APPENDIX A

MASS WASTING ASSESSMENT REPORT

**Boulder River, French Creek, and Squire Creek
Watershed Analysis**

Level 2

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1.0 Overview

The analysis of the Boulder River, French Creek, and Squire Creek Watershed Administrative Units (WAUs) is one of the first, conducted following Washington Forest Practices Board (WFPB) guidelines, in which a large percentage (i.e., at least one-fourth) of the WAU area occupies glaciated and recently deglaciated terrain with little to no influence from forest-practice activities. Approximately one-half of the WAU area lies in federally managed terrain, and only a relatively small percentage has been logged or roaded. Hence, some terms and methods were modified to perform this analysis according to state regulatory procedures (WFPB, 1997).

The history of mass wasting in the Boulder River, French Creek, and Squire Creek WAUs is influenced by several key factors. They include:

(1) rock types, which govern the spatial distribution and rates of weathering and soil formation;
(2) tectonic events (e.g., faulting and folding) that have resulted in precipitous terrain riddled by faults and other zones of weakness (e.g., brecciated dikes with associated erodible rock masses);
(3) active erosive agents, including heavy rainfall and extensive ancient and modern alpine and continental-icesheet glaciation; and,
(4) land-use practices in steeper terrain, principally logging and road-building associated with timber harvest and mine prospecting, which began in about the early 1930's.

The majority of landslides in the WAU study area occur in the following rock types: (1) erodible remnant deposits of glacial till and outwash from Pleistocene glaciations and, where formed, thick soils overlying these deposits; (2) metamorphic rocks within a major fault zone that bisects the study area, which have a highly erodible serpentinite matrix; and, (3) erodible clastic rock units north and west of Whitehorse Mountain that contain an abundance of hard metamorphosed claystone. The highest landslide frequency occurs in areas actively influenced by alpine glacial and subalpine processes, including rockfall, snow and rock avalanching, and translational failures in unconsolidated glacial deposits. Glacial processes also include mechanical and chemical sub-glacial weathering, which leads to substantial amounts of sediment production and delivery to the Boulder and Squire stream-drainage networks. A relatively high landslide density also occurs in recessional continental glacial deposits dating to the Pleistocene Epoch, where active streams (e.g., Boulder River) are undercutting toes of steep hillslopes. In general, however, deep-seated failures were observed much less frequently than shallow failures and debris torrents in the WAUs, and ancient landslides in old valley terraces on the south side of the North Fork Stilliguamish River appear to be largely inactive. The main zone of relict and active deep-seated failure behavior occurs along the lower Boulder River drainage downstream of Boulder Falls.

A total of 226 mass wasting features were identified through aerial-photo interpretations and field reconnaissance. Of the total identified landslides, 92% were shallow-rapid landslides and associated debris torrents, 7% involved sporadic deep-seated failures, and 1% corresponded to a large, persistent deep-seated landslide that delivered sediment to the Boulder channel network. About 82% of mass-wasting features are in the small (i.e., less than 500 yd^2) category, although several large features were found to overwhelm the sediment volumes estimated to have been produced by all landslides.

These two features are the large, persistent deep-seated failure triggered or reactivated by clearcutting in continental glacial deposits exposed in the lower Boulder River basin. The other is a huge, catastrophic landslide and debris-torrent complex hypothesized to have been triggered by seismic activity in the Squire Creek drainage during regional earthquake events in February 2002 (R. Hausinger, U.S.D.A. Forest Service, Darrington, Wash., pers. commun.).

Of the identified shallow-rapid landslides and associated debris torrents, 83% have occurred in unmanaged portions of the WAU study area (i.e., in the Boulder River Wilderness Area and on other unmanaged, federal land), while 28% occurred in areas managed for timber harvest. In addition, 19% of sporadic deep-seated landslides have initiated in unmanaged terrain, whereas 81% occurred on managed land and most were associated with continental glacial deposits, or the contact between them and erodible bedrock. All road failures occurred in commercial timberlands. The bulk of mass wasting on managed forestlands (72%) occurred on U.S. Forest Service property, due in large part to the fact that most federal lands occupy the steeper-gradient uplands of the WAU study area where slopes tend to be more unstable.

The zone of sporadically active and inactive deep-seated failure behavior, located downstream of Boulder Falls, was mapped as one contiguous unit on Maps A-1 and A-2. This unit, labeled “Qls” for “Quaternary landslide” (following Tabor et al., 1988) shows the extent of coalescing, ancient earthflows in recessional continental glacial deposits. It also encompasses the upslope areas of groundwater recharge for currently active headscarps identified in Map A-1. Those portions of “Qls”, determined to have been active during the period covered by available aerial photos, are mapped as discrete landslides in the WAU landslide inventory (Form A-1). The remainder of the areas within “Qls” appears to have remained relatively stable during the last century, and most of these areas have been logged at least once. Although much of the “Qls” units are subtle, relict, deep-seated features with little to no modern sediment delivery to the Boulder River, the potential does exist for slope instability within some portions of “Qls”, due to groundwater-recharge dynamics in glacial deposits. Hence, both active and historically inactive features have been identified as areas that could be impacted by land-management activities with the potential for altering groundwater-flow dynamics.

An additional 84 mass-wasting features were identified in the glaciated terrain above treeline (i.e., the mountain core containing Whitehorse Mountain and adjacent peaks), with undoubtedly many others occurring in time intervals between aerial-photo series that were not observable in this study. These features were located using aerial photos and field observations (i.e., via binoculars or identifying avalanche and run-out deposits on the ground). For a number of reasons described further in report section 4.0, however, it became difficult partway through the study to segregate and accurately map each individual feature. Hence, they were collectively mapped as two units of an alpine and subalpine erosion zone equivalent to the Alpine Denudation Zone of Perkins and Collins (1997). The frequency and volume of sediment delivery from these zones are substantial. The alpine and subalpine zones were determined to be significant sources of coarse sediment delivered to channel mainstems, particularly in Squire Creek, where they play an important role in maintaining critical fish habitat (see Fish Habitat Assessment Report).

The Boulder River Wilderness Area and other land units not managed for timber production have had a 44% higher frequency of mass wasting than commercial timberlands, most of which occupy the broader, lower-gradient terraces and toeslopes of the northern portion of the WAU study area. The most likely reasons for this disparity are the dominance of active erosion associated with glacial and subalpine processes in the wilderness area, and the abrupt decrease in hillslope gradients outside the wilderness area. Slope steepness is one of several primary driving factors that promote mass wasting in western Washington.

Estimates of sediment-delivery volume, rather than landslide-number statistics, tend to yield a better understanding of land-use associations with respect to landslide initiation and sediment production in the Boulder, French, and Squire drainages. Of the total landslide number, 49% occurred prior to 1964 (i.e., in the era of most intensive timber harvest, which began in the 1930's), whereas 23% were initiated during the 1965 to 1983 time period, and 28% occurred after 1984. While these results tend to suggest that mass wasting peaked in the WAU study area following harvest on steeper ground in the 1950's and early 1960's, estimates of sediment volumes delivered to the channel network from landslides and debris torrents provide a slightly different interpretation. Of the total sediment volume estimated to have been delivered to streams by all inventoried landslides, 46% corresponds to the 1942 to 1964 time period, 5% to the 1965 to 1983 time period, and 49% to the 1984 to 2002 time period. The relatively larger spike in percent volume estimates for the most recent period corresponds to the February 2002 landslide in Squire Creek, which is estimated to have delivered at least 220,000 yd^3 directly to the channel. It is important to note that, even though roughly half of all failures in 1942 through 1964 were timber-management-related, they are estimated to have contributed about 75% of the total sediment volume produced during that time period. Conversely, about 94% of sediment produced in 1984 through 2002 was from natural disturbances, even though relatively more landslides were initiated by timber harvest and road-related causes than by natural events.

These results suggest that natural processes of sediment production in the WAU study area have tended to dominate the sediment-delivery regime during much of the last century. However, intensive periods of logging (e.g., 1930's to 1960's and some renewed activity in the late 1980's and early 1990's) have significantly impacted the natural sediment load, adding as much as 75% more sediment volume to the channel network. Some logging practices (e.g., ground-based and partial-suspension yarding, sidecast road construction, unmaintained roads) have resulted in large failures that dominate the sediment-delivery regime even though landslide frequency has been on a par with that of natural disturbances. Slopes appear to be particularly sensitive to logging impacts in steeper, metasedimentary and metavolcanic bedrock found to the west and southwest of Whitehorse Mountain, and along terrace faces in continental glacial deposits (e.g., lower Boulder River basin). Hence, the timing, methods, and location of harvest in the WAU area can have a measurably significant effect on the naturally high rates of sediment delivery to the channel system.

Eleven mass-wasting map units (MWMUs) were assigned to the WAU study area, based primarily on landslide densities and sediment-delivery estimates, rock types, soil characteristics, proximity to the channel network, and hillslope gradients. Slope sensitivity to forest-practices activities was not used as the sole determining element, given that such a large percentage of the WAU has not been logged.

High-hazard potential ratings were assigned to:

(1) the alpine and subalpine zones, based on mass wasting frequencies and densities, geology and landform characteristics, and their importance in delivering coarse sediments to the channel network;
(2) continental glacial recessional, outwash, and till deposits in steeper terrain and along river bottoms;
(3) convergent slopes in erosive metasedimentary and metavolcanic rocks, for example in upper French Creek, where some of the largest and most active shallow-rapid landslide and debris-torrent features have formed as a result of past harvest and sidecast road construction; and,
(4) metamorphic rocks in the Darrington-Devils Mountain Fault Zone (e.g., including the 2002 landslide feature in Squire Creek).

Low ratings were assigned to marine metamorphic rocks on the southwestern side of Boulder River, due largely to very small landslide densities and other factors described in report section 6.0. A low rating also was assigned to the low-relief terraces and modern floodplain of the North Fork Stilliguamish River, where no mass-wasting features were identified. Terrace surfaces are composed of continental glacial-outwash deposits, volcanic mudflow and other eruption-related deposits, and alluvium, and they are most affected by land uses causing extensive surface erosion (e.g., tractor logging).

2.0 Summary of Geologic and Physiographic Setting Pertinent to Mass-Wasting Interpretations

The Boulder/French/Squire WAU study area lies in sedimentary, plutonic, and low-grade metamorphic rocks to the west of the Straight Creek Fault, which is a major structural feature regionally dividing rock lithologies (i.e., physical characteristics) and tectonic histories in the North Cascades Range. The geology in the area of the WAUs is structurally complex and lithologically diverse, characterized by Brown (1987) and Tabor et al. (1988) as being part of a regional mélange (i.e., heterogeneous mixture of rock materials of diverse origins and geologic ages) bordering the Northwest Cascades System (Tabor et al., 1987) to the southwest.

Geologically, the WAUs consist of the following: (1) two northwest-trending mélange belts containing erodible metasedimentary and metavolcanic rocks; (2) a relatively more resistant mélange belt that occupies a major fault zone trending northwest through the WAU area; (3) an intrusive rock body in the Squire Creek drainage (i.e., pluton) that weathers relatively easily; (4) an areally extensive fault zone containing erodible materials; (5) terraces formed by recessional continental glaciers that have a relatively high density of deep-seated features and a potential for slope instability associated with groundwater recharge; and, (6) precipitous peaks and ridgelines actively carved by extensive glacial and subalpine erosion processes. A more technical summary of the geology follows.

Blocks of rock materials in the regional mélange containing the WAU area largely were assembled in pre-late Cretaceous time (i.e., prior to about 65 million years before present (B.P.)). They subsequently were sheared and deformed by tectonic activity and by low-grade (i.e., low temperature and pressure) metamorphism during the mid-Cretaceous. Considerable rearranging of mélange materials occurred in the late

Cretaceous and early Tertiary by shearing along the Straight Creek Fault and subsidiary faults, culminating about 34 million years ago (Tabor, 1994). The three WAUs are dissected by a number of high-angle, northwest-trending faults that are part of the Darrington – Devils Mountain fault zone (DDMFZ) and are thought to be related to the Straight Creek Fault (Tabor et al., 1988). Rocks along one side of the DDMFZ appear to have slipped downward relative to the other side (Tabor, 1994), contributing to sheer, planar bedrock surfaces like those exposed in the Squire Creek drainage.

Valley carving and peak sculpting have resulted from millions of years of regional seismic activity, mechanical erosion, and glacial scour. The present landscape shows the strong influence of glacial erosion and deposition occurring approximately 15,000 to 20,000 years B.P. when the Puget Lobe of the Cordilleran ice sheet blanketed northwestern Washington and carved many of the present-day river valleys and terraces. Much of the WAU study area continues to be actively shaped and altered by alpine glacial processes (e.g., in the Whitehorse – Bullon Mountain massif, or mountain complex) and by earthquake activity in the Darrington seismic zone (e.g., Zollweg and Johnson, 1989), in which the DDMFZ is located. In addition, alluvial terraces in the northern portion of the study area contain volcanic sediments associated with Glacier Peak eruptions during Fraser deglaciation (about 11,200 – 12,700 years B.P.) and during the latest Pleistocene to mid-Holocene (about 5,100 to 5,400 years B.P.; Dragovitch et al., 2002a). The largest exposed units contain flood deposits, mudflows (lahars), and volcanic alluvium. These deposits overlie recessional outwash from continental deglaciation; river damming by glacial deposits is thought to have diverted the nearby Sauk River from its North Fork Stilliguamish confluence so that it flows northward into the Skagit River (see Dragovitch et al., 2002a). Flood deposits in the WAU area are referred to as "hyperconcentrated" and presumably formed when valley-filling lahars mixed with river water to form a sediment-laden flood (Dragovitch et al., 2002a).

Most of the WAU study area lies within the major band of disruption and faulting associated with the Darrington – Devils Mountain fault zone. Rocks within this zone are classified by Tabor et al. (1988) as belonging to: (1) the Helena – Haystack mélange, which contains a range of different lithologies, most of which have a highly erodible serpentinite matrix; (2) an eastern mélange belt, which contains variously erodible mafic volcanic rocks, cherty metasedimentary rocks, and ultramafic rocks including blocks of slightly metamorphosed igneous rocks; and, (3) a western mélange belt chiefly containing marine metasedimentary rocks in the WAU study area that has been thrust over the eastern belt along a fault now occupied by the Boulder River canyon. The Helena – Haystack mélange is thought (Tabor, 1994) to be coincident with the DDMFZ; mélange outcrops parallel the DDMFZ in the study area and contain "exotic" blocks that formed elsewhere and were shifted along faults to their present position. The Helena – Haystack mélange and DDMFZ later was intruded by the 35 million-year-old Squire Creek pluton, of tonalite and associated amphibolite composition, which is susceptible to mechanical weathering and breakdown.

The eastern mélange belt, which overlies much of the Helena – Haystack mélange rocks in the study area, contains three distinct rock units that appear to be relatively continuous in outcrop view. These rocks primarily are of submarine-fan origin (i.e., clastic or fragmented rocks shed off a land margin into submarine canyons) and relatively unmetamorphosed oceanic sources. As described by Tabor et al. (1988), the youngest unit is an erodible Middle to Late Jurassic argillite that overlies the Late

Triassic volcanic rocks composing much of Whitehorse Mountain. Volcanic rocks, in turn, overlie a Late Triassic chert (i.e., variety of quartz-rich rock) belt that is extensively disrupted (i.e., metamorphosed) in places.

The major role of Quaternary continental and modern alpine glaciation in shaping the present landscape is evident throughout the WAU study area. Outwash and recessional deposits fill the North Fork Stilliguamish Valley and much of the Boulder, French, Squire, and smaller tributary valleys, and glacial till and outwash deposits mantle most of the lower slopes of the WAU mountain core. These deposits date from the Vashon stade of the Fraser glaciation, roughly about 15,000 years B.P, when the Puget Lobe of the Cordilleran ice sheet receded northward from this region (Booth, 1987). Geomorphic features and surface deposits suggest that all but the highest peaks in the WAU mountain core were covered by ice during the height of the Fraser glaciation.

Modern alpine glaciation is responsible for altering surfaces within the WAU mountain core. Fluctuations in seasonal sediment and water discharge, influenced by subglacial processes, continue to cause channel braiding and avulsions in glacial distributaries, resulting in large pulses of sediment delivery to tributary river channels. Some of these pulses have been described as large waves of coarse sediment that inundate tributary valleys, cut new channels, and remove obstructions (e.g., roads, culverts; WDNR field staff, pers. comm..), particularly in very steep, short-length tributary channels draining the north face of Whitehorse Mountain (e.g., Ashton Creek). Debris fans in the upper watersheds are maintained by substantial rockfall, rock and snow avalanches, and translational failures of easily destabilized glacial deposits overlying steeply dipping bedrock surfaces. At times, debris from these events partially blocks mainstem channels, causing them to migrate or downcut through deposits. The upper Squire and Boulder basins show evidence of alpine glacial retreat as successive, headward deposits of glacial-toe debris, presumably related to Holocene and/or Recent climatic shifts, as has been described elsewhere in the North Cascades (e.g., Long, 1967; Brugman, 1990).

The presence of recessional continental glacial deposits coalescing with alpine till and moraine deposits indicates that the larger valleys (e.g., Squire and Boulder) were filled with a nearly continuous ice mass during the Fraser glaciation. Other evidence for glaciation includes U-shaped valleys (e.g., most of Boulder and Squire valleys, upper French basin), ancient terraces in recessional deposits filling the North Fork Stilliguamish River, kettle ponds and bogs on terrace surfaces (e.g., French Creek drainage, terrace surfaces between Furland and Squire creeks), and underfit drainages. An example of the latter is the broad valley extending west of the abrupt southward bend in French Creek; valley form and deposits suggest that a portion of the Boulder River might have flowed over what is now a low drainage divide and into the present-day French Creek valley, prior to downcutting of the Boulder River to form its present channel course. In the northern third of the WAU, successively older and higher elevation terraces with distance from the mainstem North Fork Stilliguamish River signify stages of continental glacial recession and river downcutting through recessional fill deposits and Quaternary sedimentary deposits associated with Glacier Peak eruptions. A number of Quaternary deep-seated landslides mapped on older terrace faces are interpreted to be related to Stilliguamish River groundwater regimes when the mainstem occupied a higher position in the valley fill, based on their forms and locations. In contrast to Quaternary landslide features downstream in the North Fork Stilliguamish (e.g., Hazel WAU; WDNR, 1996), where wholesale movement or partial-area reactivation has occurred, units mapped as Quaternary landslides in the Boulder/French/Squire WAUs show only isolated evidence of modern mass movement, principally as chronic headscarp ravel, with the exception of several features in the lower Boulder River valley (see discussion in section 5.0).

3.0 Summary of Methods

This mass-wasting assessment was performed in accordance with the methods outlined for Level 2 analyses in Version 4.0 of the WFPB (1997) watershed-analysis manual. All required forms and maps were produced digitally and are included in Appendix A-2. Maps and forms are labeled following module protocol as shown in the manual.

Field reconnaissance and aerial-photo interpretive work were carried out during the spring, summer, and fall of 2002, with some additional observations made in the spring and summer of 2003. Field assessments of landslide locations and characteristics were limited largely by the inaccessibility of much of the WAU study area. Nearly two-thirds of the Boulder /French/Squire WAU area lies in the roadless, virtually trail-less, Boulder River Wilderness Area and adjacent lands managed by the U.S.D.A. Forest Service. One point of entry to the Boulder River and Whitehorse–Bullon–Three Fingers complex (i.e., Trail 641 starting at Typso Pass) was made inaccessible by washouts in the 12-mile stretch of USFS Road 41 that connects with the Mountain Loop Highway west of Verlot. A field crew hiking up the Boulder River valley from Trail 734 was able to move upstream only a few miles past the end of the maintained trail over the course of four days, due to difficult terrain and dense vegetation. Ground access by helicopter is not permitted in the wilderness area. In addition, the upper French Creek basin proved to be fairly inaccessible by foot, due to difficult terrain and dense second growth and slide alder on the unmaintained access road. Field observations were made in the lower Boulder valley (i.e., from a few miles above Boulder River Falls to the river mouth); in the lower French Creek basin upstream through T32N R8E sec 21; in lower Moose Creek drainage, mid and upper Snow Gulch drainage; lower Ashton drainage; lower to upper Squire Creek drainage; and the north-facing slopes of Whitehorse Ridge and Whitehorse Mountain. Field reconnaissance primarily focused on steeper terrain south of State Highway 530, given the low-relief topography between the highway and the North Fork Stilliguamish River. In addition, aerial video footage of the February 2002 failure in the Squire Creek drainage (Hausinger, 2002; unpubl. video) was used to map the failure plane, describe morphological characteristics, and infer failure behavior.

Aerial photographs were obtained from the U.S.D.A. Forest Service and WDNR for analysis. Photos ranging in scale from about 1:12,000 to 1:16,000 were available for years 1942 (full coverage), 1949 (full), 1964 (full), 1972 (partial), 1973 (partial), 1983 (partial), 1985 (partial), 1991 (full), 1992 (partial), and 2001 (full, color). A full coverage of high-altitude (1:51,400) color photos was available for the 1979 photo year.

A number of additional sources of information were used to analyze the geologic features and landslide characteristics in the WAU study area. They include: (1) geologic maps at a 1:24000 scale (WDNR, 2001; Dragovitch et al., 2002a, 2002b) and 100,000 scale (Tabor et al., 1988); (2) completed watershed analyses for the North Fork Stilliguamish River, compiled by the U.S.D.A. Forest Service (2000), and adjacent Hazel

WAU, published by the WDNR (1996); (3) soil resource inventory data (Snyder and Wade,1970); (4) landslide inventory data compiled by Perkins and Collins (1997); and, (5) various GIS covers maintained by the WDNR, including the hydro, transportation, slope class, and slope stability layers.

Form A-1 (Mass Wasting Inventory Data) originally was created on an Excel spreadsheet and imported as multiple separate pages. This electronic reproduction of Form A-1 is in the standard format shown in the watershed-analysis manual (WFPB, 1997). The original Excel spreadsheet may be obtained from the author or the Stilliguamish Tribe of Indians, Department of Natural Resources. Form A-2 (Mass Wasting Map Unit Description) contains detailed descriptions of required information relevant to assigning Mass Wasting Map Unit (MWMU designations). It seemed logical to put all information relevant to each MWMU in one place in the report, rather than spreading it out over several report sections. Hence, the discussions in sections 5.0, 6.0, and 7.0 are abbreviated, focusing primarily on comparisons of mass-wasting behavior between units and on general study conclusions. The reader is referred to Forms A-2 and A-3 for detailed information on each MWMU.

The Boulder/French/Squire Watershed Analysis is one of the first watershed analyses, conducted per WFPB (1997), in which a substantial percentage (i.e., at least one-fourth) of the study area occupies glaciated and recently deglaciated terrain with little to no influence from forest-practices activities. Hence, some terms and procedures were modified to remain consistent with the WFPB methods. The following types of mass wasting prevalent in the alpine and subalpine zones were labeled as shallow-rapid landsliding, given their typically shallow depths and catastrophic occurrence: rockfall, rock avalanches, debris avalanches containing mixtures of snow, sediment, and organic materials, shallow translational failures containing rock, sediment, and chunks of ice calved from glacial toes, planar failures in glacial deposits, and inner-gorge failures along tributary walls that were disrupted by debris torrents or snow/rock avalanches. Many observed features in the alpine zone incorporated more than one type of failure (e.g., rockfall triggering debris avalanche, in turn causing debris torrent), making it difficult to parse features into individual categories of catastrophic mass movement.

In addition, two new land-use association categories were added: natural disturbances (i.e., land dominated by alpine or glacial and subalpine processes) and mature forest. The latter category refers to land below treeline in which forest-practices have not occurred (e.g., Boulder River Wilderness Area, U.S.D.A. Forest Service Late-Successional Reserves).

4.0 Summary of Analysis and Results

Field inventories and aerial-photo interpretations yielded a total of 100 landslides and debris torrents (see Form A-1) that were sufficiently large to be visible as polygons at a 1:24,000 map scale (see Map A-1). Thirty-two of the inventoried shallow, rapid landslides (SR) initiated debris torrents (DT) downslope in tributary channels; each debris torrent and landslide pair was mapped in Map A-1 as one polygon and defined in Form A-1 by one landslide identification number. Also, at least 12 small debris torrents were associated with cross-drain and fill failures on the USFS Road 2040 in the upper

Squire Creek drainage. They were located in the field but were not visible on aerial photos, nor were they large enough to map at a 1:24,000 scale. These 12 debris torrents are identified in the Surface and Road Erosion Assessment Report and are counted in the debris-torrent tally for Forms A-3. In addition, upwards of 84 additional mass-wasting features were identified in aerial photos but proved to be difficult to map for several reasons discussed in this report section. These features were mapped collectively within two large units encompassing the zone of active alpine glacial and subalpine erosion that corresponds to the Whitehorse – Bullon – Three Fingers peak complex (see Map A-1), comparable to the Alpine Denudation Zone identified by Perkins and Collins (1997) in their mass-wasting inventory of the upper North Fork Stilliguamish watershed. This mapping approach was taken because of the complex mass-wasting processes active in the glaciated and recently deglaciated zone. A "lumping" method was used in an attempt to avoid potentially large map inaccuracies associated with trying to map dozens of small, often superimposed features at a 1:24,000 scale. These alpine-zone mass-wasting features also were added to the landslide tally, bringing the total identified landslides and debris torrents to 226.

Within the alpine glacial zone, differentiating individual mass-wasting sites was problematic because:

(1) Mass-wasting features in many Type 5 drainages were superimposed, thereby making it difficult to clearly map individual polygons at a 1:24,000 scale. For example, in several west-side tributaries to Squire Creek, rock avalanching has over-ridden translational failures of debris overlying steep, exposed bedrock, each event originating at a different elevation but resulting in chain reactions of channel side-slope failures that were hard to differentiate on the basis of field and/or aerial-photo observations.

(2) The frequency per unit area of mass wasting in pro-glacial distributary channels and the rates of distributary channel avulsions are high. Trying to sort out and map discrete features at a 1:24,000 scale became difficult and inaccurate.

(3) Mapping only existing mass-wasting failure planes does not account for prehistoric landslide and debris-torrent occurrences whose only current signature is the presence of old debris-fan deposits (e.g., as field-identified in the upper Squire basin and interpreted from photos in the upper Boulder watershed). Much of the alpine and subalpine WAU core has been affected by glacial scour and deposition during the mid- to late Holocene (i.e., about 5000 years B.P. to present), due largely to climatic variability and consequent spatial and temporal dynamics of alpine glacial advance and retreat. The advantage of using a large polygon to delineate the full extent of the alpine core is that it not only identifies areas in which mass wasting accompanied prehistoric periods of glacial scour and deposition, but it also denotes the area in which future slope instability could occur as a result of changes in glacial morphology and dynamics.

(4) Map A-1 shows the spatial distribution of tributary channels affected by avalanching and debris torrents in just the mapped Type 5 channels, whereas field inventories and photos demonstrate that there are many more similar features in unmapped Type 5 channels. Given the number of unmapped channels (i.e., estimated 65% to 70% greater than the number of mapped Type 5 tributaries) and the complexity of accurately mapping them all, it seemed less

misleading and erroneous to incorporate them in one large mass-wasting polygon.

Consequently, the zone of mass-wasting activity associated with alpine glacial processes was mapped as two units (see map A-1):

(1) areas of identified erosion associated with recent alpine glacial activity; includes rockfall, snow and rock avalanching, small translational failures of debris overlying steep, exposed bedrock, and secondary avalanche-chute erosion and inner-gorge failures in tributary channels draining these areas; and,

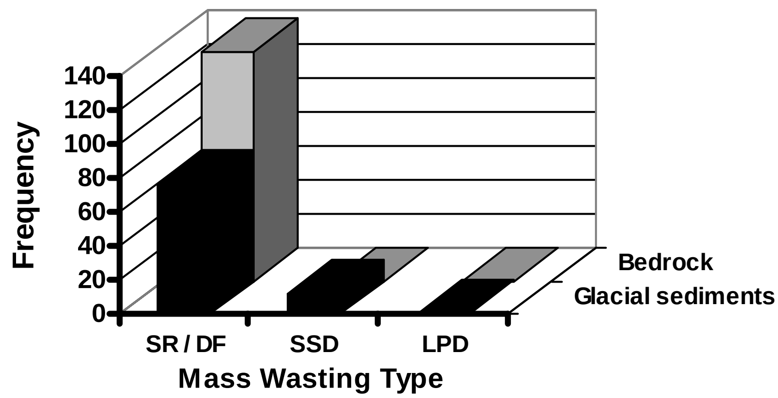
(2) areas of presumed and observed erosion associated with rock and snow avalanching; unit (2) comprises numerous mapped and unmapped Type 5 channels and avalanche chutes similar to those described in unit (1).

The principal difference between units (1) and (2) is that the former includes all mapped tributary channels, along with the mass-wasting source areas and runout paths, whereas the latter comprises intervening areas with similar failure processes but with unmapped Type 5 channels that could not be located accurately on Map A-1. Hence, unit (2) was mapped more generically as large polygons, recognizing that intervening areas between avalanche-scoured channels might also contain relatively more stable swaths of mature forest. In addition, areas covered by permanent snowpack or glacial ice were included, recognizing that substantial amounts of coarse and fine sediments are supplied to channel distributaries from chronic sub-glacial and snowmelt erosion.

Figure A-1 shows the distribution of mass-wasting features by rock type, where SR /DF represents shallow-rapid landslides associated with debris torrents, SSD are small, sporadic deep-seated landslides, and LPD are large, persistent deep-seated failures. Bedrock geology includes metasedimentary, metavolcanic, igneous, and volcanic rock types described in report section 2.0. Glacial sediments include alpine glacial drift, and continental recessional tills and outwash, and Glacier Peak lahar deposits. The majority of mass wasting (92%) involved shallow-rapid landslides and associated debris torrents (i.e., as defined in the methods section 3.0; including alpine erosional processes); of those, 60% occurred in bedrock overlain by moderately thick to no soil layers. The remaining 40% were initiated in terrain mantled by thin to relatively thick alpine and continental glacial sediments, primarily along tributary sidewalls or where mainstem channels are incising through deposits (e.g., along the lower and upper Boulder River).

Most small, sporadic deep-seated landslides occurred in continental recessional outwash deposits mantling toeslopes in bends of the Boulder River, although five of the recorded 12 SSD landslides initiated along the contact between glacial sediments and bedrock, or between relatively unconsolidated glacial sands and underlying, poorly permeable clay likely formed in proglacial lakes during continental glaciation. In the upper Boulder River drainage, failure headwalls are located in bedrock and landslide bodies typically have incised glacial sediments. In the lower valley, the failure planes are carved in thick, continental glacial deposits. In the lower Boulder and French drainages, observed, sporadically active failures occupy much larger relict landslide features. Mapped as “Qls” on Maps A-1 and A-2, they represent ancient, very large, deep-seated earthflows that appear not to have moved *en masse* during the last century (i.e., time period covered by available aerial photos and historic records). Smaller,

Figure A-1. Frequency distribution of mass-wasting (i.e., number of landslides) by rock type.



sporadically active shallow failures are superimposed on these features and are identified in Map A-1 and Form A-1 as discrete failures. In the field, SSD are determined by patches of freshly eroded sands exposed in ancient headscarps and by vegetation (i.e., slide alder and other disturbance species with few to no mature conifers).

The "Qls" units coincide roughly with the zone of groundwater recharge to these smaller, sporadically active surface features (SSD). Relict larger earthflows and recently active, superimposed failures were mapped separately to show the relationship between younger unstable and older, more stable mass-wasting features. Older relict failures are subtle and appear not to have moved wholesale following timber harvest (i.e., with the exception of one mapped, large persistent, deep-seated feature). Current forest-practices regulations, however, state that groundwater recharge areas for deep-seated failures in glacial deposits may be classified IV-special and need further investigation (WFPB, Board Manual, M-203, 2000); hence, they have been identified in this analysis as "Qls" units whether or not they exhibit active mass-wasting behavior. Original mapping of these features in 2002 was modified to incorporate more recent field observations and interpretations of Lingley (2004).

Figure A-2 shows the percent of mass-wasting features according to size. The majority, 82%, of all landslides and debris torrents fall in the small (i.e., less than 500 yd^2) category, with 8% in the medium (i.e., 500-2000 yd^2), 7% in the large (i.e., 2000-5000 yd^2), and 4% in the very large (i.e., greater than 5000 yd^2) size classes. The majority of the small features are shallow-rapid landslides and debris-torrent tracks, with most of the small, sporadic deep-seated failures falling in that category as well.

Figure A-2. Percent of mass-wasting features in each size class.

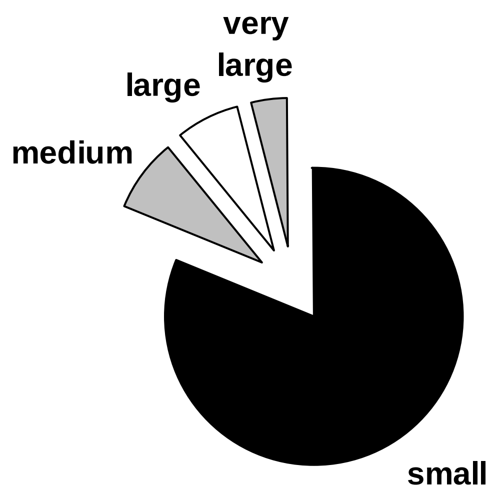


Table A-1 shows the numerical distribution of mass-wasting features by failure type and land activity. It is a compilation of Forms A-3 for the 11 identified mass-wasting map units (MWMUs; see Appendix A-2). Shallow-rapid landslides and associated debris torrents comprise at least 92% of identified mass wasting, while the remaining 8% are deep-seated landslides occurring primarily in Pleistocene glacial recessional deposits. At least 67% of all shallow-rapid landslides and associated debris torrents occurred on the portion of the landscape that has not yet been managed for timber harvest; that is, most of these failures initiated in alpine and subalpine terrain within the Boulder River Wilderness Area and adjoining federal land. An additional 13% are related largely to ground-based or partial-suspension logging on federal, state, and private commercial forestlands, and 20% are due to sidecast or cross-drain failures on logging roads. More discussion of land-use associations and trigger mechanisms appears in section 7.0 of this report.

Table A-2 shows the numerical distribution of mass-wasting features in the four landslide categories (i.e., shallow-rapid landslides and debris torrents; small, sporadic deep-seated landslides; large, persistent deep-seated landslides; and road-related failures) by land-management and ownership categories. With respect to land ownership, eight of the 28 shallow-rapid landslides that initiated in clearcuts or partial harvest units were found on non-federal land. Of those, five (18%) occurred on state-managed land and three (11%) on private timberland. Only five of the 42 identified road-related failures (i.e., 12%) occurred on private land and none were identified on state-managed land. The bias of mass wasting to federally managed terrain is not surprising since the national forest primarily occupies the upland areas with greatest topographic relief. State-managed and private lands are located largely on moderate-relief toeslopes, low-relief terraces, and the modern floodplain of the North Fork Stilliguamish River, with only

Table A-1. Summary of mass-wasting inventory data by failure type and land activity, listed by frequency and percent of total (%).

<table>
<tr><th>ACTIVITY</th><th>Shallow Rapid Landslide (SR)</th><th>Debris Torrent (DT)</th><th>Small Sporadic Deep-Seated Failures (SSD)</th><th>Large Persistent Deep-Seated Failures (LPD)</th><th>Totals</th></tr>
<tr><td>Clear Cut 0-20 years</td><td>5</td><td></td><td>11</td><td>1</td><td>17
(8%)</td></tr>
<tr><td>Clear Cut 20-50 years</td><td>10</td><td>9</td><td>2</td><td></td><td>21
(9%)</td></tr>
<tr><td>Partial Cut</td><td>2</td><td>2</td><td></td><td></td><td>4
(2%)</td></tr>
<tr><td>Road</td><td>10</td><td>32+</td><td></td><td></td><td>42+
(19%)</td></tr>
<tr><td>Stream Crossing</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Landing</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Other Forest Practices</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Wildfire</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mature Forest (unmanaged)</td><td>47+</td><td>22+</td><td>3</td><td></td><td>72+
(32%)</td></tr>
<tr><td>Non-Forest Land Use</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Natural disturbances (alpine processes)</td><td colspan="2">70+</td><td></td><td></td><td>70+
(31%)</td></tr>
<tr><td rowspan="2">Totals</td><td>74+</td><td>65+</td><td rowspan="2">16
(7%)</td><td rowspan="2">1
(0.5%)</td><td rowspan="2">226
(100%)</td></tr>
<tr><td colspan="2">70+
(92%)</td></tr>
</table>

a few private in-holdings on steeper slopes. The Mt. Baker – Snoqualmie National Forest boundary roughly coincides with the abrupt increase in relief with distance from the river.

Tables A-1 and A-2 also indicate that shallow-rapid landslides and associated debris flows represent the majority of mass-wasting events in the WAU area. Only 8% of the total mass-wasting occurrences involved deep-seated landsliding, and almost all are located in Boulder River bends where channel lateral migration continues to undermine toeslopes composed of relatively unconsolidated, glacial recessional and outwash materials deposited during Pleistocene continental deglaciation. The number of small, sporadic deep-seated failures is equally divided between managed and unmanaged land, which underscores the inherent instability of steeper slopes occupying the outsides of river bends in terrain mantled by continental glacial deposits.

Table A-2. Number and percent of total mass-wasting features, by type, on unharvested versus timber-managed lands; the latter category is further delineated by land ownership.

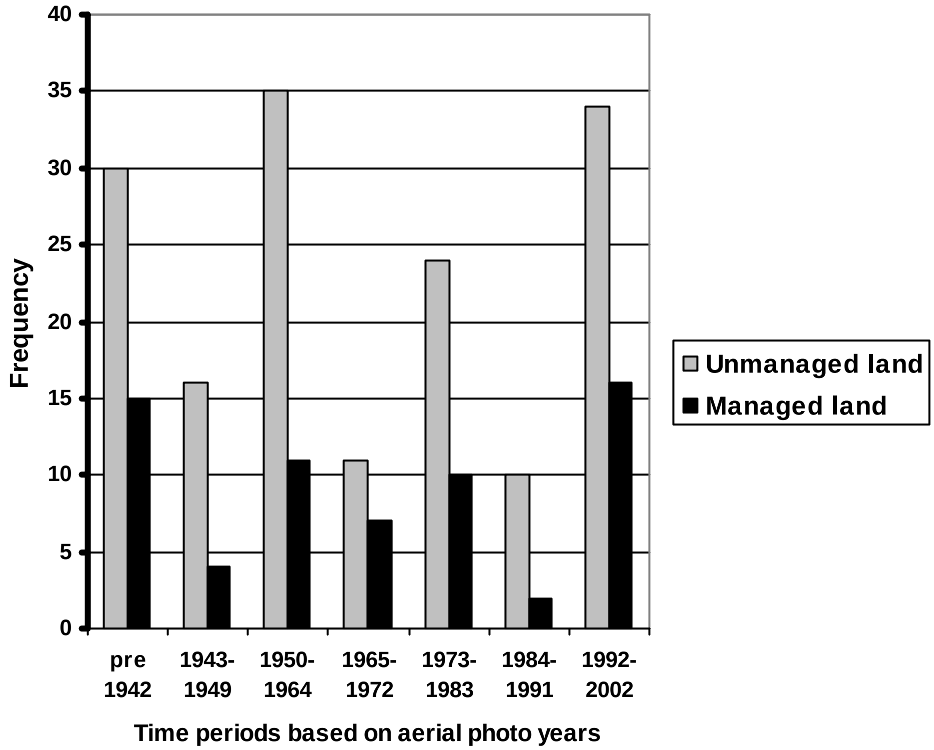
Mass wasting feature	Number and percent (%) of mass wasting features in each landslide category by land-management type		Number and percent (%) by ownership of mass wasting features on commercial timberlands		
	Unharvested	Timber-managed	USFS	WDNR	Private
Shallow-rapid landslides and associated debris torrents	139 (83%)	28 (17%)	20 (71%)	5 (18%)	3 (11%)
Small sporadic deep-seated landslides	3 (19%)	13 (81%)	1 (8%)	12 (92%)	0
Large, persistent deep-seated landslides		1 (100%)	0	1 (100%)	0
Road-related failures		42 (100%)	37 (88%)	0	5 (12%)

The sole large, persistent deep-seated (LPD) landslide identified in the study area is located in a high-amplitude river bend cutting through glacial deposits. In addition, it occupies a small portion of one much larger, relict feature described previously (i.e., “Qls unit”). The slopes within this area have been clearcut at least once with no observable destabilizing effect. The LPD landslide and the bulk of the shallow, sporadic deep-seated landslides are routinely reactivated by river undermining, judging from signs of ongoing erosion in successive aerial-photo years. Aerial photos also show evidence of logging disturbance from adjacent harvest units (e.g., yarding scars along their headwalls), suggesting that timber harvest has compounded natural disturbances promoting deep-seated failure behavior. See report section 7.0 for continued discussion.

The frequency distribution of observed mass wasting (i.e., number of landslides) is shown in Figure A-3 as a function of time periods defined by the dates of available aerial-photo series and by field observations made in 2002. The solid color in each time-period class denotes the number of landslides and debris torrents occurring on commercial timberlands as a result of harvesting and road drainage or sidecast problems. The checkered pattern shows the distribution of mass wasting resulting from natural disturbances on wilderness and unharvested federal lands.

Figure A-3 indicates that the number of mass-wasting events per time period on unharvested terrain averages 44% (± 14%) higher than on timber-managed lands. A key factor likely is the dominance of weathering processes leading to mass wasting in glaciated and deglaciated terrain, as well as the density of failures in continental glacial deposits located in the upper French Creek basin and throughout the Boulder River watershed.

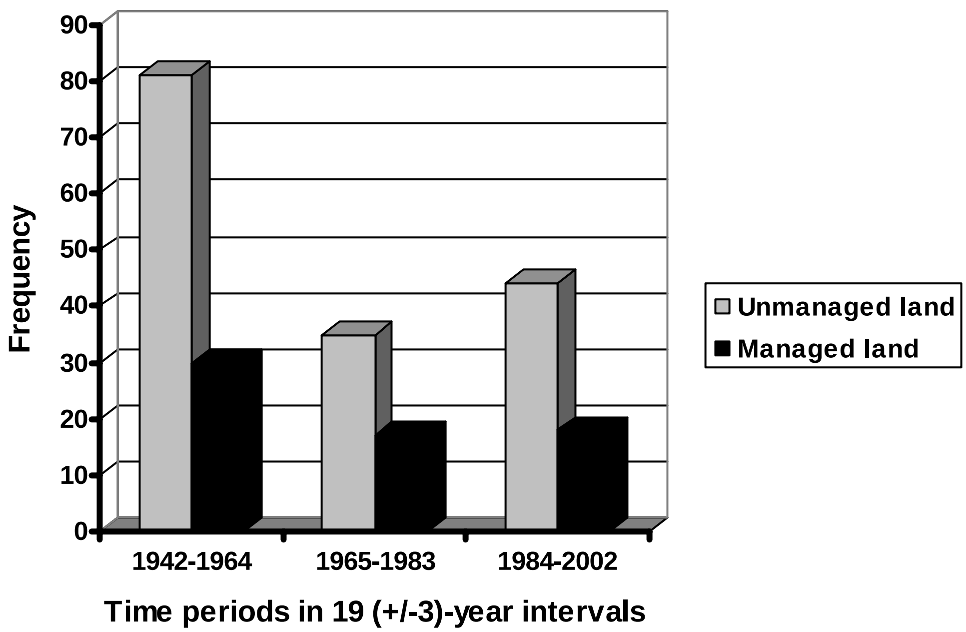
Figure A-3. Frequency distribution of mass-wasting occurrences (number of landslides) over time.



No long-term trend in terms of landslide initiation frequencies can be discerned from Figure A-3. The magnitude of data in each histogram class obviously is biased by the unequal duration of the time periods, which are based on the available aerial-photo chronology. Hence, data were normalized by reclassing them in 19 ±3 year intervals (Figure A-4) to compare histogram classes. This figure suggests that numbers of mass-wasting initiations reached a twentieth-century peak in the early 1960's, with 49% occurring prior to 1964, 23% during the 1965-1983 time interval, and 28% following 1984. The bulk of the earliest landslides occurred during the period that includes initial harvests at the lowest elevations in the WAU area, as well as first entries into mid-elevation basins. The first pulse involved extensive clearcutting of terrace surfaces and modern floodplains of the North Fork Stilliguamish River during the 1930's through early 1940's, followed by clearcutting and road-building in upper French and mid Squire creeks during the 1950's and early 1960's. Minimal harvesting and road building in steeper terrain has occurred since the early 1990's. A substantial percentage of landslide initiations following 1992 are related to natural disturbances of glacial sediments in the mid and upper Boulder River drainage, as well as terrace-face undercutting by the lower Boulder River, augmented by upslope harvest disturbances.

Figure A-4 tends to support observations of Perkins and Collins (1997), who concluded that landslide activity and accompanying coarse-sediment delivery peaked in the Boulder/French/Squire watersheds during the 1940's, based on sediment-delivery volume estimates from inventoried landslides. As these authors correctly point out, however, landslide-frequency data can be misleading as a sole measure of the magnitude and timing of sediment delivery to channels, since a large number of geographically small landslides might produce less volume than a few very large landslides.

Figure A-4. Frequency distribution of mass-wasting occurrences (number of landslides), reclassed in equal time intervals.



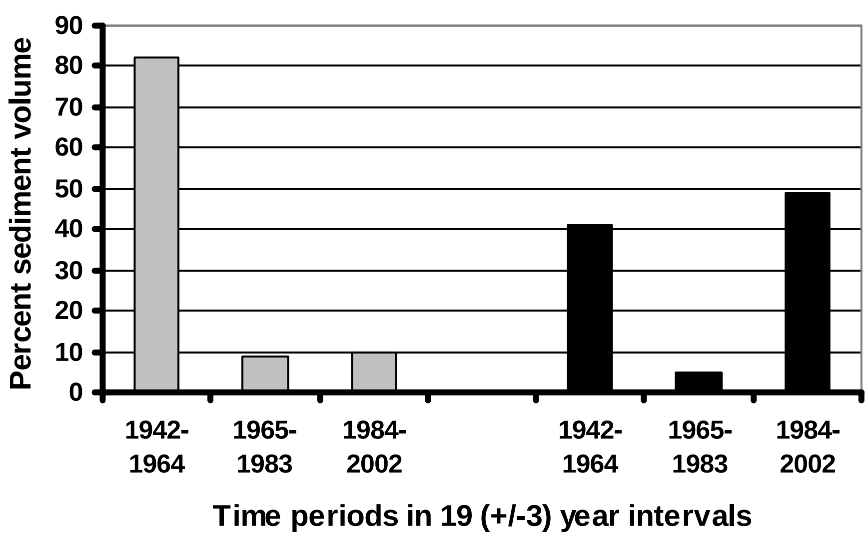
Consequently, a crude sediment-production calculation was made to estimate the relative sediment-delivery regime during the three time periods represented in Figure A-4 (i.e., 1942-1964, 1965-1983, and 1984-2002). Given the steep terrain throughout at least two-thirds of the WAU study area, there was little variation in sediment-delivery potential. All but two of the observed mass-wasting sites delivered sediment directly to the channel network (see Table A-1). The majority (95%) delivered 100% of landslide debris and debris-torrent-transported materials to the channel network. Percent sediment delivered to the channel network (i.e., Type 1-5 waters) for the 100 inventoried mass-wasting sites was determined by: (1) estimating landslide area from aerial photos or from field measurements; for sites not measured, a representative area was assumed from averaging range values for landslide sizes given in the WFPB (1997) guidelines (i.e., 250 yd^2 for small landslides, 1250 yd^2 for medium landslides, and 3500 yd^2 for large landslides); (2) measuring or assuming conservative values for landslide depth, based on field observations, averaged longitudinally across the landslide body (i.e., 1.0 yd. for

SR landslides, 1.5 yd. for SSD landslides in the small size range, and 3.0 yd. for larger deep-seated failures); and, (3) multiplying the resulting volume for each landslide by the percent sediment delivery estimated in Table A-1. In addition, sediment production for the glaciated and deglaciated areas was not estimated because of the density of mass-wasting sites and complex nature of sediment production and routing through the proglacial channels feeding Type 5 channels downslope.

Obtained sediment-yield values admittedly are very crude first-order approximations. They nevertheless can be used for comparative purposes (i.e., comparing relative volumes between time intervals) because assumptions were made uniformly for all landslides in a time class. Absolute values are not shown here because of the temptation for some readers to reference them as established fact.

Figure A-5 shows the outcome of the sediment-yield approximations, as two different scenarios. Estimates are graphed as percent sediment volume delivered by landslides in each time-interval class. The first scenario (a), shown as gray bars on the histogram, represents the percent volume estimated for landslides occurring through 2001 (i.e., most recent aerial photos). This estimate suggests that the bulk of sediment delivery to channels came from landslides occurring in the 1942 to 1964 time interval (i.e., when logging in the lower elevations and mid elevations was tapering off following initial harvest). Scenario (a) supports observations made regarding Figure A-4 that, based on frequency of landslide initiations, mass wasting activity peaked in the earlier part of the last century. Figure A-5(a) suggests that 82% of total estimated sediment volume delivered to WAU streams occurred prior to 1964. Similarly, Perkins and Collins (1997) sediment-volume estimates for the WAU study area indicate that about 67% of sediment was delivered from landslides in their inventory during roughly the same time period (1941-1956). Their inventory, however, largely excluded mass-wasting features in the alpine and subalpine zones (i.e., their Alpine Denudation Zone) and also contained 77 fewer inventoried failures.

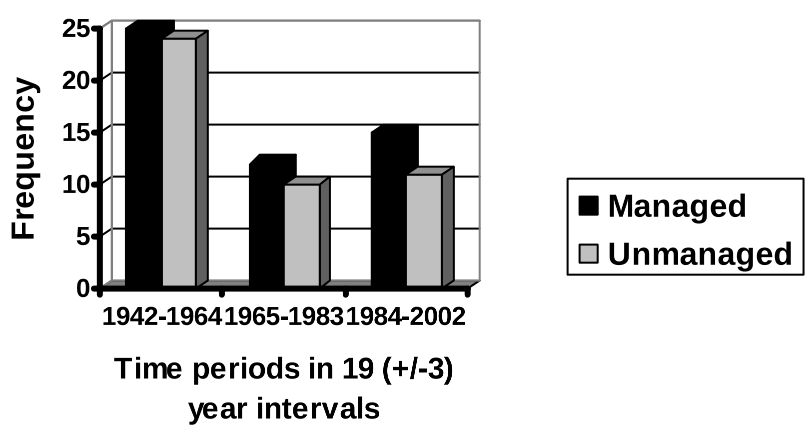
Figure A-5. Percent sediment volume delivered to streams in two scenarios: (a) excluding 2002 landslide (gray bars); (b) including 2002 landslide (black bars).



In February 2002, however, a massive, catastrophic, naturally triggered landslide occurred in the Squire Creek drainage that removed a section of the USFS Road 2040 and delivered on the order of 200,000 yds^3 of rock and debris to Squire Creek. This sediment volume, added to that estimated for all other landslides in the 1992 to 2001 time interval, pushed the sediment-yield percent from 10% to 49% of total sediment delivered from inventoried landslides (see Figure A-5(b); black bars). This result suggests that very large landslides can, in fact, dominate the sedimentation regime relative to numerous small landslides in a basin, and that landslide frequency is not necessarily directly related to volumes of sediment delivered to streams. By the same token, implying from Figure A-5(b) that landslide activity has increased over time in the WAU study area is not altogether true, since one very large, naturally caused landslide overwhelmed the estimated sediment volume for the 1984 to 2002 time period.

Figure A-4 indicates that landslide frequency was at least 20% higher in the 1942 to 1964 time period, and Figure A-5 suggests that these landslides contributed a large percentage volumetrically of sediments delivered to stream channels. The next logical question is what role timber harvest and road-building played in triggering sediment delivery to channels. Figure A-6 shows the frequency distribution of the 100 inventoried mass-wasting sites in the three time periods, according to their land-use associations. Note that this figure differs from Figure A-4 in that the mass-wasting features in the glaciated alpine and subalpine zones are not included (i.e., Figure A-6 includes forested lands only). Figure A-6 indicates that, overall, there were relatively more landslides and associated debris torrents initiated in the forested portions of the WAU study area due to clearcutting and roading than to natural disturbances, but by a rather slim margin (i.e., 52% to 48%). Figure A-6 also suggests that logging influences on mass wasting were greatest during the early 1930's through mid 1960's. Also, there has been a relatively insignificant increase in frequency and sediment production from landslides triggered by logging since the mid 1960's; this likely is due to the fact that relatively minimal logging has occurred in steeper terrain during this time.

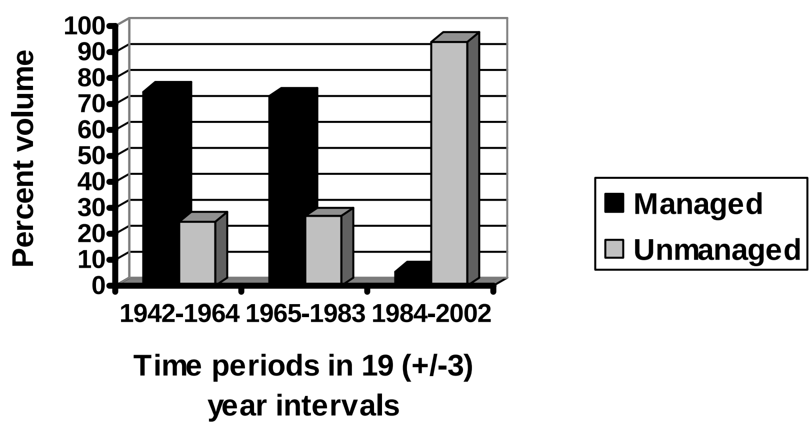
Figure A-6. Frequency distribution of 100 inventoried mass-wasting sites (i.e., number of landslides) by land-use association for the three time periods. (Excludes mass wasting in the alpine/subalpine zones.)



An additional observation is that alpine glacial and deglaciated zones in the WAU study area initiate a significant number of landslides and debris torrents. Comparing Figure A-5, that accounts for observed mass wasting in these areas, with Figure A-6, which excludes them, demonstrates the major role of the glaciated and recently deglaciated terrain in supplying sediment to the channel network. Landslides in unmanaged terrain during the 1942 to1964 time period comprise 73% of failures, versus 51% when mass wasting in the alpine and subalpine zones is excluded. Hence, although forest practices have a demonstrable effect on landslide frequencies and sediment delivery to streams, natural disturbances appear to have dominated mass wasting, in the WAU area as a whole, throughout much of the last century.

A final observation from Figure A-6 is that mass wasting in unmanaged, forested terrain during each of the three time periods is similar in magnitude to that on managed lands when landslide frequencies are compared (i.e., 24 landslides on unmanaged land versus 25 landslides in timber-harvest units and associated with logging roads). When sediment-delivery estimates are used to compare relative contributions from natural and management-related causes, however, the contrast is much more substantial. For example, 25% of estimated sediment delivery to channels in the 1942 to 1964 time period came from unmanaged terrain, compared with 75% from landslides in clearcuts and from road failures (see Figure A-7). The greatest volumes of sediment were estimated from deep-seated failures in continental glacial deposits that were triggered or reactivated by ground-based yarding impacts to landslide headscarps. Conversely, sediment-delivery volume estimates for the 1984 to 2002 time period were overwhelmed by the naturally triggered 2002 landslide in Squire Creek (see Figure A-7; this landslide accounts for virtually all sediment yield depicted in unmanaged class).

Figure A-7. Percent sediment volume delivered by 100 inventoried mass-wasting sites, according to land-use association for the three time periods. (Excludes mass wasting in the alpine/subalpine zones.)



The answer to the question of whether forest practices or natural disturbances have dominated the mass-wasting regime, at least since 1942, is complicated by the fact that sediment-delivery volume estimates have not been made for the alpine and subalpine zones. Sediment volumetric estimates appear to yield a more accurate understanding of the respective roles of managed and unmanaged terrain in contributing sediment to channels. Formulating a method for estimating sediment production and supply rates above treeline, however, is problematic for a number of reasons, including the fact that some processes are active on spatial and temporal scales much finer than those of the aerial-photo record. This means that important sources of sediment production might be missed, leading to a skewed sediment-volume estimate. In addition, clues to mass-wasting site age commonly employed in analyses of forested terrain (e.g., the type and size of vegetation regrowth) are absent from the alpine zone.

Hence, some questions regarding dominant trigger mechanisms remain unresolved. The following conclusions, however, can be drawn from this analysis:

(1) Natural processes of sediment production in the WAU area tend to dominate the sediment-delivery regime, although intensive periods of logging (e.g., 1930's to 1960's and some renewed activity in the late 1980's and early 1990's) have contributed significant amounts of sediment to stream channels.

(2) During the period of most intensive timber harvest (1930's to 1960's), at least 75% of the estimated sediment delivery to channels came from harvest units and logging roads, compared with 25% from natural disturbances within the forested zone. Hence, even though natural rates of sediment production are high, intensive forest management has significantly accelerated stream sedimentation (i.e., by several orders of magnitude).

(3) Some logging practices (e.g., ground-based and partial-suspension yarding, sidecast road construction, unmaintained roads) have resulted in large failures that dominate the sediment-delivery regime even though landslide frequency has been on a par with that of natural disturbances. And;

(4) Slopes appear to be particularly sensitive to logging impacts in steeper, metasedimentary and metavolcanic bedrock west and southwest of Whitehorse Mountain, and along terrace faces in continental glacial deposits (e.g., lower Boulder River basin).

5.0 Description of Mass-Wasting Units

Mass-wasting map units (MWMUs) were generated based on spatial distributions of landslides and debris torrents in the WAU study area (see Map A-1), in addition to rock llithologies as described by Tabor et al. (1988), WDNR (2001), and Dragovitch et al. (2002a, 2002b). Eleven MWMUs were created and are shown in Map A-2 (see Appendix A-1). Complete descriptions of each MWMU can be found in Forms A-2 (see

Appendix A-1) and will not be repeated here. Table A-3 summarizes the basic elements of the MWMU descriptions.

MWMUs have been mapped as broad polygons for a number of reasons. The rationale for MWMUs 1 and 2, which correspond nearly identically with units (1) and (2) of the alpine glacial and subalpine zones delineated on Map A-1, have been described in

Table A-3. Summary of mass-wasting unit (MWMU) physical characteristics; see Forms A-2 for full descriptions.

MWMU	LS/DF frequency	Geology	Active processes	Areal extent
1	50+	Alpine glacial and subalpine zone; metasedimentary, metavolcanic, and volcanic bedrock	Rockfall, rock avalanche, snow/debris avalanche, SR landslides, DT	Ubiquitous throughout MWMU 1
2	20+	Alpine glacial and subalpine zone; metasedimentary, metavolcanic, and volcanic bedrock mantled by glacial sediments in places	Rockfall, rock avalanche, snow/debris avalanche, SR landslides, DT	Ubiquitous throughout MWMU 1
3	37+	Quaternary continental glacial recessional deposits; Quaternary alluvium	SR landslides, DT; snow/debris avalanches	Convergent slopes only
4	35	Bedrock mantled by Quaternary continental glacial recessional deposits	SSD, SR, and LPD landslides, DT	Convergent slopes exceeding 25% slope only
5	4	Argillite, Whitehorse Mtn. Volcanics	SR landslides, DT; snow/debris avalanches	Convergent slopes exceeding 25% only
6	47	Metasedimentary and metavolcanic bedrock	SR landslides, DT, snow/debris avalanching	Convergent slopes exceeding 25% only
7	13	Quaternary continental glacial till deposits	SR landslides, DT, rockfall, snow/debris avalanching	Convergent slopes only
8	4	Metasedimentary bedrock	SR landslides, DT, rockfall, snow/debris avalanching	Convergent slopes exceeding 25% only
9	11	Metagabbro, gabbro	SR landslide, DT, rock avalanching	Convergent slopes
10	6	Quaternary continental glacial outwash-plain deposits	SR and SSD landslides, DT	Convergent slopes
11	0	Quaternary continental glacial outwash-plain deposits, Glacier Peak lahar deposits, alluvial-fan and bog deposits, alluvium	No mass-wasting processes identified	Entire MWMU area

report section 4.0. MWMUs 3 through 10 also have been mapped as broad polygons based on landslide densities and substrate characteristics, but mass-wasting behavior primarily occurs in convergent slope forms (e.g., tributary-drainage headwalls and inner gorges, outer bends of river channels undercutting relatively unconsolidated materials, zero-order basins, snow and rock avalanche chutes) and largely on slopes exceeding 25% gradient. In most cases, the mature forest canopy and inaccessibility prevented mapping at a greater resolution. Field observations suggest that, at least in accessible portions of the WAU study area, mass-wasting sites visible on the ground were hard or impossible to see in aerial photos. Hence, these units were mapped as larger polygons to incorporate mapped, unmappable, and/or suspected or potential failure sites. It is quite likely that mapped failures in these units represent only a portion of past or existing failures. Given the relative inaccessibility of much of the study area, any management activities in these MWMUs would need to account for mass-wasting sites shown on Map A-2, along with any features located in convergent slope forms identified on the ground.

Several other points pertinent to MWMU boundary designation are that several (e.g., MWMUs 4, 5, 6, 8, and 9) have been subdivided into (a) and (b) components based on observed landslide and debris-torrent density. Also,debris-torrent tracks initiated in one MWMU are mapped as part of the MWMU even if they cross another MWMU located downslope. For example, MWMU 6 is split into 6a, which corresponds to observed SR landslides and debris torrents on convergent slopes in metasedimentary and metavolcanic bedrock. MWMU 6b represents the remainder of terrain in the same geologic parent material and with the same slope and vegetational characteristics. Landslides were not visible in aerial photos within MWMU 6b, due to the thick forest canopy, but a number of very small features were identified in the field (e.g., along the nonmaintained spur road entering upper French Creek basin and along the channel side walls), indicating that there is a strong potential for mass wasting in areas underlain by the same rock lithologies. MWMU 6a also includes debris-torrent runout tracks that cross into MWMUs 6b, 7, and 8.

6.0 Description of Mass-Wasting Hazard-Potential Ratings

Form A-4 (see Appendix A-1) summarizes MWMUs by mass-wasting potential ratings, delivery potential ratings, and potential hazard ratings (see Table A-2, WFPB, 1997). Definitions for low, moderate, and high were taken from WFPB (1997), with the exception that MWMU ratings were designated irrespective of any known relationships between landslide potential and land-use practices, due to the preponderance of sites unlikely to undergo forest practices (e.g., wilderness area). For example, MWMU 1 is rated according to the forest-practices rating scheme even though the potential for timber harvest and road building in this unit probably is slim to none. Note that ratings apply only to convergent slopes in MWMUs 3 through 10; divergent and planar slope forms would be considered to have low hazard potential, given that mass-wasting features were not identified there.

Table A-4 summarizes the rationale used to assign hazard-potential ratings for each MWMU. Form A-2 (see Appendix A-1) contains more detailed information. Factors considered in applying hazard potential ratings were: (1) density of mass-wasting sites as shown in Map A-1 and Table A-3, relative to other MWMU units in the WAU study area; (2) geologic units and soil characteristics; (3) landform and slope properties; (4)

proximity to stream channels, drainage density, and evidence of sediment deliverability; (5) vegetation cover (i.e., soil and bedrock exposure); and, (6) mass-wasting potential based on geomorphic similarity with existing landslide sites. About 50% of the WAU area has been assigned a high hazard-potential rating, although high ratings apply only to convergent slope forms in about half of that area. Roughly 25% of the remaining terrain has been assigned a low hazard rating due primarily to little evidence of existing

Table A-4. Rationale for hazard potential ratings for each mass-wasting map unit (MWMU); see Forms A-2 and A-4 for more detail.

MWMU	Hazard rating	Rationale
1	High	High MW density and MW potential, high potential for sediment delivery to streams due to high stream density and proximity to sources
2	Moderate	Same parent materials and landforms as MWMU1 but MW density and potential lower (medium) based on slope morphology, vegetation, and greater distance from disturbance sources (i.e., glaciers and steep, exposed, weathered bedrock surfaces); high delivery potential
3	Moderate	Same parent materials and landforms as MWMU 4a but MW density and potential lower (medium) based on greater distance from major disturbance sources (i.e., subalpine processes and undercutting by rivers actively incising continental glacial deposits); high delivery potential; MW confined to convergent slopes (e.g. tributary channels)
4a	High	High MW density (unit with numerous active SSD and LPD landslides) and high MW potential due to parent materials and ongoing river incision; high delivery potential; MW confined to convergent slopes
4b	High	High MW density (bedrock mantled by modern and ancient alluvium); MW confined to convergent slopes
5	Moderate	MW density and potential lower relative to other MWMUs in WAU (medium), high delivery potential; MW confined to convergent slopes
6a	High	High MW density and potential; high delivery potential in erosive bedrock; MW confined to convergent slopes
6b	Moderate	Same parent materials and landforms as MWMU 6a but observed MW density lower (medium) although potential remains high on steeper convergent slopes; high delivery potential
7	High	MW density high in continental glacial-till deposits; MW potential high due to erosive substrate; high delivery potential
8a	Moderate	Same parent materials and landforms as MWMU 8b but MW density higher; high delivery potential; MW confined to convergent slopes
8b	Low	Few observed MW features, although parent materials are erosive in places and slopes locally have steep gradients; high delivery potential; MW potential is low relative to other MWMUs in the WAU
9a	High	Same parent material and landforms as MWMU 9a but MW density and potential is higher; unit contains largest SR landslide (Feb. 2002 event); high delivery potential; MW confined to convergent slopes
9b	Moderate	MW density and potential lower relative to MWMU 9a; high delivery potential; MW confined to convergent slopes
10	Moderate	Parent materials and sources similar to MWMU 11 but steeper-gradient terrain; MW density and potential higher than MWMU 11; high delivery potential; MW confined to convergent slopes
11	Low	High surface-erosion potential but low MW density (no landslides or debris torrents observed); low delivery potential relative to other MWMUs due to low-relief terrain

or recent landslides (i.e., within the period covered by the aerial-photo record). Areas in low hazard-rating categories, however, have relatively high surface-erosion rates, as discussed in the Surface Erosion Assessment Report. About 25% of the area falls in the moderate category and largely pertains to convergent slope forms exceeding 25% gradient.

An unanticipated outcome was the low hazard-potential rating for MWMU 8b. This unit occupies the southwestern valley wall of the Boulder River and is underlain by marine metasedimentary rocks composed chiefly of greywacke and argillite that appear, in general, to be less foliated and sheared than metasedimentary and metavolcanic rocks on the opposing Boulder River valley wall (i.e., bedrock underlying much of MWMU 6). These two lithologic units are in fault contact roughly coinciding with the valley floor. A couple of factors reducing mass-wasting potential in MWMU 8 relative to MWMU 6 might include: (1) bedrock underlying MWMU 8 in general could be more indurated than in MWMU 6, thereby making it less susceptible to weathering; (2) bedrock could be less weakened by shearing along the thrust-fault zone since it occupied the overriding thrust plate; (3) less steep slopes overall could reduce landslide potential; and, (4) bedrock surface inclinations generally dipping at relatively shallow angles back into the hillslope, versus with the slope (see Tabor et al., 1988 or WDNR, 2001), could result in fewer failures of thin soils overlying bedrock planes, particularly in zero-order basins and at channel initiation points where topography locally can be steep. MWMU 8 does exhibit more evidence of mass wasting with decreasing distance to glaciated and recently deglaciated terrain in the upper watershed (i.e., delineated as MWMU 8a), indicating that spatial proximity to the alpine zone and its associated erosion processes also is an important factor. Due to terrain inaccessibility and minimal opportunities for field observations, however, few of these speculations regarding mass-wasting behavior in MWMU 8 could be verified on the ground.

Map A-2 was compared with a hazard-ratings map produced for a watershed analysis of the North Fork Stilliguamish River compiled by the U.S.D.A. Forest Service (2000; see Map 3.34). Their map was generated by a computer model that used available GIS covers and empirical relationships to evaluate the potential effects on slope stability of bedrock geology, slope morphology, soil parent material, soil infiltration characteristics, precipitation zones, and designated highly unstable soils (i.e., a unique classification used by the forest service for timber-harvest management). Each of the first five categories was assigned a series of qualitative risk ratings based on identified elements. With respect to bedrock geology, for example, glacial continental recessional deposits, lahar deposits, and alluvium were rated high, whereas rocks in the Helena-Haystack mélange (e.g., igneous, volcanic, and metavolcanic rocks) were rated low. Individual ratings in each category were summed cumulatively to yield a final hazard rating for each map pixel. The primary mapping assumption was that each element in each of the six categories could be assigned a risk rating independently, and that these ratings then could be summed to establish a final rating.

The results of comparing Map A-2 of this report with Map 3.34 of the federal report are mixed. In general, much of the WAU area yielded comparable hazard potential ratings. For example, MWMUs 3, 4a, 5, 7, and 10 are in general agreement with broad patterns shown on Map 3.34. Other map polygons, however, had diametrically opposed ratings. The most obvious difference is the high hazard rating assigned to alpine and subalpine zones in MWMUs 1 and 2, compared with a low rating produced by the federal slope-stability model. Likely explanations for the difference are:

(1) This study used inventoried mass-wasting sites to establish landslide densities, as per the state methods for assigning hazard ratings. Forest-service scientists did not have access to a comprehensive landslide inventory at the time.

(2) Mass wasting was defined, in this study, to include rockfall, snow and debris avalanching, and other processes that dominate alpine erosion zones and contribute substantial amounts of coarse sediments to the channel network. Results of this study (e.g., Table A-1) suggest that mass-wasting processes in alpine and subalpine zones area are some of the more important ones in the WAU area for providing continuous sources and supplies of coarse sediments to the channel network (e.g., fish-bearing waters of Squire Creek). And;

(3) The federal study assigned low risk ratings to parent materials (e.g., bedrock, talus, colluvium, tills, boulder-rich deposits), zones of little to no soil formation, and highland precipitation zones, which cumulatively yielded an overall low hazard rating.

Other differences between the two hazard maps included a low hazard-potential rating in this study for Quaternary glacial deposits, lahar deposits, and alluvium on the low-relief terraces of the North Fork Stilliguamish River (i.e., MWMU 11) versus a moderate rating in the federal study. Again, the primary difference probably is the use of mass-wasting inventories to assign hazard ratings in this study. The higher hazard rating by the federal study largely was influenced by a highest risk value assigned to continental-recessional-outwash and lahar deposits, which appears to have outweighed the low value assigned to the lowest hillslope gradient category.

7.0 Discussion of Trigger Mechanisms

Trigger mechanisms are described in Forms A-2 (see Appendix A-1) for each MWMU. Table A-5 summarizes trigger mechanisms determined from aerial photos and field observations to cause mass wasting in each MWMU.

The primary trigger mechanisms at upper and mid elevations (i.e., in the mountain core of the WAU area) appear to be rockfall; avalanches with a mixture of rock, snow, and debris; debris slides on steeply sloped bedrock surfaces; snow-melt-generated debris torrents and peak-flow-induced erosion of tributary side walls; and side-wall slumping in glacial distributary channels as they shift laterally over time. Rockfall and rock avalanches might not deliver coarse sediments to the channel network, depending on their proximity to tributary channels. Channelized avalanches tend to erode stream beds, resulting in debris torrents that typically travel to the valley floors due to short travel distances and steep to nearly vertical slopes. These processes couple with forest-management-related triggers at mid elevations (e.g., mid Squire Creek and upper French basins, and north-facing slopes of Whitehorse Mountain and Ridge) to cause shallow-rapid landslides and debris torrents that directly enter mainstem and tributary channels, delivering substantial amounts of coarse-grain-dominated sediments to the channel network. At mid elevations, natural (e.g., headwall perturbations) and

Table A-5. Summary of triggering mechanisms for the mass-wasting map units (MWMU).

MWMU	Triggering mechanisms
1	Natural alpine-glacial, alpine-deglaciated, and subalpine erosive processes, including rockfall, snow and rock avalanching, snow-melt-generated debris torrents and peak-flow-induced erosion of tributary side walls, planar failures of debris accumulated on bedrock surfaces, slumping and lateral migration of distributary channel side slopes with time – all mechanisms defined as shallow mass wasting for this study – with high potential for delivering coarse sediments to the channel network.
2	Same as MWMU 1.
3	Snow/debris avalanching and debris torrents emanating from MWMUs 1 and 2 undercut tributary side walls in MWMU 3, causing inner-gorge failures and surface ravel; yarding and felling trees in and across incised tributary channels, causing small failures in channel beds and side slopes; inadequate road maintenance that allows sediment to clog cross drains and result in drainage failure accompanied by roadbed erosion and debris-torrent initiation; high potential for delivering coarse and fine sediments to the channel network; MW largely confined to convergent slopes.
4	River undercutting of relatively unconsolidated, continental-glacial deposits, particularly in outside river bends, promoting SR, SSD, and LPD landslides and SR failures piggy-backed on larger chronic failures; debris-torrent scour at tributary junctions in glacial deposits; in lower Boulder River, toeslope undercutting by natural river dynamics is exacerbated by timber harvest disturbances (e.g., yarding, slash piling) on headscarps of SSD and LPD landslides; introduces fine and coarse sediments to the channel network; MW largely confined to convergent slopes.
5	In MWMU 5a, channel side-wall and headwall failures associated with snow/debris avalanching and debris torrents emanating from MWMUs 1 and 2, producing SR landslides; in MWMU 5b, yarding across marble outcrops and road drainage problems have disturbed channel headwalls and side slopes, resulting in SR landslide and DT initiation; introduces coarse sediments to the channel network; MW largely confined to convergent slopes.
6	Yarding and high-lead logging, road cross-drain blockages, road sidecast failures, and landing failures have initiated SR landslides and DT in thin soils overlying bedrock in the French Creek drainage, contributing coarse and fine sediments to the channel network; tree toppling (e.g., from windthrow) and other natural disturbances (e.g., avalanching, headward channel erosion) of zero-order basins and channel-initiation points has dislodged soils and regolith, causing SR landslides and DT, and triggering secondary failures in tributary channels downslope, in unmanaged stands; introduces coarse and medium-grained sediments to the channel network; MW largely confined to convergent slopes.
7	Natural and management-related SR landslides and DT emanating from MWMU 6 have undercut channel side slopes in MWMU 7, triggering subsequent inner-gorge failures; road fillslope failures have caused SR landslides and DT in upper French Creek basin; natural processes as described in MWMU 6; introduces coarse and fine sediments to the channel network; MW largely confined to convergent slopes.
8	Snow/rock avalanching, channel-headwall disturbance from windthrow, headward erosion, and other natural processes, including SR landslide and DT emanating from MWMU 6, have incised channels, causing secondary side slope failures and DT; introduces coarse sediments to the channel network; MW largely confined to convergent slopes.
9	Snow/rock avalanching, rockfall, and possibly seismic activity (e.g., 2002 landslide) have caused channel side slope failures and DT that introduce coarse and fine sediments to the channel network; MW largely confined to convergent slopes.
10	Road construction, drainage problems, and ground-based yarding or tractor skidding have destabilized soils in tributary channels, particularly along breaks-in-slope, causing SR landslide and DT initiations in channel side slopes, introducing coarse and fine sediments to the channel network; MW largely confined to convergent slopes.
11	No mass wasting observed.

management-related disturbances (e.g., yarding, road fillslope failures, cross-drain failures) have triggered shallow-rapid landslides and debris torrents in continental glacial deposits and soils overlying bedrock, introducing coarse and fine sediments to the tributary channels. Continental glacial deposits, particularly in the upper and lower Boulder River basin, tend to be susceptible to destabilizing by river incision, resulting in a number of small, sporadic deep-seated failures. In the lower Boulder basin, these natural failures are exacerbated by harvest activity (e.g., yarding and slash piling on headscarps, yarding across the face of one identified LPD failure). Portions of “Qls” units are more susceptible to sporadic instability, particularly in headscarp and toeslope areas, due to groundwater recharge in glacial sands overlying clays. SSD landslides show evidence of instability due to the combination of logging impacts along headscarps and channel undercutting of toeslopes. At lower elevations, mass wasting is largely confined to inner gorges of channels, where breaks-in-slope have been disturbed by ground-based yarding and tractor skidding, as well as by older harvest techniques (e.g., railroad logging). Parent materials at the lowest WAU elevations on low-relief terraces and modern floodplains (e.g., continental glacial deposits, lahar layers, hyper-concentrated flood deposits, and alluvium; MWMU 11) are susceptible to disruption because of their relatively unconsolidated textures. Although substantial surface erosion has occurred in these areas, largely associated with tractor logging, no mass-wasting features were found.

8.0 Confidence in Work Products

Overall, confidence in the field observations, aerial-photo interpretations, and analysis are moderately high, given the available resources, which included relatively good aerial-photo coverage, geologic maps of the area, previous watershed-assessment work (e.g., Perkins and Collins, 1997; U.S.D.A. Forest Service, 2001), video coverage of the 2002 landslide, and field observations made in most terrain types excluding the glaciated alpine zone and MWMUs in the upper Boulder River and French Creek basins.

The largest drawback to the study was the relative inaccessibility of substantial parts of the WAU area. Lack of access by road, trail, or air into many watersheds, including most of the Boulder River Wilderness Area, relegated much of the study to remotely gathered information (e.g., aerial photos) and extrapolations based on portions of the WAUs that were accessible. Access was made even more difficult during this study by blowouts on spur-road approaches to Typso Pass and upper French Creek, where entry to the WAU area would have taken several multi-overnight expeditions. Observations were made in some less accessible areas, including upper Squire Creek basin, mid French Creek basin (accessed via the channel because the spur road was virtually impenetrable due to unthinned young second growth), and mid Boulder River basin (accessed by field crews on a multi-day trip).

This study would have benefited greatly from field investigations in upper French Creek, where the density of mass-wasting and debris-torrent features associated with road and landing failures is one of the highest. A detailed analysis of this area should be done to determine how best to decommission roads and reduce landslide impacts to French Creek. Unfortunately, the only viable access currently is by air, since massive blowouts in spots on the access spur road have removed overburden to expose nearly sheer bedrock faces, thereby effectively preventing entry of heavy equipment.

Previous years (at least five) of fieldwork in the North Cascades (i.e., in and around North Cascades National Park) greatly assisted me in making inferences regarding active processes and mass-wasting behavior in alpine and subalpine environments, especially glaciated and recently deglaciated terrain like that in the Whitehorse area. In addition, at least 12 years of experience in aerial-photo interpretation in western Washington were helpful. Hence, I feel confident about mass-wasting interpretations in the zones above treeline.

Another confounding factor in identifying mass-wasting features was the solid, old-growth canopy cover in much of the forested, unmanaged portions of the study area (i.e., Boulder River Wilderness Area, late-successional reserves also managed by the U.S. Forest Service). These areas coincidentally were some of the least accessible. Hence, it is likely that the mass-wasting inventory under-represents existing and potential mass-wasting sites in MWMUs 5, 6, and 8. Resolving this issue would have required low-elevation overflights (thereby violating airspace) in the wilderness area. In addition, some of the private lands were inaccessible on the northern flanks of Whitehorse Ridge due to locked gates and unresolved questions regarding ownership.

One method for acknowledging potential under-represented landslide densities in inaccessible areas was to map MWMUs as broad polygons with the stipulation that they apply to convergent slope forms only. While this method yields a map with relatively less resolution and detail, it does make sure that potential failure sites in given landforms are recognized. Trying to map only observed failures, given the handicaps of mature forest cover and inaccessibility, in my opinion would have resulted in a less accurate product.

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11.0 APPENDIX A-1

11.1 Forms A-1, A-2, A-3, A-4

Codes used in Form A-1

Landslide Process:

SR	shallow, rapid landslide
SSD	small, sporadic, deep-seated landslide
LPD	large, persistent, deep-seated landslide
DT	debris torrent
AT	avalanche track
SE	associated surface erosion

Certainty:

D	definite
P	probable
Q	questionable

Size:

S	small; < 500 yd^2
M	medium; 500 yd^2 – 2000 yd^2
L	large; 2000 yd^2 – 5000 yd^2
VL	very large; > 5000 yd^2

Photo year:

Y	yes; landslide observed on specified aerial-photo series

Slope form:

CC	concave or convergent
CV	convex or divergent
P	planar
IG	channel inner gorge
HW	channel headwall or incision point

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
1	1	31/8E-2M1	4a	SR, DT	D	2000 (L)			
2	1	31/8E-4A1	3	SR	D	<500 (S)			
3	1	31/8E-4F1	4a	SR	D	4000 (L)			Y
4	1	31/8E-4J1	3	SR	D	3850 (L)			
5	1	31/8E-4Q1	8	SR,SE	D	L			
6	1	32/8E-28J1	6a	SR, debris fan	D	S			Y
7	1	32/8E-29A1	6a	SR	P	S			Y
8	1	32/8E-29C1	6a	SR	P	S			Y
9	1	32/8E-29J1	4b	SR	P	S			Y
10	1	32/8E-29K1	4b	SR	D	S			Y
11	1	32/8E-32P1	8b	SR	P	S			
12	1	32/8E-33A1	4b	SR	D	S			
13	2	31/8E-2N1	4a	SSD	P	<500 (S)	Y	Y	Y
14	2	31/8E-2P1	4a	SSD	P	<500 (S)	Y	Y	Y
15	2	31/8E-2P2	4a	DT	D	S	Y	Y	
16	2	31/8E-2P3	3	SR, DT	D	S			
17	2	31/8E-2Q1	3	SR, DT	D	550 (M)			
18	2	31/8E-11B1	4a	SR	D	S			
19	2	31/8E-11B2	4a	SR	D	S			
20	2	31/8E-11B3	4a	SR	D	S			
21	2	31/8E-11C1	4a	SR	D	S			
22	2	31/8E-11G1	4a	SR	D	S			
23	2	31/8E-11G2	4a	SR	D	S			

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
24	2	31/8E-11J1	4a	SR	D	13000 (VL)			Y
25	2	31/8E-11J2	4a	SR	D	M			
26	2	31/8E-12D1	4a	chronic SR, DT	D	220 (S)			
27	2	31/8E-12D2	4a	SSD,SR	D	2000 (L)		Y	Y
28	2	31/8E-12F1	4a	chronic SR	P	550 (M)	Y	Y	Y
29	2	31/8E-12K1	4a	SR	D	S			Y
30	2	31/8E-14C1	8a	chronic SR, DT	D	<500 (S)			Y
31	3	31/9E-16A1	3	SR, AT	D	S	Y	Y	
32	3	32/9E-34H1	9a	SR,DT	D	S			
33	3	32/9E-34R1	9a	SR, DT	D	S			
34	3	32/9E-35L1	9a	SR, DT	D	1.8×10^5,VL			
35	3	32/9E-35N1	9a	DT	D	S	Y	Y	
36	4	32/9E-27N1	6a	SR, DT	P	M			
37	5	32/9E-28F1	9b	SR	P	S			
38	5	32/9E-28G1	10	DT	D	S	Y	Y	
39	9	32/8E-14B1	10	chronic sfc erosion, sporadic SR	P	S	Y	Y	
40	9	32/8E-14B2	10	chronic sfc erosion, sporadic SR	P	S	Y	Y	

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
41	9	32/8E-23A1	5b	SR	D	M			
42	9	32/8E-23A2	5b	DT	D	L			
43	9	32/8E-24A1	2	SSD	D	550 (M)			
44	9	32/8E-24E1	5b	DT	D	S			
45	9	32/8E-24L1	5b	SR	D	S			
46	10	32/8E-10K1	10	chronic SR	D	S			
47	10	32/8E-10Q1	10	SSD	D	550 (M)	Y	Y	Y
48	10	32/8E-15L1	7	DT, DBF	D	L			
49	10	32/8E-15N1	7	SSD	P	S	Y	Y	
50	10	32/8E-22B1	6a	SR	D	S			Y
51	10	32/8E-22G1	6a	SR	D	S			Y
52	10	32/8E-22F1	6a	SR	D	S			
53	10	32/8E-22K1	6a	sporadic SR, DT	D	L			Y
54	10	32/8E-22K2	6a	sporadic SR, DT	D	L			Y
55	10	32/8E-22L1	6a	SR, DT	D	M			
56	10	32/8E-22M1	6a	SR, DT	P,D	2000 (M)		Y	Y
57	11	32/8E-20F1	7	DT	P	S			Y

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
58	11	32/8E-20G1	6a	DT	D	S			
59	11	32/8E-20J1	6a	SR, DT	D	3000 (L)			
60	11	32/8E-20J2	6a	DT	D	S			
61	11	32/8E-20H1	6a	DT	D	S			Y
62	11	32/8E-21F1	6a	SR, DT	D	S (many)			
63	11	32/8E-21K1	6a	SR, DT	D	S (many)			
64	11	32/8E-21L1	6a	SR, DT	D	<500 (S)			Y
65	11	32/8E-21M1	6a	DT	D	M			Y
66	11	32/8E-21Q1	6a	SR, DT	P	<500 (S)		Y	Y
67	11	32/8E-25L1	6a	DT	D	S		Y	
68	11	32/8E-25M1	6a	DT	D	S		Y	
69	11	32/8E-25M2	6a	DT	D	S		Y	

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
70	11	32/8E-26C1	6a	SR	D	M			
71	11	32/8E-26E1	6a	SR, DT	D	L			
72	11	32/8E-26F1	6a	SR, DT	D	2000 (L)			
73	11	32/8E-26F2	6a	SR, DT	D	2000 (L)			
74	11	32/8E-26K1	7	SR, DT	D	M			
75	11	32/8E-26L1	6a	SR, DT	D	M			
76	11	32/8E-27D1	6a	SR, DT	D	L			Y
77	11	32/8E-27E1	7	SR, DT	D	<500 (S)			
78	11	32/8E-27F1	7	DT	D	6000 (VL)			
79	11	32/8E-27F2	7	DT	D	S			Y
80	11	32/8E-27J1	7	SR, DT	D	M			
81	11	32/8E-28A1	6a	SR, DT	D	<500 (S)			Y
82	11	32/8E-28A2	7	SR, DT	D	<500 (S)			
83	11	32/8E-28H1	7	SR, DT	D	<500 (S)			
84	12	32/8E-17B1	4a	SR, surface erosion	D	S			
85	12	32/8E-17C1	4a	LPD	D	17,000(VL)	Y	Y	Y

	Sub-Basin	Landslide I.D. No.	MWMU	Landslide Process	Certainty	Size (yd^2)	Photo Yr 1942	Photo Yr 1949	Photo Yr 1964
86	12	32/8E-17D1	10	SR, surface erosion	D	<500 (S)	Y	Y	Y
87	12	32/8E-17E1	4a	SSD	D	7000 (VL)	Y	Y	Y
88	12	32/8E-17E2	4a	SSD	D	3400 (L)	Y	Y	
89	12	32/8E-17E3	4a	SSD	D	2000 (M)	Y	Y	
90	12	32/8E-17E4	4a	SSD	D	3400 (L)	Y	Y	
91	12	32/8E-17M1	4a	SSD	D	11,000(VL)	Y	Y	
92	12	32/8E-17M2	4a	SSD	D	S	Y		
93	12	32/8E-17N1	4a	SSD	D	70 (S)	Y	Y	
94	12	32/8E-17N2	4a	SSD	D	S	Y		
95	12	32/8E-18R1	4a	SSD	D	8900 (VL)		Y	
96	12	32/8E-18R2	4a	SSD	D	M		Y	
97	12	32/8E-19L1	6a	SR, surface erosion	D	S			Y
98	14	32/9E-26N1	9a	SR, DT	D	13,000(VL)			Y
99	14	32/9E-27F1	9b	DT	D	S			Y
100	15	31/8E-1A1	1	rock avalanche	D	M			
	12	1005	10	LPD	Q	M			
	12	1010	10	LPD	Q	L			

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
1	31/8E-2M1				Y		Y, 100%	T2	100
2	31/8E-4A1	Y	Y	Y	Y		Y, 100%	T5	100
3	31/8E-4F1	Y	Y	Y	Y		Y, 100%	T2	50
4	31/8E-4J1		Y	Y	Y		Y, 100%	T2	100
5	31/8E-4Q1				Y		Y, unknown	T5	25
6	32/8E-28J1						Y, 100%	T5	20
7	32/8E-29A1	Y					Y, 100%	T5	50
8	32/8E-29C1						Y, 100%	T5	50
9	32/8E-29J1	Y					Y, 100%	T5	50
10	32/8E-29K1						Y, 100%	T5	50
11	32/8E-32P1				Y		Y, 100%	T5	100
12	32/8E-33A1				Y		Y, 100%	T4	50
13	31/8E-2N1	Y	Y	Y	Y		Y, 100%	T3	80
14	31/8E-2P1	Y	Y	Y	Y		Y, 100%	T3	100
15	31/8E-2P2		Y		Y		Y, 100%	T3	100
16	31/8E-2P3	Y	Y				Y, 100%	T5	50
17	31/8E-2Q1				Y		Y, 100%	T5	100
18	31/8E-11B1		Y				Y, 100%	T3	100
19	31/8E-11B2		Y				Y, 100%	T3	100
20	31/8E-11B3		Y				Y, 100%	T3	100
21	31/8E-11C1		Y				Y, 100%	T3	100
22	31/8E-11G1		Y				Y, 100%	T3	100
23	31/8E-11G2		Y				Y, 100%	T3	100

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
24	31/8E-11J1		Y				Y, 100%	T3	50
25	31/8E-11J2				Y		Y, 100%	T3	100
26	31/8E-12D1		Y	Y			Y, 100%	T5	80
27	31/8E-12D2	Y	Y	Y	Y		Y, 100%	T3	30
28	31/8E-12F1	Y	Y	Y	Y		Y, 100%	T3	50
29	31/8E-12K1						Y, 100%	T3	100
30	31/8E-14C1	Y	Y	Y	Y		Y, 100%	T5	80
31	31/9E-16A1						Y, 100%	T5	30
32	32/9E-34H1		Y	Y			Y, 100%	T5	100
33	32/9E-34R1		Y (1979)				probable	T5	100
34	32/9E-35L1					Feb. 2002	Y, 80%	T1	100
35	32/9E-35N1						Y, 100%	T5	100
36	32/9E-27N1				Y		Y, 100%	T5	50
37	32/9E-28F1				Y		Y, 100%	T5	100
38	32/9E-28G1				Y		Y, 50%	T5	100
39	32/8E-14B1						Y, 100%	T3	50
40	32/8E-14B2						Y, 100%	T3	75

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
41	32/8E-23A1		Y		Y		Y, unknown	T5	100
42	32/8E-23A2	Y	Y		Y		Y, 100%	T5	10
43	32/8E-24A1				Y		Y, 100%	T4	100
44	32/8E-24E1	Y					Y, 100%	T5	100
45	32/8E-24L1		Y (1985)				Y, 100%	T5	100
46	32/8E-10K1				Y		Y, 100%	T1	75
47	32/8E-10Q1		Y		Y		Y, 100%	T5	50
48	32/8E-15L1		Y				Y, 100%	T5 to T3	100
49	32/8E-15N1						Y, 100%	T5	75
50	32/8E-22B1				Y		Y, 100%	T5	100
51	32/8E-22G1				Y		Y, 100%	T5	100
52	32/8E-22F1				Y		Y, 100%	T5	75
53	32/8E-22K1				Y		Y, 100%	T5	100
54	32/8E-22K2				Y		Y, 100%	T5	100
55	32/8E-22L1				Y		Y, 100%	T5	100
56	32/8E-22M1	Y	Y	Y	Y		Y, 100%	T5	20, 100
57	32/8E-20F1						Y, 100%	T5	75

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
58	32/8E-20G1	Y					Y, 100%	T5	100
59	32/8E-20J1	Y	Y	Y <500 (S)			Y, 100%	T5	100
60	32/8E-20J2	Y					Y, 100%	T5	100
61	32/8E-20H1						Y, 100%	T5	50
62	32/8E-21F1				Y		Y, 100%	T3	75
63	32/8E-21K1				Y		Y, 100%	T3	75
64	32/8E-21L1	Y		Y			Y, 100%	T5	100
65	32/8E-21M1				Y		Y, 100%	T5	100
66	32/8E-21Q1			Y			Y, 100%	T5	10
67	32/8E-25L1						Y, 100%	T5	100
68	32/8E-25M1						Y, 100%	T5	100
69	32/8E-25M2						Y, 100%	T5	100

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
70	32/8E-26C1				Y		unknown	indeterminate	100
71	32/8E-26E1		Y (M)		Y		Y, 100%	T5	100
72	32/8E-26F1			Y (1992; 600 (M))	Y		Y, 100%	T5	100
73	32/8E-26F2				Y		Y, 100%	T5	100
74	32/8E-26K1				Y		Y, 100%	T5	100
75	32/8E-26L1				Y		Y, 100%	T5	100
76	32/8E-27D1		Y				Y, 100%	T2	100
77	32/8E-27E1			Y			Y, 100%	T5	100
78	32/8E-27F1	Y (S)	Y				Y, 100%	T3	100
79	32/8E-27F2						Y, 100%	T3	100
80	32/8E-27J1				Y		Y, 100%	T5	100
81	32/8E-28A1			Y			Y, 100%	T3	100
82	32/8E-28A2			Y			Y, 100%	T5	100
83	32/8E-28H1			Y			Y, 100%	T5	100
84	32/8E-17B1				Y		N		100
85	32/8E-17C1	Y	Y	Y	Y	Y	Y, 75%	T1	50

	Landslide I.D. No.	Photo Yr 1972/73	Photo Yr 1983	Photo Yr 1991/92	Photo Yr 2001	Post 2001	Sed. Delivery	Stream Type	% Exposed
86	32/8E-17D1	Y	Y	Y	Y	Y	N		50
87	32/8E-17E1			Y			Y, 100%	T1	75
88	32/8E-17E2						Y, 100%	T1	50
89	32/8E-17E3						Y, 100%	T1	50
90	32/8E-17E4						Y, 100%	T1	50
91	32/8E-17M1						Y, 100%	T1	50
92	32/8E-17M2						Y, 100%	T1	90
93	32/8E-17N1			Y			Y, 100%	T1	90
94	32/8E-17N2						Y, 100%	T1	90
95	32/8E-18R1						Y, 100%	T1	75
96	32/8E-18R2	Y	Y		Y		Y, 100%	T1	50
97	32/8E-19L1						Y, ?	indeterminate	100
98	32/9E-26N1						Y, 100%	T5	80
99	32/9E-27F1						Y, 100%	T5	100
100	31/8E-1A1		Y (1985)		Y		unknown	indeterminate	100
	1005		Y				N	T5	<15
	1010		Y			Y	N	T5	<15

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
1	31/8E-2M1	Wilderness	56-65	CC, IG	silt loam, silty clay	continental glacial outwash	
2	31/8E-4A1	Indeterminate	26-55	CC, IG	silt loam, silty clay	continental glacial outwash	
3	31/8E-4F1	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
4	31/8E-4J1	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
5	31/8E-4Q1	Wilderness	26-55	CC	gravel/sand loam, silt loam	metased.- graywacke, argillite	
6	32/8E-28J1	Wilderness	116-125	CC, HW	gravel/sand loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
7	32/8E-29A1	Wilderness	106-115	CC, HW	gravel/sand loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
8	32/8E-29C1	Wilderness	76-85	CC, IG	gravel/sand loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
9	32/8E-29J1	Wilderness	56-65	CC	sand/silt loam	metased.- graywacke, argillite	
10	32/8E-29K1	Wilderness	56-65	CC	sand/silt loam	metased.- graywacke, argillite	
11	32/8E-32P1	Wilderness	56-65	CC, IG	gravel/sand loam	metased.- graywacke, argillite	
12	32/8E-33A1	Wilderness	26-55	CC	sand/silt loam	metased.- graywacke, argillite	
13	31/8E-2N1	Wilderness	56-65	CC, IG	silt loam, silty clay	continental glacial outwash	
14	31/8E-2P1	Wilderness	56-65	CC, IG	silt loam, silty clay	continental glacial outwash	
15	31/8E-2P2	Wilderness	56-65	CC, IG	silt loam, silty clay	continental glacial outwash	
16	31/8E-2P3	Wilderness	56-65	CC, IG	silt loam, silty clay	continental glacial outwash	
17	31/8E-2Q1	Wilderness	56-65	CC, HW	silt loam, silty clay	continental glacial outwash	
18	31/8E-11B1	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
19	31/8E-11B2	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
20	31/8E-11B3	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
21	31/8E-11C1	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
22	31/8E-11G1	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	
23	31/8E-11G2	Wilderness	26-55	CC	silt loam, silty clay	continental glacial outwash	

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
24	31/8E-11J1	Wilderness	26-55	CC to P	silt loam, silty clay	continental glacial outwash	
25	31/8E-11J2	Wilderness	26-55	CC, IG	silt loam, silty clay	continental glacial outwash	
26	31/8E-12D1	Wilderness	56-65	CC, HW	silt loam, silty clay	continental glacial outwash	
27	31/8E-12D2	Wilderness	26-55	P, CC	silt loam, silty clay	continental glacial outwash	
28	31/8E-12F1	Wilderness	26-65	CC	silt loam, silty clay	continental glacial outwash	
29	31/8E-12K1	Wilderness	56-65	CC	silt loam, silty clay	metased.- cherty greenstone	
30	31/8E-14C1	Wilderness	>135	CC, IG	fine sandy loam, gravel/sand loam	metased.- graywacke, argillite	
31	31/9E-16A1	Wilderness	76-85	CC, IG	gravel/sand loam	tonalite, alpine glacial drift	
32	32/9E-34H1	clearcut, road	56 - >135	CC	gravelly/cobbly sand loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
33	32/9E-34R1	clearcut, road	56-65	CC	gravelly/cobbly loam, sandy loam	alpine glacial drift	
34	32/9E-35L1	clearcut, road, none	116-125	P,CC	thin loams, gravelly silt loam	gabbro in fault contact with metaserpentinite	
35	32/9E-35N1	Wilderness	96-105	CC, IG	gravelly silt loam	sandstone in fault contact with peridotite, metasperpentinite	
36	32/9E-27N1	wilderness; adjacent to harvest unit	26-55	CC	alternating layers of sands, silts, sandy loams, silty clay loams	metased., metavolc.- greenstone with graywacke, argillite, chert	
37	32/9E-28F1	road crossing	26-55	CC	thin gravelly loam	continental glacial outwash	
38	32/9E-28G1	Road	26-55	P	2409	continental glacial outwash	
39	32/8E-14B1	Clearcut	26-55	IG	4344	continental glacial outwash	
40	32/8E-14B2	Clearcut	26-55	IG	5233	continental glacial outwash	

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
41	32/8E-23A1	clearcut, road	76-85	CC	gravelly/sand loam	andesite, basaltic andesite	
42	32/8E-23A2	Road	76-85	CC	gravelly/sand loam	andesite, basaltic andesite	
43	32/8E-24A1	Clearcut	26-55	CC, IG	gravelly/sand loam	continental glacial outwash	
44	32/8E-24E1	Road	26-55	CC, HW	gravelly/sand loam	andesite, basaltic andesite	
45	32/8E-24L1	Road	86-95	CC	none (talus)	andesite, basaltic andesite	
46	32/8E-10K1	old clearcut	26-55	CC, IG	5233	Glacier Peak lahar deposits	
47	32/8E-10Q1	clearcut	26-55	IG	5233	continental glacial outwash	
48	32/8E-15L1	road, landing	56-65	CC, IG	thin gravelly loam	contact between tonalite and continental glacial till	
49	32/8E-15N1	Clearcut	86-95	IG	thin gravelly loam	continental glacial till	
50	32/8E-22B1	FS unmanaged	76-85	CC	thin gravelly loam	metased.- cherty greenstone	
51	32/8E-22G1	FS unmanaged	76-85	CC	thin gravelly loam	metased.- cherty greenstone	
52	32/8E-22F1	FS unmanaged	86-95	CC	thin gravelly loam	metased.- cherty greenstone	
53	32/8E-22K1	FS unmanaged	126-135	CC,HW,IG	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
54	32/8E-22K2	FS unmanaged	126-135	CC,HW,IG	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
55	32/8E-22L1	FS unmanaged	126-135	CC, HW	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
56	32/8E-22M1	FS unmanaged	116-125	CC,HW,IG	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
57	32/8E-20F1	clearcut, road	76-85	CC	alternating layers of sand, silt, clay loams	continental glacial till	

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
58	32/8E-20G1	Road	86-95	CC, IG	alternating layers of sand, silt, clay loams	contact between continental glacial till and greenstone	
59	32/8E-20J1	Road	86-95	CC, IG	alternating layers of sand, silt, clay loams	metased., metavolc.- greenstone with graywacke, argillite, chert	
60	32/8E-20J2	Road	76-85	CC, IG	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
61	32/8E-20H1	Road	56-65	CC	alternating layers of sand, silt, clay loams	continental glacial till	
62	32/8E-21F1	past selective harvest; blowdown	76-85	CC	thin gravelly loam	contact between continental glacial till and greenstone	
63	32/8E-21K1	past selective harvest and road exascerbated natural causes of instability	96-105	CC	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
64	32/8E-21L1	Clearcut	86-95	CC, IG	gravelly sand loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
65	32/8E-21M1	Road	116-125	CC	thin gravelly loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
66	32/8E-21Q1	Road	86-95	CC, IG	thin loams, gravelly silt loam	metased., metavolc.- greenstone with graywacke, argillite, chert	
67	32/8E-25L1	wilderness	86-95	CC, IG	thin gravelly loam	contact between andesite and cherty greenstone	
68	32/8E-25M1	wilderness	106-115	CC, IG	thin gravelly loam	metased.- cherty greenstone	
69	32/8E-25M2	wilderness	106-115	CC, IG	thin gravelly loam	metased.- cherty greenstone	

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
70	32/8E-26C1	Clearcut	56-65	P	thin gravelly loam	metased., metavolc.-greenstone with graywacke, argillite, chert	
71	32/8E-26E1	Road	96-105	CC	thick gravelly sandy clay loams	metased., metavolc.-greenstone with graywacke, argillite, chert	
72	32/8E-26F1	Clearcut	96-105	CC,HW,IG	thick gravelly sandy clay loams	metased., metavolc.-greenstone with graywacke, argillite, chert	
73	32/8E-26F2	Road	96-105	CC	thick gravelly sandy clay loams	metased., metavolc.-greenstone with graywacke, argillite, chert	
74	32/8E-26K1	Road	56-65	CC	gravelly sand loam	continental glacial till	
75	32/8E-26L1	clearcut, road	86-95	CC	thick gravelly sandy clay loams	continental glacial till	
76	32/8E-27D1	clearcut?	86-95	IG	thick gravelly sandy loams	metased., metavolc.-greenstone with graywacke, argillite, chert	
77	32/8E-27E1	Road	76-85	CC. HW	thick gravelly sandy loams	continental glacial till	
78	32/8E-27F1	Road	86-95	CC	thick gravelly sandy loams	continental glacial till	
79	32/8E-27F2	Road	56-65	CC	thick gravelly sandy loams	continental glacial till	
80	32/8E-27J1	Road	66-75	CC	gravelly sand loam	continental glacial till	
81	32/8E-28A1	Clearcut	86-95	CC (seep)	thick gravelly sandy loams	metased., metavolc.-greenstone with graywacke, argillite, chert	
82	32/8E-28A2	Road	86-95	CC, HW	none (talus)	continental glacial till	
83	32/8E-28H1	Road	86-95	CC, HW	none (talus)	continental glacial till	
84	32/8E-17B1	Clearcut	86-95	P, midslope	5233	continental glacial outwash	
85	32/8E-17C1	Clearcut	56-65	CC, IG	5233	continental glacial outwash	

	Landslide I.D. No.	Assoc. Land Use	Gradient (percent)	Slope Form	Soils	Bedrock	Elevation
86	32/8E-17D1	Clearcut	86-95	CV, P	5233	continental glacial outwash	
87	32/8E-17E1	indeterminate	56-65	CC, IG	5233	continental glacial outwash	
88	32/8E-17E2	Clearcut	56-65	CC, IG	1956	continental glacial outwash	
89	32/8E-17E3	Clearcut	96-105	CC, IG	5237	continental glacial outwash	
90	32/8E-17E4	Clearcut	76-85	CC, IG	1956	andesite, basaltic andesite	
91	32/8E-17M1	Clearcut	96-105	CC, IG	5237	metased., metavolc.- greenstone with graywacke, argillite, chert	
92	32/8E-17M2	Clearcut	76-85	CC, IG	1956	metased., metavolc.- greenstone with graywacke, argillite, chert	
93	32/8E-17N1	indeterminate	56-65	CC, IG	5237	metased., metavolc.- greenstone with graywacke, argillite, chert	
94	32/8E-17N2	Clearcut	56-65	CC, IG	5237	metased., metavolc.- greenstone with graywacke, argillite, chert	
95	32/8E-18R1	Clearcut	26-55	CC, IG	5233	continental glacial outwash	
96	32/8E-18R2	Clearcut	26-55	CC, IG	5233	continental glacial outwash	
97	32/8E-19L1	Road	96-105	CC	5660	metased., metavolc.- greenstone with graywacke, argillite, chert	
98	32/9E-26N1	FS unmanaged	>135	CC, HW	5660	gabbro	
99	32/9E-27F1	Road	56-65	CC	1956	continental glacial outwash	
100	31/8E-1A1	Wilderness	116-125	CC	thin gravelly sandy loams	metased.- cherty greenstone	
	1005	Clearcut	56-65	CC	5233	continental glacial outwash	
	1010	Old clearcut	56-65	CC	5233	continental glacial outwash	

	Landslide I.D. No.	Comments
1	31/8E-2M1	Located across Boulder River from Germain Cr. confluence
2	31/8E-4A1	Occurred in >50 year old stand; roaded area upslope
3	31/8E-4F1	River undercut hillslope toe; probably both SR and LPD behavior
4	31/8E-4J1	
5	31/8E-4Q1	Large area of blowdown and root-throw; activity has caused numerous small, localized failures and associated debris tracks
6	32/8E-28J1	Large debris fan upstream of T-5 confluence might have been initiated by rockfall; black/white photo contrast too bad to see HW area clearly
7	32/8E-29A1	
8	32/8E-29C1	
9	32/8E-29J1	Looks like toeslope has been undercut on concave-planar slope with numerous seeps
10	32/8E-29K1	Looks like toeslope has been undercut on concave-planar slope with numerous seeps
11	32/8E-32P1	Toeslope has been undercut.
12	32/8E-33A1	Small area unraveling in inner gorge.
13	31/8E-2N1	Bank undercut by river
14	31/8E-2P1	Bank undercut by river
15	31/8E-2P2	Associated with T5 confluence
16	31/8E-2P3	In 2001, fresh HW scar and DT track is overgrown
17	31/8E-2Q1	Toppled trees can be seen in 2001 photo.
18	31/8E-11B1	River undercut slope toe; overgrown with hardwoods by 2001
19	31/8E-11B2	River undercut slope toe; overgrown with hardwoods by 2001
20	31/8E-11B3	River undercut slope toe; overgrown with hardwoods by 2001
21	31/8E-11C1	River undercut slope toe; overgrown with hardwoods by 2001
22	31/8E-11G1	River undercut slope toe; overgrown with hardwoods by 2001
23	31/8E-11G2	River undercut slope toe; overgrown with hardwoods by 2001

	Landslide I.D. No.	Comments
24	31/8E-11J1	Shows both SR and LPD geomorphic features
25	31/8E-11J2	Toeslope failure
26	31/8E-12D1	Chronic SR in what appears to be large seepage area; deciduous cover appears to be regularly disturbed by unravelling hillslope
27	31/8E-12D2	Extensive seepage area with complex landslide feature (SSD plus sporadic SR and surface ravel); erosion activity sporadic throughout area between 1942-2001.
28	31/8E-12F1	Chronic SR in what appears to be large seepage area; deciduous cover appears to be regularly disturbed by unravelling hillslope
29	31/8E-12K1	Toeslope undercut by river
30	31/8E-14C1	Bank undercut by river
31	31/9E-16A1	Avalanching undercut adjacent hillslope, causing SR failure
32	32/9E-34H1	Clearcut and road drainage at fault contact between gabbro and metasedimentary/ metavolcanic rocks.
33	32/9E-34R1	Fillslope failure from spur road; identified in 1979 high-elevation photos; scale of photo precluded analyzing runout path.
34	32/9E-35L1	Field and video-tape verified; might be related to regional earthquake activity; associated with bedrock-outcrop failure at headwall; clearcut and road in failure tail, although relationship to failure mechanics not clear; see report for other refs.
35	32/9E-35N1	
36	32/9E-27N1	SR and DT associated with patch of blowdown; toeslope undercut; opposite side of stream channel from old clearcut extending into riparian area, the disturbance from which appears to have increased channel-bed mobility and associated toeslope undercutting.
37	32/9E-28F1	Appears to be a drainage problem on an old, unmaintained road.
38	32/9E-28G1	Initiated by road and yarding activity.
39	32/8E-14B1	
40	32/8E-14B2	

	Landslide I.D. No.	Comments
41	32/8E-23A1	Occurred in unmapped T5 channel; initiated close to marble outcrop.
42	32/8E-23A2	Old DT scar and runout; starts from uppermost road switchback; DT track cuts through marble outcrop.
43	32/8E-24A1	Toeslope failure.
44	32/8E-24E1	Between road switchbacks at the initiation point of a T5 channel; initiated close to marble outcrop.
45	32/8E-24L1	Initiated close to marble outcrop.
46	32/8E-10K1	Toeslope failure.
47	32/8E-10Q1	At confluence of T1 and T5 channels; initiated in fault zone.
48	32/8E-15L1	Failure of road fillslope at road switchback; initiation point at contact between tonalite and glacial till.
49	32/8E-15N1	
50	32/8E-22B1	Appears to be secondary failure associated with DT undercutting toeslope.
51	32/8E-22G1	Appears to be secondary failure associated with DT undercutting toeslope.
52	32/8E-22F1	
53	32/8E-22K1	Sporadic SR with associated DT. Cause not definite, although logging upslope to ridgeline on back side of ridge might have destabilized first-order basin (contributing area) containing failure activity.
54	32/8E-22K2	Sporadic SR with associated DT; see 32/8E-22K1 notes.
55	32/8E-22L1	Actively retreating headwall; scarp active in 2001 based on vegetation disturbance.
56	32/8E-22M1	In 2001, SR scar mostly overgrown (80%) but DT track still eroded (100%).
57	32/8E-20F1	Black/white photo contrast bad, so definitive identification is problematic.

	Landslide I.D. No.	Comments
58	32/8E-20G1	DT track initiates at uppermost road switchback and extends to lowermost switchback.
59	32/8E-20J1	Road-drainage related; sidecast problems also.
60	32/8E-20J2	Road-drainage related; sidecast problems also.
61	32/8E-20H1	Road-drainage problem on switchback
62	32/8E-21F1	At least 6 small SR failures initiated by downed trees (one or several at a time); tree tip-overs or removals have initiated SR and DT entering creek, providing substantial LWD; based on field observations.
63	32/8E-21K1	Numerous small SR failures initiated by downed trees; some big trees harvested at downstream end; farther upstream tree tip-overs related to toeslope undercutting by DT in French Creek, DT from road via T-5 channels, and root-rot; French Creek shows numerous signs of DT, DBF, and scour affecting toeslopes; per field observations.
64	32/8E-21L1	<20 year old clearcut
65	32/8E-21M1	T-5 initiation point retreated headward to road cutslope in 2001; road bed is gone.
66	32/8E-21Q1	Road drainage appears to have exascerbated natural slide behavior; in 1949 and 1973, DT track is vegetated with slide alder but still identifiable.
67	32/8E-25L1	Forested, but probably developed in unconsolidated glacial sediments
68	32/8E-25M1	Forested, but probably developed in unconsolidated glacial sediments
69	32/8E-25M2	Forested, but probably developed in unconsolidated glacial sediments

	Landslide I.D. No.	Comments
70	32/8E-26C1	Occurred near ridgeline; probably yarding-related, as yarding trails lead from scarp downslope to road and landing.
71	32/8E-26E1	Culvert- or sidecast- related; upper road failure occurred in 2001 and lower switchback faillure observed in 1983 photos.
72	32/8E-26F1	Yarding disturbance to headwall; initial failure triggered two others downslope in IG; can see DT track in French Cr. for about 1500 linear ft. downstream; failure plane enlarging laterally as failures retreat upslope to channel breaks-in-slope.
73	32/8E-26F2	Sidecast and/or culvert-function failure.
74	32/8E-26K1	Sidecast and/or culvert-function failure.
75	32/8E-26L1	Sidecast failure.
76	32/8E-27D1	Starts at edge of clearcut; unmanaged stand upstream on T5
77	32/8E-27E1	Road-drainage related
78	32/8E-27F1	
79	32/8E-27F2	Road-drainage related
80	32/8E-27J1	Sidecast and/or culvert-function failure.
81	32/8E-28A1	Adjacent to mapped T5
82	32/8E-28A2	Road-drainage related, in addition to HW disturbance.
83	32/8E-28H1	Road-drainage related, in addition to HW disturbance.
84	32/8E-17B1	Probably associated with yarding disturbances.
85	32/8E-17C1	Secondary river channel has undercut toeslope; pond has formed along toeslope in bend of secondary channel (see 2001 photos) due to blockage of secondary or overflow channels by logging slash and jettisoned logs.

	Landslide I.D. No.	Comments
86	32/8E-17D1	Scars from cable logging.
87	32/8E-17E1	Toeslope undercut by Boulder River in sharp channel bend.
88	32/8E-17E2	Toeslope undercut by Boulder River.
89	32/8E-17E3	Toeslope undercut by Boulder River.
90	32/8E-17E4	Toeslope undercut by Boulder River.
91	32/8E-17M1	Toeslope undercut by Boulder River.
92	32/8E-17M2	Series of slides; IG slopes disturbed by yarding and slopes were unravelling.
93	32/8E-17N1	
94	32/8E-17N2	Initiated at contact between metasedimentary/metavolcanic rocks and continental glacial outwash.
95	32/8E-18R1	Toeslope undercut by Boulder River in sharp channel bend.
96	32/8E-18R2	Toeslope undercut by Boulder River.
97	32/8E-19L1	Sediment was delivered to Boulder River by runoff or unmapped T-5 channel.
98	32/9E-26N1	Rock avalanche initiated DT; see photo EMM 7-115 (7/23/64).
99	32/9E-27F1	Road-drainage related.
100	31/8E-1A1	Rock avalanche appears active or fresh in 2001 photos.
	1005	Identified as discrete feature by W. Lingley (2004) based on fresh headscarp erosion in 2004.
	1010	Identified as discrete feature by W. Lingley (2004) based on fresh headscarp erosion in 2004.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 1

Description: MWMU 1 comprises areas of recently active, currently active, or potential future glacial and periglacial alpine erosion. Catastrophic and chronic mass-wasting processes include: (1) alpine glacial erosion; e.g., side-slope failures associated with bedrock scour and avulsions in shifting glacial-outflow distributary channels, and consequent delivery of coarse and fine sediments through distributary networks to Type 5 stream channels; this activity could also be classified partly as surface erosion and, consequently, appears simultaneously on Surface-Erosion module map B-4; (2) rockfall from precipitous bedrock exposures in glaciated and recently deglaciated areas (e.g., knife ridges, cirque walls, and arêtes of the Whitehorse - Bullon - Three Fingers massif) associated with freeze-thaw and other forms of mechanical weathering; (3) snow and rock avalanching, largely in avalanche chutes emanating from glaciated or recently deglaciated areas throughout MWMU 1; (4) secondary debris avalanches along sidewalls of snow-debris avalanche chutes associated with seasonal snowmelt events; and (5) inner-gorge failures in unconsolidated, glacially derived materials downcut by channels draining areas of ice, permanent snow, and seasonal snow cover. MWMU 1 also includes avalanche-chute runouts that cross into other mass-wasting map units, because their side-slope instability primarily is maintained by alpine processes of snowmelt runoff and snow - debris avalanching.

Materials: Rock flour, regolith, and weathered rock fragments (e.g., boulder- to sand-sized clasts) from parent bedrock (volcanic, metavolcanic, and metasedimentary rocks in the Whitehorse - Bullon - Three Fingers massif; igneous rocks in the Squire Creek drainage); remobilized Quaternary alpine glacial drift and alluvial-fan deposits; and snow and ice. Little to no soils have formed in higher-elevation deglaciated areas. Soils at lower elevations (e.g., upper Squire Creek basin), where present, are very shallow, very gravelly loams; principally, lower-elevation slopes in MWMU 1 comprise thick, colluvial boulder deposits or talus, with interspersed colluvial fans supporting very shallow soils and disturbance-regime vegetation (e.g., slide alder, willow, vine maple, devils club).

Landform: Alpine glacial processes have been active in MWMU 1 at least since the Fraser glaciation of the Pleistocene Epoch (i.e., beginning about 18,000 years B.P. (before present)). Deglaciated valleys contain alpine glacial moraine and drift deposits associated with glacial retreat; based on vegetation type and maturity, several ages of side-slope colluvial-fan and valley-bottom alluvial-fan deposits can be identified that presumably are related to successive stages of glacial retreat. Mass-wasting features are evident across all slope forms in MWMU 1, with rockfall and debris avalanches occurring ubiquitously across the unit (i.e., where rock faces are exposed to weathering). Small, shallow-rapid landslides tend to be confined more to slope concavities (e.g., glacial-outflow distributaries, tributary channels) and concave or planar slopes dissected by avalanche chutes. No deep-seated failure behavior was observed, likely due to the thinness or nonexistence of developed soils in the unit.

Slope: Estimated 25% - ∞.

Elevation: About 2400 ft. to 6854 ft., with alpine-process-dominated avalanche chutes and channels runoff-triggered inner-gorge failures extending downslope approximately

MWMU Number: 1 continued

Elevation continued: to 1400 ft. elevation.

Total Area:

MW Processes: Rockfall; rock and debris avalanching; mixed snow and debris avalanching; debris torrents; small, shallow-rapid landslides and inner-gorge failures in avalanche chutes, glacial outflow distributaries and Type 5 channels.

Non-road-related Landslide Density: (optional) None of the failures in MWMU 4 appear to have been caused or influenced by roads.

Forest (and other) Practice Sensitivity: Most of MWMU1 lies in the Boulder River Wilderness; mass wasting is related to natural disturbances. If wilderness legislation was to change and such activities as forest harvest or surface mining were permitted, much of MWMU 1 would not be considered for either because it is above tree-line, snow- or ice- covered almost year-round or permanently, and practically inaccessible using conventional extraction techniques. Side slopes of Squire Creek and other drainages, however, that do support mature forests should be considered high hazard for slope stability because of the steep slopes, thin soils, unconsolidated glacial-drift and alluvial-fan deposits mantling mid- to lower slopes, and the frequency of mapped and unmapped Type 5 drainages and avalanche chutes that have delivered, or have the potential to directly deliver, debris avalanches and torrents from upslope alpine and subalpine basins to mainstem channels. Similarly, mid-slope road building would have the potential to destabilize slope deposits, particularly where routes cross Type 5 channels and avalanche chutes, as has been documented for the present roadbed in Squire Creek (see Surface and Road Erosion Module).

MW Potential: High

Delivery Potential: **High** for subglacial transport of sediment routed through glacial outflow distributaries to Type 5 channels; **high** for snow- and debris- avalanche delivery to the channel network; **high** for debris torrent delivery from Type 5 channels to mainstem channels, based on aerial-photo and field observations; **high to low** for rockfall and rock – debris avalanche delivery, depending on their proximity to channel contribution areas.

Delivery Criteria Used: Field and aerial-photo evidence of road-, snow-, and/or debris-avalanche delivery of sediments directly to Type 5 through Type 3 channels.

Hazard Potential Rating: High

Trigger Mechanism(s): Natural alpine-glacial erosive processes. Seasonal snow avalanching, snowmelt, and glacial peak outflows are chronic catalysts for eroding and transporting snow, ice, and debris downslope to the channel network.

Confidence: Confidence is high, based on historic and recent aerial-photo information and field observations in Squire, Buckeye, Ashton, and Snow Gulch drainages.

MWMU Number: 1 continued

Comments: MWMU1 is mapped as one contiguous block. Above roughly 3000 ft. elevation, mass wasting features (i.e., rockfall and avalanching, inner-gorge failures in distributary channels), associated with past and present alpine glacial activity, are so ubiquitous and interrelated that it is difficult and misleading to attempt to map each as an individual numbered site. Below about 3000 ft. elevation, mass-wasting activity is confined largely to avalanche chutes, mapped and unmapped Type 5 drainages, and talus fields, with the exception of some actively forming talus fields (i.e., exhibiting fresh deposits) that reach the channel upstream of SQ5b in the Squire Creek drainage. There are far more unmapped than mapped Type 5 channels in Squire Creek and elsewhere in MWMU 1 (i.e., those mapped on the hydrolayer maintained by DNR); the number is underrepresented by an estimated 65% to 70%. Consequently, it was difficult, and inaccurate at best, to attempt to map (at 1:24,000 scale) individual avalanche chutes and Type 5 channels delivering materials to Squire, Buckeye, Ashton, Snow Gulch, Gerkman, and Boulder creek drainages. Hence, MWMU 1 is drawn as one large feature. As a result, further delineation of MWMU 1 below tree line needs to be done on the ground, to ensure that unmapped channels and avalanche chutes transporting materials from upslope alpine areas are accurately recorded. For example, it would be important to field-identify the numerous debris chutes and unmapped channels crossing the road spur in upper Snow Gulch, so that the road is adequately maintained and/or decommissioned over the long term.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 2

Description: MWMU 2 units are influenced by the same alpine glacial and periglacial processes described in MWMU 1. These areas largely fall at and below tree line, in currently glaciated or recently deglaciated terrain, and they are disturbed by rockfall, snow and debris avalanching, inner-gorge failures in glacial-outflow or snowmelt channels and associated mapped and unmapped Type 5 stream channels, and small, rapid-shallow landslides in unconsolidated glacial deposits along valley side-slopes (e.g., in Snow Gulch near the toe of the permanent snowpack and, coincidentally, the end of the spur road). Although MWMU 2 units are mapped as blocks, mass-wasting activity is confined principally to slope concavities (e.g., occupied by mapped and unmapped Type 5 channels) and avalanche chutes, as well as talus fields, for example in the upper Gerkman Creek and Boulder River drainages.

Materials: Same as MWMU 1.

Landform: Same as MWMU 1.

Slope: Estimated 25% - ∞.

Elevation: About 2200 ft. to 4800 ft., with alpine-process-dominated avalanche chutes and channels with runoff-triggered inner-gorge failures extending downslope to approximately 1400 ft. elevation.

Total Area:

MW Processes: Rockfall; rock and debris avalanching; mixed snow and debris avalanching; debris torrents; small, shallow-rapid landslides and inner-gorge failures in avalanche chutes, glacial outflow distributaries and Type 5 channels.

Non-road-related Landslide Density: (optional) None of the failures in MWMU 4 appear to have been caused or influenced by roads.

Forest (and other) Practice Sensitivity: Same as MWMU 1; see comments related to areas in MWMU 1 that have been identified below tree line.

MW Potential: Medium. Although the same features are evident in MWMUs 1 and 2, their frequency per area is somewhat less than in MWMU 1. In addition, chutes and snowmelt channels tend to drain smaller areas of permanent or seasonal snowpack and many fewer are associated with glacial outflow. For example, relatively more of the Type 5 channels and avalanche chutes along the northwestern flanks of Whitehorse Mountain appear to be partially vegetated, with less exposed bedrock and soils than those closer to glacial margins or permanent snowfields, suggesting that they are less active temporally.

Delivery Potential: High

Delivery Criteria Used: Based on aerial-photo observations and field reconnaissance,

MWMU Number: 2 continued

Delivery Criteria Used, continued: materials introduced to avalanche tracks and glacial outflow or snowmelt distributaries are delivered directly to the channel network due to the precipitous slopes and short delivery distances.

Hazard Potential Rating: Moderate

Trigger Mechanism(s): Natural, alpine glacial and periglacial erosive processes. Seasonal snow avalanching, snowmelt, and glacial peak outflows are chronic catalysts for eroding and transporting snow, ice, and debris downslope to the channel network.

Confidence: Confidence is high, based on historic and recent aerial-photo information and field observations in Squire, Buckeye, Ashton, and Snow Gulch drainages.

Comments: Similar to MWMU 1, the sizable number of unmapped channels and chutes makes it difficult to map individual features accurately, so that more stable areas between less stable channel inner gorges and avalanche chutes unavoidably are included in MWMU 2. Any projects undertaken on the ground, therefore, need to delineate mapped and unmapped avalanche chutes and Type 5 channels in the field. They also need to provide adequate runout area (e.g., avoid active avalanche-prone slopes) and bank protection of channel inner gorges or side slopes (e.g., when maintaining or decommissioning the USFS road (2040) in Squire Creek). Additionally, current roads (e.g., USFS roads in Snow Gulch and Squire Creek) in general appear to have inadequate cross-drains; many culverts on the Squire Creek road are too small to handle peak snowmelt discharges.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 3

Description: MWMU 3 identifies areas prone to inner-gorge surface erosion and slope failures, the former resulting in chronic raveling and small translational slippage, and the latter as episodic small, shallow-rapid landslides that are too small to be mapped at a 1:24,000 scale. Inner-gorge erosion primarily is linked to peak snowmelt and glacial-discharge flows and associated debris torrents. MWMU 3 is differentiated from other valley-bottom or lesser-gradient-slope areas because it coincides largely with exposed deposits of Quaternary continental glacial outwash (e.g., upper Boulder River and Gerkman Creek drainages) and alpine glacial drift, outwash, and alluvial fans (e.g., upper Squire Creek valley floor and lower Squire Creek floodplain, respectively). These minimally consolidated deposits are prone to destabilization where they mantle slopes exceeding about 25% gradient. Although the triggering mechanisms are similar to those in MWMU 2, the combination of natural alpine-erosive processes in easily mobilized, minimally consolidated Quaternary glacial deposits resulted in the decision to differentiate MWMUs 2 and 3. Deposits of snow avalanche debris, rockfall, and debris torrents in Type 5 channels, linked to channels and avalanche tracks identified in MWMU 2, can be found in MWMU 3 also. Although MWMU 3 units are mapped as blocks, mass-wasting and surface-erosion activities are confined principally to hillslope concavities (e.g., occupied by mapped and unmapped tributaries to the Boulder, Gerkman, and Squire mainstem channels).

Materials: In the upper Boulder River and Gerkman Creek drainages, materials consist of continental-glacier recessional outwash deposits, including well- stratified and sorted sands and gravels (i.e., lithologic unit *Qvr* of Tabor et al., 1988, *Qgo* of WDNR, 2001). In upper Squire Creek, deposits include boulder till (i.e., coincident with channel segment SQ6 and upstream in the valley bottom), gravel and sand outwash in the valley bottom, and drift (i.e., relatively unsorted boulder- to silt- sized clasts) mantling the lower valley walls except where it is displaced by colluvial fans, bedrock exposures, and debris fans at the bases of avalanche chutes and tributary channels (i.e., lithologic unit *Qag* of Tabor et al., 1988; *Qad* of WDNR, 2001). In lower Squire Creek (i.e., SQ3 mainstem segment), steeper side slopes exposed by channel undercutting contain poorly sorted cobble- to boulder- gravels of Holocene age (i.e., roughly 5000 yr. B.P.), presumed to have been deposited where the antecedent Squire Creek emptied onto the Stilliguamish valley plain.

Landform: Same as MWMU 1.

Slope: 25% - 90% in Boulder and Gerkman subunits of MWMU 3; 25% - ∞ in upper Squire Creek; 20% - 25% in lower Squire Creek.

Elevation: 1000 ft. – 2600 ft. (upper drainages); 520ft. – 600 ft. (lower Squire Creek)

Total Area:

MW Processes: Inner-gorge failures and surface raveling; small, shallow-rapid landslides; snow and debris avalanching; debris torrents.

MWMU Number: 3 continued

Non-road-related Landslide Density: (optional)

Forest (and other) Practice Sensitivity: MWMU 3 subunits are located in the Boulder River Wilderness (i.e., upper Boulder River and Gerkman Creek), and managed USFS land (i.e., Squire Creek) with one established USFS road (2040) that parallels the mainstem into the mid-portion of the basin. MWMU 3 roughly coincides with the Squire Creek Late-Successional and Old Growth designated forest (USDA Forest Service, 2000) where timber harvest and road construction are restricted. Hence, future forest practices might not be a near-term issue. However, the conditions of the 2040 road and adjacent old harvest units indicate that slopes in MWMU 3 are sensitive to forest practices where activities disrupt tributary channels, channel side slopes, and avalanche tracks with seasonal snowmelt runoff. As described in the Surface and Road Erosion Module, this road has numerous small failures, primarily in fillslope materials, most of which are associated with inadequate, faulty, or non-existing cross drains. While none of these failures has been large enough to appear on aerial photos, field inventories demonstrate that native materials in the fillslopes are readily eroded and are compromising the integrity of the roadbed. Similar small failures also occur in old harvest areas where thin soils overlying Quaternary cobble-gravel-sand deposits on tributary side slopes have been disrupted by felling and dragging logs. In the last half mile of this road, at least 12 cross-drain-related failures in fill slopes were noted. If left unattended, continued wasting of these unstable sites probably will promote and enlarge shallow-rapid landslides capable of directly delivering substantial coarse and fine sediments to Squire Creek.

MW Potential: Medium. Densities and volumes of small failures initiated in MWMU 3 are relatively less than MWMU 4 in similar parent materials. MWMU 3 is rated medium for mass wasting initiated within the unit and medium for erosive events emanating from upslope areas (i.e., debris flows initiated in MWMU 1) that traverse MWMU 3 and cause secondary failures in tributary inner gorges or avalanche tracks.

Delivery Potential: High.

Delivery Criteria Used: Mass-wasting and surface erosion debris directly enter the channel network from tributary side slopes and avalanche tracks with seasonal snowmelt discharges.

Hazard Potential Rating: Moderate.

Trigger Mechanism(s): Primary mechanisms are: (1) natural alpine erosive processes that introduce materials to glacial and snowmelt distributary channels and tributary channels of Squire, Boulder, and Gerkman mainstems; (2) impedance of channel flow by inadequate, faulty, or non-existing road cross-drains; and, (3) disruption of minimally consolidated parent materials in channel beds and margins caused by tree felling and yarding. In addition, inadequate road maintenance has led to failure of fillslope materials due to misplaced or missing cross-drain outfalls, improper diameter culverts and consequent culvert undermining, and insufficient cross drains for the number of tributary channels present.

MWMU Number: 3 continued

Confidence: High in Squire Creek based on field observations; relatively high in Boulder and Gerkman drainages given the range of aerial photos used.

MWMU Number continued: 3

Comments: The 2040 road presents a management challenge, given its current inaccessibility upvalley of the massive February 2002 landslide (I.D. number 32/9E-35L1). However, road-drainage problems between the washed-out road segment and the road end need to be fixed to minimize initiation and enlargement of fillslope failures.

Similar to MWMU 2, the sizable number of unmapped channels and chutes makes it difficult to map individual features accurately, so that more stable areas between less stable channel inner gorges and avalanche chutes unavoidably are included in MWMU 3. Any projects undertaken on the ground, therefore, need to delineate mapped and unmapped avalanche chutes and Type 5 channels in the field.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 4

Description: MWMU 4 comprises two subunits: (1) *4a* in erodible Quaternary glacial outwash deposits located in the upper Boulder River basin and in the lower-gradient valley of the mainstem downstream of Boulder Falls; and, (2) *4b* in highly sheared meta-sedimentary rocks located in the mid-Boulder drainage between Boulder Falls and the confluence with Gerkman Creek. MWMU 4 encompasses channel margins and toeslopes along the mainstem Boulder River that are highly susceptible to translational and rotational failures (e.g., inner-gorge slab failures, shallow-rapid landslides (SR), and small, sporadic deep-seated failures (SST)) and subsequent chronic slope raveling, as a result of slope undercutting by the Boulder River. In addition MWMU 4a includes the only large, persistent deep-seated failure (LPD) identified within the Boulder-French-Squire WAUs boundary (landslide I.D. number 32/8E-17C1), which occupies a relatively abrupt bend of the Boulder mainstem and has been maintained via upslope groundwater seepage and toeslope undermining by the former main channel (i.e., now a secondary channel).

Materials: In MWMU 4a, materials consist of continental-glacier recessional outwash deposits, including well- stratified and sorted sands and gravels (i.e., lithologic unit *Qvr* of Tabor et al., 1988, *Qgo* of WDNR, 2001). In the upper Boulder River basin, these deposits are veneered by unconsolidated modern alpine glacial drift. In MWMU 4b, materials include Cretaceous-Tertiary-age (i.e., about 65 million years B.P.) metamorphosed sediments that are highly sheared and disrupted, notably along the course of the Boulder River. The present-day river, between Boulder Falls and the upper basin, occupies a zone of shearing created by a thrust fault that is a component of the Darrington-Devils Mountain fault zone (Tabor et al., 1988). Locally along the valley bottom, the metasedimentary rocks are overlain in places by modern, unconsolidated, fluvially transported glacial sediments.

Landform: MWMU 4 occupies the glacially carved, lower and upper valleys of the Boulder River. Between these relatively broader, lower-gradient valley sections lay the steeper-gradient, tightly confined Boulder canyon and Boulder Falls. In the broader valley sections, the river has room to meander, to a moderate degree. It is assumed that, during higher discharge events (e.g., spring runoff, fall discharge of glacially stored water), the river has sufficient stream power to mobilize and transport bedload, as well as undercut toeslopes, leading to the high frequency of observed failures (e.g., at least 16 SR and SSD failures between the Gerkman Creek confluence and the Boulder valley headwall). All failures appear to occur on convergent toeslopes on the outsides of river bends.

The LPD landslide noted previously occurs where the Boulder River has cut into the outwash plain that filled the North Fork Stilliguamish valley during recession of the Quaternary-age Puget Lobe icesheet. The local slope comprises a terrace face undercut by a large bend of the Boulder River; the LPD failure plane occupies only a portion of a larger (i.e., $0.6 mi^2$) arcuate slump feature that appears to be relatively stable today, although the larger failure surface is noticeably hummocky and groundwater seepage is evident. This topography is very similar to another massive slump feature located a couple of river bends to the east, which is mapped by Tabor et al. (1988) as a Holocene-age landslide deposit and shows little recent signs of mass movement or

MWMU Number: 4 continued

Landform continued: instability during the time period covered by available aerial photos (see Map A-2 appended to this report). Given the similarity of these features, it is very likely that the present LPD failure occurs within a much larger, previously unmapped Holocene landslide that most probably was initiated and maintained by an antecedent river channel with significantly greater discharge. At present-day discharge regimes, it is unlikely that either of these antecedent landslides would be reactivated wholesale.

Slope: Estimated 20% - 65% in MWMU 4a and 25% - 100% in MWMU 4b.

Elevation: 1400ft. – 2400ft. for MWMU 4a in upper Boulder basin; 1200ft. – 1400ft. in MWMU 4b; 500ft. – 1000ft. for MWMU 4a in lower Boulder valley.

Total Area:

MW Processes: Mass wasting consists primarily of small to large SR landslides and SSD failures, whose exposed surfaces ravel chronically until vegetation is reestablished. Over the time period covered by aerial photos, many of these features have failed, revegetated, and failed again in response to channel-bend migration and glacially driven stream hydraulics. One LPD failure was identified in the lower basin, as described above. In MWMU 4a, erosive glacial outwash deposits are readily undermined by the river; in the upper basin, a continual supply of alpine glacial drift contributes substantially to slope instability, as evidenced by the frequency of toeslope SR failures. In MWMU 4b, relatively smaller, less frequent SR landslides are observed in metamorphosed sediments overlain locally by modern alpine glacial materials. Debris flows entering the mainstem from initiation points in MWMU 6 upslope have also contributed to destabilizing mainstem sidewalls at tributary junctions. It is likely that toeslopes in MWMU 4b are prone to failure because of the combination of locally erodible bedrock, unconsolidated glacial sediments, and debris-flow activity, coupled with active toeslope undermining by the Boulder River.

Non-road-related Landslide Density: (optional): None of the failures in MWMU 4 appear to have been caused or influenced by roads.

Forest (and other) Practice Sensitivity: The upper unit of MWMU 4a (i.e., upper Boulder basin) and MWMU 4b fall in the Boulder River Wilderness. The lower unit of MWMU 4a lies on state-managed land (State Forest Board Transfer sections 17 and 18, T32N, R8E). All identified failures in this lower unit were present in the earliest photo records available (e.g., 1942, 1949), both prior to and following clearcutting along the channel margins, suggesting that convergent slopes in channel bends, where the flow undermines loosely consolidated glacial materials, are naturally predisposed to instability. However, fresh erosion following timber harvest on failure scarps that were partially revegetated (e.g., landslide I.D. numbers 32/8E-17C1 and 32/8E-17E1), indicates that timber harvest contributes to renewed mass wasting. Therefore, slopes greater than 25% on outside slopes of river bends (i.e., convergent slopes) are naturally prone to failure and appear to be highly sensitive to substrate disturbances from timber harvest, and probably road construction as well. Similar river-bend sites in MWMU 4a and 4b theoretically would be flagged as highly sensitive to management activities also.
.

MWMU Number: 4 continued

MW Potential: High

Delivery Potential: High.

Delivery Criteria Used: Sediment and debris from toeslope failures are delivered directly to the mainstem Boulder River.

Hazard Potential Rating: High.

Trigger Mechanism(s): Upstream of Boulder Falls, natural slope-undercutting processes, caused by a dynamic, glacially influenced river, are the primary mechanism for SR landslides, SSD failures, and chronic slope ravel. In MWMU 4b, debris-flow scour at tributary junctions also plays a role. Downstream of Boulder Falls, natural slope-undercutting processes are accelerated or reactivated by timber harvest and presumably any other management activity that would compact or remove soils and underlying loosely consolidated parent materials.

Confidence: Moderately high. Field observations were made in portions of the lower valley (MWMU 4a) and mid-basin (MWMU 4b). The upper basin proved to be inaccessible during this study, so observations were relegated to aerial-photo interpretation. The time span of the photo record (i.e., 1942 – 2001), however, improved the confidence level in being able to analyze landslide behavior and deduce associated geomorphic hillslope and channel processes from photo information, combined with field knowledge of similar glacially dominated systems in the North Cascades.

Comments: MWMU 4 includes stable and unstable slopes; the hazard rating is specific to convergent slopes, primarily in the outside of river bends and generally exceeding 25% gradient. Intervening areas might have lower susceptibility to failure; however, it was difficult to delineate stable vs. unstable areas at a scale of 1:24,000. The inaccessibility of the upper watershed also made it hard to refine the map unit based on field reconnaissance. In addition, the number of failures in MWMU 4b and parts of 4a likely is underrepresented due to mature forest canopy obscuring the ground. Management or other activities on the ground would benefit from field mapping of individual features and their upslope contribution areas to ensure that unstable slopes are identified accurately.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 5

Description: MWMU 5 is broken into two sub-units: (1) *5a*, in locally foliated, black argillite of Jurassic age (i.e., lithologic unit *TKea* of Tabor et al., 1988, *Jar* of WDNR, 2001), and in continental-derived, Eocene-age feldspathic sandstone and pebble conglomerate (i.e., lithologic unit *Tbs* of Tabor et al., 1988; *Ec(b)* of WDNR, 2001); and (2) *5b*, in late-Triassic volcanics (i.e., Whitehorse Mountain Volcanics, *TKev,* of Tabor et al., 1988; *TRv(ew)* of WDNR, 2001). Mass wasting in MWMU *5a* largely is confined to channel side-wall and headwall failures associated with channel high-discharge events (e.g., spring snowmelt, glacial discharge). Headwall failures are sufficiently small that they are not visible on aerial photographs, especially under mature forest canopies. Channel side-wall failures in MWMU *5a* are visible on aerial photographs and are associated with pulses of avalanching, debris flows, and high discharges emanating from MWMUs 1 and 2. In addition to channel side-wall and headwall failures in MWMU *5b*, there is evidence of in-unit or mid-slope, shallow-rapid landsliding and yarding-trail erosion, particularly near or around prominent outcrops of marble. Portions of MWMUs 1 and 2 are in the same lithologic units on the north flank of Whitehorse Mountain; however, these areas have been differentiated from MWMU 5 because the former are dominated by alpine glacial and periglacial processes, whereas failures in the latter are either secondarily related (e.g., debris-torrent-undermining of channel side-walls) or non-related to alpine processes (e.g., ground disturbance of channel headwalls).

Materials: Debris-torrent-runout deposits in MWMU *5a* contain a mixture of black argillite and glacial debris (i.e., drift and outwash), suggesting that debris flows and high-discharge events mobilize glacial sediments from upstream sources, and then these sediment-laden flows undercut *in-situ* deposits and exposures of black argillite along channel margins. Black argillite exposures are variously erodible locally; they are slightly less indurated (i.e., hardened) than shale and, in the vicinity of Whitehorse Mountain, are dissected by brecciated dikes of metamorphosed dacite, making them more susceptible to erosion. Likewise, exposures of continental sediments are fairly erodible, due in part to their feldspathic, fine-grained content and exposed interbeds of argillite and siltstone. Whitehorse Mountain Volcanics (MWMU *5b*) consist of slightly metamorphosed andesite and basaltic andesite that are fairly competent except around sedimentary interbeds and marble outcrops. Soils are thin to non-existent.

Landform: MWMU 5 occupies the steep sideslopes of Whitehorse Mountain. Most mass wasting has occurred in association with the numerous mapped, and even more numerous unmapped, channels in which seasonal discharges fluctuate substantially due to glacial discharges and snowmelt.

Slope: 26% - ∞

Elevation: 1000 ft. – 5200 ft.

Total Area:

MW Processes: Most mass-wasting activity is debris-torrent- and avalanche- related, with small to very-small channel side-wall and headwall failures. In MWMU *5a*,

MWMU Number: 5 continued

MW Processes continued: channelized debris torrents combine glacial deposits with clasts eroded from continental sedimentary exposures to form distinct waves of sediment that typically move down channels during snowmelt and glacial-discharge events. In some channels (e.g., Buckeye, Ashton), DNR field staff have noted small walls of sediment (e.g., some several feet deep) crossing and burying road surfaces at channel-road intersections during spring runoff events. In MWMU 5b, identified failures have been associated with ground disturbances of channel side-walls and headwalls (e.g., most related to logging and road drainage or sidecast).

Non-road-related Landslide Density: (optional) An estimated 95% of mass wasting is not related to roads; most of MWMU *5a* lies in non-roaded or harvested areas.

Forest (and other) Practice Sensitivity: MWMU *5a* occupies steep-gradient slopes on the flanks of Whitehorse Mountain that largely have not been clearcut or roaded. The frequency of naturally occurring channel-margin failures indicates that channel side-walls and headwalls are susceptible to failure and that management activities (e.g., logging, roading for mining or logging access) would have the potential for accelerating natural rates of slope destabilization. The combination of steep slopes, erodible parent material, and high channel-discharge regimes suggests that management-related ground disturbance would increase failure potential significantly. While parent materials in MWMU 5b are relatively less erodible overall, photo and field observations suggest that in areas where erodible sedimentary interbeds and outcrops exist in conjunction with stream channels, the channel margins are more susceptible to failure. Most of the larger, mappable failures in this sub-unit are related to logging and roads; inadequate road maintenance appears to be one of the main issues.

MW Potential: Medium

Delivery Potential: High

Delivery Criteria Used: All observed debris avalanches and torrents, as well as channel side-wall and headwall failures, have delivered sediments directly to the channel network.

Hazard Potential Rating: Moderate

Trigger Mechanism(s): In MWMU *5a*, channel-margin failures appear to be triggered primarily by snow and rock avalanches, debris torrents, and high stream discharges that undermine channel side-slopes and headwalls. In MWMU *5b*, channel-margin failures and erosion in the vicinity of marble outcrops are related to ground disturbances from management activities; in the upslope areas not yet harvested, natural processes of avalanching and debris flows also are active.

Confidence: Confidence levels are reasonably high based on aerial-photo analyses, field observations, and anecdotal information supplied by DNR field staff.

Comments: MWMU 5 includes stable and unstable slopes; the hazard rating is specific to convergent slopes (i.e., mapped and unmapped channel margins typically to the break-in-slope, generally exceeding 25% gradient). Intervening areas might be less

MWMU Number: 5 continued

Comments continued: susceptible to failure; however, it was difficult to delineate stable vs. unstable areas at a scale of 1:24,000. The number of failures in MWMU 5a and parts of 5b likely is underrepresented in this study, due to mature forest canopy obscuring the ground. Management or other activities on the ground would benefit from field mapping of unstable channel margins and headwalls, and their upslope contribution areas, to ensure that unstable slopes are identified accurately. In MWMU 5b, exposures of sedimentary interbeds and marble outcrops should be located and assessed in the field to determine stability issues, as these areally limited features were hard to locate and map at a 1:24,000 scale.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 6

Description: MWMU 6 has two sub-units: (1) *6a*, shows observed mass wasting in mapped and unmapped Type 5 and larger channels dissecting metamorphosed sedimentary and volcanic rocks of late Triassic and Jurassic age (about 195 m.y. BP.; i.e., lithologic units *TKeg* of Tabor et al., 1988, and *JTRmt(e)* of WDNR, 2001); and, (2) *6b* in the same parent materials, includes observed mass wasting in unmapped Type 5 channels that were too small to map accurately at a 1:24,000 scale, as well as channel areas with the potential for similar mass-wasting occurrences. In MWMU *6b*, the number of existing failures likely is underrepresented in this study, within the Boulder River Wilderness area, due to the thick, old-growth forest canopy that obscures the ground in aerial photographs. Observed mass wasting throughout MWMU 6 largely is associated with channel-headwall failures and associated debris flows that undercut and erode channel side-slopes, causing a series of inner-gorge failures down the lengths of these channels.

Materials: Parent materials consist of highly sheared and disrupted greenschist accompanied by other types of foliated sedimentary and metasedimentary rocks (e.g., greywacke, argillite, phyllitic argillite, chert, marble; Tabor et al., 1988). Soils are derived from hillslope residuum and colluvium, and they generally consist of thin gravelly loams in the surface with very thin, gravelly sandy loams in the subsurface.

Landform: Steep, dissected hillslopes of Boulder Ridge, Buckeye Basin, upper French Creek basin, and the ridge dividing Buckeye and Squire drainages, extending from ridge crests to toeslopes. These steep, relatively planar side-slopes are moderately dissected by mapped and unmapped Type 5 and larger channels. Hillslopes are highly susceptible to surface raveling where ground vegetation is not fully established. Planar and divergent slopes appear to be relatively stable between intervening drainages or convergent slopes; no mass wasting was observed on planar and divergent slopes except where extensive road sidecast failures occurred in the upper French Creek basin.

Slope: 25% - ∞

Elevation: 1000 ft. – 4500 ft.

Total Area:

MW Processes: Mass wasting primarily involves snow and debris avalanching, shallow-rapid landslides, and associated debris flows initiated in zero-order basins (e.g., channel initiation points) that subsequently undercut channel side-slopes as they travel downstream, causing secondary side-wall failures. Because of the thin soil layers, most of these channel side-slope failures essentially are thin slabs that slide into channels when toeslopes are undercut.

Non-road-related Landslide Density: (optional) About 65% of observed landslides and debris-flow scars are non-road-related; however, this value is artificially biased because only a small portion of MWMU 6 is roaded (i.e., French Creek basin and the 2040 road that cuts through the southeastern corner of the MWMU 6b polygon in Squire

MWMU Number: 6 continued

Non-road-related Landslide Density continued: Creek). The density of road-related failures in these areas suggests that if the remainder of MWMU 6 in the Boulder River Wilderness and Squire Creek areas designated as Late-Successional Old Growth were opened to mid-slope road construction, there would be a significantly greater proportion of failures related to roads.

Forest (and other) Practice Sensitivity: The density of road- and clearcut- related failures in the French Creek basin, as well as road-drainage-related slumps along the 2040 road in Squire Creek, indicates that convergent slopes with ephemeral and perennial flows are highly susceptible to slope disturbances associated with ground-based yarding, road building, and landing construction. Slope failures also are associated with inadequate maintenance and/or abandonment of roads and landings. Road side-cast failures are extensive in the upper French Creek basin, as well as debris flows resulting from failing cross drains (e.g., 020 and 022 spurs in French Creek basin, and 2040 road). The French Creek drainage is designated a timber-management area; given the density of existing failures and the underlying parent-material characteristics, the entire basin should be considered a hazardous area for timber harvest and road construction. The French Creek road network continues to contribute significant volumes of sediment to the channel network via sidecast and roadbed failures and associated debris flows; routine road maintenance or official, comprehensive road abandonment are critically needed to minimize future road-related mass wasting and sediment delivery to French Creek. Given the geomorphic and geologic similarities between the French Creek and Boulder River basins in MWMU 6, it is predicted that forest management and road building in the latter drainage also would accelerate substantially the natural rates of mass wasting.

MW Potential: High in MWMU 6a; high in the French Creek watershed; high for unmapped Type 5 and larger channel headwalls and side-slopes in MWMU 6b; medium on other convergent slope forms in MWMU 6b.

Delivery Potential: High

Delivery Criteria Used: All existing failures have delivered directly to the channel network; given the steep slopes and parent materials, potential failures are expected also to deliver directly to the channel network.

Hazard Potential Rating: High for MWMU 6a; **high** for unmapped Type 5 and larger channel headwalls and side-slopes in MWMU 6b; **moderate** on other convergent slope forms in MWMU 6b.

Trigger Mechanism(s): Ground-based disturbances associated with timber harvest, road construction (i.e., mid-slope roads, inadequate cross drainage, sidecast build-up), and landing construction have disturbed shallow soils overlying erodible bedrock, particularly on convergent slope forms, initiating shallow-rapid landslides and debris flows in the upper French and mid-Squire Creek drainages. Infrequent or nonexistent road maintenance has further promoted shallow-rapid landslides, debris flows, and secondary channel-wall failures that have been occurred episodically since initial forest-harvest or road-building activities. Aerial-photo observations also indicate that tree toppling (e.g., from windthrow or other causes) in zero-order basins (e.g., channel

MWMU Number: 6 continued

Trigger Mechanism(s) continued: initiation points) is responsible for triggering many of the initial failures in the Boulder River Wilderness Area and in unmanaged stands elsewhere on Forest Service land; debris avalanches or flows emanating from these sites then undermine channel side-slopes as they move downstream, creating a succession of channel-side-wall failures. In general, individual failures on unmanaged land appear to have resulted in less areally extensive failure scarps and debris-flow scour than those observed on managed lands in French Creek.

Confidence: Confidence levels are reasonably high based on aerial-photo analyses, field observations, and anecdotal information supplied by U.S.F.S. field staff.

Comments: MWMU 6 includes stable and unstable slopes; the hazard rating is specific to convergent slopes (i.e., mapped and unmapped channel margins typically to the break-in-slope, generally exceeding 25% gradient). Intervening areas might be less susceptible to failure; however, it was difficult to delineate stable vs. unstable areas at a scale of 1:24,000. The number of failures in MWMU 6a and parts of 6b likely is underrepresented in this study, due to mature forest canopy obscuring the ground in aerial photographs. Management or other activities on the ground would benefit from field mapping of unstable channel margins and headwalls, and their upslope contribution areas, to ensure that unstable slopes are identified accurately.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 7

Description: MWMU 7 occupies the lower slopes and valley bottom of upper French Creek watershed, as well as the lower slopes flanking the south side of lower French Creek, where soils are derived from continental glacial till. On the south-facing slopes of upper French Creek and slopes west of lower French Creek, failure scars and debris-flow scour are associated with sidecast decay from the 020 road, spurs and landings, as well as channel side-wall failures resulting from debris-flow scour that can be traced to upslope road and landing failures in MWMU 6. In upper French Creek, substantial, chronic surface ravel also has occurred following removal of vegetative cover and disruption of thin surface soils; in some areas, vegetation remains sparse following decades-old harvest, due to continued sidecast failures and drainage problems with the unmaintained road system. On north-facing slopes of upper French Creek and slopes southeast of lower French Creek, debris flows and avalanches entering the mainstem have initiated on unharvested, nonroaded, steeply convergent slopes in MWMU 6.

Materials: Parent materials are tills deposited by the continental icesheet during the Quaternary-age Fraser glaciation (*Qvt* of Tabor et al., 1988, and *Qgt* of WDNR, 2001). Thin sandy loams overlie deeper, variably compacted, very gravelly sandy loams that are moderately well-drained.

Landform: MWMU 7 includes lower mid-slopes to the valley bottom in upper French Creek basin. In the lower basin, MWMU 7 encompasses the lower mid-slopes of the snouts of Boulder and Whitehorse ridges, which are highly dissected by tributary channels. MWMU 7 extends westward from where French Creek makes an abrupt southeastern bend; west of the bend, MWMU 7 coincides with continental glacial-till deposits that mantle the southern wall of a relatively broad, shallow valley occupied by several kettle ponds. This gentle depression likely represents a portion of the outwash plain following icesheet recession; the present-day French Creek east of the bend has downcut through outwash deposits to form a moderately confined canyon. MWMU 7 corresponds to convergent slope forms at gradients exceeding about 10% (i.e., tributary wide-walls upslope of the relatively flat valley bottom associated with the French Creek mainstem), although aerial photographs indicate that most debris flows have scoured the length of tributary channels from their initiation points to their confluence with French Creek.

Slope: 4 – 125%

Elevation: 1000 – 3200 ft.

Total Area:

MW Processes: North of upper French Creek and west of the lower French Creek bend, shallow-rapid landslides and debris flows are associated primarily with the 020 road, spur roads, and landings (i.e., sidecast collapse, decay of landing fill, roadbed failures due to blocked or inadequate cross drains). Failure scarps and debris-flow tracks, as well as tributary side-walls undermined by debris flows, tend to be sparsely vegetated and prone to surface ravel, due to continued instability most likely related to

MWMU Number: 7 continued

MW Processes continued: seasonal snowmelt and unmaintained road drainage. South of upper French Creek and southeast of the bend in lower French Creek, mass wasting appears to be related largely to natural processes of snow avalanching, rockfall, and tree windthrow in channel-initiation areas, with associated debris flows that scour tributary channels to their confluences with French Creek. Many of these features are relatively less active in upper French Creek than those on the north side of the creek, judging from the small amount of bare or sparsely vegetated ground evident in successive aerial-photo years.

Non-road-related Landslide Density: (optional) Estimated 30%; road-related failures and associated debris flows account for relatively more of the observed mass-wasting sites (i.e., includes sites identified on Map A-1 and Form A-1, as well as smaller sites like slumps of the road cut- and fill-slope that were too small to outline at map scale).

Forest (and other) Practice Sensitivity: Soils on convergent slopes north of upper French Creek and west of the lower French Creek bend appear to be destabilized readily by debris avalanches and flows generated upslope by failures in the 020 road prism. Chronic surface ravel and slumping on 020 road cut- and fill-slopes, largely on convergent slope forms, indicates that soils generated from these glacial tills are sensitive to road construction type, prism location, and amount and frequency of maintenance. Given similar geomorphic and geologic characteristics of slopes on the south side of upper French Creek and east of the lower French Creek bend, it is assumed that harvest and road-building would also accelerate natural rates of mass wasting and surface erosion there.

MW Potential: High

Delivery Potential: High

Delivery Criteria Used: All identified mass-wasting sites have delivered sediment to the channel network and, given the relatively steep channel side-walls, drainage density, and parent materials, potential failure sites are expected also to deliver directly to the channel network.

Hazard Potential Rating: High

Trigger Mechanism(s): Failures in MWMU 7 primarily are associated with: (1) timber-harvest- and road-related mass wasting from upslope areas in MWMU 6 (north side of upper French Creek and west of the lower French Creek bend); (2) the 020 road (i.e., mid-slope road with no recent road maintenance, inadequate cross drainage, and sidecast build-up); and, (3) natural processes (south side of French Creek and east of the lower French Creek bend). Shallow-rapid landslides and debris flows initiated in MWMU 6 have undercut channel side-walls in MWMUs 6 and 7, causing small landslides and surface raveling along the length of tributary channels, some of which have coalesced to form larger, chronically devegetated erosional surfaces in channel inner gorges. Small fillslope failures on the 020 road in MWMU 7 have delivered sediment directly to channels where the roadbed cuts across tributary drainages. Failures on the south side of French Creek and east of the lower French Creek bend mostly are related to snow and rock avalanching, tree windthrow, and probably

MWMU Number: 7 continued

Trigger Mechanism(s) continued: other natural disturbances at channel initiation points where slope-destabilizing processes (e.g., headward erosion, water seepage) are active.

Confidence: Confidence is reasonably high, given the aerial-photo coverage from the early 1940's (i.e., pre-logging era) through 2001 (i.e., years after maintenance work was done on the road system), as well as field observations in lower French Creek. This study would have benefited from on-the-ground surveys of upper French Creek, given the extent of disturbance and critical need for road maintenance; however, the relative inaccessibility of the site made direct observations difficult. See main report for discussions regarding upper French Creek mass-wasting behavior and site recommendations.

Comments:

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 8

Description: MWMU 8 has two sub-units: (1) *8a*, indicates mass wasting has been observed in mapped and unmapped Type 5 and larger channels dissecting marine metamorphosed sedimentary rocks of late Jurassic to early Cretaceous age (about 136 m.y. BP.; i.e., lithologic units *TKwg* of Tabor et al., 1988, and *KJmm(w)* of WDNR, 2001); and, (2) *8b* in the same parent materials, includes observed mass wasting in unmapped Type 5 channels that were too small to map accurately at a 1:24,000 scale, as well as channel areas with the potential for similar mass-wasting behavior. In MWMU *8b*, the number of existing failures likely is underrepresented in this study, within the Boulder River Wilderness area, due to the thick, old-growth forest canopy that obscures the ground in aerial photographs. Observed mass wasting throughout MWMU 8 largely is associated with channel-headwall failures and associated debris flows that undercut and erode channel side-slopes, causing a series of inner-gorge failures down the lengths of these channels. With the exception of debris-flow scour in tributaries cutting through MWMU 8a, connected with failures upstream in MWMU 6b, the frequency of failures in MWMU 8 is substantially less than in MWMU 6. Although the two map units are similar lithologically, they were differentiated on the basis of their respective mass-wasting frequencies.

Materials: Rocks consist mostly of clastic, feldspathic sandstones (i.e., greywacke, argillite) and low-grade schist that are strongly foliated and locally contain abundant cobble conglomerates (Tabor et al., 1988). Bedrock locally is interbedded with argillite or phyllite, and, where less foliated, some sections show features (e.g., grading, load casts) associated with their local depositional setting. Soils typically are derived from colluvium and residuum, and they consist of thin gravelly loams overlying gravelly sandy loam. They are well-drained with rapid permeability.

Landform: MWMU 8 occupies steep, slightly to highly dissected ridgelines, side slopes, and toeslopes along the south side of Boulder River. A sliver of MWMU 8a also includes toeslopes of Boulder Ridge upstream of Boulder Falls. Hillslopes are highly susceptible to surface raveling where ground vegetation is not fully established. Planar and divergent slopes appear to be relatively stable between intervening tributary drainages or other convergent slope forms; no mass wasting was observed on planar and divergent slope forms.

Slope: 4% - 135%

Elevation: 1000 – 4500 ft.

Total Area:

MW Processes: Mass wasting primarily involves snow and debris avalanching, and shallow-rapid landslides with accompanying debris flows initiated in zero-order basins (e.g., channel initiation points) that subsequently undercut channel side-slopes as they travel downstream, causing secondary side-wall failures. In addition, tree windthrow appears to be a factor in destabilizing channel margins and initiating small failures with associated debris torrents (e.g., landslide 31/8E-4Q1; see Map A-1, Form A-1).

MWMU Number: 8 continued

Non-road-related Landslide Density: (optional) 100%; MWMU 8 lies in the Boulder River Wilderness Area.

Forest (and other) Practice Sensitivity: Given the steep slopes, erodibility of thin surface soils, and drainage densities, it is assumed that forest-management, mining, or similar extractive activities would increase natural rates of mass wasting, similar to observations in MWMU 6, if such activities were permitted in the Boulder River Wilderness Area. Zero-order basins (e.g., channel initiation points) and mid-slope seepage zones appear to be particularly susceptible to disturbance.

MW Potential: Medium in MWMU 8a; low in MWMU 8b assuming wilderness-management policies do not change.

Delivery Potential: High

Delivery Criteria Used: All identified mass-wasting sites have delivered sediment to the channel network and, given the relatively steep channel side-walls, drainage density, and parent materials, potential failure sites are expected also to deliver directly to the channel network.

Hazard Potential Rating: Moderate in MWMU 8a; low in MWMU 8b

Trigger Mechanism(s): Primary mechanisms are snow and rock avalanching, disturbance to channel headwalls and margins by tree windthrow or other natural events, and debris flows initiated in upslope sites (e.g., zero-order basins in MWMUs 6 and 8) that undercut channel side-slopes as they travel downstream, creating a succession of channel-margin failures. MWMU 8a comprises all sites in which mass-wasting features were observed on aerial photographs; it is assumed that similar mass-wasting behavior occurs, or could occur, in MWMU 8b, although only a few small shallow-rapid landslides were detected there. The frequency of failure distinguishes MWMUs 8a and 8b. The relative increase in mass-wasting frequency toward the eastern edge of MWMU 8b might be due to a combination of much steeper slopes, thinner soils, greater proximity to permanent snowfields from which avalanching is common, and greater exposure of bedrock to surface weathering (i.e., soils are thinner to non-existent in outcrop areas).

Confidence: Moderate, based on the good range in aerial-photo years used in this analysis. Field observations in the mid-Boulder basin indicated a greater frequency of debris-flow tracks emanating from the north vs. south sides of the river. The upper basin, however, was inaccessible during the field seasons. Direct observations would undoubtedly improve confidence in the aerial-photo interpretations, although making them would be very difficult given the precipitous terrain, thick vegetation, and minimal trail access.

Comments: MWMU 8 includes stable and unstable slopes; the hazard rating is specific to convergent slopes (i.e., mapped and unmapped channel margins typically to the break-in-slope, generally exceeding 25% gradient). Intervening areas might be less susceptible to failure; however, it was difficult to delineate stable vs. unstable areas at a scale of 1:24,000. The number of failures in MWMU 8 likely is underrepresented in this study, due to mature forest canopy obscuring the ground in aerial photographs.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 9

Description: MWMU 9 occupies the ridge crest and side-slopes on the northern end of Jumbo Mountain and has two sub-units: (1) *9a*, where mass wasting has been observed in mapped and unmapped Type 5 and larger channels downcut through igneous plutonic rocks of late Jurassic to early Cretaceous age (about 136 - 122 m.y. BP.; i.e., lithologic units *TKegg* of Tabor et al., 1988, and *Jigb(e)* of WDNR, 2001); and, (2) *9b* in the same parent materials, includes observed mass wasting, accompanied by chronic surface raveling, in unmapped Type 5 channels that were too small to map accurately at a 1:24,000 scale, as well as channel areas with the potential for similar mass-wasting behavior. MWMU 9a includes the very large, shallow-rapid landslide and debris-flow event that occurred in late February 2002 (i.e., landslide 32/9E-35L1). MWMU 9a is superimposed on MWMU 6b where debris-flow runouts cross over into metasedimentary parent materials.

Materials: Parent material is medium-grained, massive gabbro that has been highly dissected by swarms of diabase dikes (Tabor et al., 1988). Surface soils consist of thin gravelly loams, while subsurface soils typically are thin (i.e., ridgeline areas) to moderately thick (i.e., lower mid-slopes), very gravelly silt loams.

Landform: MWMU 9 occupies the steep, moderately dissected, ridge crests and side-slopes of Jumbo Mountain. Upper slopes toward the south end of MWMU 9 are dominated by sub-alpine processes of snow and rock avalanching; hillslopes are highly susceptible to surface raveling where ground vegetation is not fully established. Initiation points for the larger mass-wasting features (e.g., landslide 32/9E-35L1) appear to be associated with locally discontinuous, cliff-like exposures of bedrock riddled with diabase dikes, as well as a high-angle fault of the Darrington – Devils Mountain Fault Zone (Tabor et al., 1988) that places gabbroic bedrock against a thin exposed band of less resistant metaserpentinite (i.e., ultramafic rock consisting of altered pyroxene and olivine; lithologic units *TKhm* of Tabor et al., 1988, and *MZu(h)* of WDNR, 2001). Mass wasting largely is confined to convergent slope forms (e.g., tributary channels) with surface ravel occurring across all slope forms where vegetation is sparse.

Slope: 25% - ∞

Elevation: 1000 – 4500 ft.

Total Area:

MW Processes: Mass wasting primarily involves shallow-rapid landslides, snow and rock avalanching, and debris flows associated with both processes. At least one mappable failure is associated with road-drainage and clearcut disturbances (i.e., 32/9E-34H1); the headwall of this failure also coincides with the high-angle fault contact between gabbro and metasedimentary rocks (i.e., MWMU 6b). It is not clear what role the fault played in failure initiation; in fact, the headwall – fault juxtaposition could also be a result of headward retreat of failures in the road cutbank. The largest feature (i.e., landslide 32/9E-35L1) is speculated to have been associated with earthquake activity in northwestern Washington that might have initiated rockfall from a cliff-like bedrock

MWMU Number: 9 continued

MW Processes continued: exposure below the ridgeline (R. Hausinger, U.S.F.S., pers.comm.); there might also have been some movement along faults in the Darrington – Devils Mountain Fault Zone, associated with earthquake-related seismic activity. Rockfall caused an erosive mixture of mobilized rock, snow, and organic debris to course down two closely spaced tributaries, scouring the channel beds and banks to bedrock in many places and removing a section of the 2040 road. The resulting debris torrent also undercut side slopes and caused secondary failures in adjacent tree plantations and mature forest stands. A temporary debris dam blocked Squire Creek, leaving evidence of valley-bottom flooding in the vicinity of the failure and remnants of debris from impoundment; the debris torrent also ramped up the opposing valley wall a short distance.

Non-road-related Landslide Density: (optional) estimated 20%.

Forest (and other) Practice Sensitivity: The occurrence of several management-related mass-wasting events indicates that natural erosion rates are accelerated by ground-based harvest and road-drainage problems. Although the sample size is small (i.e., only one road and several small, discontiguous clearcuts), it is highly likely that further forest-management, mining, or similar extractive activities would significantly increase natural rates of mass wasting, given the steep slopes, high erodibility of thin surface and subsurface soils, and relative incompetence of serpentinized bedrock in an active fault zone.

MW Potential: High for MWMU 9a; medium for MWMU 9b

Delivery Potential: High

Delivery Criteria Used: All identified mass-wasting sites have delivered sediment and organic debris to Squire Creek and its tributaries.

Hazard Potential Rating: High for MWMU 9a and **moderate** for MWMU 9b. Units 9a and 9b have been differentiated on the basis of observed failure frequency.

Trigger Mechanism(s): Natural mechanisms include rockfall, snow avalanching and creep, seismic activity. Management-related factors include inadequate road-drainage maintenance and disturbances to highly erosive soils from ground-based yarding, particularly along and across incised channels.

Confidence: High, based on field observations and the good chronologic range of aerial photographs available.

Comments: If the rates of harvest and road construction were to accelerate in MWMU 9b, the potential for shallow-rapid landslides and debris flows likely would increase substantially, due to slope characteristics described above. The erosive nature of the substrate also presents some challenges for reconstructing the 2040 road, in terms of managing road drainage and fill materials. If the road segment taken out by the 2002 failure is rebuilt, it would be necessary to increase the size and spacing of cross drains, institute a seasonal road-maintenance schedule to avoid blockage problems, and minimize fill. Most of the road failures on the 2040 road have occurred in fillslope

MWMU Number: 9 continued

Comments continued: deposits lacking adequate drainage and/or outfall structures. Removing old sidecast materials also would minimize road-prism failures in MWMUs 9 and 3.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 10

Description: MWMU 10 encompasses continental glacial outwash-plain deposits exposed across the lower, northern flanks and toeslopes of Whitehorse Mountain, Whitehorse Ridge, and Boulder Ridge. It also includes French Point, the area separating French Creek and Boulder River, and the ridge to the north of Boulder River. Mass wasting largely is confined to convergent slope forms (e.g., tributary channels, swales with groundwater seeps), with surface ravel occurring across all slope forms where vegetation is sparse. Most observed failures of road cut- and fill- slopes have occurred in conjunction with stream crossings.

MWMU 10 also includes largely dormant features mapped as *Qls*, or Quaternary landslides, in the northwestern and northeastern corners of Map A-2. Portions of these features have been identified separately as SSD failures where they show signs of recent movement (e.g., freshly exposed glacial sands outcropping on steep headscarps and along toeslopes). These smaller failures appear to have been activated by a combination of logging disturbances, channel undercutting, and likely groundwater influences during the last century. “Qls” are coalescing large, deep-seated landslides that might have been created by toeslope undercutting, groundwater-recharge regimes, and other natural disturbances prior to the last century (i.e., before the time period of record). These features have been clearcut at least once and show little evidence of wholesale reactivation but, rather, only isolated patches of headscarp, surface, and toe erosion. “Qls” includes two new, recently active features, superimposed on the ancient large deep-seated failures, which were identified by Lingley (2004); they are shown as landslides 1005 and 1010 on Form A-1 and Maps A-1 and A-2. Other deep-seated features identified by Lingley (2004) are modified boundaries of landslides already identified in this report and field-checked after this study was concluded. They are collectively mapped as “Qls” in this report, to ensure that all existing and potentially unstable areas are delineated for further investigation in the field.

Materials: MWMU 10 largely encompasses the lithologic units *Qvr* of Tabor et al. (1988) and *Qgo* of DNR (____) exposed in the northern end of the WAUs. Parent materials are recessional outwash deposits of the Vashon stade of the Fraser continental glaciation (i.e., about 20,000 yr. B.P). They are described (Tabor et al., 1988) as moderately to well-sorted sands and gravels with interbeds of silty sand to silty clay. Surface soils generally are thin loams, and subsoils are very thick (e.g., 3.7m or more), very gravelly loamy sands. Soils typically are well-drained.

Landform: Glacial deposits, exposed along the toeslopes of Whitehorse Mountain and Ridge, are remnants of the broad outwash plain that blanketed the North Fork Stilliguamish valley during icesheet advance and recession. Slopes generally are moderately dissected by channels whose margins seasonally are disturbed by high discharges associated with snowmelt runoff and, in some tributaries (e.g., Ashton, Snow Gulch) by high bedload mobility during runoff events. Recessional outwash deposits drape glaciated terrain between Hazel and the northwestern ends of Boulder and Whitehorse ridges. Features there include truncated or flat ridge crests (e.g., the ridge separating Boulder River and Hazel; French Point) that might represent the approximate elevation of the outwash-plain surface following icesheet recession; the Boulder River

MWMU Number: 10 continued

Landform continued: subsequently has carved through thick outwash deposits to occupy its present location. Between French Point and Boulder Ridge, a relatively broad, shallow valley, lying at a similar elevation to the truncated ridge on the north of the Boulder River, likely is another remnant outwash-plain surface. To the west of the abrupt bend in French Creek (i.e., where the creek trends from northeast to southeast as it enters a narrow canyon), this valley contains a number of small kettle ponds and bogs that probably formed from decaying chunks of ice during glacial ablation and recession. East of the bend, French Creek has downcut through outwash deposits to form a moderately confined canyon that empties onto an old alluvial terrace formed by the antecedent North Fork Stilliguamish River (i.e., MWMU 11).

Slope: Typically < 35%

Elevation: Estimated 500 – 1000 ft.

Total Area:

MW Processes: Identified mass-wasting sites generally are confined to convergent slope forms (e.g., channel inner gorges, incised-channel margins, depressions with groundwater seeps), where road drainage problems, ground-based yarding, or natural disturbances have promoted shallow-rapid landsliding and debris-flow initiation.

Non-road-related Landslide Density: (optional) Estimated 50%.

Forest (and other) Practice Sensitivity: Forest management or mining activities have the potential to destabilize slopes composed of outwash depositional sediments where convergent slope forms exceeding about 25% gradient are encountered. Inner-gorge slopes, particularly at the break-in-slope point, are susceptible to ground disturbances that remove vegetative groundcover and expose soils to episodic translational failures and chronic surface ravel. The “Qls” units roughly correspond with the zones of groundwater recharge for most of the currently active destabilized slopes. Glacial sands overlie more impermeable glacial clays in these areas, which likely promotes slope instability due to groundwater-recharge regimes. Hence, “Qls” units have been identified as possible sites of further slope instability that should be investigated more thoroughly in the field when forest practices are proposed.

MW Potential: Medium

Delivery Potential: High

Delivery Criteria Used: All identified mass-wasting sites delivered sediment directly to the channel network.

Hazard Potential Rating: Moderate

Trigger Mechanism(s): Observed shallow-rapid landslides and associated debris flows have been initiated by road construction and ground-based yarding or tractor skidding in which one or both ends of logs scraped channel inner-gorge slopes. Breaks-in-slope (i.e., the point where hillslope gradients abruptly steepen into incised channels or inner

MWMU Number: 10 continued

Trigger Mechanism(s) continued: gorges) appear to be natural points of unraveling in places where soils are exposed through removal of the vegetative cover; management activities have exacerbated break-in-slope instability in several drainages (e.g., Little French Creek, Moose Creek, and tributaries to Squire Creek).

Confidence: High, based on field observations and the good chronologic range of aerial photographs available.

Comments: Other MWMUs lapse over onto MWMU 10 where debris-flow runouts from failures in upslope MWMUs scour into and through recessional outwash deposits. MWMUs 10 and 11 are distinguished based primarily on hillslope gradient and frequency of mass wasting.

Form A-2 Mass Wasting Map Unit Descriptions

MWMU Number: 11

Description: MWMU 11 includes the remaining low-gradient surfaces in the study area that are blanketed by Quaternary deposits. Lithologic units include: (1) lahar deposits related to Glacier Peak volcanic activity (i.e., *Qlh* of Tabor et al., 1988; *Qvl(gp)* of WDNR, 2001); (2) alluvial-fan deposits (i.e., *Qf* of Tabor et al., 1988; *Qaf* of WDNR, 2001); (3) bog deposits (i.e., *Qb* of Tabor et al., 1988; *Qp* of WDNR, 2001); (4) icesheet recessional outwash deposits (i.e., *Qvr* of Tabor et al., 1988; *Qgo)* of WDNR, 2001); (5) continental glacial till deposits (i.e., *Qvt* of Tabor et al., 1988; undifferentiated *Qgo* of WDNR, 2001); and, (6) alluvium (i.e., undifferentiated *Qvr* of Tabor et al., 1988; *Qa* of WDNR, 2001). Unit (1) above further has been subdivided into volcanic sediment deposits correlated with the 5,100 – 5,400 yr. B.P. Kennedy Creek Assemblage and the approximately 11,200 – 12,700 yr. B.P. White Chuck Assemblage (Qvs_k and Qvs_w, respectively; see Dragovitch et al., 2002a). Both units contain hyperconcentrated flood deposits, lahars, and volcanic alluvium associated with eruptive episodes of Glacier Peak that inundated the Sauk and North Fork Stilliguamish River valleys with volcanic-sediment-laden flows. No mass-wasting features were identified in MWMU 11, although extensive surface erosion was noted and is described in the Surface Erosion Assessment Report.

Materials: Parent materials include lahar deposits that consist primarily of poorly sorted to well-sorted silty sands, sands, and gravels with inclusions of volcanic clasts and pumice from Glacier Peak volcanic activity. Locally, the correlative of the Kennedy Creek Assemblage is topped by a light-colored volcanic ash. Nonlahar volcanosedimentary units typically are nonstratified and non-graded to crudely graded. Also present are outwash and till deposits associated with Quaternary continental glaciation; outwash deposits are associated with icesheet recession and include stratified sands and gravels and tills are relatively compact with subangular to rounded clasts. Holocene alluvial-fan deposits contain poorly sorted gravels, cobbles, and boulders; discrete lobes have been mapped as Qaf on Map A-2; these features are stable and show little evidence of mobility other than surface erosion associated with land-use activities. Alluvial-fan deposits also form a broad apron filling the lower Squire Creek valley, as well as low-gradient segments of Ashton, Snow Gulch, Brown's, and other unnamed tributaries of Squire Creek. Holocene bog deposits consist of poorly drained and seasonally wet peat and alluvium. Quaternary alluvial deposits primarily are heterogeneous, well- to poorly mixed and sorted sediments transported by the mainstem North Fork Stilliguamish River. Surface soils typically are thin loams or silt loams. Subsurface soils are very thick, weak to moderately compact, layers of gravelly sands that might alternate with sublayers of sands, silts, sandy loams, and silty clay loams where outwash, alluvial, and lahar deposits are interbedded.

Landform: Most of MWMU 11 consists of low-gradient terrace surfaces and low-relief hillocks with intervening unconfined to loosely confined tributary drainages. Terrace margins, along the North Fork Stilliguamish River, mouth of Boulder River, and mouth of French Creek show minimal instability. MWMU 11 also includes truncated ridge crests most likely representing the outwash-plain surface following ice-sheet recession (e.g., west of Boulder Falls on the northern flanks of Wheeler Mountain). The volcanic-

MWMU Number: 11 continued

Landform continued: sedimentary correlative of the Kennedy Creek Assemblage typically forms a prominent 15 – 25 foot high terrace (Dragovitch et al., 2002a).

Slope: Generally < 10%.

Elevation: Estimated 350 – 800 ft.

Total Area:

MW Processes: None identified.

Non-road-related Landslide Density: (optional) N/A

Forest (and other) Practice Sensitivity: Ground surfaces in MWMU 11 appear to be most sensitive to activities promoting surface erosion; see Surface Erosion Module for discussion.

MW Potential: Low

Delivery Potential: Low

Delivery Criteria Used: N/A

Hazard Potential Rating: Low

Trigger Mechanism(s): N/A

Confidence: High, based on field observations and the good chronologic range of aerial photographs available.

Comments:

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 1

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years					
Partial Cut					
Road					
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)					
Non-Forest Land Use					
Natural Disturbances (Alpine processes)	High frequency of coalescing, coincident, or closely spaced mass-wasting features, including shallow, translational failures, rockfall, snow and rock avalanching, debris torrents, secondary failures in avalanche chutes, and debris dam-burst floods. No deep-seated (LPD or SSD) features were observed.				50+
Totals	I stopped counting at 50 individual or coincident mass-wasting features. Failures are mapped within one all-inclusive polygon (i.e., not mapped as discrete polygons); see section 4.0.				50+

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 2

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years			1		1
Clear Cut 20-50 years					
Partial Cut					
Road					
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)					
Non-Forest Land Use					
Natural Disturbances (Alpine processes)	Relatively lower frequency compared with MWMU 1 of coalescing, coincident, or closely spaced mass-wasting features, including shallow, translational failures, rockfall, snow and rock avalanching, debris torrents, and secondary failures in avalanche chutes. No deep-seated (LPD or SSD) features were observed.				21+
Totals	I stopped counting at 20 individual or coincident mass-wasting features. Failures are mapped within one all-inclusive polygon (i.e., not mapped as discrete polygons); see section 4.0.				21+

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 3

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years					
Partial Cut					
Road				12+ unmapped	
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)	5[1] 10+ unmapped			5[1] 5+ unmapped	10 15+ unmapped
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	5[1] 10+ unmapped			5[1] 17+ unmapped	10 27+ unmapped

[1] MWMU 3 also contains at least 12 small SR landslides and DT from USFS road 2040 that were too small to be mapped at a 1:24,000 scale; see discussion on Form A-2.

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 4

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years	1	1	8; plus 2 of indeterminate cause		10; 2 of indeterminate cause
Clear Cut 20-50 years					
Partial Cut					
Road					
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)	17		3	3	23
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	18	1	13	3	35

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 5

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years	1				1
Clear Cut 20-50 years					
Partial Cut					
Road	1			2	3
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)					
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	2			2	4

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 6

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years	6			5	11
Partial Cut	2			2	4
Road	5			8	13
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)	11			8	19
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	24			23	47

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 7

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years			1	1	2
Partial Cut					
Road	4			7	11
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)					
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	4		1	8	13

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 8

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years					
Partial Cut					
Road					
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)	3			1	4
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	3			1	4

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 9

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					
Clear Cut 20-50 years	3			3	6
Partial Cut					
Road	1			1	2
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)	1			2	3
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	5			6	11

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 10

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years	3				3
Clear Cut 20-50 years	1		1		2
Partial Cut					
Road				1	1
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest (unmanaged)					
Non-Forest Land Use					
Natural Disturbances (Alpine processes)					
Totals	4		1	1	6

Form A-3 Mass Wasting Summary Table

Mass-Wasting Map Unit (MWMU) 11

ACTIVITY	Shallow Rapid Landslide (SR)	Large Persistent Deep-Seated Failures (LPD)	Small Sporadic Deep-Seated Failures (SSD)	Debris Torrent (DT)	**Totals**
Clear Cut 0-20 years					0
Clear Cut 20-50 years					0
Partial Cut					0
Road					0
Stream Crossing					0
Landing					0
Other Forest Practices					0
Wildfire					0
Mature Forest (unmanaged)					0
Non-Forest Land Use					0
Natural Disturbances (Alpine processes)					0
Totals	0	0	0	0	0

Form A-4 Summary of Mass Wasting and Delivery Potential

MWMU	Mass Wasting Potential	Delivery Potential	Potential Hazard Rating
1	High	High	High
2	Medium	High	Moderate
3	Medium	High	Moderate
4	High	High	High
5	Medium	High	Moderate
6a	High	High	High
6b	Medium/high on unmapped, convergent slopes	High	Moderate
7	High	High	High
8a	Medium	High	Moderate
8b	Low	High	Low
9a	High	High	High
9b	Medium	High	Moderate
10	Medium	High	Moderate
11	Low	Low	Low

11.2 Maps A-1 and A-2