rapidly and have 'probable' or 'yes' delivery rating (see Form A-1); the category excludes deep-seated landslides, except a few in MWMUs 1, 3, and 4 considered to deliver because they are on very steep slopes and/or were observed as such during field examination. *Vulnerability factor* is called *landslide area rate for delivery* in later LHZ projects.

MWMU1: Deep-Seated Landslides and Contiguous Lands in Glacial Terrace Deposits (≥ 40 slopes)

MWMU1 includes glacial terrace deposits near the mouth of Jackman Creek, including three large deep-seated landslides (I.D. number 1001 is 25 acres; 1007, 55 acres; 1011, 52 acres) and a number of smaller and secondary slides. The terrace, at about 880 ft elevation, is composed of flat-lying layers of impermeable till and lake deposits overlain by free-flowing gravelly sand. The large landslides are textbook examples of deep recharge in glacial materials, and have resulted in at least six superimposed shallow rapid failures. Several of the inventoried slides occurred on moderate slopes, due to weak materials and previous deep-seated movement, dictating the relatively low slope threshold of ≥ 40%. Field observation indicates that the largest of the secondary landslides (I.D. number 1012) has a 150 ft high headscarp and displaced ~100,000 yd^3 of gravelly sand, much of which continues to be delivered directly to Jackman Creek. The elevation of MWMU1 ranges from 280 to 900 ft. MWMU1 has been historically sensitive to forest management, with all of the superimposed shallow rapid failures relating to forest practices. Moreover, landslide 1012 and recent large-scale displacement of deep-seated landslide 1011 appear to be directly related to construction and/or maintenance of the old Jackman Creek Mainline, which defines the eastern boundary of both failures. The delivery potential of mass wasting in MWMU1 is high, with more than half of the slides in this unit delivering to Jackman Creek. MWMU1 is rated as high mass wasting potential with an observed delivering landslide frequency of 663. Although the vulnerability factor of 37 is low, the possibility of massive sliding and sediment release justifies a higher rating.

The hazard rating for MWMU1 is high.

MWMU2: Highly Dissected Glacial Terrace Deposits (≥ 45 slopes)

MWMU2 includes most of the discontinuous terrace between Concrete and Rockport State Park, below the prominent slope break at about 880 ft elevation. It is geologically similar to MWMU1, except that the glacial deposits have been dissected or locally removed by subsequent erosion. Like MWMU1, MWMU2 may be prone to movement resulting from deep-seated sliding in glacial materials, a1though no large failures were identified in this unit. However, arcuate headwalls north of Sauk (in S/2 section 17 and N/2 section 21, T35N, R9E) and a linear depression bounding the north side of the terrace between Everett Lake, its inlet and outlet, and Jackman Creek (sections 2, 11, and 12 of T35N, R8E) are suggestive of deep-seated failure. Of the seven small landslides present in this unit, most occurred on slopes steeper than 45%; only one delivered sediment to surface waters. MWMU2 appears to have low or medium sensitivity to forest management. The historic delivery potential is low with a vulnerability factor of 18; half of the landslides in MWMU2 did not deliver sediment to public resources. MWMU2 is rated as having a low mass wasting potential with an observed landslide rate of ~0.5 slides/yr between 1962 and 2001. However, many small stream channels cross the terrace, some of which have been mapped as inner gorges of MWMU5, rated as high hazard. In addition, most of MWMU2 lies directly uphill of Highway 20, and about half is above the Skagit River. Considering this location, and by comparison with similar landforms with apparently greater instability in the Lower Finney–Miller WAUs, the hazard potential rating for this unit is raised to moderate. Proposed forest practices near the ravines should be examined for characteristics of the high-hazard MWMU5.

The overall hazard rating for MWMU1 is moderate.

MWMU3: Landslides Superimposed on Relict Deep-Seated Landslides within the Middle and Upper Jackman Creek Drainage (≥ 55 slopes)

MWMU3 consists of 12 relict deep-seated landslides that have remarkably high rates of secondary failure (~2.4 slides/yr between 1965 and 2003). Eight of these relict landslides are located on the northwestern slope of Jackman Creek, where gradients typically range from 30 to 70% in mid-slope areas to steeper than 100% at the headwall area along the northwest boundary of the watershed. The five largest of the relict slides were also mapped by Tabor and others (2003), but with slightly different configurations. It is possible that this study underestimates the number and size of deep-seated landslides in the project area; the bench at 3,700 ft that parallels the northwestern basin boundary suggests that the entire northern side of the drainage may be a relict landslide complex. The toes of these relict slides mostly form the northwest side of the steep inner gorge of Jackman Creek. However, the northernmost features (ID numbers 1257 and 1284) slid across and probably dammed that stream, which then reestablished its course in the center of the valley through subsequent incision of the toes.

The substrate of MWMU3 is composed of meta-sedimentary and meta-volcanic rocks of the Chilliwack Group (Fig. 1); at least some of the relict slides involve bedrock (e.g., ID number 1033, which appears to displace black marble outcrops). However, most of the superimposed landslides appear to displace thick soils and glacial sediments that cover the bedrock. The 12 large landslides thoroughly disturbed these sediments, leaving relict landslide deposits locally in excess of 30 ft thick and highly prone to failure.

Relict landslides created over-steepened slopes, reduced soil cohesion, disrupted drainage, and altered permeability in the near-surface. About 90% of the 105 inventoried slides (primary and secondary) in this unit failed at slopes steeper than 55%. Incision within the landslide deposits, in part by secondary debris flows, results in unstable inner gorges and hollows. This remobilized sediment forms several small fans that have built out across the floor of Jackman Creek. Of interest is the large up-valley deposit of older alluvium (Fig. 1), which varies from 1,500 to 4,000 ft wide and is likely tens of feet thick. This geologic unit is here interpreted as the product of erosion of relict landslides, especially at the toes of those landslides that crossed to the southeast side of Jackman Creek.

The resulting landscape is unusually sensitive to forest management. Observe, for example, the proliferation of secondary failures superimposed on relict landslide number 1170 following clearcut harvest during the middle 1960s (Fig. 9). There, 30 shallow-rapid landslides and debris flows have deeply scarred the land and delivered enormous volumes of sediment to Jackman Creek. Note the large number of road-related failures visible on this high-altitude photograph. Many of the secondary slides mapped as shallow-rapid failures are themselves very large. For example, field observation of slides 1034 and 1061 suggest that each displaced on the order of 200,000 yd^3, much of which is being delivered to Jackman Creek. The delivery potential of mass wasting occurring in MWMU3 is extremely high with most of the failures delivering material to Jackman: total sediment delivery to the creek from shallow-rapid and small sporadic deep-seated slides and debris flows over relict landslides may be in excess of 1,000,000 yd^3. In addition, the elevation of MWMU3, ranging from ~740 to 4,000 ft, renders it susceptible to rain-on-snow events. MWMU3 has one of the highest vulnerability factors (1218) of all units analyzed in the LHZ Project thus far; it is rated as having an extremely high mass wasting potential (940) as well.

The overall hazard rating of MWMU3 is high.

MWMU4: Inner Gorge of Jackman Creek (≥ 60 slopes)

MWMU4 occurs in the steep inner gorge of Jackman Creek proper, in areas not affected by the relict deep-seated slides of MWMU3. Slopes along the southern margin of the drainage are particularly precipitous with steeper gradients commonly on the order of 90 to 150%; about 89% of inventoried failures occurred on slopes steeper than 60%. In this area, a series of broad bedrock hollows and convergent headwalls have developed, resulting in unstable conditions. Mass wasting processes for MWMU4 include shallow rapid landslides, small sporadic deep-seated failures, and debris flows.

MWMU4 is underlain by glacial till and by meta-sedimentary and meta-volcanic rocks of the Chilliwack Group (Fig. 1). Meta-sedimentary rocks dominate the southwestern part, but these softer rocks do not appear to be less stable than harder meta-volcanic rocks, which dominate the northeastern part. Elevation of MWMU4 ranges from 400 to about 4,000 ft, mostly within the rain-on-snow zone. MWMU4 has been historically sensitive to forest management practices, as 90% of inventoried landslides were associated with forestry land uses. The delivery potential of mass wasting in MWMU4 is high, with 50% of inventoried landslides delivering sediment to surface waters. The vulnerability factor is 1168, among the highest calculated in the LHZ Project to date.

The overall hazard rating of MWMU4 is high.

MWMU5: Other Steep Inner Gorges, Hollows, and Convergent Headwalls (≥ 70 slopes)

MWMU5 comprises steep to very steep inner gorges, convergent headwalls, and bedrock or soil hollows scattered across the project area. In general, these are mapped rule-identified landforms: although more than 90% of inventoried slides in this unit have gradients steeper than 80%, the slope threshold is set at 70% to conform to rules. Mass wasting in MWMU5 is dominated by shallow rapid and debris flow processes, but small sporadic deep-seated landslides are also present. Elevation in MWMU5 ranges from ~180 to 3,800 ft; materials are chiefly glacial deposits (mostly Vashon stade advance outwash and till) below 900 ft, and colluvial deposits, till, and Chilliwack Group metamorphic rocks at higher elevations. MWMU5 has been historically sensitive to management, and many slides are associated with forestry activities. The delivery potential of mass wasting is high, with 50% of identified landslides definitely moving sediment to surface waters. MWMU5 is rated as having high mass wasting potential with an observed landslide rate of 0.6 slides/yr between 1962 and 2001, and a vulnerability factor of 1142.

Because the landforms of MWMU5 can be small in area, and possibly obscured in the surrounding terrain and/or by forest canopy, it is likely that some of these features have been missed or the boundaries of mapped polygons poorly located. This may be particularly true in MWMUs 2 and 6, both rated as moderate hazard potential partly in recognition of possible misidentification. Field reconnaissance is warranted for landforms qualifying as MWMU5 when forest practices are proposed in steep, dissected ground.

The overall hazard rating of MWMU5 is high.

MWMU6: Cliff-Dominated Steep Slopes, Rockport to Marblemount (≥ 85 slopes)

MWMU6 is mapped on cliffs and steep footslopes along the north side of Highway 20 between Rockport and Marblemount. Few inventoried slides originated within this unit on non-federal project lands (elevation ~280 to 1,600 ft), but debris flows periodically move down from alpine and forested slopes to the north and west. A few shallow rapid and questionable deep-seated slides are also present. Paradoxically, steepness seems to limit landslide frequency (Fig. 7), presumably because thick soils are unable to accumulate on these surfaces. Most of the small number of recorded slides failed on slopes steeper than 85%.

However, the possibility of instability on these slopes cannot be discounted. Rockfalls and rockslides (some large) have occurred in valley walls upstream. Locally, many small stream channels crossing the bluffs and cliffs have been mapped as inner gorges of MWMU5, rated as high hazard. Moreover, most of MWMU6 lies directly uphill of Highway 20 and the Skagit River. Large alluvial fans have formed where the creeks issue out onto the floodplain (Tabor and others, 2002, 2003; Fig. 1) and likely result from repeated large debris flows. The fan deposits are commonly compact, non-layered, and consist mainly of angular rock. Note that removal of timber from these fans could increase the propensity for future debris flows to spread laterally and cause greater damage; for this reason the fans are considered landforms of concern. MWMU6 is thought to be sensitive to forest land uses, although insufficient features are present to quantify that concern. The delivery potential of mass wasting occurring in MWMU6 is rated moderate because a large proportion of the landslides originating on cliffs and ledges do not deliver. As noted above, the frequency of mass wasting is low; the vulnerability factor is 214.

Despite the small number of recorded slide features, the overall hazard potential for MWMU6 is rated as moderate, in recognition of its location above a major highway corridor, and fans and terraces along the Skagit River occupied by scattered homes and other buildings. It should be noted that the few landslides that occur could be catastrophic, owing to the steep slopes of the unit. In particular, proposed forest practices near ravines should be examined for characteristics of the high-hazard MWMU5.

MWMU7: Lower Hazard Areas

This unit encompasses ridge tops, mountain slopes, and valley floors having gentle to moderate gradients; it also includes steeper ground where delivery to public resources is unlikely, and/or a higher hazard cannot be defended owing to a paucity of landslides. These are mainly areas of bedrock underlying a thin veneer of relatively stable glacial till, but other rocks and sediments are present locally. Slopes mostly range from 0 to 50% with minor inclusions of steeper terrain where sediment delivery from mass wasting is limited. Elevation in MWMU7 ranges from ~180 to 4,000 ft. Small shallow rapid slides account for most of the inventoried features; about 80% failed at >65%. MWMU7 has low mass wasting potential and low deliverability; a vulnerability factor of 10 has been calculated.

MWMU7 is rated as having a low overall hazard rating.

6.0 Summary of Critical Questions

In order to address the critical questions posed by the *Standard Methods for Conducting Watershed Analysis*, the following summaries are included:

What evidence is present for mass wasting or mass wasting potential in the watershed?

During this review of the Jackman Creek and Corkindale WAUs, 295 landslides were identified over a 38-yr photo history; five large deep-seated slides mapped by Tabor and others (2003) were also remapped and included (Maps A-1 and A-2, Form A-1), for a total of 300 features. Mass wasting map units were defined based on the location of identified landslides, or similarities in slope form, class, and geology to terrain where slides were identified. Within these WAUs are areas identified as having both high mass wasting potential and high delivery potential. Four of the seven MWMUs, covering 34.5% of the study area, have high overall hazard ratings; two with moderate ratings cover ~15%. The basin-averaged mass wasting potential of the Jackman–Corkindale WAUs is high compared to other watersheds in steep topographic regions of the Cascades and Olympics (e.g., Paulson, 1997; Parks, 2000; Wegmann, 2004).

What mass wasting processes are active?

Shallow rapid slides, debris flows, debris avalanches, rotational and translational deep-seated landslides, and snow avalanches are active mass wasting processes in the Jackman–Corkindale WAUs (Form A-1).

How are mass wasting features distributed throughout the landscape?

See Map A-1. A preponderance of the landslides inventoried in this assessment are located in MWMUs 1, 3, 4 and 5, within unstable landforms as defined in WAC 222-16-050.

Do landslides deliver sediment to stream channels or other waters, or threaten public works or safety?

Yes. At least 71% of landslides observed in the Jackman–Corkindale WAUs probably or definitely delivered sediment to stream channels or other waters (Form A-1). Landslides starting in bedrock hollows, inner gorges, and on steep slopes in the southern parts of both WAUs pose a potential safety hazards to life, private property, and Highway 20 from Concrete to the northeast edge of the Corkindale basin.

How do forest management activities create or contribute to instability?

Of the observed mass wasting features in the Jackman–Corkindale WAUs, at least 85% are associated with forestry-related land uses. Clearcut timber harvest, road building and maintenance, and yarding on relict landslides and in steep inner gorges of Jackman Creek all contribute markedly to slope instability.

What areas of the landscape are susceptible to slope instability?

Relict landslides, steep inner gorges, convergent headwalls, and bedrock hollows of Jackman Creek are susceptible to shallow rapid and debris flow processes. Less prone to failure, but of considerable concern owing to the high potential for delivery to public and private resources, are inner gorges, bedrock hollows, and steep slopes above Highway 20 and the Skagit River, from Rockport State Park east to the edge of the study area near Marblemount. Similarly, the large glacial terrace extending from the southwest edge of the study area east to the vicinity of Van Horn has potential for shallow rapid and deep-seated failures, owing to groundwater recharge of deep-seated landslides in glacial materials, originating at the interface of outwash sands and lacustrine or till deposits within the terrace (Maps A-1 and A-2).

7.0 Confidence in Work Products

The confidence in this mass wasting assessment is moderate, due mainly to time considerations. The Landslide Hazard Zonation Project is designed to provide a statewide overview of slides as quickly as possible, rather than a detailed assessment of each watershed. As a consequence, field work and the number of aerial photograph sets examined were held to reasonable minimums. A decision was made to limit this assessment to only two large-scale air-photo sets and 300 newly identified/mapped features.

It is critical for the reader to understand that while these procedures are sufficient to characterize aspects of slope instability as related to forest management, this assessment would be entirely insufficient and misleading if used alone to protect private and public resources and/or to assist in land-use planning.

In addition, several sources of systematic error reduce the confidence in the work products of this analysis, including omission, misinterpretation, inaccuracy, and imprecision. Omission occurs when mass wasting features are not identified on aerial photographs or in the field due to canopy cover, gaps in the air-photo record, quality of air-photos, or interpreter errors. Misinterpretation occurs when a feature is identified but incorrectly classified, data are transposed, or 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 well variability can be controlled when making multiple measurements over varying time and spatial scales (Parks, 2000); both can be sources of error.

This assessment was conducted chiefly using remotely sensed data (interpretation of aerial photographs). As a result, there is a high likelihood that errors of omission occurred primarily in areas covered by mature forest canopies at any given time. The scarcity of mass wasting features identified under heavy canopy is not necessarily an indication of the relative stability of slopes with mature vegetation.

Misinterpretation or incorrect identification/classification of features are also possible sources of error. Such errors are considered minimal for shallow rapid slides, debris flows, and debris avalanches; but considerable with respect to deep-seated slide processes. Because many deep-seated landslides are quite large, remain heavily vegetated during movement, and may not have obvious scars visible through the vegetation canopy, misinterpretation of these features is more likely. A recent study in Cowlitz County, Washington, suggests that up to 25% of inferred deep-seated landslides identified from air-photo analysis are misinterpreted (Wegmann and Walsh, 2001; Wegmann, 2003). Therefore, confidence in products related to the classification of landslide process is low to moderate.

Another important source of potential error in this assessment is inaccuracy and imprecision of measurements of mass wasting features. Because very few landslides were actually visited in the field, and none of those visited were surveyed using precise techniques, it is not possible to report the degree to which location and measurement error in the GIS environment compares to on-the-ground field observations. Similarly, measurements of slope angle from digital elevation models typically underrepresent true hillslope gradients. Given these sources of error, confidence in the precise location and accuracy of measurements of individual landslides is considered moderate.

8.0 Acknowledgements

This report was written using a format developed by Dave Parks (2000) and modified by Karl Wegmann (2004). Leslie Lingley of the Quinault Indian Nation cross-checked the data sheets. Lorraine Powell, Laura Vaugeois, Karl Wegmann, and Leslie Lingley spot-checked many of the mass-wasting features identified during this assessment. Karl Wegmann and Laura Vaugeois assisted with many problems relating to ArcGIS, and edited an earlier version of this text. Tom Boyd was especially helpful in developing the mass wasting layers and performing statistical landslide analysis using ESRI Spatial Analyst software. Matt Brunengo performed final formatting, editing, and post-review revisions in 2007.

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10.0 Appendix A – A-1 Form: Landslide Inventory

Form A-1 Mass Wasting Inventory Data for the Jackman Creek and Corkindale WAUs

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1001	4	Q	1965	5	2001	5	7	2	54	Y	4	WFPA65_39_37	1	25.56
1002	1	P	2001	3			8	1	45	P	2	NWC01_35_72_175	1	0.28
1003	2	Q	2001	4		5	8	1	64	N	3	NWC01_35_72_175	1	0.48
1004	2	Q	2001	3			8	1	69	N	3	NWC01_35_72_175	1	0.32
1005	1	P	2001	3			8	2	72	N	1	NWC01_35_72_175	1	0.13
1006	2	Q	1978	3			1	1	82	Y	1	NW78_88C_42	1	0.22
1007	4	Q	1965	5	2001	5	4	4	69	N	4	WFPA65_39_37	1	55.44
1008	1	D	1965	3	2001	4	9	3	81	Y	4	WFPA65_39_37	1	0.28
1009	1	D	1965	3	2001	4	9	3	87	Y	3	WFPA65_39_37	1	0.24
1010	1	D	1965	3	2001	4	9	3	71	Y	3	WFPA65_39_37	1	0.31
1011	6	D	1965	5	2001	5	4	2	50	Y	4	WFPA65_39_37	1	51.66
1012	6	D	2001	5			8	1	51	P	5	NWC01_35_72_175	1	2.06
1013	1	P	1965	5	1998	5	5	3	150	I	4	WFPA65_39_38	1	2.25
1014	4	Q	2001	5			7	2	65	N	2	NWC01_35_72_175	2	11.61
1015	1	D	2001	3			2	1	30	N	2	NWC01_35_72_175	1	0.26
1016	2	Q	2001	2			1	1	41	P	5	NWC01_35_72_175	1	0.10
1017	2	Q	2001	3			1	1	54	P	5	NWC01_35_72_175	1	0.15
1018	4	Q	2001	5			5	1	67	Y	5	NWC01_35_72_175	4	2.17
1019	5	Q	1978	5	2001	5	7	3	134	P	1	NW78_86F_8	4	12.13
1020	5	Q	1978	5	2001	5	2	1	119	P	3	NW78_86F_8	4	7.27
1021	4	Q	1965	5	2001	5	5	1	118	Y	5	WFPA65_39_37	4	9.92
1022	2	D	2001	5			1	1	103	Y	3	NWC01_35_74_50	3	2.18
1023	5	Q	1978	5	2001	5	5	4	114	Y	3	NW78_86F_8	4	5.92
1024	5	P	1978	5	2001	5	8	2	149	Y	3	NW78_86F_8	4	4.44
1025	5	Q	2001	5			2	1	126	Y	2	NWC01_35_74_50	3	1.33
1026	5	P	1965	5	2001	5	5	1	116	Y	5	WFPA65_39_37	4	7.52
1027	4	Q	2001	5			8	1	118	Y	3	NWC01_35_74_50	3	2.48
1028	2	Q	2001	5			2	1	129	Y	5	NWC01_35_74_50	4	2.22
1029	5	P	2001	5			5	2	141	Y	5	NWC01_35_74_50	4	5.21
1030	5	Q	2001	4			5	1	101	Y	3	NWC01_35_74_50	4	1.99
1031	4	Q	2001	5			8	2	105	Y	3	NWC01_35_74_50	3	11.77
1032	2	D	1978	5	2001	5	8	1	102	Y	3	NW78_87D_42	4	1.80
1033	6	Q	1965	5	2001	5	6	3	103	Y	7	WFPA65_39_38	4	34.03
1034	3	P	1978	5	2001	5	8	2	98	Y	3	NW78_87D_43	4	3.73
1035	2	P	2001	5			1	1	127	Y	3	NW78_87D_43	4	5.01
1036	1	P	1978	3	2001	4	6	3	89	Y	3	NW78_87D_43	4	0.31
1037	1	D	1978	4	2001	5	6	3	126	Y	5	NW78_87D_43	4	0.77
1038	5	P	1978	4	2001	5	5	1	135	P	2	NW78_87D_43	4	1.02
1039	1	P	2001	3			2	1	88	Y	7	NWC01_35_74_50	7	0.30
1040	1	P	2001	3			2	1	111	Y	7	NWC01_35_74_50	7	0.25
1041	2	P	1978	5	2001	5	1	1	111	Y	1	NW78_87D_43	5	3.27
1042	1	D	2001	3			9	1	113	Y	2	NWC01_40_75_208	4	0.13

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1043	1	D	2001	3			9	1	72	Y	3	NWC01_40_75_208	3	0.15
1044	1	P	2001	3			7	3	111	N	5	NWC01_40_75_208	5	0.12
1045	4	Q	2001	5			1	2	85	Y	2	NWC01_40_75_208	3	11.73
1046	1	D	2001	3			9	2	95	Y	2	NWC01_40_75_208	3	0.29
1047	1	D	2001	3			9	2	63	Y	2	NWC01_40_75_208	3	0.40
1048	1	Q	2001	3			3	2	54	Y	8	NWC01_40_75_208	5	0.10
1049	2	P	2001	4			1	1	103	Y	2	NWC01_40_75_208	4	0.64
1050	1	P	2001	4			9	2	64	Y	2	NWC01_40_75_208	3	1.01
1051	9	P	2001	5			3	1	82	P	8	NWC01_40_75_208	5	1.55
1052	1	P	2001	4			3	1	49	Y	8	NWC01_40_75_208	5	0.53
1053	2	D	2001	5			1	1	87	Y	2	NWC01_40_75_208	4	1.33
1054	2	P	2001	4			1	1	61	Y	2	NWC01_40_75_208	4	0.44
1055	2	D	2001	3			1	1	89	Y	2	NWC01_40_75_208	4	0.27
1056	1	P	2001	2			2	1	92	I	2	NWC01_40_75_209	3	0.09
1057	1	D	2001	5			1	1	79	Y	2	NWC01_40_75_209	3	1.30
1058	2	D	2001	3			1	1	86	I	2	NWC01_40_75_209	3	0.19
1059	5	P	2001	5			8	2	82	Y	2	NWC01_40_75_209	3	3.66
1060	1	D	2001	4			1	1	66	P	2	NWC01_40_75_209	3	0.72
1061	5	D	2001	5			1	1	109	Y	2	NWC01_40_75_209	3	14.33
1062	1	D	2001	4			9	4	51	Y	2	NWC01_40_75_209	3	0.69
1063	1	D	2001	4			9	2	81	Y	3	NWC01_40_75_209	3	0.42
1064	1	Q	2001	2			1	1	94	I	3	NWC01_40_76_277	3	0.09
1065	1	P	2001	4			8	1	72	N	1	NWC01_40_75_209	3	0.51
1066	1	P	2001	3			2	2	90	Y	2	NWC01_40_76_277	4	0.29
1067	2	P	2001	5			1	1	81	Y	2	NWC01_40_76_277	4	1.21
1068	2	Q	2001	2			1	1	97	Y	5	NWC01_40_76_277	3	0.09
1069	2	Q	2001	3			1	1	67	P	5	NWC01_40_76_277	3	0.24
1070	1	P	2001	4			7	2	69	N	5	NWC01_40_76_277	3	0.47
1071	2	Q	2001	3			1	1	67	P	5	NWC01_40_76_277	3	0.29
1072	2	Q	2001	5			1	1	68	Y	5	NWC01_40_76_277	3	1.29
1073	1	D	2001	2			6	2	104	N	8	NWC01_40_76_277	5	0.08
1074	2	P	2001	5			1	1	79	Y	1	NWC01_40_76_279	4	3.01
1075	2	P	1965	5	2001	5	1	1	85	Y	1	WFPA65_39_38	3	1.72
1076	1	D	1965	5	2001	5	8	2	80	I	1	WFPA65_39_38	3	1.97
1077	1	D	1965	5	2001	5	8	2	93	N	2	WFPA65_39_38	3	4.08
1078	2	Q	2001	3			2	1	111	N	8	NWC01_40_76_280	5	0.27
1079	2	P	2001	2			2	1	76	Y	5	NWC01_40_76_280	3	0.08
1080	1	P	2001	4			2	2	96	Y	8	NWC01_40_76_280	3	0.58
1081	2	Q	2001	4			8	2	81	Y	1	NWC01_35_71_238	2	0.93
1082	5	Q	2001	5			5	2	84	N	4	NWC01_35_73_111	2	1.90
1083	1	P	2001	2			5	2	14	N	1	NWC01_35_73_111	5	0.05
1084	1	P	2001	2			5	2	39	N	1	NWC01_35_73_111	2	0.03
1085	5	Q	2001	5			5	2	73	N	4	NWC01_35_73_112	2	3.94
1086	1	P	2001	4			7	5	88	N	5	NWC01_35_73_112	7	0.98
1087	1	P	2001	3			7	2	66	N	5	NWC01_35_73_112	7	0.41

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1088	1	P	2001	3			7	2	37	N	5	NWC01_35_73_112	7	0.25
1089	1	Q	2001	2			1	1	55	N	7	NWC01_35_74_48	7	0.10
1090	1	Q	2001	2			1	1	50	N	7	NWC01_35_74_48	7	0.05
1091	1	P	2001	4			8	2	87	N	5	NWC01_35_74_48	7	0.48
1092	5	Q	1998	5			8	2	103	N	4	NWC01_35_74_48	5	0.00
1093	1	P	2001	3			8	2	101	N	1	NWC01_35_74_48	7	0.17
1094	1	P	2001	3			8	2	113	N	1	NWC01_35_74_48	7	0.26
1095	1	P	2001	2			8	2	103	N	1	NWC01_35_74_48	7	0.05
1096	1	D	1965	5	1998	5	2	1	130	I	4	WFPA65_39_38	7	1.41
1097	1	Q	1965	3	1998	5	5	2	86	N	4	WFPA65_39_38	7	0.32
1098	1	P	1965	2			5	3	54	N	2	WFPA65_39_37	2	0.06
1099	2	P	1965	3			1	1	81	Y	5	WFPA65_39_37	5	0.18
1100	1	P	1965	2			5	2	32	I	2	WFPA65_39_37	2	0.05
1101	2	D	1965	5			8	1	133	Y	5	WFPA65_39_37	5	4.04
1102	2	D	1965	4			1	1	88	Y	2	WFPA65_39_37	5	0.43
1103	1	P	1965	4			8	2	71	I	1	WFPA65_39_37	7	0.45
1104	2	P	1965	5			8	1	107	Y	1	WFPA65_39_37	5	1.98
1105	2	P	1965	5			8	1	109	Y	1	WFPA65_39_37	3	1.23
1106	1	P	1965	5	2001	5	8	2	54	I	1	WFPA65_39_37	3	1.08
1107	1	P	1965	4	2001	5	8	2	106	P	1	WFPA65_39_37	3	0.70
1108	1	Q	1965	3	2001	4	8	1	83	Y	1	WFPA65_39_37	3	0.21
1109	1	Q	1965	3	2001	4	8	1	64	Y	1	WFPA65_39_37	3	0.16
1110	2	D	1965	4	2001	5	8	1	121	P	5	WFPA65_39_37	3	0.92
1111	1	D	1965	5	2001	5	8	2	82	P	5	WFPA65_39_37	3	1.12
1112	4	P	1978	4	2001	5	8	2	79	P	2	NW_78_86F_10	3	1.01
1113	2	P	1965	4	2001	5	8	1	84	Y	1	WFPA65_39_37	3	0.82
1114	2	D	1965	4	2001	5	8	1	112	Y	1	WFPA65_39_37	3	0.73
1115	1	P	1965	4	2001	5	8	2	54	Y	1	WFPA65_39_37	3	0.94
1116	1	P	1965	3	2001	4	8	1	70	Y	1	WFPA65_39_37	3	0.20
1117	1	Q	1965	3	2001	4	8	1	59	Y	1	WFPA65_39_37	3	0.12
1118	1	D	1965	5	2001	5	8	1	80	Y	1	WFPA65_39_37	3	1.82
1119	2	D	1965	3	2001	4	8	1	125	Y	1	WFPA65_39_37	3	0.19
1120	2	D	1965	3	2001	5	8	1	79	Y	1	WFPA65_39_37	4	0.60
1121	2	D	1965	4	2001	5	8	1	69	Y	1	WFPA65_39_37	7	0.43
1122	2	P	1965	3	2001	4	8	1	80	I	1	WFPA65_39_37	3	0.11
1123	1	D	1965	3	2001	4	8	1	62	Y	1	WFPA65_39_37	3	0.19
1124	2	D	1965	3	2001	4	8	1	78	Y	5	WFPA65_39_37	3	0.41
1125	2	D	1965	5	2001	5	8	1	82	Y	5	WFPA65_39_37	3	1.05
1126	2	D	1965	4	2001	5	8	1	99	Y	5	WFPA65_39_37	3	1.00
1127	1	D	1965	3	2001	4	8	1	86	Y	2	WFPA65_39_37	7	0.29
1128	1	P	1965	3	2001	4	8	2	62	Y	2	WFPA65_39_37	7	0.21
1129	1	P	1965	3	2001	4	8	2	60	Y	2	WFPA65_39_37	7	0.11
1130	2	D	1965	4	2001	5	1	1	66	Y	2	WFPA65_39_37	7	0.65
1131	2	D	1965	5	2001	5	1	1	63	Y	2	WFPA65_39_37	7	1.60
1132	2	D	1965	5	2001	5	2	1	87	Y	2	WFPA65_39_37	7	1.41

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1133	1	D	1965	5	2001	5	1	1	84	Y	2	WFPA65_39_37	7	2.04
1134	2	D	1965	5	2001	5	1	1	89	Y	2	WFPA65_39_37	3	2.02
1135	2	Q	1965	5	2001	5	1	1	96	Y	2	WFPA65_39_37	3	3.07
1136	2	Q	1965	4	2001	5	2	1	108	Y	2	WFPA65_39_37	3	0.96
1137	2	D	1965	5	2001	5	8	1	81	Y	2	WFPA65_39_37	3	3.38
1138	2	D	1965	3	2001	4	8	1	95	Y	2	WFPA65_39_37	3	0.37
1139	2	D	1965	5	2001	5	1	1	100	Y	3	WFPA65_39_37	7	3.57
1140	1	D	1965	4	2001	4	1	1	104	Y	8	WFPA65_39_37	7	0.60
1141	1	D	1978	3			2	2	62	Y	5	NW78_87D_43	4	0.25
1142	1	D	1978	4			2	2	99	Y	5	NW78_87D_43	4	0.96
1143	4	P	1965	5	2001	5	6	2	118	Y	4	WFPA65_39_38	7	51.18
1144	1	P	1965	3			8	1	67	P	4	WFPA65_39_39	3	0.32
1145	1	D	2001	4			2	1	64	N	8	NWC01_40_76_277	5	0.62
1146	1	D	1965	5	2001	5	8	1	89	Y	3	WFPA65_39_38	3	1.37
1147	1	D	1965	5			8	2	103	P	4	WFPA65_39_38	3	6.02
1148	1	Q	1978	3	2001	4	8	2	81	Y	1	NW78_87D_41	5	0.18
1149	4	P	1965	5			5	2	132	Y	8	WFPA65_39_37	7	431.08
1150	1	D	1965	5			8	1	93	Y	1	WFPA65_39_37	3	2.94
1151	2	Q	1965	3			8	1	118	Y	1	WFPA65_39_37	3	0.24
1152	4	Q	1965	5			2	2	103	I	2	WFPA65_39_37	7	2.92
1153	2	P	1965	3			1	1	60	Y	2	WFPA65_39_37	7	0.34
1154	2	P	1965	3			1	1	72	Y	5	NW78_87D_41	7	0.36
1155	1	P	1965	4	1998	4	5	2	118	I	4	WFPA65_39_38	7	0.72
1156	4	Q	1965	5			8	2	87	Y	4	WFPA65_39_37	7	157.62
1157	4	Q	1965	5			7	2	112	Y	4	WFPA65_39_38	7	656.77
1158	1	P	1965	2			8	1	74	Y	4	WFPA65_39_38	3	0.11
1159	1	D	1978	2			8	5	78	P	5	NW78_89D_45	3	0.04
1160	1	P	2001	5			7	3	86	I	2	NWC01_35_72_175	4	1.29
1161	1	P	2001	4			7	2	104	P	2	NWC01_35_72_175	4	0.42
1162	1	P	2001	4			7	3	83	P	2	NWC01_35_72_175	4	0.92
1163	1	P	2001	3			7	2	74	I	2	NWC01_35_72_175	4	0.16
1164	1	Q	2001	4			2	2	78	Y	2	NWC01_35_72_175	4	0.95
1165	4	Q	2001	5			7	2	90	Y	4	NWC01_35_72_175	7	47.40
1166	1	P	2001	2			1	1	96	Y	1	NWC01_35_72_175	4	0.10
1167	1	Q	2001	3			2	1	114	Y	3	NWC01_51_80_177	5	0.23
1168	1	Q	2001	3			2	1	125	Y	3	NWC01_51_80_177	5	0.14
1169	4	Q	2001	5			7	3	91	Y	3	NWC01_51_80_177	5	11.70
1170	4	Q	1965	5			7	2	118	Y	4	WFPA65_39_38	7	809.20
1171	2	D	2001	4			1	1	65	Y	3	NWC01_35_73_114	3	0.68
1172	1	P	2001	3			2	2	111	N	1	NWC01_41_78_110	3	0.21
1173	2	P	2001	4			1	1	110	Y	2	NWC01_40_77_47	5	0.93
1174	2	D	2001	4			6	1	226	Y	3	NWC01_40_77_47	5	0.69
1175	1	D	2001	3			6	1	302	Y	3	NWC01_40_77_47	5	0.30
1176	1	D	2001	3			6	1	181	P	2	NWC01_40_77_47	5	0.36
1177	1	D	2001	5			6	1	224	Y	2	NWC01_40_77_47	5	7.07

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1178	1	P	2001	3			6	2	227	Y	2	NWC01_40_77_47	5	0.38
1179	1	D	2001	2			2	2	100	Y	3	NWC01_41_78_109	7	0.06
1180	1	P	2001	3			2	2	161	Y	3	NWC01_41_78_109	6	0.14
1181	1	P	2001	5			6	1	179	Y	1	NWC01_41_78_109	5	1.52
1182	1	D	2001	5			2	1	103	Y	1	NWC01_41_78_109	5	1.07
1183	2	D	2001	3			1	1	64	Y	3	NWC01_41_78_109	6	0.31
1184	2	P	2001	3			5	1	126	Y	3	NWC01_51_79_113	5	0.27
1185	2	P	2001	4			5	1	116	Y	3	NWC01_51_79_113	5	0.87
1186	2	P	2001	4			5	1	140	Y	3	NWC01_51_79_113	5	0.89
1187	2	P	2001	3			5	1	104	Y	3	NWC01_51_79_113	5	0.23
1188	5	Q	2001	5			5	1	131	Y	3	NWC01_47_81_7	6	2.26
1189	4	Q	2001	5			9	2	195	Y	4	NWC01_47_81_8	6	15.95
1190	1	P	2001	3			2	2	91	Y	3	NWC01_47_81_10	6	0.19
1191	2	P	2001	5			1	1	169	Y	3	NWC01_47_81_10	5	2.55
1192	1	D	2001	5			6	2	126	P	1	NWC01_51_80_180	6	6.42
1193	2	D	2001	5			8	2	97	I	2	NWC01_40_75_210	3	1.08
1194	1	D	1998	5			8	2	123	Y	2	NWH_98	3	3.43
1195	1	Q	1998	2			8	1	63	P	2	NWH_98	3	0.09
1196	1	D	1998	2			2	2	67	I	3	NWH_98	4	0.09
1197	1	D	1998	3			5	2	116	I	8	NWH_98	4	0.20
1198	1	D	1998	3			5	2	104	I	8	NWH_98	4	0.16
1199	1	D	1998	4			9	3	50	Y	2	NWH_98	3	0.44
1200	6	P	1978	5	2001	5	8	1	134	Y	5	NW78_87D_41	3	5.42
1201	7	D	1978	5	2001	5	8	1	115	Y	5	NW78_86F_8	3	4.27
1202	2	P	1978	3			8	1	70	P	2	NW78_86F_8	3	0.20
1203	7	D	1978	5			8	1	84	Y	5	NW78_86F_8	3	7.51
1204	4	Q	1965	5	2001	5	7	2	131	Y	4	WFPA65_39_37	4	137.45
1205	2	Q	1978	4			8	1	105	P	2	NW78_86F_8	4	0.59
1206	1	D	1978	4	2001	5	7	3	56	N	5	NW78_86F_8	4	0.57
1207	6	Q	1978	5	2001	5	5	2	105	Y	2	NW78_86F_9	4	3.99
1208	2	D	1978	2			8	1	98	Y	1	NW78_86F_9	5	0.03
1209	2	D	1978	2			8	1	99	Y	1	NW78_86F_9	5	0.09
1210	1	Q	1978	2			7	3	36	N	5	NW78_85B_43	3	0.20
1211	1	Q	1978	3			7	3	34	N	5	NW78_85B_43	3	0.22
1212	1	Q	1965	5	1978	5	2	2	67	Y	1	WFPA65_39_37	3	1.78
1213	1	P	2001	3			2	1	96	Y	2	NWC01_40_75_208	5	0.13
1214	1	D	2001	5			2	1	113	P	3	NWC01_35_74_52	3	1.89
1215	1	D	2001	4			2	1	142	I	3	NWC01_35_74_52	3	0.54
1216	4	Q	2001	5			7	2	81	Y	1	NWC01_35_74_52	4	16.81
1217	1	Q	2001	4			2	1	87	P	2	NWC01_35_74_52	4	0.73
1218	1	Q	2001	2			2	1	101	Y	7	NWC01_35_74_49	7	0.06
1219	4	Q	2001	5			7	4	81	Y	4	NWC01_40_76_279	3	4.25
1220	1	Q	2001	5			6	3	80	N	8	NWC01_40_76_277	5	0.13
1221	2	P	1965	3			8	1	84	Y	2	WFPA65_39_39	3	3.90
1222	4	Q	1996	5			2	2	75	Y	2	NWH_98	3	3.16

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1223	2	Q	1996	3			1	1	85	Y	2	NWH_98	3	0.26
1224	1	Q	1996	3			1	2	66	Y	2	NWH_98	7	0.27
1225	2	Q	1965	5			6	1	156	Y	2	WFPA65_40A_38	5	13.66
1226	4	Q	1978	5			7	4	112	Y	4	NWH_98	7	301.53
1227	4	Q	1978	5			2	2	106	Y	4	NWH_98	6	39.81
1228	1	Q	1978	4			7	2	119	N	3	NWH_98	7	0.84
1229	2	Q	1978	5			1	1	117	Y	3	NWH_98	5	4.27
1230	1	P	1978	3			2	1	89	Y	1	NW78_89D_45	4	0.15
1231	2	D	1978	3			1	1	98	Y	1	NW78_89D_45	4	0.32
1232	1	Q	1978	2			2	1	67	N	1	NW78_89D_45	4	0.06
1233	2	Q	1978	2			2	1	58	N	1	NW78_89D_45	4	0.06
1234	2	D	1978	3			1	1	57	N	1	NW78_89D_45	4	0.24
1235	2	P	1978	3			1	1	60	N	5	NW78_89D_45	4	0.16
1236	1	P	1978	4			7	2	63	N	5	NW78_89D_45	4	0.00
1237	1	P	1978	3			7	3	64	N	5	NW78_89D_45	4	0.12
1238	1	D	1978	3			2	1	50	Y	1	NW78_89D_45	4	0.12
1239	1	P	1978	2			8	2	55	I	1	NW78_89D_45	3	0.07
1240	1	P	1978	2			2	2	53	N	1	NW78_89D_45	3	0.05
1241	1	Q	1978	4			2	1	36	Y	1	NW78_89D_45	3	0.45
1242	1	Q	1978	3			1	1	69	Y	1	NW78_89D_45	3	0.15
1243	1	D	1978	3			2	2	67	N	1	NW78_89D_45	4	0.15
1244	4	Q	1978	5			9	2	40	Y	4	NW78_89D_46	4	27.80
1245	2	D	1978	2			1	1	45	I	5	NW78_89D_46	4	0.06
1246	1	Q	1978	5			8	1	62	P	5	NW78_89D_46	3	0.00
1247	1	Q	1978	2			2	2	58	N	1	NW78_89D_46	4	0.09
1248	1	Q	1978	2			2	2	64	N	1	NW78_89D_46	4	0.08
1249	1	Q	1978	1			2	3	58	N	1	NW78_89D_46	4	0.02
1250	1	P	1978	2			7	3	70	N	5	NW78_89D_46	3	0.08
1251	4	Q	1978	5			9	2	97	Y	4	NW78_89D_46	4	72.04
1252	2	D	1978	4			8	1	36	Y	1	NW78_89D_46	3	0.60
1253	1	Q	1978	4			4	2	118	Y	5	NW78_90D_35	6	0.80
1254	1	P	1978	4			4	3	127	Y	5	NW78_90D_35	6	0.61
1255	1	P	1978	4			4	3	135	Y	5	NW78_90D_35	6	0.68
1256	4	Q	1978	5			6	2	280	I	4	NW78_90D_35	6	120.06
1257	4	D	1965	5			8	4	101	Y	8	NW78_90D_45	7	174.21
1258	3	D	1978	5			2	1	94	P	1	NW78_90D_45	3	4.30
1259	1	P	1978	2			7	3	57	N	5	NW78_90D_45	3	0.06
1260	2	D	1978	3			2	1	68	I	1	NW78_90D_45	3	0.18
1261	1	P	1978	2			7	2	60	I	1	NW78_90D_45	3	0.05
1262	2	D	1978	3			2	1	43	I	1	NW78_90D_45	3	0.23
1263	3	D	1978	5			2	1	79	Y	5	NW78_90D_45	3	2.05
1264	1	P	1978	2			2	2	29	N	1	NW78_90D_45	3	0.06
1265	1	P	1978	2			2	2	71	Y	1	NW78_90D_45	3	0.07
1266	2	P	1978	3			1	1	71	Y	1	NW78_90D_45	3	0.19
1267	2	D	1978	3			1	1	104	Y	1	NW78_90D_45	4	0.29

Slide_id	Lsi_process	Certainty	Id_date	Ls_size	Id2_date	Id2_size	Landform	Slp_shp	Gradient	Delivery	Landuse	Photo_number	MWMU	Acreage
1268	3	D	1978	2			2	1	20	Y	1	NW78_90D_45	3	0.08
1269	4	Q	1978	5			1	2	101	Y	2	NW78_87D_39	5	1.21
1270	1	P	1978	2			1	2	137	Y	2	NW78_87D_39	5	0.05
1271	1	Q	1978	3			1	1	101	Y	2	NW78_87D_39	5	0.17
1272	1	Q	1978	4			1	2	118	Y	2	NW78_87D_39	5	0.94
1273	1	Q	1978	2			2	2	111	I	2	NW78_87D_39	5	0.08
1274	1	Q	1978	2			8	1	80	Y	1	NW78_87D_41	5	0.03
1275	1	Q	1978	2			8	1	80	I	2	NW78_87D_41	5	0.19
1276	1	Q	1978	2			8	1	132	Y	2	NW78_87D_41	5	0.04
1277	1	Q	1978	4			8	1	91	Y	1	NW78_87D_41	7	0.56
1278	1	Q	1978	1			8	3	57	N	1	NW78_87D_41	7	0.02
1279	2	Q	1978	3			2	1	69	I	1	NW78_87D_41	7	0.12
1280	5	Q	1978	2			2	2	21	Y	2	NW78_83E_40	7	0.06
1281	5	Q	1978	5			2	2	107	I	3	NW78_91F_1	5	1.78
1282	1	Q	1978	3			6	2	70	N	3	NW78_95C_12	6	0.28
1283	4	Q	1965	5			5	2	128	P	8	NW78_90D_46	6	63.32
1284	4	Q	1965	5			5	2	98	Y	8	NW78_90D_46	7	235.80
1285	4	Q	1978	5			8	2	62	Y	1	NW78_90D_45	3	10.93
1286	1	Q	1998	3			7	2	61	N	5	NWH_98	4	0.26
1287	1	Q	1998	3			2	1	87	I	2	NWH_98	4	0.18
1288	1	P	1998	4			5	3	93	I	8	NWH_98	3	0.87
1289	1	D	1998	2			2	2	62	I	1	NWH_98	4	0.06
1290	1	P	1998	3			8	2	45	P	2	NWH_98	3	0.28
1291	2	P	1998	2			7	1	77	P	5	NWH_98	7	0.05
1292	1	Q	1998	2			8	2	83	N	2	NWH_98	3	0.05
1293	1	D	1998	3			9	3	39	Y	3	NWH_98	1	0.31
1294	1	D	1998	3			7	2	51	N	8	NWH_98	7	0.34
1295	2	Q	1998	3			1	1	98	Y	1	NWH_98	3	0.18
1296	2	Q	1998	3			1	1	80	Y	1	NWH_98	5	0.13
1297	2	P	1998	2			1	1	79	Y	1	NWH_98	3	0.04
1298	1	P	1998	2			2	1	81	Y	3	NWH_98	5	0.09
1299	9	D	1998	5			8	2	104	I	8	NWH_98	3	14.46
1300	5	P	1978	5			8	1	132	Y	1	NW78_86F_9	3	3.30

11.0 Appendix B – Form A-2: Mass Wasting Map Unit Descriptions

Notes: In the following descriptions, most information on MWMU areas, elevations, and slope gradients were generated in GIS from digital elevation data. Total area, minimum, maximum, mean, and standard deviation (s.d.) statistics were calculated by ArcGIS tools from 10-m DEMs. Those data labeled "typical" are semi-quantitative analysts' estimates, based on examination of available maps and field experience.

Review comments regarding the initial analysis (WSL, 2004) noted that more precise slope limits could aid in the identification of potentially unstable terrain in the field. Based on reexamination (MJB, 2007) of the landslide inventory data, slope thresholds were calculated which can be used as criteria to discriminate problematic areas for special attention. Within each MWMU, the gradients of the inventoried slides (Appendix A, Form A-1) were analyzed to determine the values approximately one standard deviation below the mean, encompassing ~84% of a supposedly normal distribution; to check for abnormal samples, the ~85th percentiles were also determined separately. Analysis was done on gradients expressed as both percent and degrees: the rapid inflation of % values for steeper slopes can cause distortion of the parameters, so degrees produce better statistics. For MWMUs rated high hazard, thresholds were generally rounded down to the nearest 5% (i.e., more conservatively, including somewhat gentler slopes); these levels capture 80 to >95% of the inventoried slides. For MWMUs rated moderate and low hazard, the levels were usually rounded upward to the next 5%.

"Confidence" statements refer to the confidence in the mass-wasting unit as a whole. Generally, confidence in landslide identification and the precision of mapping is generally low to moderate, as the study is designed to provide representative samples rather than exhaustive analysis.

MWMU Number: 1 Deep-Seated Landslides & Contiguous Lands in Glacial Terrace Deposits (≥ 40%) – High Hazard

Description: MWMU1 occupies moderate to steep margins of the glacial terrace along lower Jackman Creek valley. Where Jackman Creek cut through the prominent bench between Concrete and Van Horn, stream incision was accompanied by landsliding (some deep-seated, with probable deep groundwater recharge). MWMU1 occupies ~2% of the Jackman–Corkindale study area.

Materials: Glacial materials line the Skagit Valley wall between Concrete and Rockport: thick deposits of free-flowing to compact gravelly sand (>100 ft thick) locally overlain or interlayered with blue-gray clay and olive till. Most deposited as the continental ice sheet dammed the Skagit Valley, creating a lake, early in the latest major glaciation; uppermost parts of the terrace modified during later glacial phases.

Landform: Slopes descending from a prominent bench (surface nearly flat, elevation ~880 ft) toward Jackman Creek, modified by stream incision and shallow and deep-seated landslides.

Slope (determined via DEM):	Min: 9%	Max: 113%	Typical: 40%
on Failures (DEM & field):	Min: 30%	Max: 150%	Mean: 65%, s.d.= 27%
Elevation:	Min: 280’	Max: 900’	Typical: 600’

Total Area: 357.3 acres.

Total Landslide Area: 140.1 acres.

Total Number of Landslides: 17

Number of Delivering Landslides: 9

MW Processes: Predominantly deep-seated slumps with superimposed debris flows and other shallow rapid landslides, some of which are large. See Forms A-1 and A-3.

Forest Practice Sensitivity: High. The larger slides appear to be influenced by deep recharge; superimposed slides are associated with forestry uses, especially relating to the now-abandoned section of the Jackman Creek Mainline.

Mass Wasting Potential: High. Observed landslide frequency of 17 landslides identified in a 38-yr record (includes relict failures). These slides currently cover much of MWMU1 and several are very active.

Delivery Potential: High. 53% of inventoried slides delivered to Jackman Creek. Although the vulnerability factor is only 37, the possibility of massive movement and delivery indicates a higher potential.

Delivery Criteria Used: Observed delivery during field investigation; active streamside failures in all photo years.

Hazard Potential Rating: High. MWMU1 is mostly composed of high-hazard rule-identified landforms (recharge areas of glacial deep-seated slides) as per WAC 222-16-050.

Trigger Mechanisms: Road building and use, especially as these apply to water management. Clear-cutting on terrace margins reduces effective soil cohesion contributed by tree roots on slopes in convergent channel heads. Ditches appear to contribute water to headscarps, increasing rate of movement and/or causing shallow rapid failures. The superposition of permeable glacial sand over impermeable clay creates textbook glacial-deep-seated recharge hydrology. Management effect on deep-seated failure in this area is supported by the arcuate headscarp of landslide # 1011 near the mouth of Jackman Creek that exactly parallels the now-abandoned Jackman Creek Mainline. Much of the movement on this landslide post-dates management.

Confidence: High. This terrace probably shares a cogenetic relation with terraces in the Stilliguamish River valley that have been sites of some large and active deep-seated failures (Dragovich and others, 2003).

MWMU Number: 2 Dissected Glacial Terrace Deposits (≥ 45%) – Moderate Hazard

Description: MWMU2 comprises slopes around the glacial terrace lining the Skagit Valley wall. From Concrete to Van Horn, these slopes skirt a prominent bench; eastward to Sauk, subsequent erosion has obliterated most of the original form. This unit is geologically and topographically similar to MWMU1, but only two deep-seated landslides were identified. However, many small streams cut across the terrace deposits: several have been mapped as inner gorges, and all should be checked for MWMU5 characteristics when forest practices are proposed in this unit. MWMU2 occupies 8% of the area of the Jackman–Corkindale study area.

Materials: Glacial materials line the Skagit Valley wall between Concrete and Rockport: thick deposits of free-flowing to compact gravelly sand (>100 ft thick) locally overlain or interlayered with blue-gray clay and olive till. Most deposited as the continental ice sheet dammed the Skagit Valley, creating a lake, early in the latest major glaciation; uppermost parts of the terrace modified during later glacial phases. Some bedrock exposures where the sediments have been removed by the Skagit River or slope processes.

Landform: Variation due to original extent of glacial deposits and degree of subsequent removal. NW of Van Horn, a prominent bench (nearly flat, elevation ~880 ft) is preserved on the north wall, except where cut by Jackman Creek, and the few tributary channels have not cut deeply into terrace slopes. East from Van Horn, the Skagit seems to have removed much of the valley fill, and there may never have been a large postglacial bench; deposits were dissected by many streams flowing off Jackman Ridge and Sauk Mountain. The combination of stream incision and landsliding left deeper ravines and narrower terrace remnants, so the original morphology is mostly lost.

Slope (determined via DEM):	Min: 9%	Max: 113%	Typical: 40%
on Failures (DEM & field):	Min: 32%	Max: 84%	Mean: 61%, s.d.= 20%
Elevation:	Min: 280’	Max: 900’	Typical: 600’
Total Area:	1295.6 acres.		
Total Landslide Area:	18.5 acres.		
Total Number of Landslides:	7		
Number of Delivering Landslides:	1		

MW Processes: Predominantly deep-seated slumps with superimposed debris flows and other shallow rapid landslides, some of which are large. See Form A-1 and A-3.

Forest Practice Sensitivity: Low. Although management was a factor in a preponderance of the landslides, only one delivered sediment to a stream. Also sensitive to surface erosion and gullying where runoff concentrated from roads.

Mass Wasting Potential: Low. Only seven landslides were identified on photos between 1965-2003.

Delivery Potential: Moderate. The vulnerability factor of inventoried slides in MWMU2 is 18 (high-delivery units in the study area >1000). However, most of MWMU2 is directly above S.R. 20 and/or the Skagit River.

Delivery Criteria Used: Many ravines/channels on slopes directly above S.R. 20 and/or the Skagit River.

Hazard Potential Rating: Moderate. This rating is based on the possibility of unmapped ravines that would qualify as MWMU5 (high hazard); and potential for affecting state shorelines, state highway, and populated lands.

Trigger Mechanisms: Road building and clear-cutting on terrace margins reduces effective soil cohesion contributed by tree-root strength. Water control is critical to precluding failure owing to glacial deep recharge or gullying.

Confidence: Moderate. This terrace shares a cogenetic relation with terraces in the Stilliguamish River.

MWMU Number: 3 Landslides Superimposed on Relict Deep-Seated Landslides within the Middle and Upper Jackman Creek Drainage (≥ 55%) – High Hazard

Description: MWMU3 comprises 12 large, relict, deep-seated landslides on steep convergent hillslopes and channel adjacent side-slopes. Most of these are on the northwestern wall of Jackman Creek. Superimposed on these relict slides are 93 deep-seated and shallow rapid slides, many of which impinge on, and deliver sediment to, Jackman Creek. MWMU3 occupies ~15% of the surface area of the Jackman–Corkindale study area.

Materials: The Jackman Creek valley is cut in Chilliwack Group metasedimentary and metavolcanic rocks, glacial till, and locally thick soils composed of relict landslide detritus.

Landform: Relict landslides are recognizable on aerial photographs by the presence of arcuate headwalls, marginal drainages, hummocky or benched mid-slope terrain, which may reflect large scale flow (planar-convex topography), and steep toes, some of which cross Jackman Creek. Superimposed are numerous smaller-scale inner gorges and hollows.

Slope (determined via DEM):	Min: 19%	Max: 143%	Typical: 50%
on Failures (DEM & field):	Min: 20%	Max: 142%	Mean: 81%, s.d.= 24%
Elevation:	Min: 740’	Max: 3,993’	Mean: 3,201’
Total Area:	2351.0 acres.		
Total Landslide Area:	177.3 acres.		
Total Number of Landslides:	105		
Number of Delivering Landslides:	84		

MW Processes: A wide variety of shallow rapid and small sporadic deep-seated processes.

Forest Practice Sensitivity: High. The proportions of delivering features associated with clear cuts (0–5 yr), young stands (6–15 yr), sub-mature stands (16–50 yr) and roading are 36%, 28%, 10%, and 20% respectively for a total of 93% of the mapped slides.

Mass Wasting Potential: High. A total of 105 landslides have been identified in MWMU3, including the 12 relict slides that define the unit.

Delivery Potential: High. The vulnerability factor for MWMU2 is 1218. Thick accumulations of sediment in Jackman Creek attest to high delivery.

Delivery Criteria Used: Inner gorges and debris flow tracks entering directly into Jackman Creek. Ongoing delivery observed during field reconnaissance.

Hazard Potential Rating: High.

Trigger Mechanisms: Clear-cut harvest and roading on any slope. Any disturbance of the thick and highly unstable soils results in landslides that have been shown to persist for years.

Confidence: High. (See Fig. 9.)

MWMU Number: 4 Inner Gorge of Jackman Creek (≥ 60%) – High Hazard

Description: MWMU4 occupies the steep inner gorge of Jackman Creek proper, in areas where the inner gorge is not affected by the deep-seated slides of MWMUs 1 and 3. Slopes along the southern margin of the drainage are particularly precipitous. In this area, a series of broad bedrock hollows and convergent headwalls have developed resulting in unstable conditions. Mass wasting processes for MWMU4 include shallow rapid landslides, small sporadic deep-seated failures, and debris flows. MWMU4 covers ~11% of the study area.

Materials: The Jackman Creek valley is cut in Chilliwack Group metasedimentary and metavolcanic rocks, glacial till, and locally thick soils composed of landslide detritus. Metasedimentary rocks dominate the SW part of MWMU4, but these softer rocks do not appear to be less stable than harder metavolcanic rocks, which dominate the NE part.

Landform: A steep inner gorge having walls ~700 ft deep with many superimposed small-scale inner gorges and hollows.

Slope (determined via DEM):	Min: 19%	Max: 143%	Typical: 50%
on Failures (DEM & field):	Min: 40%	Max: 149%	Mean: 89%, s.d.= 26%
Elevation:	Min: 400'	Max: 3,993'	Mean: 3,201'
Total Area:	1696.6 acres.		
Total Area of Landslides:	381.3 acres.		
Total Number of Landslides:	63		
Number of Delivering Landslides:	43		

MW Processes: Shallow rapid–undifferentiated, debris avalanches, debris flows, and small sporadic deep-seated landslides.

Forest Practice Sensitivity: High. All but five of the identified landslides have occurred in logged areas or along logging roads. A large number of failures initiate on or a few feet below the Jackman Creek Mainline.

Mass Wasting Potential: High. Many of the older failures have grown larger over time and the Mainline Road is subject to constant slope stability problems. Landslides affect >20% of the area of MWMU4.

Delivery Potential: The vulnerability factor is 1168, one of the highest among MWMUs analyzed by the LHZ Project team to date. A large proportion of the volume of any slide that begins in MWMU4 is likely to enter Jackman Creek immediately because the slopes are steep and end in the wetted area.

Delivery Criteria Used: Inner gorges and shallow rapid tracks entering directly into Jackman Creek. Ongoing delivery observed during field reconnaissance.

Hazard Potential Rating: High.

Trigger Mechanisms: Clear-cut harvest and roading on any slope. Failure of side-cast and/or fill material associated with forest roads and landings. Inadequate road drainage (lack of/undersized/unmaintained culverts) may also contribute to instability.

Confidence: Moderate. Landslides in Jackman Creek cannot be accurately mapped without additional field study.

MWMU Number: 5 Other Steep Inner Gorges, Bedrock Hollows, Convergent Headwalls (≥ 70%) – High Hazard

Description: MWMU5 comprises rule-identified (WAC 222-16-050) inner gorges, bedrock and soil hollows, and convergent headwalls steeper than 70% gradient, common in the North Cascades physiographic province. MWMU5 covers 7% of the study area. In addition, there are probably similar but unmapped landforms in these basins, particularly in MWMUs 2 and 6.

Materials: Chilliwack and Easton Group metasedimentary and metavolcanic rocks, Bell Pass mélange, glacial till, and locally thick soils.

Landform: Inner gorges, bedrock hollows, and convergent headwalls. In the Corkindale area these are generally V-shaped and defined by intersecting steep planar slope panels; in Jackman Creek, they are cut in convex topography or bound faceted spurs; on the south side of Sauk Mountain, they are generally cut in gentler planar slopes. Many of these gorges, hollows, and headwalls culminate in alpine basins or arêtes.

Slope (determined via DEM):			
Corkindale:	Min: 10%	Max: 215%	Typical: 110%
Jackman:	Min: 20%	Max: 140%	Typical: 70%
South Sauk Mountain:	Min: 30%	Max: 160%	Typical: 65%
on Failures (DEM & field):	Min: 14%	Max: 302%	Mean: 117%, s.d.= 51%
Elevation:	Min: 180	Max: 3,760'	Typical: highly variable
Total Area:	1108.9 acres		
Total Area of Landslides:	65.6 acres.		
Total Number of Landslides:	48		
Number of Delivering Landslides:	37		

MW Processes: A variety of shallow rapid processes. Most inventoried slides occurred on slopes >80%, although some failed at moderate gradients; the slope threshold of 70% is the default for rule-identified unstable landforms.

Forest Practice Sensitivity: High. Clear cuts, young stands, sub-mature stands, and roading account for 23%, 29%, 27%, and 6% of all landslides, respectively

Mass Wasting Potential: High. 48 landslides have been identified.

Delivery Potential: High. The vulnerability factor of MWMU5 is 1142. Normally, slides from inner gorges in western Washington deliver sediment/debris to streams; only the shallow rapid failures on alpine convergent headwalls have a lower likelihood of delivery.

Delivery Criteria Used: Inner gorges and slide tracks entering directly into various drainages.

Hazard Potential Rating: High.

Trigger Mechanisms: Failure of side-cast and/or fill material associated with forest roads and landings. These kinds of road-related failures tend to translate into fast-moving debris flows, scouring sediment from low-order channels and depositing it in higher-order channels.

Confidence: Moderate. The photographic record is not adequate to thoroughly analyze the Corkindale watershed.

MWMU Number: 6 Cliff-Dominated Steep Slopes, Rockport to Marblemount (≥ 85%) – Moderate Hazard

Description: MWMU6 consists of cliffs and very steep planar slopes north of Highway 20 between Rockport and Marblemount. Landslides are rare in MWMU6, presumably because thick soils are unable to accumulate on the steep slopes. However, catastrophic natural and management-induced rockfalls and debris flows can occur. Many small streams crossing the cliffs have been mapped as inner gorges, but all should be checked for MWMU5 characteristics when forest practices are proposed in this unit. MWMU6 occupies 7% of the study area.

Materials: Bedrock includes northwest-trending Chilliwack Group metasedimentary rocks, Easton Metamorphic Suite, and Bell Pass mélange. Sediments include glacial till, undifferentiated glacial sediments, alluvial fan deposits, and thin soils.

Landform: Steep planar and convex-planar slope panels separated by the inner gorges and hollows of MWMU5.

Slope (determined via DEM):	Min: 25%	Max: 240%	Typical: 70%
on Failures (DEM & field):	Min: 64%	Max: 280%	Mean: 133%, s.d.= 56%
Elevation:	Min: 280’	Max: 3,993’	Mean: 3,201’
Total Area:	1130.2 acres.		
Total Area of Landslides:	250.9 acres.		
Total Number of Landslides:	13		
Number of Delivering Landslides:	7		

MW Processes: Rare debris flows and shallow rapid landslides; several very questionable deep-seated failures are also mapped. Most inventoried slides occurred on slopes >85%, although two failed at moderate gradients.

Forest Practice Sensitivity: Possibly moderate, but the lack of landslides and recent management activities preclude meaningful assessment.

Mass Wasting Potential: Low. Only 13 landslides observed, several of which have ‘questionable’ level of certainty.

Delivery Potential: Moderate to high. Delivery is likely because of the steep unbroken slopes; Highway 20 and scattered buildings below. The vulnerability factor is 214.

Delivery Criteria Used: Unknown. The paucity of landslides precludes meaningful assessment.

Hazard Potential Rating: Moderate. This rating is based on the possibility of unmapped ravines that would qualify as MWMU5 (high hazard); and potential for affecting state shorelines, state highway, and populated lands. Although rare, catastrophic landslides can occur, and the highway corridor and fans at the base of the slopes deserve concern.

Trigger Mechanisms: Unknown. Lack of landslides precludes meaningful assessment.

Confidence: Low.

MWMU Number: 7 Lower Hazard Areas

Description: MWMU7 comprises a wide variety of landforms, elevations, and materials, but is mostly characterized by few landslides.

Materials: A wide variety of rocks and sediments.

Landform: A wide variety, but dominated by convex low- to medium-gradient slopes in the higher elevations of the Jackman Creek drainage, and the flat Skagit River floodplain. Excludes inner gorges and most bedrock hollows (MWMU5).

Slope (determined via DEM):			
Jackman Creek	Min: 10%	Max: 150%	Typical: 45%
Skagit floodplain			Typical: 1%
on Failures (DEM & field):	Min: 21%	Max: 132%	Mean: 86%, s.d.= 25%
Elevation:	Min: 180’	Max: 3,993’	

Total Area: 8060 acres.

Total Area of Landslides: 3.2 acres

Total Number of Landslides: 10 on study area lands (47 total, including federal lands)

Number of Delivering Landslides: 5

MW Processes: A wide variety of shallow rapid and small sporadic deep-seated processes.

Forest Practice Sensitivity: Low.

Mass Wasting Potential: Low.

Delivery Potential: Low. Only 10 landslides were identified in the study area.

Delivery Criteria Used: Inner gorges and shallow rapid tracks directly entering Jackman Creek. Ongoing delivery observed during field reconnaissance.

Hazard Potential Rating: Low.

Trigger Mechanisms: Yarding scars, otherwise random.

Confidence: Moderate.

12.0 Appendix C – Mass Wasting Summary Tables

Note: The large persistent deep-seated landslide category includes earth flows.

Mass Wasting Summary Table: MWMU # 1

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanches	Totals
Clear Cut (timber 0-5 yrs)	1	1						2
Young Stands (timber 5-15 yrs)	2							2
Submature (timber 15-50 yrs)	3	2						5
Mature (timber > 50 yrs)	2			2		2		6
Road		2						2
Partial Cut								
Yarding								
Alpine								
Other (e.g. housing, agriculture)								

Mass Wasting Summary Table: MWMU # 2

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanches	Totals
Clear Cut (timber 0-5 yrs)	1	1						2
Young Stands (timber 5-15 yrs)	2							2
Submature (timber 15-50 yrs)								
Mature (timber > 50 yrs)				1	2			3
Road								
Partial Cut								
Yarding								
Alpine								
Other (e.g. housing, agriculture)								

Mass Wasting Summary Table: MWMU # 3

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanches	Totals
Clear Cut (timber 0-5 yrs)	21	13	2	1	1			38
Young Stands (timber 5-15 yrs)	13	10		3	3			29
Submature (timber 15-50 yrs)	6	2		2				10
Mature (timber > 50 yrs)	3			1				4
Road	8	9	1			3		21
Partial Cut								
Yarding								
Alpine	2						1	3
Other (e.g. housing, agriculture)								

Mass Wasting Summary Table: MWMU # 4

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanche	Totals
Clear Cut (timber 0-5 yrs)	10	6		1	1			18
Young Stands (timber 5-15 yrs)	9	6			1			16
Submature (timber 15-50 yrs)	2	2	1		4			9
Mature (timber > 50 yrs)				3				3
Road	7	3		2	2			14
Partial Cut								
Yarding								
Alpine	2							2
Other (e.g. housing, agriculture)						1		1

Mass Wasting Summary Table: MWMU # 5

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanches	Totals
Clear Cut (timber 0-5 yrs)	5	5		1				11
Young Stands (timber 5-15 yrs)	10	3		1				14
Submature (timber 15-50 yrs)	4	7		1	1			13
Mature (timber > 50 yrs)					1			1
Road	1	2						3
Partial Cut								
Yarding								
Alpine	5						1	6
Other (e.g. housing, agriculture)								

Mass Wasting Summary Table: MWMU # 6

Activity	Shallow Rapid Landslides	Debris Flows	Debris Avalanches	Undiff'd Deep-Seated Landslides	Shallow Sporadic Deep-Seated Landslides	Large Persistent Deep-Seated Landslides	Snow Avalanches	Totals
Clear Cut (timber 0-5 yrs)	1							1
Young Stands (timber 5-15 yrs)								
Submature (timber 15-50 yrs)	3	1			1			5
Mature (timber > 50 yrs)				3				3
Road	3							3
Partial Cut								
Yarding								
Alpine				1				1
Other (e.g. housing, agriculture)								