APPENDIX A: MASS WASTING ASSESSMENT

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A1.0 Introduction

Forestry activities can alter the erosion regime in mountain drainage basins. An increase in the frequency of landsliding may change the existing channel morphology and sediment transport, which may have detrimental effects on fisheries. The slope stability assessment identifies which hillslopes are most prone to failure naturally and therefore where forestry activities are most likely to trigger landsliding. This chapter describes how geology, topography, hydrology and land use combine to influence landsliding in the Deer Creek watershed and to use this information to identify and map land areas according to their potential for mass wasting for the purpose of avoiding stream sedimentation from future timber harvest and road siting.

A2.0 Methods

This report is based on an earlier investigation into the history of watershed processes, land use, and salmonid habitat in the Deer Creek watershed (Collins and others, 1994). Significant portions of this chapter are derived from "Chapter 3: Hillslope Erosion and Hazard Assessment" of that document, co-authored by Lee Benda and Paul Kennard. While the initial study was not conducted as an official Washington watershed analysis, the standardized methodology of that time (WFPB 1993) was followed. This report has been updated to conform to the current protocol (WFPB 1994).

The procedure uses aerial photography and a landslide inventory to examine the time and space relationships among landforms, timber harvest, logging roads and mass wasting. For this analysis, landslides found in clearcuts younger than 20 years and on or adjacent to roads are assumed to relate to those forest practices. Slope stability mapping units are developed using information on landslide type, rate or density, delivery of sediment to channels, and landforms that distinguishes one or more of those characteristics.

Geologic and geomorphic information on the study area was obtained from Tabor and others (1988), Eide (1991), and GeoEngineers (1992). Landslides and slope stability were mapped on U.S. Geological Survey 1:24,000-scale topographic maps. In the upper three-fourths of the watershed, we used a landslide inventory from Eide (1991) which was made from aerial photographs taken in 1942, 1956, 1964, 1972, 1983, and 1989; the persistence of some landslide scarps effectively increases the length of record another 10 to 20 years back to about 1922-1932. Not all landslides can be identified on photographs, particularly small landslides in inner gorges under forest canopy. The 1991 aerial photographs and field observations, made in upper Deer Creek, Little Deer Creek, and Higgins Creek sub-basins during summer 1993, were used to verify and update Eide's (1991) inventory. For the remaining one-fourth of the watershed, landslides were inventoried using only 1983 and 1991 aerial photographs to verify the extrapolation of slope stability map units developed in the upper watershed.

Slope stability mapping units describe general physiographic areas having distinct landforms, mass movement processes, and mass movement probability. Landforms were mapped using stereographic pairs of aerial photographs. The boundaries separating mapping units are approximate. Only a small percentage of the study area was field mapped (less than 10%). Areas not observed in the field were mapped exclusively from aerial photographs and topographic maps and in many areas, particularly under canopy, it is not possible to accurately locate the position of certain landform boundaries on topographic maps or on aerial photographs.

Therefore, boundaries between mapping units need to be verified and possibly revised during field use of the slope stability map.

A3.0 Types of Mass Wasting

In the Deer Creek watershed there are diverse landsliding processes having varying susceptibilities to forestry activities and differing abilities to deliver sediment to streams. These slope stability types are one criteria used to develop the slope stability map. Mass wasting processes in Deer Creek include shallow-rapid landslides, debris flows, small, sporadic deep-seated slumps, larger slump-earthflows and dam-break floods as described below:

(1) **Shallow-rapid landslides** in the study area are located primarily on steep hillslopes underlain by bedrock or glacial materials. Shallow-rapid landslides occur most often along steep, inner gorges or near the heads of first- and second-order channels in convergent topography (commonly called bedrock hollows). Inner gorges are usually demarcated from adjacent lower-gradient hillslopes by an abrupt break in slope near the stream. Shallow-rapid landslides typically occur in thin soils and colluvium of various origins (generally less than 2 m thick) overlying steep bedrock or other compacted surficial materials. Soil thickness is small compared to slope or landslide length. During failure, debris moves quickly downslope and can break apart and form a debris flow. Shallow failures are controlled primarily by the slope of the hillside, thickness of the soil and colluvium, root strength within the soil, and soil saturation (which relates in part to intensity and duration of storms) and are less controlled by specific rock lithologies. Shallow-rapid failures often occur in convergent topography (hollows) because they focus subsurface flow during high intensity rainstorms.

(2) A **debris flow** is a highly mobile slurry of soil, rock, vegetation and water that can travel many kilometers from its point of initiation and usually travels through steep (more than 5°) confined mountain channels. Debris flows are initiated by liquefaction of landslide material concurrently with failure or immediately thereafter as the soil mass and reinforcing roots break up. Debris flows contain 70 to 80 percent solids and only 20 to 30 percent water. Entrainment of additional sediment and organic debris in first- and second-order channels can increase the volume of the original landslide by 1000 percent or more, enabling debris flows to become more destructive as their volume increases with distance traveled (Benda and Cundy 1990). Debris flow deposits also release a pulse of fine sediment that is available for immediate fluvial transport, which increases the downstream influence of this form of mass wasting. Other names given to debris flows include debris torrents, sluice outs and mud flows.

(3) Debris flows and other types of landslides can dam a narrow valley floor or canyon. If the landslide dam fails catastrophically, an extreme flood can form. These events are referred to as **landslide/dam-break floods**. The flood may entrain additional organic debris thereby causing the flood to increase in magnitude as the flood propagates downstream (Coho and Burges 1993). Although debris flows and dam-break floods have often both been referred to as "debris torrents" in the Pacific Northwest, the use of the term debris torrent has fallen into disfavor because of the need to differentiate between different mobile mass movements for the purpose of hazard recognition.

(4) **Slump-earthflows** involve a combination of slumping and slow flow. Typically, slump blocks exist in portions of the failing mass, and breakup and weakening of failed material lead to hummocky ground patterns and fast creep rates in other portions of the failure. Slump-earthflows

are often triggered by the build up of pore water pressure in mechanically weak, and often clay-rich rocks or sediments. Slumping involves the downward movement and backward rotation of a soil block or group of blocks. In the Deer Creek watershed, slump-earthflows are associated with both bedrock and glacial sediments. Movement of slump-earthflows is controlled in large part by the residual shear strength of the weathered and strained rock located at the base of the failure. The susceptibility, rate and degree of weathering and shearing is controlled to a large extent by specific lithologies. Small, sporadic deep-seated, rotational slumps are common in the Deer Creek watershed, primarily in glacial sediments having significant clay content. Small slumps often occur in association with inner gorges adjacent to first- through third-order channels. In addition, small slumps occur at terrace margins, and in these locations the failures are less likely to directly deliver sediment to streams.

A4.0 Influence of Landforms and Geology on Mass Wasting Types in Deer Creek

Bedrock in the watershed is comprised of Mesozoic phyllite, greenschist, barroisite schist, Eocene sedimentary rocks (Chuckanut Formation), which has been deformed by younger Tertiary folds and faults (Tabor and others 1988). Thick glacial sediments mantle the valley floors (Map A-3) of almost all of the low-gradient channel network. In addition, glacial sediments, including till, clays and outwash also occur locally on the upper, steeper parts of the watershed. For a detailed discussion of the glacial geologic history of Deer Creek, see GeoEngineers (1992) and Collins and others (1994).

Steep soil at the heads of first-order channels, or in bedrock hollows underlain by bedrock are the primary source of long-runout debris flows in the Deer Creek valley (see landslide inventory). Rapid channel incision into glacial fills of the valley floors and in tributary valleys during the early to mid Holocene created a series of erosional terraces. The relief created by these terraces in conjunction with groundwater create a favorable environment for slumps and earthflows to form in the Deer Creek watershed. In addition, channels form inner gorges immediately adjacent to them, and the inner gorges are prone to small, deep-seated slumps and shallow-rapid landslides. There are also several earthflows in bedrock in the Deer Creek watershed which are on or directly adjacent to mapped faults (Tabor and others 1988).

A5.0 Mass Wasting Inventory

The landslide inventory is comprised of: 1) Eide's (1991) inventory that was partly field verified during 1993; 2) landslides located in the upper watershed during this study in the area originally mapped by Eide; 3) landslides and landslide zones (areas encompassing numerous slides) that were mapped in the lower one-fourth of the watershed to verify extrapolating the slope stability map units that were developed in the upper three-fourths of the Deer Creek watershed. Inventoried landslides are shown on Map A-1 and Form A-1 contains information on each landslide or landslide zone, including location, type of landslide process, photo year the feature was first observed, whether sediment was delivered to a stream (and stream order), and the associated forest practice, if any. Geomorphic characteristics of the landslide initiation areas, such as hillslope gradient and landform type, are also compiled in Form A-1 and summarized in Table A-1.

A total of 240 landslides were identified in the upper watershed using Eide's (1991) inventory and additional field-inventoried slides in the same area. The density of landslides is highest in inner gorges within glacial sediments in DeForest and Rick Creek sub-basins. The largest landslide is the deep-seated DeForest Creek failure which originated within a glacial terrace and contributed more than three million tons of sediment to Deer Creek. A thorough discussion of the DeForest slide is in GeoEngineers (1992).

The majority of landslides are shallow-rapid (60%), and the remainder were debris flows and deep-seated landslides, in approximately equal numbers (Table 3-1). Over two-thirds of all landslides occurred in glacial sediments, including half of the debris flows and over 90% of deep-seated failures. All deep-seated landslides within glacial sediments are known to be historically active (within the last several decades covered by the photographic record), and one deep-seated landslide in bedrock was field checked, and found to be currently active. The highest density of shallow-rapid failures are in inner gorges and deep-seated landslide scarps (Table A-1). Most debris flows initiated in steep (over 35°) hollows, and in steep first- and second-order inner gorges.

Over four-fifths of all inventoried landslides in the upper watershed delivered sediment directly to streams, and half of all landslides reached third and higher order channels. The vast majority (95%) of all debris flows and deep-seated landslides contributed sediment to streams and of those, two-thirds of debris flows, and 90% of deep-seated landslides delivered sediment to third and higher order channels.

A6.0 Mass Wasting Map Unit Delineation

Each slope stability map unit is unique with respect to: 1) process; 2) frequency (or density) of landsliding; and 3) sediment delivery to streams. Map units are based on the landform characteristics necessary to differentiate the basin into unique combinations of process, frequency of sliding, and sediment delivery. The processes covered in the map units include: shallow-rapid landslides (located on bedrock and in glacial sediments); large slump-earthflows differentiated according to bedrock or glacial origin; debris flows; and small, sporadic, deep-seated failures. Dam-break floods may occur in association with any of the other mass wasting processes. To predict where in a watershed dam-break floods are most likely to occur requires detailed field investigation of prior events, including differentiation of dam-break floods from debris flows. It is generally not possible to differentiate between debris flows and dam-break floods using aerial photographs alone. Hence Eide (1991) referred to them collectively as debris torrents. In this study only one dam-break flood (in DeForest Creek in 1983) was verified in the field, and one other is tentatively identified on aerial photographs in the lower portion of a left-hand tributary of Higgins Creek, herein informally called the West Fork of Higgins Creek. These two observations are insufficient to develop basin-specific predictions of dam-break floods in Deer Creek. Although we do not address the potential for dam-break floods in Deer Creek, Coho and Burges (1993) found from examining a number of dam-break floods in the west Cascades that, in mountain drainage basins, relatively narrow (less than 65 feet) and steep (4-20°) channels appear to be most susceptible to dam-break floods.

A6.1 Delivery Criteria

Delivery of sediment to channels is a criterion used to define slope stability map units. Several guidelines were used to determine sediment delivery: 1) Shallow-rapid landslides travel over slopes of any form when gradients exceed 25° based on an analysis of residual shear strength of saturated landslide debris that has lost its reinforcing network of roots (Benda and Cundy, 1990). Landslides deposit when slopes are less than 25°, and can run out for 500 feet based on field observations made in Deer Creek; 2) Debris flows travel in confined channels and deposit at tributary junctions with intersection angles in excess of 70°, or when channel gradients are less than 3.5° (Benda and Cundy 1990). In the latter case, debris flows can run out for an additional 1000 feet because of momentum (Benda and Cundy 1990); 3) Small, sporadic, deep-seated slumps in inner gorges deposit into streams, unless separated from the stream by terraces exceeding 500 feet in width based on field observations in the Deer Creek watershed.

A6.2 Stream Order Criteria

Several map units are divided into two sub-units based on whether sediment is delivered into a first- and second-order channel (as defined by Strahler, 1952), or a lower-gradient third- and higher-order channel. This is because steep, first- and second-order channels can be highly sediment retentive for many sizes of sediment when supply is dominated by landsliding and armoring and log jams reduce transport efficiency (Benda and Dunne 1987). Trapping efficiency of the smallest particles (clay and silt) should be less, and efficiency should also be less overall if sediment enters first- and second-order channels by steady-state soil creep processes. Third- and higher-order channels, in contrast, do not store sediment as efficiently, and these channels are typically habitat to resident and anadromous fish.

A6.3 Landslide Densities

A criterion for differentiating map units, where the primary mass wasting process is shallow-rapid or debris flow landsliding, is frequency of landsliding. This information is also used in developing the hazard ratings for the map units (subsection A8.3).

To correctly compare frequencies from map units of different sizes, the frequencies must be area-weight averaged, and if the frequencies are calculated from aerial photos, the results should be time-weight averaged to account for different time intervals between the photo sets. To avoid these cumbersome calculations, the mass wasting module manual (WFPB 1994) recommends using landslide densities as a surrogate for frequencies.

Table A-2 lists landslide densities, as the number of landslides per acre for each map unit considered, and the ratio of landslide densities to the density of map unit 5, which had the lowest density of any forested map unit.

A7.0 Mass Wasting Map Unit Descriptions

The following describes the ten slope stability map units that were developed for the Deer Creek watershed. The location of map units is shown on Map A-2, and map unit descriptions are summarized in Forms A-2.

(1) Map unit 1 contains deep-seated earthflows in bedrock in their entirety. Sediment delivery is always to third- and higher-order streams. Map unit 1 contains all slope forms and gradients, including steep scarps (more than 35°) and lower gradients (less than 30°) on earthflows. While one mapped landform was observed in the field, and it showed evidence of current movement, the activity levels of the other features is unknown.

(2) Map unit 2 contains large (greater than 500 feet in map length) glacial deep-seated landslides. Map unit 2 is typically contained in lacustrine valley-train deposits. Slope gradients are mostly

shallow (less than 25°), because these glacial materials are mechanically-weak and unable to maintain much steeper slopes, particularly when wet. All map unit 2 slides that were field checked are currently active based on presence of tension cracks and unvegetated scarps. The remainder of failures that were not field checked are assumed to be active (either currently moving, or having moved in the last 50 years) based on identification on aerial photographs of lobate topography, scarps, and tipped trees. Toes of earthflows impinge on streams and thereby deliver sediment directly to streams. Map unit 2A delivers sediment to third- and higher-order channels. Map units 2B delivers sediment to first- and second-order channels.

(3) Map unit 3 contains small (map length less than 500 feet) sporadic, deep-seated landslides in glacial sediments. Field observations revealed many active map unit 3 slides not detectable from aerial photographs. To account for these, the mapped unit includes area with topography similar to that in identified failures, and therefore contains lands that are not failing, or that may not be susceptible to failures. Surface slopes can range from relatively shallow (about 20°) to steep (greater than 30°). Map unit 3 can contain all slope forms (planar, divergent and convergent). Unchanneled valleys, small grabens, and oversteepened toes indicate recent slide activity. Map unit 3A delivers to third and higher-order channels. Map unit 3B delivers to first- and second-order streams. Small, deep-seated slides that do not deliver sediment to channels are included in map unit 5.

(4) Map unit 4 represents unvegetated alpine areas. The altitude of these areas is commonly greater than 5000 feet and the most distinguishing characteristic is lack of permanent vegetation. Mass wasting is generally limited to rock falls or topples, and lack of significant soil accumulations limits landsliding. Map unit 4 may contain accumulation basins for snow avalanches. Timber harvest immediately below map unit 4 may enlarge accumulation areas of snow avalanches, and create avalanche-prone areas. Topography in map unit 4 is generally very steep (greater than 35-40°) and contains all slope forms. Delivery is not considered in this map unit.

(5) Map unit 5 is any area having either no significant landslide activity of any type, or having low potential to deliver sediment to channels, regardless of landslide hazard. Included in this map unit are stable landforms including: ridge tops; steep, divergent areas; valley floors and terraces; and unstable sites with low delivery potential.

(6) Map unit 6 contains debris flow source areas. Typically landforms are steep (greater than 35°), and include bedrock hollows, first-order channel heads, and first- and second-order inner gorges with channel gradients 20° or greater. Map unit 6 can include bedrock or glacial sediments. Map unit 6A delivers debris flow sediment directly to third- and higher-order channels. Map unit 6B delivers sediment to first- and second-order channels. To be detected using 1:12,000-scale photography, an inner gorge must have a minimum relief of approximately 15 feet.

(7) Map unit 7 contains areas that are most prone to shallow-rapid landslides. These areas include steep (greater than 35°) inner gorge topography adjacent to channels having a gradient less than 20°. To be detected using 1:12,000-scale photography an inner gorge must have a minimum relief of approximately 15 feet. All slope forms can be present. Map unit 7A delivers sediment directly to third- and higher-order channels. Map unit 7B delivers sediment directly to first- and second-order channels.

(8) Map unit 8 is characterized by gradients between 25° and 35°, and is, in general, not inner-gorge topography. Shallow-rapid landsliding is the dominant form of mass wasting in map unit 8, although frequency of sliding is less than in map unit 7. Although map unit 8 contains all slope forms, convergent topography in general is relatively more susceptible to sliding (Sidle and others 1985). Map unit 8A delivers sediment directly to channels of third- and higher order. Map unit 8B delivers sediment to channels of first- and second-order.

(9) Map unit 9 is predominantly a planar slope form, with minor inclusions of convergent topography. Map unit 9 has topography greater than 35°, although areas steeper than 35° within deep-seated map units are not included. Landsliding is not a major process because of the general lack of convergent topography and very shallow (less than 3 feet) soils. Map unit 9A delivers sediment to channels of third- and higher-order, and map unit 9B delivers sediment to channels of first- and second-order.

(10) Map unit 10 contains the large DeForest Creek deep-seated landslide, other active deep-seated slides, and additional unfailed areas with deep-seated slide potential (based on topography and stratigraphy). The upslope groundwater recharge zone is not included. The unit encompasses a portion of terrace, with gradients ranging from greater than 35° to less than 10°. The valley-train sediments include bedded deposits of fine-grained lacustrine sediments and outwash, in addition to tills (GeoEngineers 1992). The unit is primarily distinguished from map unit 2 by its extreme instability, evidenced by the creation (as opposed to reactivation) of at least two large, deep-seated landslides since 1972, in apparent response to forest activities. Map unit 10 generally delivers to third- and higher-order streams.

A8.0 Mass Wasting Map Unit Hazard Ratings

Hazard ratings (or more accurately, delivered hazard ratings) are developed for each map unit. Consistent with the mass wasting module methodology (WFPB 1994), the criteria for assessing relative hazards of high, moderate, and low are the map unit's: 1) type of mass wasting process; 2) frequency (or density) of landslides; 3) ability to deliver sediment to streams; and 4) susceptibility to influence from forest activities on slope stability. The first three criteria were used to differentiate separate map units (section A6.0) and the fourth criterion is discussed later in this section. Information on the controls to landsliding and the specific forest activities that influence these controls for each map unit is found on Forms A-2.

Going beyond the standard methodology, the high delivered hazard ratings were further subdivided into more detailed rankings based on the probability of the undesirable mass wasting occurrence and the magnitude of impact. Information on these additional categories is in subsection A8.3.

A8.1 Background on Landsliding and Land Use

Numerous studies document that timber harvest increases certain types of slope failures during the period following harvest when root decays (Sidle and others 1985). In addition, changes in slope hydrology, including rain-on-snow runoff can increase certain forms of slope failures. Inadequate road design and construction can also increase in the rate of landslides in managed forests (NCASI 1985). For a summary review of how forestry activities influence various forms of erosion in the Pacific Northwest, including mass wasting, see Benda and others (1991).

The effects of forestry activities on slope instability varies with type of erosion and forestry activity. Because root strength is important on steep slopes with shallow soils, clearcut harvesting can increase shallow-rapid landslides. Deep-seated failures, such as slumps and earthflows, are controlled less by root strength and hence clearcutting has less of a mechanical impact. Changes in hydrology that substantially increase subsurface flow may accelerate slump or earthflow activity, though few studies have systematically investigated the interaction between failure rate, climate and land use.

In general, it is not feasible to compute analytically the effects of clearcutting and road construction on the stability of individual hillslopes. This is because soil depth, slope hydrology, soil mechanical strength and root strength are highly spatially variable and therefore would have to be measured in great detail. In the case of slumps and earthflows where the mechanism of failure is poorly understood and failure planes are located at greater depths, it is very difficult to predict failure and movement with any degree of accuracy.

One way to determine empirically the effects of forestry activities on landsliding is to make a landslide inventory, including a comparison of landslide occurrence with timber harvest activities in time and space. This has been done numerous times for shallow-rapid failures (for example Eide 1991 in Deer Creek), and is the method employed in this module (WFPB 1994). Typically, an empirical or statistically significant relationship has been found between shallow failures and forestry activities (logging roads and harvest).

Much less work has been done on deep-seated landslides. Several regional studies have temporally correlated failure and harvest on the slide or in the groundwater recharge zone (Swanston and Swanson, 1976; Swanston, 1981; Swanston and others, 1988). The groundwater recharge zone to a slide is the upslope area where infiltrating and subsurface water flows to the slide mass. Other studies have shown that forestry activities have not reactivated existing dormant or inactive deep-seated landslides in bedrock (Benda, 1993 and 1994).

Deep-seated slides in glacial sediments may be more susceptible to the destabilizing effects of forestry compared to failures in bedrock. In a regional study of landsliding in glacial deposits in the Skagit River system, Heller (1981) showed that timber harvest and roads increased certain types of mass wasting, including small, deep-seated failures. Additionally, three studies of large deep-seated landslides in glacial sediments in the Stillaguamish basin (Benda and others 1988; Benda and Collins, 1992; Kennard and Pess 1994) found that landslide activity occurred following timber harvest in the groundwater contribution zone during a period when vegetation was hydrologically immature (less than 25 years). The three local studies include five instances of harvest within the ground water recharge area of deep-seated landslides. In all cases, the portion of the slide below the harvest area was relatively inactive before harvest, and activity increased following harvest (time period 5 to 25 years). In four of the cases the period of increased activity was followed by reduced slide activity. In the most recent example of deep-seated landsliding (Kennard and Pess 1994), slide activity continues at the present.

A8.2 Effects of Forestry Activities on Landsliding in the Deer Creek Basin

The history of landsliding during the period 1942 through 1991 in Deer Creek is presented in the landslide inventory (Form A-1). The association of landsliding with forestry activities is summarized in Table A-1. There was a significant empirical association between forest practices and landsliding. One-fifth of the 240 landslides originated from areas with mature timber, approximately 60% from clearcut units, and one fifth from forest roads. Approximately one-half of shallow-rapid landslides and debris flows originated in clearcut units, as did over 80% of deep-seated landslides. One-third of debris flows, one-quarter of shallow-rapid features, and under 10% of deep-seated features were associated with roads.

A8.3 Specific Delivered Hazard Rating Criteria for Mass Wasting Map Units

All map units were assigned a delivered hazard rating of low, moderate, high, very high, and, in one case, extremely high. The potential influence of forestry activities on slope stability for each of the ten map units is detailed in Forms A-2 and summarized in Table A-3. These delivered hazard ratings are based on the type and density of landslides in each map unit, their land-use association, and the delivery potential. While some map units are subdivided by delivery to higher or lower order streams (subsection A6.2), this information was not explicitly considered for the hazard ratings. Rule calls, and other related information, for map units with non-trivial hazard ratings are found in the mass wasting casual mechanism reports.

Low hazard map units met one of the following conditions, being: 1) naturally unvegetated (map unit 4); 2) naturally stable (map unit 5); or 3) unable to deliver sediments to water (map unit 5).

Map units were rated moderate hazard if they had the potential for shallow-rapid landslides with delivery, a significant landslide and land use association (Table A-1), and the density of landslides exceeded the lowest map unit landslide density by at least an order of magnitude (Table A-2). Additionally, map unit 1 was assigned a moderate hazard for deep-seated failure in bedrock, based on the association of forest activities and landslide movement in regional studies, summarized in subsection A8.1. Field observations revealed that the one deep-seated landslide visited is active, but the photographic evidence is inconclusive on landslide movement of the other features.

High hazard ratings were assigned to map units with shallow-rapid landslides that met the criteria for moderate hazard, and additionally had landslide densities at least an order of magnitude higher than map units with a moderate rating (and two orders of magnitude higher than the lowest map unit density). Additionally, the ground water recharge areas (which are not on Map A-2) to deep-seated landslides in glacial materials (map units 2,3, and 10) are considered high hazard because of the association of harvest and failure observed in Deer Creek, and other geologically similar areas, summarized in subsection A8.1. For additional information on the ground water recharge areas, please see the mass wasting causal mechanism reports.

Map units are considered very high hazard if : 1) the primary mass wasting type is deep-seated landsliding in glacial sediments (map units 2 and 3) or the map units are debris flow source areas (map unit 6). Deep-seated landsliding in glacial materials have an unambiguous association with forest activities, and represent a chronic source of sediment to streams, persisting for decades after reactivation of movement. Debris flows have extreme erosive potential relative to shallow-rapid landslides, motivating the very high rating. Additionally the debris flow map unit landslide density is higher than the density of map unit 7, which has a high hazard rating.

Map unit 10, containing the large DeForest slide, is rated extremely high hazard because of the large amount of sediment produced (GeoEngineers 1992), the chronic nature of the sediment source, and the unusual sensitivity to most land uses, including mitigation efforts.

A9.0 Use of this Assessment for Prescriptions

A prescription objective for 'prevent and avoid' and 'minimize' rule calls is to reduce erosion associated with forestry to near natural levels. In this section, a process is presented to determine a site's erosion potential and improve the accuracy of the prediction with field data.

The slope stability map (A-2) shows the predicted level of sensitivity to land management at a given site. For map units with deep-seated failures in glacial sediments, harvest in the ground water recharge areas above the slides can contribute to the slide's instability, and it is necessary to establish if a given site is within one of these areas. These areas are not included on Map A-2, but guidance on how to determine these areas is found in the mass wasting causal mechanism reports. The ground water recharge areas of interest are the sub-basins above slides in map unit 3, and above all of map units 2 and 10.

Land use sensitivity ratings are dependent on the resolution of the map units, which are limited by the reliance on aerial photos, particularly in areas mapped under mature forest canopies (section A2.0). The boundaries of map units should be adjusted as necessary using the physical characteristics of the map units (detailed on Forms A-2) based on more accurate field data. No changes should be made to the map unit trigger mechanism descriptions or delivered hazard ratings without analysis by a level 2 certified mass wasting analyst, strictly following the mass wasting methodology protocol and using new information.

Additionally, in map units 1, 2, 3, and 10 and in the groundwater recharge areas of map units 2, 3, and 10, the erosion potential varies depending upon site conditions. In map units 1, 2, and 10, with large deep-seated failures, there is a potential for increased shallow-rapid landslides on slopes over 25 degrees with the potential to deliver sediment to streams. Map unit 3 is an area prone to small deep-seated failures, since many individual features were impossible to identify from the aerial photos. For an individual site in map unit 3, it is necessary to determine if there are actually active slides in the area. Zones with no slides are considered to have a low sensitivity to land use.

In general, consistent with the overall goal to minimize erosion from forestry, forestry activities in map areas with a low sensitivity to land use will not typically require special prescriptions. In practice, these areas are portions of map unit 5 not in the groundwater recharge areas of map units 2, 3, and 10. An exception is when previously unmapped surface waters are identified. In all map units, delivery potential to these waters should be determined by a certified level 2 mass wasting analyst, using the delivery criteria in subsection A6.1. In map unit 5, it will be additionally necessary for the analyst to evaluate the landslide hazard (using the physical criteria of other map units) when new waters are found.

Forest practice opportunities in map unit areas with a moderate rating (1, 8, and 9) will typically require identifying the less stable portions within the map units (see the causal mechanism reports for guidance), and applying appropriate prescriptions to these areas, such as fully engineered roads, or restricting harvest to maintain slope stability. There are fewer opportunities for forest practices in the most unstable map units, particularly 2, 3, 6, 7, and 10.

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Tables

Table A-1. Summary of landslide inventory from the upper 77% of the Deer Creek drainage basin.

Landslide Type	Number	Geology		Forest Activity			Delivery		
		Bedrock	Glacial	Mature	Clearcut	Road	None	1-2 Order	3+ Order
Shallow-rapid	145	35%	65%	26%	50%	24%	20%	49%	31%
Debris flow	41	49%	51%	15%	51%	35%	3%	35%	62%
Deep-seated	54	9%	91%	11%	81%	8%	5%	6%	89%
All Landslides	240	32%	68%	20%	58%	22%	14%	37%	49%

Table A-2. Map unit landslide densities.

Map unit	Landslide Type	Landslide Densities (#/acre)	Relative to map unit 5
3	small deep-seated	0.0088	149
5	shallow-rapid	0.000059	1
6	shallow-rapid	0.072	1220
7	shallow-rapid	0.047	797
8	shallow-rapid	0.004	68
9	shallow-rapid	0.0034	58

Tables-continued

Table A-3. Slope stability map units.

Map Unit	Landslide Type	Delivery (Stream Order)	Land Use Sensitivity Harvest	Road
1	DS SR[2]	3+ 3+	M H	M[1] H
2a	DS SR[2]	3+ 3+	VH H[3,4]	VH[1] H
2b	DS SR[2]	1,2 1,2	VH[4] H	VH[1] H
3a	DS	3+	VH[3,4]	VH[1]
3b	DS	1,2	VH[3,4]	VH[1]
4	-	-	-	L
5	-	-	-	L
6a	DF	3+	VH	VH
6b	DF	1,2	VH	VH
7a	SR	3+	H	H
7b	SR	1,2	H	H
8a	SR	3+	M	M
8b	SR	1,2	M	M
9a	SR	3+	M	M
9b	SR	1,2	M	M
10	DS SR[2]	3+ 3+	VVH[4] H	VVH H

[1]On slide only; [2] On portions of map unit with slopes >25∞ and with delivery potential; [3]Only if slide is historically active; [4]Includes upslope groundwater recharge area. DS: Deep seated; SR: Shallow rapid; DF: Debris flow.

Form A-1

Landslide Inventory

Sub-basin: 1-Below Little Deer; 2-Little Deer; 3-DeForest; 4-Lower Upper Deer; 5-Higgins; 6-Upper Upper Deer. **Eide#:** Number used in Eide (1991) landslide survey. **Type:** SR: shallow-rapid landslide; DS: deep-seated; DF: debris flow; DB: dam break. **Del:** stream order landslide delivers to;N: non-delivery. **Slope form:** P: planar; C: convergent; D: divergent. **Landform:** H: hollow; IG: inner gorge; DS: deep-seated scarp; GT: glacial terrace. **Landuse:** RD:road; cc: clearcut; M: mature timber **Geology:** BR: bedrock; G:glacial.

SUB	LS # BY	Eide #	Type	Del	Slope	Slope	Land	Geol	Land Use	
BASIN #	BASIN				degrees	Form	Form		1	2
2	1	TT106	DF	3	35	C	H	BR	RD	CC
2	2	102	SR	1	26	P	IG	BR	RD	
2	3	103	SR	1	27	P	IG	BR	RD	
2	4	106	SR	2	28	C	IG	BR	CC	
2	5	105	SR	1	30	P		BR	RD	CC
2	6		SR	3	30	P	IG	G	RD	
2	7		DS	3	25	C	IG	G	RD	
2	8		SR	1	30	C	H	BR	CC	RD
2	9		SR	3	30	P	IG	G	CC	
2	10		SR	3	30	P	IG	G	CC	
2	11		SR	3	30	P	IG	G	CC	
2	12		SR	3	30	P	IG	G	CC	
2	13		SR	2	30	P	IG	G	CC	
2	14		SR	2	30	P	IG	G	CC	
2	15	TT101	DF	4	10	C	IG	G	RD	
2	16		SR	3	30	P	IG	G	CC	RD
2	17		SR	3	30	P	IG	G	CC	
2	18	115	SR	N	20	P	IG	G	CC	
2	19	114	DS	4	15	C	GT	G	M	
2	20	113	SR	3	35	P	IG	G	CC	
2	21	118	SR	N	35	P	GT	G	CC	
2	22	119	SR	N	35	P	GT	G	CC	
2	23		SR	N	30	P	GT	G	CC	
2	24	120	SR	1	35	C	GT	G	CC	
2	25	121	SR	1	35	C	GT	G	CC	
2	26	122	SR	1	35	C	GT	G	CC	
2	27		DS	4	20	C	GT	G	CC	
2	28		DS	4	20	C	GT	G	CC	
2	29		DS	4	20	C	GT	G	CC	
2	30		DF	2	>35	P	IG	BR	CC	
2	31	131	SR	2	>35	P	IG	G	CC	

SUB BASIN #	LS # BY BASIN	Eide #	Type	Del	Slope degrees	Slope Form	Land Form	Geol	Land Use 1	Land Use 2
2	32	129	SR	2	>35	C	IG	G	RD	
2	33	130	SR	2	>35	C	IG	G	RD	
2	34	139, 138	DS	4	25-40	C	GT	G	CC	
2	35	133	SR	2	>35	P	GT	G	CC	
2	36	134	SR	1	>35	P	GT	G	CC	
2	37	136	DS	4	25	C	GT	G	CC	
2	38	140	SR	N	30	P	GT	G	CC	RD
SUB	LS # BY	Eide #	Type	Del	Slope	Slope	Land	Geol	Land Use	
BASIN #	BASIN				degrees	Form	Form		1	2
2	39	140	SR	N	30	P	GT	G	CC	RD
2	40	140	SR	N	30	P	GT	G	CC	RD
2	41	140	SR	N	30	P	GT	G	CC	RD
2	42	142	DF	1	30	C	IG	G	CC	RD
2	43	143	DF	1	35	C	IG	G	CC	RD
2	44		DS	4	10	C	GT	G	CC	
2	45		DS	4	15	C	GT	G	CC	
2	46		DS	4	25	C	GT	G	CC	
2	47	146	DS	4	30	C	GT	G	CC	
2	48	TT107	DF	4	35	C	H	G	CC	
2	49		SR	N	35	C	IG	G	CC	
2	50		DS	4	25	C	GT	G	CC	
2	51	TT108	DF	4	35	C	IG	G	CC	
2	52		DS	4	25	C	GT	G	CC	
2	53		DS	3	20->35	C	DS	BR	CC	RD
2	54	151	DF	3	30	C	IG	BR	RD	CC
2	55		SR	3	30	P	IG	BR	CC	
2	56		SR	3	30	P	IG	BR	RD	
2	57		SR	3	30	P	IG	G	RD	
2	58		SR	3	35?	P	IG	G	CC	
2	59		SR	1	35	P	IG	BR	CC	
2	60	TT109	DF	2	>35	P	IG	BR	CC	
2	61		SR	1	25	P	IG	?	RD	
2	62		SR	1	>35	P	IG	?	CC	
2	63		SR	N	25	P	IG	?	RD	
2	64		DS	2?	25-35	C	DS	BR	RD	CC
2	65	TT104	DF	5	30	P	IG	BR	RD	
2	66	151	DF	1	35	C	IG	BR	CC	
2	67	150	SR	N	35	C	H	BR	RD	
2	68	149	SR	1	>35	C	IG	BR	RD	
2	69	149	SR	1	>35	C	IG	BR	RD	
2	70	149	SR	1	>35	C	IG	BR	RD	
2	71		DS	5	25->35	C	DS	G	M	CC

2	72		SR	2	>35	C	IG	G	M	CC
2	73		DF	5	>35	C	IG	G	M	CC
2	74		DS	5	20	C	DS	G	CC	
2	75	153, 155	DS	5	34	C	DS	G	CC	RD
2	76		DS	5	25	C	DS	G	CC	RD
2	77	102	DF	3	30	C	IG	BR	RD	
2	78		DS	3	25	C	GT	G	?	
2	79		SR	1	>35	P	IG	G	M	RD
2	80		SR	1	>35	P	IG	G	M	RD
2	81		SR	1	>35	P	IG	G	M	RD
2	82	160	SR	1	35	P	IG	G	RD	
SUB	**LS # BY**	**Eide #**	**Type**	**Del**	**Slope**	**Slope**	**Land**	**Geol**	**Land Use**	
BASIN #	**BASIN**				**degrees**	**Form**	**Form**		**1**	**2**
2	83	161	SR	1	35	P	IG	G	RD	
2	84		DS	5	<20	C	GT	G	CC	
3	1	320	SR	2	32	P	IG	BR	CC	RD
3	2		SR	2	32	P	IG	G	M	RD
3	3	319	SR	2	32	P	IG	G	M	RD
3	4		DB	5	<10	P	IG	G	M	CC
3	5	317	SR	3	32	P	IG	G	M	CC
3	6		SR	3	32	P	IG	G	M	CC
3	7	316	SR	3	32	P	IG	G	M	CC
3	8	315	SR	3	32	P	IG	G	M	CC
3	9	314	SR	3	32	P	IG	G	M	CC
3	10		SR	3	32	P	IG	G	M	CC
3	11		SR	3	32	P	IG	G	M	CC
3	12		SR	3	35	P	IG	G	M	
3	13		SR	3	35	P	IG	G	M	
3	14		SR	3	35	P	IG	G	M	
3	15	312	SR	3	35	P	IG	G	M	
3	16		SR	3	35	P	IG	G	M	CC
3	17		SR	3	35	P	IG	G	M	
3	18	308	SR	3	35	P	IG	G	M	
3	19		SR	N	30	P		BR	RD	
3	20		SR	1	35?	C	H	BR	RD	
3	21	322	SR	1	35	C	H	BR	RD	
3	22		SR	3	35	P	IG	G	M	CC
3	23		SR	3	35	P	IG	G	M	CC
3	24		SR	3	35	P	IG	G	M	CC
3	25		SR	3	35	P	IG	G	M	CC
3	26	309	SR	3	35	P	IG	G	M	CC
3	27	307	SR	3	35	P	IG	G	M	

3	28	306	SR	3	35	P	IG	G	M	CC
3	29	321	SR	2	35	C	IG	BR	RD	
3	30		SR	2	35	P	IG	G	CC	
3	31		SR	2	35	P	IG	G	CC	
3	32		SR	2	35	P	IG	G	CC	
3	33	305	SR	3	35	P	IG	G	CC	
3	34	304	SR	3	35	P	IG	G	CC	
3	35	304	SR	3	35	P	IG	G	CC	
3	36		SR	3	35	P	IG	G	CC	
3	37		SR	3	35	P	IG	G	CC	
3	38		SR	3	35	C	IG	G	CC	
3	39		SR	1	30	C	IG	G	CC	
3	40		SR	1	30	C	IG	G	CC	
3	41		DS	3	20	C	IG	G	CC	RD
4	1		SR	N	35	P		BR	RD	CC
SUB	**LS # BY**	**Eide #**	**Type**	**Del**	**Slope**	**Slope**	**Land**	**Geol**	**Land Use**	
BASIN #	**BASIN**				**degrees**	**Form**	**Form**		**1**	**2**
4	2	TT408	DF	N	35	P	IG	BR	RD	
4	3	TT408	DF	2	32	C	C	BR	RD	M
4	4	451	SR	2	35	P	IG	G	M	
4	5		SR	2	35	P	IG	BR	M	
4	6		SR	2	35	P	IG	BR	M	
4	7	TT409	DF	2	35	P	IG	BR	RD	
4	8		DS	5	30	C	GT	G	CC	
4	9	449	DS	5	30	C	GT	G	CC	
4	10	451	SR	N	32	P	GT	G	RD	
4	11		SR	N	35	C	H	BR	CC	
4	12		SR	N	35	P		BR	RD	
4	13	450	SR	N	32	P	GT	G	RD	
4	14		SR	N	30	P	GT	G	RD	
4	15	456, 447	DS	5	30	C	GT	G	CC	
4	16		SR	5?	35	C?	IG	G	M	
4	17		SR	2	35	C?	IG	G	M	
4	18	443	SR	2	35	C?	IG	G	M	
4	19		DF	3	35	P	IG	BR	RD	
4	20	401?	DF	1	30	?	IG	BR	M	
4	21		DF	3	30	?	IG	BR	CC	
4	22	402	SR	N	35	C	IG	G	CC	
4	23	403	DF	5	35	C	IG	G	CC	RD
4	24	404	SR	2	35	P	IG	G	CC	RD
4	25		SR	1	30	C	IG	G	CC	
4	26	409	SR	1	30	C	IG	G	CC	

4	27	406	DF	5	30	C	IG	G	CC	
4	28	408	DF	5	30	C	IG	G	CC	
4	29		DS?	N?	25?	C	DS	G	CC	
4	30		SR	N	30	P	?	BR	RD	
4	31		SR	N	30	C	H	G	CC	
4	32		SR	N	30	C	H	G	CC	
4	33		?	1	15?	C	IG	G	CC	
4	34		SR	1	35	P	IG	G	CC	
4	35	TT411	DF	2	30?	C	H	G	CC	
4	36	410-412	SR	N?	30	C	H	G	CC	
4	37	413	DF	1?	30	C	H	G	CC	
4	38	416?	DF	1?	30	C	H	G	CC	
4	39	417?	SR	1?	30	C	H	G	CC	
4	40	418?	SR	1?	30	C	H	G	CC	
4	41		?	N	10	P	GT	G	RD	
4	42		SR	N	20	P	DS	G	CC	
4	43	424	SR	N?	20	P	DS	G	CC	
4	44		DS	5	20	C	GT	G	CC	
4	45	425-430	SR	N?	30	P	DS	G	CC	
SUB	**LS # BY**	**Eide #**	**Type**	**Del**	**Slope**	**Slope**	**Land**	**Geol**	**Land Use**	
BASIN #	**BASIN**				**degrees**	**Form**	**Form**		**1**	**2**
4	46	422, 423	DS	N	20	C	GT	G	CC	
4	47		DF	5	30	C	IG	G	CC	
4	48		DS	5	20	C	GT	G	CC	
4	49	TT411	DF	5	20	C	IG	G	CC	
4	50		DS	5	15	C	GT	G	CC	
4	51	436	DS	5	20	C	GT	G	CC	
4	52	437	DS	1	35	C	GT	G	CC	RD
5	1	501	SR	2	>35	P	IG	G	M	
5	2	504	SR	2	>35	P	IG	G	M	
5	3	506	SR	2	>35	P	IG	G	M	
5	4	507	DS	2	30	C	IG	G	M	
5	5		DS	3	30	C	GT	C	M	
5	6		DS	4?	>35	C	DS	BR	M	
5	7		DS	4	25	C	GT	G	CC	RD
5	8		DS	4	20	C	GT	G	CC	RD
5	9		DS	4	20	C	GT	G	CC	RD
5	10		DS	N	25	C	GT	G	CC	RD
5	11		DS	4	<20	C	GT	G	CC	
5	12		DS	4	<10	C	GT	G	CC	
5	13	TT501	DF	4	>35	C	H	BR	RD	
5	14	TT502	DF	4	>35	C	IG	BR	CC	

5	15		DF	4	35	P	IG	G	CC	RD
5	16	TT503	DF	2	>35	C	IG	BR	CC	
5	17	TT504	DB?	3	?	?	?	G	M	
5	18	508	SR	3	35	P	GT	G	M	
5	19	514	DS	4	35	C	GT	G	CC	
5	20	515	DS	4	35?	C	GT	G	CC	
5	21	518	SR	2	>35	P	IG	BR	CC	
5	22	519	SR	2	>35	C	IG	BR	CC	
5	23	520	SR	2	>35	C	IG	BR	CC	
5	24	521	SR	2	>35	C	IG	BR	CC	
5	25	522, 523	SR	2	>35	C	IG	BR	CC	
5	26		DS	4	15	C	GT	G	M	
6	1		SR	1	25	C	CH	BR	CC	
6	2		SR	N?	25	P	HS	BR	RD?	
6	3		SR	2	25	C	CH	BR	RD	
6	4		SR	N?	25	P	HS	BR	RD	
6	5		SR	N?	25	P	HS	BR	RD	
6	6		SR	2	>35	C	H	BR	CC	
6	7	477	SR	2	>35	C	IG	BR	M	
6	8	473, TT403	DF	3	>35	P	IG	G	CC	
6	9	TT404, TT406	DF	4	~20	P	IG	G	RD	
6	10	472	SR	N	30	P	GT	G	RD	
6	11		DS	4	10-15	C	GT	C	CC	
SUB	**LS # BY**	**Eide #**	**Type**	**Del**	**Slope**	**Slope**	**Land**	**Geol**	**Land Use**	
BASIN #	**BASIN**				**degrees**	**Form**	**Form**		**1**	**2**
6	12	471	DF	1	30	C	CH	BR	RD	
6	13		DS	4	15?	C	GT	G	CC	
6	14	469	SR	1	35	C	CH	BR	CC	
6	15	479	SR	3	35	C	IG	BR	CC	
6	16	TT401	DF	3	35	C	CH	BR	M	
6	17		DS	4	>35	C	DS	BR	M	CC
6	18	466	SR	3	30	P	GT	G	CC	
6	19	467	SR	1	30	P	GT	G	CC	
6	20	468	SR	3	30	P	GT	G	CC	
6	21	454	DS	4	20-25	C	DS	BR	CC	
6	22	453	DS	4	25	P	GT	G	CC	
6	23		DS	4	20	C	GT	G	RD	CC
6	24	462	DS	4	20	C	GT	G	CC	
6	25		DS	4	20	C	GT	G	CC	
6	26	463	SR	4	>35	P		BR	RD	
6	27	460	SR	4	>35	P		BR	RD	
6	28	TT406,TT407	DF	3	30	C	H	BR	CC	

6	29	456	SR	3	30	P	IG	BR	RD	
6	30		SR	1	30	P	IG	BR	RD	
6	31	455	SR	2	35	?	IG	BR	CC	
6	32		SR	2	35	?	IG	BR	CC	
6	33		DF	4	35	?	IG	BR	CC	
6	34		SR	1	35	P	IG	BR	CC	
6	35		SR	1	35	P	IG	BR	CC	
6	36		SR	1	35	P	IG	BR	CC	
6	37		DS	4	20	C	GT	G	CC	

SUB	LS # BY	Type	Del	Land	Land Use	
BASIN #	BASIN			Form	1	2
1	1	SR	Y	GT	CC	
1	2	SR	Y	IG	CC	
1	3	SR	Y	IG	CC	
1	4	SR	?	IG	CC	RD
1	5	DS	Y	GT	CC	
1	6	DS	Y	IG	CC	
1	7	DS	?	IG	CC	
1	8	DS	Y	GT	CC	
1	9					
1	10	DS	Y	IG	CC	
1	11	DS	Y	GT		
1	12	SR	?	IG	CC	
1	13	SR	Y	IG	CC	
1	14	DR	Y	IG	CC	RD
SUB	LS # BY	Type	Del	Land	Land Use	
BASIN #	BASIN			Form	1	2
1	15	SR	Y	IG	CC	
1	16	SR	Y	IG	CC	
1	17	SR	Y	IG	CC	
1	18	SR	N	H	CC	RD
1	19	DF	Y	H	CC	RD
1	20	SR	N	H	CC	RD
1	21	DS	Y	IG	CC	
1	22	SR	Y	IG	CC	
1	23	SR	N	H	CC	RD
1	24	DS	?	H	CC	
1	25	DS	Y	IG	CC	RD
1	26	SR	Y	IG	CC	
1	27	SR	Y	IG	CC	
1	28	SR	Y	IG	CC	
1	29	SR	N	H	CC	

1	30	SR	N	H	RD	
1	31	SR	Y	IG	CC	RD
1	32	SR	N	H	CC	RD
1	33	SR	Y	H	CC	RD
1	34	SR	N	H	CC	
1	35	SR	N	H	CC	
1	36	SR	Y	P	CC	
1	37	DF	Y	?	CC	
1	38	SR	N	H	CC	RD
1	39	SR	Y	IG	CC	
1	40	DF	Y	IG	CC	RD
1	41	SR	Y	IG	CC	RD
1	42	DF	Y	IG	CC	RD
1	43	DS	Y	IG	CC	
1	44	SR	Y	IG	CC	
1	45	SR	Y	IG	CC	
1	46	DS	Y?	IG	CC	RD
1	47	DS	N	H	CC	
1	48	SR	Y	IG	CC	
1	49	DF	Y	IG	CC	
1	50	SR	Y	IG	CC	RD

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 1

Description: Deep-seated earthflows in bedrock

Materials: Bedrock and sapprolite

Landforms: Valley walls

Slope: All gradients for entire map unit and greater than 25 degrees for portions susceptible to shallow rapid landslides

Slope forms: All (convergent, planar, and divergent)

Elevation: 2400 - 4000 feet

MW Processes: Deep-seated slump/earthflows and associated shallow rapid landslides (on slopes in excess of 25 degrees)

Forest Practice Sensitivity: Roads and harvest

Delivery: Third and higher order streams

Delivery Criteria Used: Historic delivery

Delivered Hazard Rating: Moderate on slopes 25 degrees and less, and high elsewhere

Trigger Mechanisms: The primary control to stability of existing deep-seated landslides in bedrock is related to geology and tectonics, and forest practices are a secondary influence. Landslide movement is accelerated by increases in pore water pressures and mechanical loading. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Clearcut and partial harvest on the slide increases the pore pressures within the slide.

Shallow-rapid hillslope failures, on the deep-seated failures, are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Confidence: Medium. High confidence in mapping deep-seated failures, and low confidence in determining the influence of forest practices on deep-seated stability. High confidence in identifying portions of the map unit subject to shallow rapid landslides.

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 2A and 2B

Description: Large (more than 500 feet in map length) deep-seated earthflows in glacial materials, and the associated up slope ground water recharge areas (not delineated on Map A2)

Materials: Lacustrine and other glacial and glacio-fluvial deposits

Landforms: Valley trains, including terrace risers and treads

Slope: All gradients for entire map unit and greater than 25 degrees for portions susceptible to shallow rapid landslides

Slope forms: All (convergent, planar, and divergent)

Elevation: 280 - 2760 feet (not including ground water recharge areas)

MW Processes: Deep-seated slump earthflows, and associated shallow rapid landslides

Forest Practice Sensitivity: Harvest and roads

Delivery: MWMU 2A - third and higher order streams. MWMU 2B - first and second order streams.

Delivery Criteria Used: Historic delivery

Delivered Hazard Rating: Very high for the deep-seated slump earthflows. High for the up slope ground water recharge areas.

Trigger Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the slide, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and over-steepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Shallow-rapid hillslope failures, on the deep-seated failures, are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Confidence: Medium. High confidence in the existence of mapped deep-seated features, though there may be additional unmapped deep-seated failures. High confidence in the temporal association of harvest and roads with deep-seated movement, but low confidence in determining the spatial extent of the up slope ground water recharge areas. Additionally, low confidence in determining the importance of river incision and erosion relative to pore pressure changes in controlling slope failure. Modeling results indicate that large deep-seated failures are more sensitive to pore water changes than toe erosion, compared to small deep-seated failures (Miller, 1995).

High confidence in identifying portions of the map unit subject to shallow rapid landslides.

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 3A and 3B

Description: Glacial materials prone to small (less than 500 feet in map length) deep-seated earthflows, and the associated up slope ground water recharge areas (not delineated on Map A2)

Materials: Lacustrine and other glacial and glacio-fluvial deposits

Landforms: Valley trains, including terrace risers and treads

Slope: All gradients

Slope forms: All (convergent, planar, and divergent)

Elevation: 640 - 3120 feet (not including ground water recharge areas)

MW Processes: Deep-seated slump earthflows

Landslide Density: 0.0088 per acre

Forest Practice Sensitivity: Harvest and roads

Delivery: MWMU 3A - third and higher order streams. MWMU 3B - first and second order streams.

Delivery Criteria Used: Historic delivery

Delivered Hazard Rating: Very high for the deep-seated slump earthflows. High for the up slope ground water recharge areas.

Trigger Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the slide, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and over steepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Confidence: Medium. Many small glacial deep-seated slides were not detectable on the aerial photos. To account for these, the mapped unit includes areas with similar topography and geology to the failures, and therefore includes land that is not failing , or that may not be susceptible to failure. High confidence in the temporal association of harvest and roads with deep-seated movement, but low confidence in determining the spatial extent of the up slope ground water recharge areas. Additionally, low confidence in determining the importance of river incision and erosion relative to pore pressure changes in controlling slope failure. Modeling results indicate that small deep-seated failures are more sensitive to toe erosion than pore water changes, compared to large deep-seated failures (Miller, 1995).

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 4

Description: Unvegetated alpine areas

Materials: Bedrock and shallow colluvial soils over bedrock

Landforms: Ridges, headwalls, and valley walls

Slope: All gradients

Slope forms: All (convergent, planar, divergent)

Elevation: 3100 - 5176

MW Processes: Snow avalanches, and rock falls and topples

Forest Practice Sensitivity: Harvest (adjacent to map unit)

Delivery: Not considered

Delivered Hazard Rating: Low

Trigger Mechanisms: Map unit 4 contains accumulation basins for snow avalanches. Harvest immediately adjacent to map unit 4 may enlarge snow accumulation basins, and create avalanche prone areas.

Confidence: High

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 5

Description: Areas with low landslide hazard or low delivery potential.

Materials: Shallow colluvial soils, bedrock, and glacial materials

Landforms: Ridge tops, and valley floors, terraces, and walls

Slope: All gradients

Slope forms: All (convergent, planar, and divergent)

Elevation: 200 - 4440 feet

MW Processes: Shallow rapid landslides

Landslide Density: 0.000059 per acre

Forest Practice Sensitivity: Not considered

Delivery: Low

Delivery Criteria Used: Historic delivery, predicted debris flow run out (Benda and Cundy, 1990), and predicted shallow rapid landslide run out, based on observations made in Deer Creek.

Delivered Hazard Rating: Low

Trigger Mechanisms: Not considered

Confidence: Medium. High confidence in delivery analysis to known streams. Low confidence in delivered hazard to unknown, unmapped streams.

Comments: The delivery criteria were applied to streams on the USGS 1:24,000 topographic maps, or identified on aerial photographs or in the field. Many streams were undoubtedly not detected. When additional streams are identified, the delivered hazard should be reevaluated using the methods of this mass wasting analysis, by a certified level 2 mass wasting analyst with experience in the area. Appropriate prescriptions should be applied, as necessary.

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 6A and 6B

Description: Inner gorges, with debris flow potential

Materials: Shallow colluvial soils over bedrock or glacial materials

Landforms: Hollows, first order channel heads, and first and second order inner gorges (with a minimum relief of 15 feet to be detected using 1:12,000 scale aerial photography)

Slope: Hillslope gradients 35 degrees or greater, and channel gradients exceeding 20 degrees

Slope forms: Convergent and planar

Elevation: 1200 - 4400 feet

MW Processes: Debris flows and shallow rapid landslides

Landslide Density: 0.072 per acre

Forest Practice Sensitivity: Harvest and roads

Delivery: MWMU 6A - third and higher order streams. MWMU 6B - first and second order streams.

Delivery Criteria Used: Historic delivery and the Benda and Cundy (1990) debris flow run out model.

Delivered Hazard Rating: Very high

Trigger Mechanisms: Debris flow initiation and shallow rapid failure are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) in the inner gorge and increases pore water pressures. Harvest in the ground water recharge area up slope of the inner gorges of DeForest Creek may also influence stability, as suggested by the multiple failures in the old growth inner gorges of DeForest Creek following the harvest of the upper slopes.

Roads can destabilize downslope sites by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water, and pirating and concentrating surface flows. Road cuts, fills, and sidecast are subject to failure. Undersized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid and debris flow failures. Over-steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure.

Confidence: High. High confidence in the existence of mapped inner gorges, though there may be additional unmapped inner gorges, not detectable under closed canopy using aerial photography. High confidence in the association of harvest and roads with debris flow failure, but low confidence in determining how significant harvest above inner gorges of DeForest Creek is to stability within the inner gorges.

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 7A and 7B

Description: Inner gorges prone to shallow rapid landslides

Materials: Shallow colluvial soils over bedrock or glacial materials

Landforms: Inner gorges (with a minimum relief of 15 feet to be detected using 1:12,000 scale aerial photography)

Slope: Hillslope gradients 35 degrees or greater, and channel gradients 20 degrees or less

Slope forms: All (convergent, planar, and divergent)

Elevation: 320 - 4400 feet

MW Processes: Shallow rapid landslides

Landslide Density: 0.047 per acre

Forest Practice Sensitivity: Harvest and roads

Delivery: MWMU 7A - third and higher order streams. MWMU 7B - first and second order streams.

Delivery Criteria Used: Historic delivery and predicted shallow rapid landslide run out, based on observations of Deer Creek landslides.

Delivered Hazard Rating: High

Trigger Mechanisms: Shallow rapid failures are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, in the inner gorges reduces root strength (Krogstad, 1995) and increases pore water pressures. Harvest of the ground water recharge area up slope of the inner gorges of DeForest Creek may also influence stability, as suggested by the multiple failures in the old growth inner gorges of DeForest Creek following the harvest of the upper slopes.

Roads can destabilize downslope sites by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows. Road cuts, fills and sidecast are subject to failure. Undersized or blocked culverts at stream crossings, or inadequate road drainage can result in saturated road fills and sidecast, causing shallow-rapid failures. Over steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure.

Confidence: High. High confidence in the existence of mapped inner gorges, though there may be additional unmapped inner gorges, not detectable under closed canopy using aerial photography. High confidence in the temporal association of harvest and roads with debris flow failure, but low confidence in determining how significant harvest above inner gorges of DeForest Creek is to stability within the inner gorges.

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 8A and 8B

Description: Moderately steep slopes prone to shallow rapid landslides

Materials: Shallow colluvial soils over bedrock or glacial materials

Landforms: Valley walls

Slope: Hillslope gradients between 25 and 35 degrees

Slope forms: Planar and convergent (which are relatively less stable)

Elevation: 400 - 4640 feet

MW Processes: Shallow rapid landslides (one debris flow)

Landslide Density: 0.004 per acre

Forest Practice Sensitivity: Harvest and roads

Delivery: MWMU 8A - third and higher order streams. MWMU 8B - first and second order streams.

Delivery Criteria Used: Historic delivery and predicted shallow rapid landslide run out, based on observations of Deer Creek landslides.

Delivered Hazard Rating: Moderate

Trigger Mechanisms: Shallow rapid failures are controlled by root strength and pore water pressures. Harvest (clearcut and partial cut) increases pore water pressures and reduces root strength, and the influence on slope stability is more pronounced in areas of convergent topography.

Failure of road cuts, fills, and sidecast are controlled by hydrology and mechanics. Under sized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid failures. Over steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure. Additionally, roads can destabilize sites immediately downslope by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows.

Confidence: High

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 9A and 9B

Description: Steep slopes prone to shallow rapid landslides

Materials: Very shallow (typically less than 3 feet thick) colluvial soils over bedrock or glacial sediments

Landforms: Headwalls and valley hillslopes

Slope: Gradients exceeding 35 degrees

Slope forms: Planar

Elevation: 2200 -5083 feet

MW Processes: Shallow rapid landslides

Landslide Density: 0.0034 per acre

Forest Practice Sensitivity: Roads and possibly harvest

Delivery: MWMU 9A - third and higher order streams. MWMU 9B - first and second order streams.

Delivery Criteria Used: Historic delivery and predicted shallow rapid landslide run out, based on observations of Deer Creek landslides.

Delivered Hazard Rating: Moderate

Trigger Mechanisms: Failure of road cuts, fills, and sidecast are controlled by hydrology and mechanics. Under sized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid failures. Over steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure. Additionally, roads can destabilize sites immediately downslope by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows.

Shallow rapid failures in harvest units are controlled by root strength and pore water pressures. Harvest (clearcut and partial cut) increases pore water pressures and reduces root strength. Areas with thicker soils (3 or more feet deep) are relatively less stable than lands with very shallow soils.

Confidence: High generally. Confidence is moderate in forest practice sensitivity to harvest, as there were no in-unit failures associated with harvest. Potential sensitivity to harvest was included for two reasons: 1) the map unit area was small and may not have been of sufficient size to test an association of landslides and harvest, and 2) similar areas in other WAUs experience failures following harvest, particularly if deeper soils are present.

Form A-2

MASS WASTING MAP UNIT DESCRIPTION FORM

MWMU Number: 10

Description: DeForest Creek landslide area and the associated up slope ground water recharge areas

Materials: Lacustrine and other glacial and glacio-fluvial deposits

Landform: Valley trains, including terrace risers and treads

Slope: All gradients

Slope forms: All (convergent, planar, and divergent)

Elevation: 1500 - 2500 feet (not including ground water recharge areas)

MW Processes: Deep-seated slump earthflows, and associated mud flows and shallow rapid landslides

Forest Practice Sensitivity: Harvest and roads

Delivery: High, generally to third and higher order streams

Delivery Criteria Used: Historic delivery

Delivered Hazard Rating: Extremely high for the deep-seated slump earthflows. High for the up slope ground water recharge areas.

Trigger Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the side, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and oversteepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Shallow-rapid hillslope failures, on the deep-seated feature, are controlled by root strength and pore water pressures. Clearcut harvest and high grade, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Confidence: Medium. High confidence in the mapping and assessment of existing deep-seated failures, medium confidence in the hazard rating of the unfailed areas, and low confidence in determining the spatial extent of the up slope ground water recharge areas. Additionally, low confidence in determining the importance of river incision and erosion relative to pore pressure changes in controlling slope failure. Modeling results indicate that large deep-seated failures are more sensitive to pore water changes than toe erosion, compared to small deep-seated failures (Miller, 1995).

Comments: This map unit is distinguished from map unit 2 by its extreme instability, evidenced by the creation (as opposed to reactivation) of at least two large deep seated landslides, since 1972, in apparent response to forest activities.

Form 4

GENERAL NOTES ON CAUSAL MECHANISM REPORT SUMMARIES

1) Guidance to the prescription team

Section A9.0 of the mass wasting assessment outlines a process on how to use the mass wasting assessment to minimize forestry related erosion to Deer Creek, and how to improve the predictive capability of the assessment using additional field information.

2) Triggering mechanisms

Forestry activities that affect slope stability are listed in decreasing order of importance in the causal mechanism reports, based on information from the landslide survey (Forms A-1). For example, harvest is the primary association to slope instability in map unit 8, while forest roads are the principal driver to landslides in map unit 9.

3) Delivered hazard ratings

In addition to the customary high, moderate, and low hazard ratings, the high ranking has been further subdivided in to very high and, in one case, extremely high categories. The additional groupings are done based on the probability of the undesirable mass wasting occurrence and the severity or degree of impact. The specific ranking criteria are discussed in section A8.3 of the mass wasting assessment report.

4) Ground water recharge areas

For several map units, delivered hazard ratings are assigned to the upslope ground water recharge areas to the map units, and these areas are not indicated on Map A-2. Guidance on how to determine the ground water recharge areas is given in the causal mechanism reports.

5) Forms A-2, mass wasting map unit description forms

These forms contain information useful to the prescription team, including: the level of confidence in the hazard call and the sensitivity to forest activities, secondary types of landslides, and the physical characteristics used to delineate the map units. Additionally, there is information on map units 4 and 5 for which there are currently no causal mechanism reports, but could potentially pose hazards under certain conditions.

6) Stream size

Map units are further subdivided (e.g. 3A and 3B) by the size of stream potentially impacted by mass wasting (subsection A6.2). Stream order (Strahler, 1952) is used as a surrogate for stream size, and map units delivering to smaller streams (stream order 1 through 3) are labeled with an "A", and larger streams (greater than third order) are followed by a "B". This information was not used in the hazard determinations, but may be of use in prescriptions.

The specific mass wasting causal mechanism reports follow.

GENERAL NOTES ON CAUSAL MECHANISM REPORT SUMMARIES

1) Guidance to the prescription team

Section A9.0 of the mass wasting assessment outlines a process on how to use the mass wasting assessment to minimize forestry related erosion to Deer Creek, and how to improve the predictive capability of the assessment using additional field information.

2) Triggering mechanisms

Forestry activities that affect slope stability are listed in decreasing order of importance in the causal mechanism reports, based on information from the landslide survey (Forms A-1). For example, harvest is the primary association to slope instability in map unit 8, while forest roads are the principal driver to landslides in map unit 9.

3) Delivered hazard ratings

In addition to the customary high, moderate, and low hazard ratings, the high ranking has been further subdivided in to very high and, in one case, extremely high categories. The additional groupings are done based on the probability of the undesirable mass wasting occurrence and the severity or degree of impact. The specific ranking criteria are discussed in section A8.3 of the mass wasting assessment report.

4) Ground water recharge areas

For several map units, delivered hazard ratings are assigned to the upslope ground water recharge areas to the map units, and these areas are not indicated on Map A-2. Guidance on how to determine the ground water recharge areas is given in the causal mechanism reports.

5) Forms A-2, mass wasting map unit description forms

These forms contain information useful to the prescription team, including: the level of confidence in the hazard call and the sensitivity to forest activities, secondary types of landslides, and the physical characteristics used to delineate the map units. Additionally, there is information on map units 4 and 5 for which there are currently no causal mechanism reports, but could potentially pose hazards under certain conditions.

6) Stream size

Map units are further subdivided (e.g. 3A and 3B) by the size of stream potentially impacted by mass wasting (subsection A6.2). Stream order (Strahler, 1952) is used as a surrogate for stream size, and map units delivering to smaller streams (stream order 1 through 3) are labeled with an "A", and larger streams (greater than third order) are followed by a "B". This information was not used in the hazard determinations, but may be of use in prescriptions.

The specific mass wasting causal mechanism reports follow.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 1, deep-seated earthflows in bedrock

Module: Mass Wasting Module, Map A-2

Situation Sentence:
Coarse and fine sediment from past (and potential future) movement of existing deep-seated slump/earthflows in Mass Wasting Unit 1, possibly associated with roads and harvest (clearcut and partial cut) on the landslides, have contributed to decreased summer rearing capacity for steelhead and resident trout by filling pools in GMUs 5 and 7, and in the fish-bearing segments of GMU 9.

Affected GMUs (without fluvial routing): 5, 7, 9

Triggering Mechanisms: The primary control to stability of existing deep-seated landslides in bedrock is related to geology and tectonics, and forest practices are a secondary influence. Landslide movement is accelerated by increases in pore water pressures and mechanical loading. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Clearcut and partial harvest on the slide increases the pore pressures within the slide.

Shallow-rapid hillslope failures, on the deep-seated failures, are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Rule Call for Management Response:
Delivered hazard: Moderate (on slopes 25 degrees or less), High (all other slopes)
Resource vulnerability: High (GMU 5 - all slopes, GMUs 7 and 9 - slopes greater than 25 degrees), Moderate (GMUs 7 and 9 - slopes 25 degrees and less)
Rule Call: Prevent or avoid (GMU 5- all slopes, GMUs 7 and 9 - slopes greater than 25 degrees), Minimize (GMUs 7 and 9- slopes 25 degrees and less)

Additional comments:
1) Please note the confidence statement on Form A-2 for this map unit.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 2A and 2B, large (more than 500 feet in map length) deep-seated earthflows in glacial materials, and the associated groundwater recharge areas (not delineated on Map A2)

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) movement of existing deep-seated slump/earth flows in Mass Wasting Unit 2, associated with harvest (clearcut and partial cut) on the landslides and within its upslope ground water recharge, and roads on and upslope of the feature, have caused (could cause) shallowing of pools and decreased summer rearing habitat capacity in GMUs 1, 2, 3, 5, and the fish-bearing segments of GMU 8.

Affected GMUs (without fluvial routing): *map unit 2A:* 1, 2, 3, 5, 8 and *map unit 2B:* 8

Triggering Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the slide, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and over-steepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Shallow-rapid hillslope failures, on the deep-seated failures, are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Rule Call for Management Response:
Delivered hazard: Very high for the active failure. High for the upslope ground water recharge area.
Resource vulnerability: High, Moderate
Rule Call: Prevent or avoid

Additional Comments:
1) It is likely that additional active, large deep-seated earthflows in glacial materials exist, that meet the criteria for map units 2A and 2B, but were not included because they were not detected during mapping. These additional features are most likely located in the vicinity of map units 2 and 3, or within map unit 3.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 3A and 3B, glacial materials prone to small (less than 500 feet in map length) deep-seated earthflows, and the associated groundwater recharge areas (not delineated on Map A2).

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) movement of existing deep-seated slump/earth flows in Mass Wasting Unit 3, associated with harvest (clearcut and partial cut) on the landslide and within its upslope ground water recharge area, and roads on and up slope of the feature, have caused (could cause) shallowing of pools and decreased summer rearing habitat capacity in GMUs 3, 5, and the fish-bearing segments of GMU 8.

Affected GMUs (without fluvial routing): *map unit 3A:* 3, 5, 8, *map unit 3B:* 8

Triggering Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the slide, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and over steepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Rule Call for Management Response:
Delivered hazard: Very high for the active failure. High for the upslope ground water recharge area.
Resource vulnerability: High, Moderate
Rule Call: Prevent or avoid

Additional Comments:
1) Map units 3A and 3B delineate the lands most likely to have small deep-seated failures, and includes areas not failing and not susceptible to failure that are considered low hazard. The actively failing (high hazard) areas should be distinguished, by field observations, from the stable lands within the map unit by a certified level 2 mass wasting analyst with experience in glacial landslides, and the appropriate prescriptions applied. Evidence of deep-seated activity of small landslides includes unchanneled valleys, small grabens, and over steepened toes.

2) The upslope ground water recharge area includes the sub-basin draining directly to the active failure and is not delineated on Map A2. A common method (e.g. Benda and others, 1988, and Collins and Benda, 1991) to estimate the spatial extent of this area can be applied using existing maps or, more accurately, field observations. The method assumes an underlying impermeable

These features should be identified in the field by a certified level 2 mass wasting analyst, with experience in glacial landslides, and the appropriate prescriptions applied. Evidence of active deep-seated failure includes scarps, lobate topography, and tipped trees.

2) The up slope ground water recharge area includes the sub-basin draining directly to the active failure and is not delineated on Map A2. A common method (e.g. Benda and others, 1988, and Collins and Benda, 1991) to estimate the spatial extent of this area can be applied using existing maps or, more accurately, field observations. The method assumes an underlying impermeable layer, and the recharge area is considered to be the topographically defined sub-basin directly above the active failure.

3) Please note the confidence statement on Form A-2 for this map unit.

layer, and the recharge area is considered to be the topographically defined sub-basin directly above the active failure.

3) Please note the confidence statement on Form A-2 for this map unit.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 6A and 6B, inner gorges with debris flow potential

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) debris flows and shallow rapid landslides in Mass Wasting Unit 6, associated with harvest (clearcut and partial cut) and roads in and up slope of the inner gorges, have caused (could cause) shallowing of pools and decreased summer rearing habitat capacity in GMUs 3, 4, 5, and the fish-bearing segments of GMUs 8 and 9.

Affected GMUs (without fluvial routing): *Map unit 6A:* 3, 4, 5, 8, 9 and *map unit 6B:* 9

Triggering Mechanisms: Debris flow initiation and shallow rapid failure are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) in the inner gorge and increases pore water pressures. Harvest in the ground water recharge area up slope of the inner gorges of DeForest Creek may also influence stability, as suggested by the multiple failures in the old growth inner gorges of DeForest Creek following the harvest of the upper slopes.

Roads can destabilize downslope sites by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water, and pirating and concentrating surface flows. Road cuts, fills, and sidecast are subject to failure. Undersized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid and debris flow failures. Over-steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure.

Rule Call for Management Response:
Delivered hazard: Very high for the inner gorges. High for the ground water recharge areas upslope of the inner gorges in DeForest Creek only.
Resource Vulnerability: High, Moderate, Low
Rule Call: Prevent or avoid

Additional Comments:
1) It is likely that additional inner gorges, with debris flow potential that meet the criteria for map units 6A and 6B, exist, but were not included because they were not detected during mapping. These additional features are most likely located in map units 5, 8, and 9.

These inner gorges should be identified in the field by a certified, level 2 mass wasting analyst with experience in the area, and the appropriate prescriptions applied. Geomorphic criteria for map units 6A and 6B are summarized on Form A-2, and include all of the following: 1) inner gorge hillslope gradients of 35 degrees or greater, 2) channel gradients in excess of 20 degrees, and 3) minimum 15 feet of vertical relief of the inner gorge side slopes.

2) The up slope ground water recharge area includes the sub-basin draining directly to the inner gorges of DeForest Creek and is not delineated on Map A2. A common method (e.g. Benda and others, 1988, and Collins and Benda, 1991) to estimate the spatial extent of this area can be applied using existing maps or, more accurately, field observations. The method assumes an underlying impermeable layer, and the recharge area is considered to be the topographically defined sub-basin directly above the active failure.

3) Please note the confidence statement on Form A-2 for this map unit.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 7A and 8B, inner gorges prone to shallow rapid landslides

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) shallow rapid landslides in Mass Wasting Unit 7, associated with harvest (clearcut and partial cut) and roads in and up slope of the inner gorges, have caused (could cause) shallowing of pools and decreased summer rearing habitat capacity in GMUs 2, 3, 4, 5, 6, and the fish-bearing segments of GMUs 8 and 9.

Affected GMUs (without fluvial routing): *Map unit 7A:* 2, 3, 4, 5, 8, 9 *and map unit 7B*: 4, 6, 7, 8, 9

Triggering Mechanisms: Shallow rapid failures are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, in the inner gorges reduces root strength (Krogstad, 1995) and increases pore water pressures. Harvest of the ground water recharge area up slope of the inner gorges of DeForest Creek may also influence stability, as suggested by the multiple failures in the old growth inner gorges of DeForest Creek following the harvest of the upper slopes.

Roads can destabilize downslope sites by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows. Road cuts, fills and sidecast are subject to failure. Undersized or blocked culverts at stream crossings, or inadequate road drainage can result in saturated road fills and sidecast, causing shallow-rapid failures. Over steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure.

Rule Call for Management Response:
Delivered hazard: High for the inner gorges. High for the ground water recharge areas upslope of the inner gorges in DeForest Creek only.
Resource Vulnerability: High, Moderate, Low
Rule Call: Prevent or avoid

Additional Comments:
1) It is likely that additional inner gorges, with shallow rapid landslide potential that meet the criteria for map units 7A and 7B, exist, but were not included because they were not detected during mapping. These additional features are most likely located in map units 5 and 8.

These inner gorges should be identified in the field by a certified, level 2 mass wasting analyst, with experience in the area, and the appropriate prescriptions applied. Geomorphic criteria for map units 7A and 7B are summarized on Form A-2, and include all of the following: 1) inner gorge hillslope gradients of 35 degrees or greater, 2) channel gradients 20 degrees or less, and 3) minimum 15 feet of vertical relief of the inner gorge side slopes.

2) The up slope ground water recharge area includes the sub-basin draining directly to the inner gorges of DeForest Creek and is not delineated on Map A2. A common method (e.g. Benda and others, 1988, and Collins and Benda, 1991) to estimate the spatial extent of this area can be applied using existing maps or, more accurately, field observations. The method assumes an underlying impermeable layer, and the recharge area is considered to be the topographically defined sub-basin directly above the active failure.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 8A and 8B, moderately steep slopes prone to shallow-rapid landslides.

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) shallow rapid landslides in Mass Wasting Unit 8, associated with roads and harvest (clearcut and partial cut), within the map unit, have caused (could cause) shallowing of pools and decreased summer rearing habitat capacity in GMUs 2, 4, 5, and the fish-bearing segments of GMUs 8 and 9.

Affected GMUs (without fluvial routing): *Map unit 8A:* 2, 4, 5, 8, 9 and *map unit 8B:* 4, 8, 9

Triggering Mechanisms: Shallow rapid failures are controlled by root strength and pore water pressures. Harvest (clearcut and partial cut) increases pore water pressures and reduces root strength, and the influence on slope stability is more pronounced in areas of convergent topography.

Failure of road cuts, fills, and sidecast are controlled by hydrology and mechanics. Under sized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid failures. Over steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure. Additionally, roads can destabilize sites immediately downslope by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows.

Rule Call for Management Response:
Delivered hazard: Moderate
Resource Vulnerability: High (GMUs 2, 4, ,5), Moderate (GMUs 8 and 9)
Rule Call: Prevent or avoid (GMUs 2, 4, 5), Minimize (GMUs 8 and 9)

Additional Comments:
Areas within map units 8A and 8B, with convergent topography, are relatively less stable than lands with planar slope forms. These areas can be identified in the field by a competent forester, and the stability can be assessed by a certified level 2 mass wasting analyst.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 9A and 9B, steep slopes prone to shallow rapid landslides

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) shallow rapid landslides in Mass Wasting Unit 9, associated with roads and, to lesser extent, harvest (clearcut and partial cut) within the map unit have caused (could cause) shallowing of pools and decreased summer rearing habitat quality in GMUs 3, 4, 5 and the fish-bearing segments of GMU 9.

Affected GMUs (without fluvial routing): *Map unit 9A:* 3, 5 and *map unit 9B:* 4, 9

Triggering Mechanisms: Failure of road cuts, fills, and sidecast are controlled by hydrology and mechanics. Undersized or blocked culverts at stream crossings, or inadequate road drainage, can result in saturated road fills and sidecast, causing shallow-rapid failures. Over-steepened cutslopes and road fill and sidecast are vulnerable to mechanical failure. Additionally, roads can destabilize sites immediately downslope by delivering increased amounts of water. Mechanisms for increasing water include road surfaces capturing subsurface water flow, and pirating and concentrating surface flows.

Shallow rapid failures in harvest units are controlled by root strength and pore water pressures. Clearcut harvest increases pore water pressures and reduces root strength. Areas with thicker soils (3 or more feet deep) are relatively less stable than lands with very shallow soils.

Rule Call for Management Response:
Delivered hazard: Moderate
Resource Vulnerability: High (GMUs 3, 4, 5), Moderate (GMU 9)
Rule Call: Prevent or avoid (GMUs 3, 4, 5), Minimize (GMU 9)

Additional Comments:
1) Areas within map units 9A and 9B, thicker soils (3 feet or greater), are relatively less stable than lands with shallower soils. These areas can be identified in the field by a competent forester, and the stability can be assessed by a certified level 2 mass wasting analyst.

2) Please note the confidence statement on Form A-2 for this map unit, regarding sensitivity to harvest.

Form 4

CAUSAL MECHANISM REPORT SUMMARY

WAU: Deer Creek

Sensitive Area: Mass Wasting Unit 10, DeForest Creek landslide area, and the associated upslope groundwater recharge areas (not delineated on Map A2)

Module: Mass Wasting Module, Map A-2

Situation Sentence: Coarse and fine sediment from past (and potential future) movement of existing (and potential new) deep-seated slump/earth flows and associated mud flows and shallow rapid landslides in Mass Wasting Unit 10, associated with harvest (clearcut and partial cut) on the landslides and within its up slope ground water recharge areas, and roads on and up slope of the map unit, have caused (could cause) a decrease in the capacity of steelhead summer rearing habitat in the low gradient mainstem (GMU 3).

Affected GMUs (without fluvial routing): 3

Triggering Mechanisms: Deep-seated landslide movement is accelerated by increases in pore water pressures and changes in mechanical loading. Clearcut and partial harvest on the slide, and in the ground water recharge area above the side, increase the pore pressures within the slide. Road cuts and fills can mechanically destabilize a feature by overloading and oversteepening. Road surfaces on and above a slide alter the surface and ground water hydrology, by capturing subsurface water, and pirating and concentrating surface flows. Additionally, river incision and river erosion of the landslide toe can mechanically destabilize a slide by removing buttressing material, and oversteepening the toe. In a true cumulative effect, up valley forest activities may influence stream flows and sediment and wood loadings, that, in turn, control river incision and side bank erosion, and subsequent deep-seated failure.

Shallow-rapid hillslope failures, on the deep-seated feature, are controlled by root strength and pore water pressures. Clearcut harvest and high grade thinning, by removal of the largest trees, reduces root strength (Krogstad, 1995) and increases pore water pressures. Deep-seated movement can oversteepen roadways and cutslopes, and derange road drainage, saturating road fills and sidecast, causing shallow-rapid failures.

Rule Call for Management Response:
Delivered hazard: Extremely high for the active and potential failure areas. High for the up slope ground water recharge areas.
Resource vulnerability: High
Rule Call: Prevent or avoid

Additional Comments:

1) Landslide activity has increased with all land uses, including attempts at landslide mitigation. No activity is recommended without a clear understanding of the controls on slope failure within this map unit, including the effects of river erosion.

2) The upslope ground water recharge area includes the sub-basin draining directly to the

active failure and is not delineated on Map A2. A common method (e.g. Benda and others, 1988, and Collins and Benda, 1991) to estimate the spatial extent of this area can be applied using existing maps or, more accurately, field observations. The method assumes an underlying impermeable layer, and the recharge area is considered to be the topographically defined sub-basin directly above the active failure.

3) Please note the confidence statement on Form A-2 for this map unit.