



MEMORANDUM

October 24, 2014

TO: Forest Practices Board

FROM: Marc Ratcliff 
Forest Practices Policy and Services Section

SUBJECT: Board Manual Section 16

On November 12, 2014, staff will request the Board's approval of the amended Board Manual Section 16, *Guidelines for Evaluating Potentially Unstable Slopes and Landforms* as presented to the Board. The amendments to this section were completed in accordance with the first phase of the Board's May 2014 motion directing DNR to, ". . . assemble qualified experts . . . to review and amend guidance specific to the identification and delineation of groundwater recharge areas."

In keeping with the Board direction, DNR assembled a qualified expert panel and facilitated weekly meetings during July, August and the first of September. This accelerated schedule was necessary in order to meet the Board's timeline for completion of this phase in time for the November Board meeting. In this short timeframe, the qualified experts performed the enormous task of researching, drafting, and editing guidance to be used by landowners, foresters and geologists to identify and delineate glacial deep-seated landslides and groundwater recharge areas.

The panel members put much thought and effort into developing language that would provide clear guidance related to detection and identification of glacial deep-seated landslides and groundwater recharge areas; better background information on the geographical influences and descriptions of unstable slopes and landforms; an easy-to-use description of screening processes to help users make sound conclusions and recommendations; and a logical way to insert their contributions into the existing language. They also determined that the approach used to identify and delineate the groundwater area of influence for glacial deep-seated landslides can be applied to all deep-seated landslides.

The significant amendments to the manual include:

- § Additional descriptions of universal landslide classifications commonly used by geologists to identify and describe landslides, Part 2.1;
- § Enhanced descriptions of the relationships between groundwater and deep-seated landslides and groundwater flow through glacial materials, Part 5.2;
Specific guidance for the assessment and delineation of groundwater recharge areas and assessment options when the topographical method for the delineation of a groundwater recharge area lacks certainty, Parts 6.3 and 6.4;

- § Field and office review guidance for the general practitioner and qualified expert, Part 6;
- § Remote sensing tools, including LiDAR, in Part 6.1.4 and various appendices; and
- § Guidance to the qualified expert when assessing the activity level of a landslide, decision pathways for evaluating risk, and guidance on how to synthesize the results of landform assessments, Part 7.

The new method to determine the presence and delineation of the groundwater recharge area enhances the method in the existing manual. It provides guidance to the qualified expert through office review and field assessment to locate the topographic recharge area, and then to develop a hydrogeologic framework of the groundwater flow to determine the extent of the groundwater recharge area influencing a glacial deep-seated landslide.

The manual adds further guidance for the qualified expert to perform additional analysis to determine the influence of groundwater on a glacial deep-seated landslide based on an assessment of landslide activity, water budget and hydrologic contribution to slope stability and a slope stability and delivery assessment.

These additions to the manual in combination with the rule making to clarify that DNR may require additional geologic information prepared by a qualified expert, will significantly improve the necessary information for the forest practices forester and geologist in determining the degree of precision in the delineation of the groundwater recharge area in association with proposed forest practices activities and to appropriately classify an FPA.

As directed by the Board in September, staff invited the TFW Policy caucuses to provide comments. We convened a meeting with caucus representatives prior to the October TFW Policy Committee and heard the various perspectives, received written comments from several of the caucuses (attached) and offered one-on-one meetings at their request. The more substantive comments we received were related to:

- § Insufficient time allowed for stakeholders and reviewers to make well informed comments and fully understand the implications of the amended material;
- § The amendment went beyond the Board's May motion by including aspects unrelated to groundwater recharge areas and glacial deep-seated landslides;
- § Some caucuses feeling excluded from the revision process;
- § The language sounding like administrative rule, not guidance; and
- § The new guidance lacks sufficient direction for requiring subsurface investigations when delineating groundwater recharge areas.

After considering all of the comments and concerns, we made the following changes to the draft:

- § Added explicit language to assure users of the manual the listed methodologies are technical guidance to best achieve the rule requirements and objectives, not the rule itself, and are intended to educate and expedite their review and layout of proposed forest practices activities;
- § Edited the writing to read as one voice and have a conversational tone;
- § Indicated which parts of the manual are for field practitioners and which parts are for qualified experts; and
- § Moved highly technical methods for analysis to the appendices.

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In conclusion, staff recommends the Board approve the amended Board Manual16 and direct staff to convene a stakeholder group for the second phase of manual development to “. . . amend guidance specific to assessing delivery potential”. We believe that phase two can be completed in time for the Board to approve it in May 2015.

Attached for review are the strikeout version and a clean copy of Board Manual16, *Guidelines for Evaluating Potentially Unstable Slopes and Landforms*, and all received written comments from the TFW Policy caucuses. If you have any questions, please contact me at 360.902.1414 or marc.ratcliff@dnr.wa.gov.

MR

Attachment

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PART 1. INTRODUCTION

~~This section of the board manual provides guidelines to evaluate potentially unstable slopes and landforms. It can be used to determine if additional information or a detailed environmental statement will be required before the submittal of a forest practices application for timber harvest or the construction of roads, landings, gravel pits, rock quarries, or spoil disposal areas on potentially unstable slopes or landforms that have the potential to deliver sediment or debris to a public resource or have the potential to threaten public safety.~~

~~It begins with an overview of the forest practices rules for potentially unstable slopes, which unstable landforms that are of concern, and the effects of landslides. Also included are important tools and concepts that can be used to determine if slopes are potentially unstable, descriptions of rule-identified unstable slopes and landforms, information and guidance on how to identify potentially unstable slope situations, the influence of forest practices activities on slope stability, and how to determine if delivery of material to public resources could occur. If you need to hire a qualified expert, guidelines for the contents of the expert report are listed at the end of this Section. Board Manual Section 16 contains guidelines to evaluate potentially unstable slopes and landforms on forest land. Like all Board Manual sections, it does not contain rules or impose requirements. Instead, it is an advisory technical supplement to the forest practices rules, offering approaches for~~

landowners and other forest professionals to achieve complete assessments that will lead to complete Forest Practices Applications (FPAs) and successful proposals.

The intended audience is:

- Landowners, foresters, and company engineers or private consultants who assist in field work; this group is referred to as “general practitioners” in this Board Manual section; and
- Qualified experts, as that term is defined in WAC 222-10-030(5).

The objectives of Section 16 are: 1) to provide general practitioners with tools to better understand the geology and hydrology in the area of a proposed forest practices activity, and to determine when a qualified expert is needed to conduct further geotechnical analysis; and 2) to assist qualified experts with methods to conduct geotechnical investigations and prepare complete geotechnical reports.

The section is composed of eight parts:

- The first five parts contain general background information for all readers on the various landslide types and provinces in Washington State (Part 2), how to measure slope angles (Part 3), how to recognize slope form (Part 4), and how to recognize potentially unstable slopes and landforms for purposes of identifying them in the area of a proposed forest practices activity (Part 5).
- The final three parts contain recommended procedures and resources for conducting reviews and assessments of potentially unstable areas in relation to proposed forest practices. **General practitioners** will find Parts 6.1.1 and 6.2.1 most useful for their office reviews and field assessments. The remainder of Part 6 and all of Parts 7 and 8 are geared toward the work of **qualified experts** to conduct expert-level office reviews and field assessments, and to prepare geotechnical reports.

The section ends with a glossary of terms that may not be familiar to many readers; a list of the references cited throughout the document; and several appendices containing lists of resources that any reader may find informative or useful.

PART 2. OVERVIEW OF LANDSLIDE TYPES AND PROVINCES

Landslides occur naturally in forested basins and are an important process in the delivery of wood and gravel to streams and nearshore environments. Wood and gravel play significant roles in creating stream diversity that is essential for fish use as habitat and spawning grounds (e.g., Reeves et al., 1995; Geertsema and Pojar, 2007; Restrepo et al., 2009).

In the Under past, forest practices rules, forest practices-caused landslides accelerated the contributed to the acceleration of naturally occurring landslide processes that promote balance in nature creating a catastrophic regime that has (e.g., Swanson et al., 1977; Robinson et al., 1999; Montgomery et al., 2000; Turner et al., 2010) and may have contributed to the threatened and endangered status of certain species; (e.g., Sidle et al., 1985; Beechie et al., 2001) as well as endangering endangered human life in some instances (e.g., Oregon Landslides and Public Safety Project Team, 2001). The current forest practices rules are intended were developed to protect public resources and prevent threats to public safety. The rules They apply where therewhen it is determined that proposed forest practices activities may contribute to the potential for sediment and debris to be delivered to a stream, lake, marine water, or other fish ~~or~~and wildlife habitat, domestic water supplies, ~~or~~ public capital improvements, or to cause a threat to public safety. When the

potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety ~~is must be~~ considered. ~~Many Other~~ factors ~~are part of that consideration including include~~ initial failure volume, ~~and the~~ nature of ~~athe~~ landslide, landslide runout distance, and ~~landscape geometry the slope or channel conditions to determine the potential to deliver to a public resource or threaten public safety.~~

2.1 Potentially Unstable Landforms

Certain landforms are particularly susceptible to slope instability ~~or indicate past slope instability.~~ ~~Because of this,~~ Forest practices applications (FPAs) ~~that proposeing~~ activities on ~~orand~~ near these landforms may be classified “Class IV-special” and receive additional environmental review under the State Environmental Policy Act (SEPA). ~~Rule-identified unstable landforms that are described in this Section include~~ These landforms, commonly referred to as “rule identified landforms”, are listed in WAC 222-16-050(1). They are:

- ~~Bedrock hollows~~ Inner gorges, convergent headwalls, ~~and inner gorges and bedrock hollows~~ with slopes >70% (35° degrees);
- ~~toes~~ of deep-seated landslides with slopes >65% (33° degrees);
- ~~g~~ Groundwater recharge areas for glacial deep-seated landslides;
- ~~o~~ Outer edges of meander bends and other indications of slope instability, along valley walls or high terraces of an unconfined meandering stream; and
- Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes.

“Landslide” is a general term for any downslope movement of rock, unconsolidated sediment, soil, and/or organic matter under the influence of gravity. It also refers to the deposit itself, and slide materials in mountainous terrain typically are separated from more stable underlying material by a zone of weakness variously called the failure zone, plane, or surface.

Landslides can be classified in several ways. The method shown in Part 2.1 describes the type of movement (fall, topple, slide, spread, or flow) and the types of materials involved (rock, soil, earth, or debris). The failure surface can range from roughly planar (called “translational”), to curved (called “rotational” or a combination of failure surface geometries) (Figure 1).

Translational failures can also occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes (Robinson et al., 1999; Turner et al., 2010) with little observed rotation or backward tilting of the slide mass. Landslides can be small (a few cubic yards) or very large (millions of cubic yards). They can range from very fast moving as in free fall, to very slow as in creep. Landslides can come to rest quickly or can continue to move for years or even centuries. Landslides that stop moving, only to be later reactivated are considered dormant slides. A landslide can also permanently cease moving and undergo erosion and revegetation over long periods of geologic time; this is considered a relic slide.

Ground failures resulting in landslides occur when gravitational forces, in combination with soil and other factors, overcome the strength of the soil and rock on a slope. Contributing factors may include:

- The presence of an impermeable stratigraphic layer beneath a permeable stratigraphic layer.
- Saturation by rain on snow events or heavy and/or prolonged rains that can saturate soils and create instability in soil and weakened bedrock.

- Erosion by rivers, glaciers, or ocean waves that over-steepen slopes resulting in removing support from the base of the slopes.
- Ground shaking caused by earthquakes that increases the driving force and weakens the supporting soil structure.
- Volcanic eruptions that produce lahars and instability on the lateral flanks of the volcano.
- Excess weight from accumulation of rain or snow, stockpiling of rock or earth from waste piles, or manmade structures that exert excessive stress on slopes.
- Human activities such as timber harvest and construction activities that disturb soils, weaken or remove the support for slopes, or increase runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.

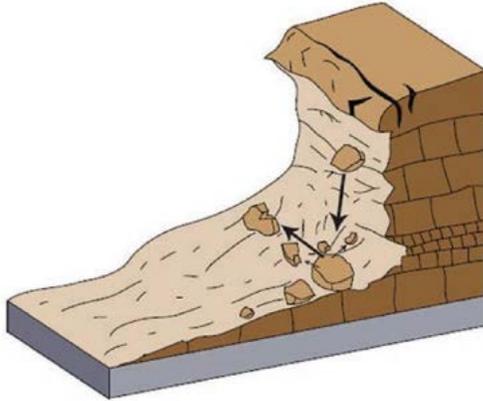
2.1 Landslide Types and Effects

Several classification schemes are used by geologists, engineers, and other professionals to identify and describe landslides. The classification scheme of Varnes (1978), modified by the U.S. Geological Survey (U.S. Geological Survey, 2004), is used for the purposes of this Board Manual section (see Table 1).

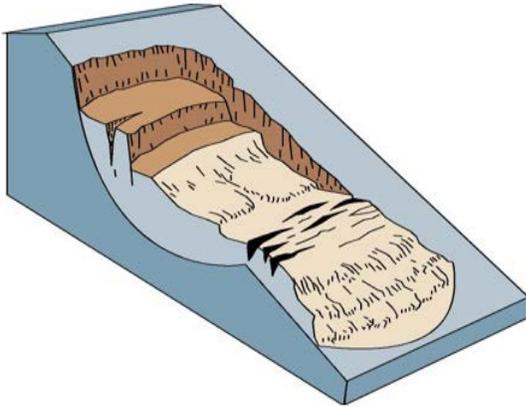
Table 1. Landslide Classification
(modified from U.S. Geological Survey (2004) and Varnes (1978))

<u>Type of Movement</u>	<u>Type of Material</u>		
	<u>Bedrock</u>	<u>Soils</u>	
		<u>Predominately Coarse</u>	<u>Predominately Fine</u>
<u>Falls</u>	<u>Rock Fall</u>	<u>Debris Fall</u>	<u>Earth Fall</u>
<u>Topples</u>	<u>Rock Topple</u>	<u>Debris Topple</u>	<u>Earth Topple</u>
<u>Slides</u>	<u>Rotational</u>	<u>Rock Slide</u>	<u>Debris Slide</u>
	<u>Translational</u>		
<u>Lateral Spreads</u>	<u>Rock Spread</u>	<u>Debris Spread</u>	<u>Earth Spread</u>
<u>Flows</u>	<u>Rock Flow</u>	<u>Debris Flow</u>	<u>Earth Flow</u>
<u>Complex</u>	<u>Combination of two or more principal types of movement</u>		

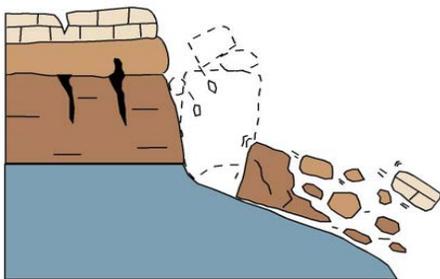
In this scheme, landslides are classified by types of materials and movement. Materials in a landslide mass are either rock or soil (or both) and may also include organic debris. In this context, Soil- is composed of sand-sized or finer particles and debris is composed of coarser fragments. The types of landslides commonly found in forested areas in Washington include slides, flows, and complex landslides. The types of movement describe the actual internal mechanics of how the landslide mass is displaced: fall, topple, slide, spread, or flow. Thus, landslides are described using two terms that refer respectively to the type of material and method of movement (rockfall, debris flow, and so forth). Landslides may also occur as a complex failure encompassing more than one type of movement (e.g., debris slide - debris flow). Some of the landslide types shown in Table 1 can be further divided into shallow or deep-seated depending on whether the failure plane is above (shallow) or below (deep) the rooting depth of trees. Simplified illustrations of the major types of landslides are shown in Figure 1.



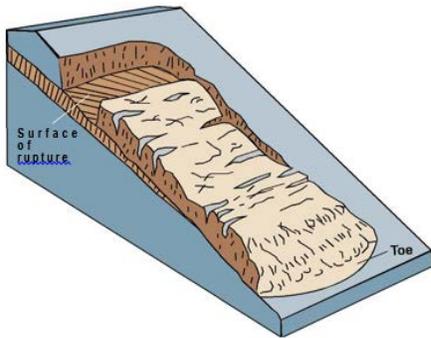
Falls: Falls occur when a mass of rock or soil detach from a steep slope or cliff, often caused by undercutting of the slope. The failure is typically rapid to very rapid. The fallen mass may continue down the slope until the terrain flattens.



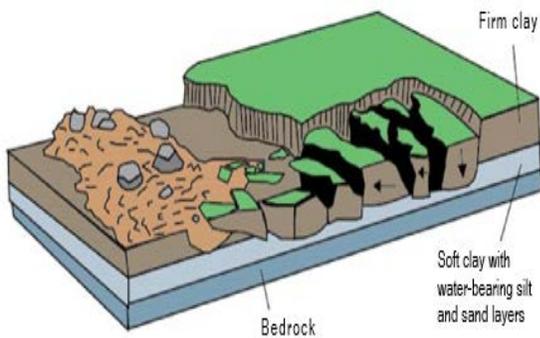
Rotational slides: These are landslides where the surface of rupture is concave-up and the slide movement is rotational about an axis that is parallel to the contour of the slope. Glacial deep-seated landslides can be rotational slides developed in glacial sediments common in the Puget Sound area, but they can also involve more complex types of movement.



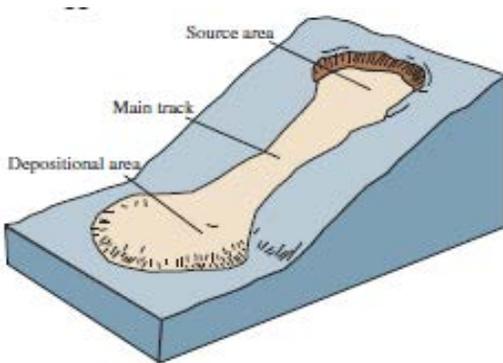
Topples: Landslides where the forward rotation of a mass of rock or soil breaks away or 'topples' from the slope. Their failure rates range from extremely slow to extremely fast.



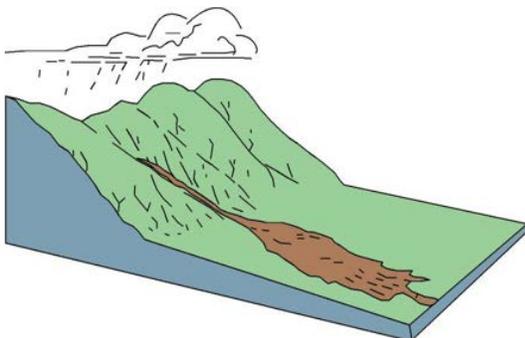
Translational slides: Landslides where the surface of the rupture is roughly planar.



Lateral spreads: Landslides that generally occur on very gentle or level slopes and are caused by subsidence of a fractured mass of cohesive material into softer, often liquefied underlying material.



Earth flows: Landslides consisting of fine-grained soil or clay-bearing weathered bedrock. They can occur on gentle to moderate slopes.



Debris flows: Landslides where loose rock, soil, and organic matter combine with water to form a slurry that flows rapidly downslope.

Figure 1 Illustrations of the major types of landslide movement (all from Highland and Bobrowsky, 2008, except Earth flows from U.S. Geological Survey, 2004).

2.2 Shallow Landslide Types and Effects

Shallow landslides are unstable features which typically fail within the vegetation rooting zone and may respond to rainfall events over periods of days to weeks. They occur in a variety of landforms including bedrock hollows, convergent headwalls, and inner gorges with slopes > 56%, on toes of deep-seated landslides, with slopes > 65%, and on the outer edges of meander bends, and in other areas with steep slopes. There are generally three types of shallow landslides: debris slides, debris flows, and hyper-concentrated floods. They are distinguished from each other by the ratio of water to solids contained in them. The amount of water and the materials contained within shallow landslides affect the manner and the distance in which they move.

Debris slides consist of aggregations of coarse soil, rock, and vegetation that lack significant water and move at speeds ranging from very slow to rapid down slope by sliding or rolling forward. The results are irregular hummocky deposits that are typically poorly sorted and non-stratified. Debris slides include those types of landslides also known as shallow rapid, soil slips, and debris avalanches. If debris slides entrain enough water they can become debris flows.

Debris flows are slurries composed of sediment, water, vegetation, and other debris. Solids typically constitute >60% of the volume (Pierson and Scott, 1985). Debris flows usually occur in steep channels; as ~~landslide~~ debris becomes charged with water (from soil water, or upon entering a stream channel) and liquefies as it breaks up. Channelized debris flows often entrain material and can significantly bulk up in volume during transport. These landslides can travel thousands of feet (or ~~even miles~~) from the point of initiation, scouring the channel to bedrock in steeper channels. Debris flows commonly slow where the channel makes a sharp bend and stop where the channel slope gradient becomes gentler than about 3° degrees (5%), or the valley bottom becomes wider and allows the flow to spread out. Hyper-concentrated floods may travel greater distances and on shallower slopes than debris flows based on their water content (Iverson and Reid, 1992).

Hyper-concentrated floods are ~~flowing mixtures a subset of debris flows containing a mixture~~ of water, and sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains, they are commonly caused by the collapse of dams, such as those formed by landslide dams (Figure 2) or debris jams (Figure 1). Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel, and, the active floodplain, if present, ~~the active floodplain~~.

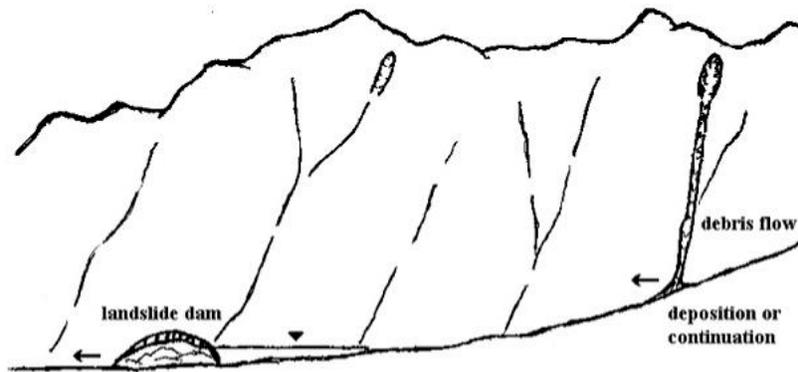


Figure 24. Debris flows, and hyper-concentrated floods

Debris flows and hyper-concentrated floods can occur in any unstable or potentially unstable terrain with susceptible valley geometry. In natural systems, debris flows and hyper-concentrated floods caused by dam-breaks are responsible for moving sediment and woody debris from hillslopes and small channels down into larger streams. But debris flows can also cause damage to streams by scouring channel reaches, disturbing riparian zones, impacting habitat and dumping debris onto salmonid spawning areas. Debris flows can cause elevated turbidity, adversely affect water quality downstream, pose threats to public safety, and damage roads and structures in their paths (Figure 23).



Figure 32. Road-initiated debris flows in inner gorges, Sygitowicz Creek, Whatcom County (Photo: DNR, 1983).

These debris flows shown in Figure 3 coalesced and, after exiting the confined channel at the base of the mountain, formed at the new debris flow spreading across a 1,000-foot wide swath for a distance of 2,000 feet before entering the South Fork Nooksack River. Between the base of the mountain and the river, the debris flow affected (if not severely damaged) a county road, farmyard, and house sites, and more than 60 acres of cultivated farm fields.

2.3 Deep-Seated Landslides

~~A more detailed explanation of deep-seated landslides is covered later in this section because deep-seated landslides are also landforms. Regardless of failure mechanism,~~ Deep-seated landslides are those in which the slide plane or zone of movement is ~~well~~ below the maximum rooting depth of forest trees (generally greater than ~~three meters (10 feet or 3 meters)~~), ~~and~~ may extend to hundreds of feet in depth, ~~often including and may involve underlying~~ bedrock. Deep-seated landslides can occur almost anywhere on a hillslope and are ~~typically usually~~ associated with hydrologic responses in permeable ~~geologic~~ materials overlying less permeable materials. ~~Deep-seated slides may respond to rainfall events over periods of days to weeks, or to weather patterns over months to years or even decades (Washington State Department of Emergency Management, 2013).~~ The larger deep-seated landslides can usually be identified from LiDAR, topographic maps, and aerial photos, whereas the identification of smaller landslides often requires a field inspection and comprehensive inventory maps.

~~Certain key areas of deep-seated landslides may be sensitive to forest practices.~~ The bodies and toes of deep-seated landslides ~~and earth flows~~ are made up of incoherent collapsed materials ~~that were~~ weakened from previous movement ~~of the materials~~ and therefore may be subject to ~~debris slide and~~ debris flow initiation ~~in response to harvest or road building.~~ Sediment delivery is common from shallow landslides on steep stream-adjacent toes of deep-seated landslides and from steep side slopes of marginal streams flowing on the bodies of deep-seated landslides ~~is common.~~ More detailed descriptions of deep-seated landslides are provided in Part 5 (5.3 and 5.5.1).

2.4 Geographic Distribution of Landslides in Washington

Landsliding is a widespread geomorphic process which actively modifies the varied topography and diverse underlying geologic materials present throughout the state. This overview focuses on areas within the state where forest practices activities are prevalent and draws from Thorsen's (1989) organization and discussion by physiographic provinces.

The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by the continental, and to a lesser extent alpine glaciations. Unconsolidated sediments formed by glaciation include thick layers of fine-grained glacial lake sediments (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits. Translational and complex landslides occur within some of the very weak bedrock units exposed within the foothills and lowlands, such as the Chuckanut Formation, Darrington Phyllite, and Puget Group rocks.

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower

reaches of the Quinault, Queets, Hoh, and Bogachiel valleys. Large rock slides and rock avalanches are common in the steep upper reaches of Olympic mountain drainages. Translational landslides and large landslide complexes are also abundant in the very weak marine sedimentary rocks (often occurring along inclined bedding surfaces) and mantling residual soils in the western and northwestern portions of the Peninsula, such as the Twin Creek Formation, and the Western Olympic and Hoh Lithic Assemblages (Tabor and Cady, 1978; Badger, 1993). Debris flows and avalanches are often generated in steeper drainages and slopes.

The Willapa Hills of Southwest Washington are comprised primarily of very weak marine sedimentary and volcanic rocks. Because the region has not been glaciated, thick and especially weak residual soils have developed on these rocks. Translational landslides and coalescing landslides forming earthflows are widespread in these weak rocks and overlying soils, such as in the Lincoln Creek Formation (Gerstel and Badger, 2002). Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches (Thorsen, 1989). These deposits are prevalent along the lower Columbia River valley, as well as other areas where colluvial deposits have accumulated on slopes and in drainages underlain by strong and relatively unweathered rock.

The Cascade Range is generally divided on the basis of rock types into northern and southern provinces occurring geographically in the vicinity of Snoqualmie Pass. Strong crystalline rocks intensely scoured by alpine glaciations occur to the north. Weaker volcanic flows, typically pyroclastic and volcanoclastic rocks occur to the south, much of which was beyond the reach of the last continental glaciation. Rockfalls and complex rock slides are dominant in the steep bedrock slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control large translational failures in the Chumstick and Roslyn Formations (Tabor et al., 1987), the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone (Wegmann, 2003). Shallow landslides generating debris avalanches and flows are common on steep slopes and drainages.

Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides. Rockfalls and rock slides are common from the many steep bedrock exposures in the region. The Blue Mountains in southeastern Washington also have experienced recurring and widespread shallow landsliding and debris flows related to storm events (Harp et al., 1997).

PART 3. MEASUREMENT OF SLOPE ANGLES

The forest practices rules contain specific slopes gradients (degrees and percent) for defining landform descriptions. Part 3 is provided for guidance in determining slope gradients when evaluating the feature on site. Slope gradients are commonly expressed in two different but related ways, as degrees of arc or percent rise to run. It is important to understand the relationships between them.

3.1 Degrees

A circle is divided into 360° degrees of arc. Each degree is further divided into 60 minutes (60'), and each minute into 60 seconds (60"). The quadrant of the circle between a horizontal line and a vertical line comprises 90° degrees of arc (Figure 43a).

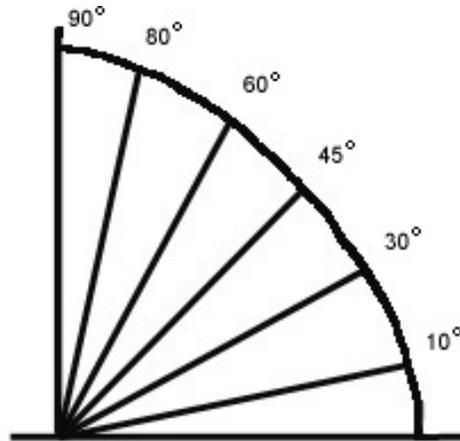


Figure 43a- Angles in degrees.

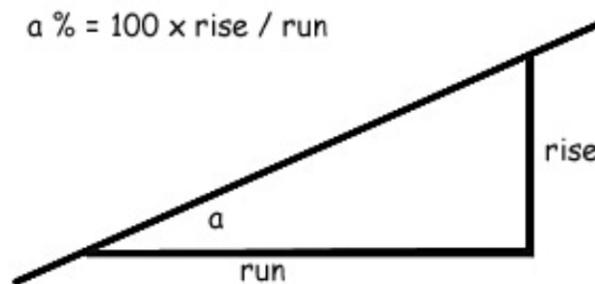


Figure 43b- Angles in percent.

3.2 Percent

In [Figure 43b](#), the horizontal distance between two points (distance between the points on a map) is called the run. The vertical distance (difference in elevation) is called the rise. The gradient can be expressed as the ratio of rise divided by run, a fraction that is the tangent of angle α . When multiplied by 100, this fraction is the percent slope.

3.3 Relationship of Degrees to Percent

Because of the differences in the ways they are calculated, each of these two slope measurements is better for certain applications. Because it is more precise at gentle slopes, percent is best for measuring and expressing small angles, such as the gradients of larger streams. But for steeper slopes, the constant angular difference and smaller numbers (an [85° degree](#) slope is 1143%) make degrees more useful.

[Figure 54](#) shows approximate equivalences for gradients expressed in degrees and percent. Note that there is a rough 2:1 ratio in the 30 to 40° [degree](#) range (e.g., [35° degrees](#) = 70% slope), but beware - this relationship changes dramatically at gentler and steeper angles.

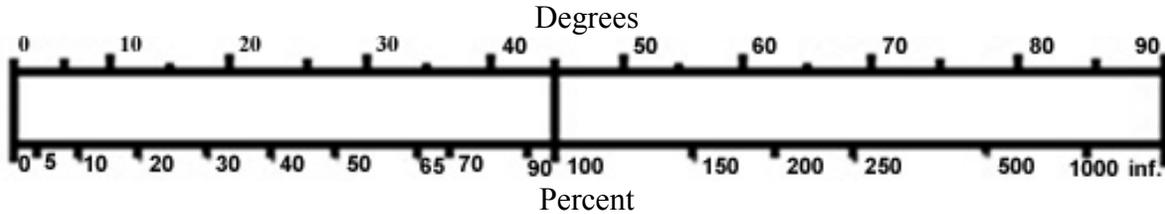


Figure 54. Slope gradients in degrees and percent.

PART 4. SLOPE FORM

Slope shape is an important concept when considering the mechanisms behind shallow landsliding. Understanding and recognizing the differences in slope form is essential key in to recognizing potentially unstable landforms s-recognition. There are three major slope forms to be observed when looking across the slope (contour direction): divergent (ridgetop); planar (straight); and convergent (spoon-shaped) (Figure 65a). Landslides can occur on any of these slope forms but divergent slopes tend to be more stable than convergent slopes because water and debris spread out on a divergent slopes whereas water and debris concentrate on convergent slopes. Convergent slopes tend to lead into the stream network, encouraging delivery of landslide debris to the stream system. Planar slopes are generally less stable than divergent slopes but more stable than convergent slopes. In the vertical direction, ridgetops are convex areas (bulging outward) and tend to be more stable than planar (straight) mid-slopes and concave areas (sloping inward) (Figure 65b).

Additionally, slope steepness can play a significant role in shallow landsliding. Steeper slopes tend to be less stable. The soil mantle, depending upon its make-up, has a natural angle at which it is relatively stable (natural angle of repose). When hillslopes evolve to be steeper than the natural angle of repose of the soil mantle, the hillslope is less stable and more prone to shallow landslides, especially with the addition of water. The combination of steep slopes and convergent topography has the highest potential for shallow landsliding.

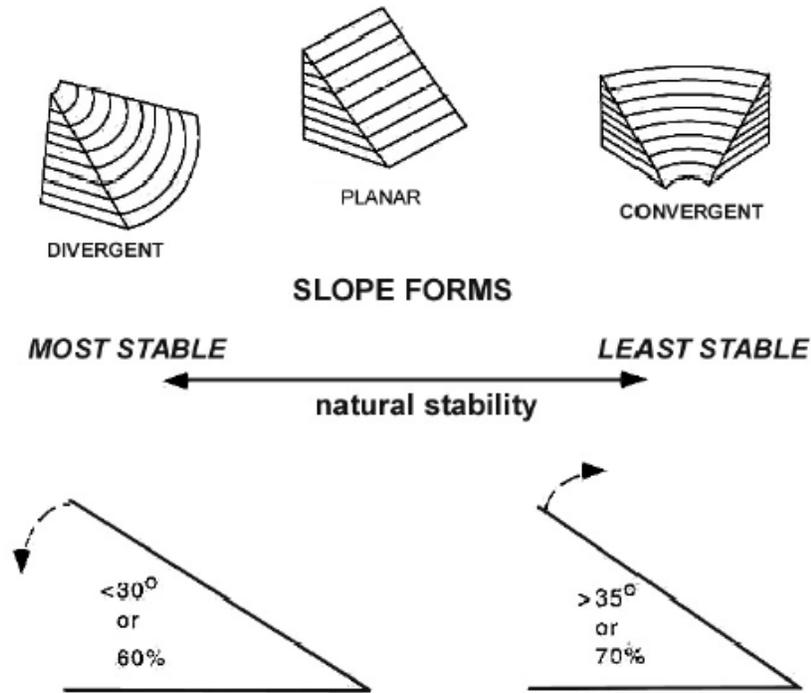


Figure 5a6a. Slope configurations as observed in map view.

This Figure 6a shows three major slope forms (divergent, planar, and convergent) and their relative stability. These slope form terms are used in reference to contour (across) directions on a slope. Convergent areas with slope greater than 35° degrees (70%) are the most shallow landslide-prone (Benda, et al, 1997/1998).

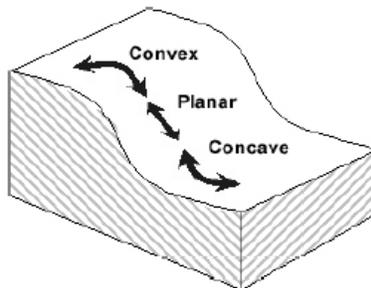


Figure 5b6b. Slope configurations as observed in profile: convex, planar, and concave. These terms are used in reference to up and down directions on a slope (Drawing: Jack Powell, DNR, 2004).

PART 5. DESCRIPTION CHARACTERISTICS OF UNSTABLE AND POTENTIALLY UNSTABLE SLOPES AND LANDFORMS AND PROCESSES

This part describes the characteristics of the unstable slopes and landforms listed in WAC 222-16-050(1)(d)(i), commonly referred to as “rule-identified landforms”:

- Inner gorges, convergent headwalls or bedrock hollows with slopes steeper than 35 degrees (>70 percent) (see 5.1);
- Toes of deep-seated landslides with slopes steeper than 33 degrees (>65 percent) (see 5.3);
- Groundwater recharge areas for glacial deep-seated landslides (see 5.2);
- Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (see 5.4); or
- Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes (see 5.5).

~~Areas of u~~Unstable landforms can usually initially be identified with a combination of topographic and geologic maps, aerial photographs, ~~watershed analysis mass wasting map unit (MWMU) maps, landslide hazard maps from the Regional (Unstable) Landform Identification Project (RLIP), Landslide Hazard Zonation Project (LHZ), and modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps~~LiDAR data and a variety of private- and public agency-derived landform screening maps and tools. ~~However, f~~Field observation is normally required to then needed to verify their presence and precisely delineate landform boundaries, gradients, and other characteristics. In addition to the information provided in this part, more information for identifying unstable landforms is offered in Part 6, and tools and resources are listed in appendices A through G.

In most instances, the landform terms described here~~in~~ are also used in the scientific literature. For the purposes of Washington forest practices, the rule-identified landform terms, definitions, and descriptions ~~supereedes~~supersede those used in the scientific literature. Note that all sizes, widths, lengths, and depths are approximate ~~infor~~ the following discussion ~~of unstable landforms,~~ and are not part of the rule-identified landform definitions, unless parameters are specifically provided. ~~Sizes are included to help visualize the landforms.~~

5.1 Bedrock Hollows, Convergent Headwalls, Inner Gorges

These three landforms are commonly associated with each other as shown in Figures ~~67~~ and ~~78~~.

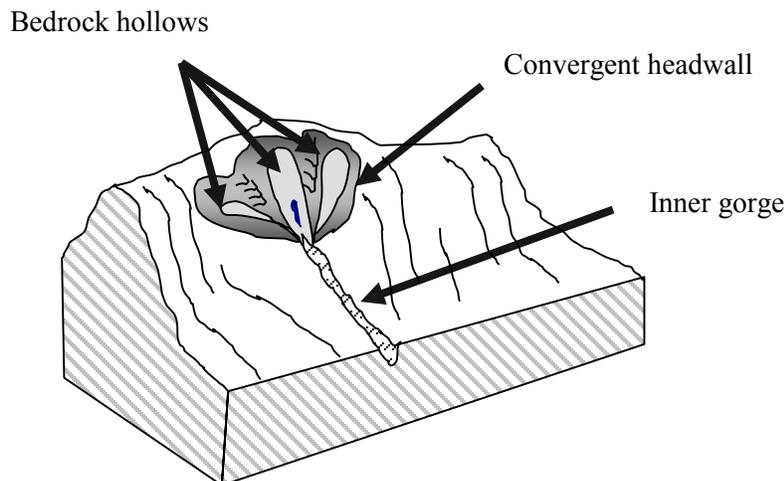


Figure 67: Typical hillslope relationships between bedrock hollows, convergent headwalls, and inner gorges (Drawing: Jack Powell, DNR, 2003).

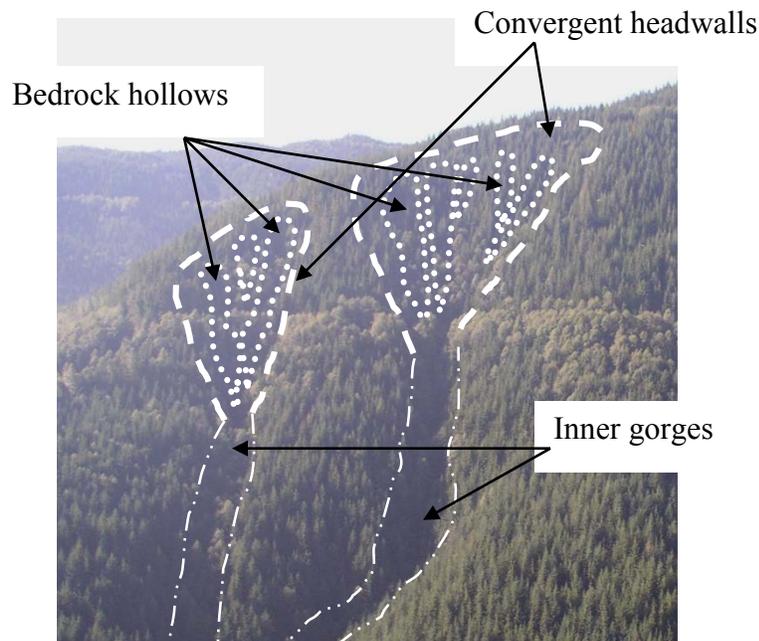


Figure 78: Common hillslope relationship: bedrock hollows in convergent headwalls draining to inner gorges (Photo and drawing: Jack Powell, DNR, 2003).

Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows (Crozier et al., 1990; Dietrich et al., 1986). Not all hollows contain bedrock so the term “bedrock” hollow can be a misnomer. However, the forest practices rules cite these features as “bedrock” hollows so this is the term used in [the Board Manual](#)[this document](#). Hollows are commonly spoon-shaped areas of convergent topography with concave profiles on hillslopes. They tend to be oriented linearly up- and down-slope. Their upper ends can extend to the ridge or begin as much as several hundred feet below [the](#) ridge line. Most hollows are approximately 75 to 200 feet wide at their apex (but they can also be as narrow as several feet across at the top), and narrow to 30 to 60 feet downhill. Hollows should not be confused with other hillslope depressions such as small valleys, sag areas (closed depressions) on the bodies of large deep-seated landslides, tree ~~wind-throw~~[windthrow](#) holes (pit and mound topography), or low-gradient swales.

Hollows often form on other landforms such as head scarps and toes of deep-seated landslides. Bedrock hollows can occur singly or in clusters that define a convergent headwall. They commonly drain into inner gorges (Figure 89).

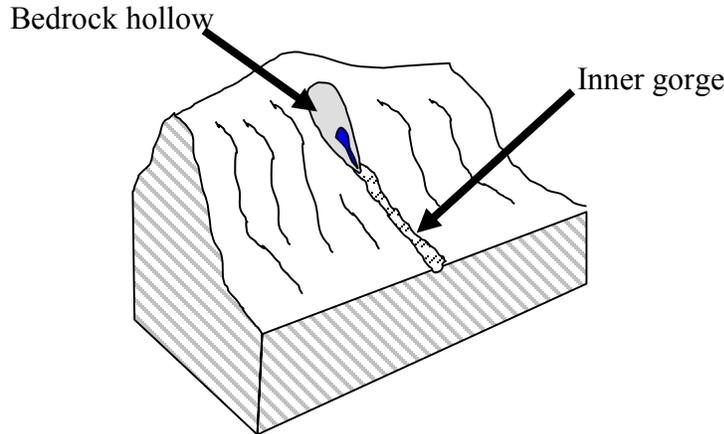


Figure 89- Bedrock hollow and relationship to inner gorges (Drawing: Jack Powell, DNR, 2003).

Hollows usually terminate where distinct channels begin. This is at the point of channel initiation where water emerges from a slope and has carved an actual incision. Steep bedrock hollows typically undergo episodic evacuation of debris by shallow-rapid mass movement (a debris flow), followed by slow refilling with colluvium that takes years or decades. Unless they have recently experienced evacuation by a landslide, hollows are partially or completely filled with colluvial soils that are typically deeper than those on the adjacent spurs and planar slopes. Recently evacuated hollows may have water flowing along their axes, whereas partially evacuated hollows will have springs until they fill with sufficient colluvium to allow water to flow subsurface.

Figure 910 illustrates the evolution of a bedrock hollow. Drawing “a” shows that over a period of tens to hundreds or thousands of years in some places, sediment accumulates in a hollow. When the soil approaches a depth of 3 to 5 feet (1-2 meters), the likelihood of landslides increases. Recurrent landsliding within the hollow slowly erodes bedrock and maintains the form of the hollow (Drawing “b”). After a landslide, bedrock may be exposed (and also seeps or springs) and the risk of additional sliding is often reduced, but not gone. Drawing “c” shows soil from the surrounding hillsides (colluvium) slowly re-filling the hollow. As vegetation and trees establish the site after past failures, the Rroots help stabilize the soil.

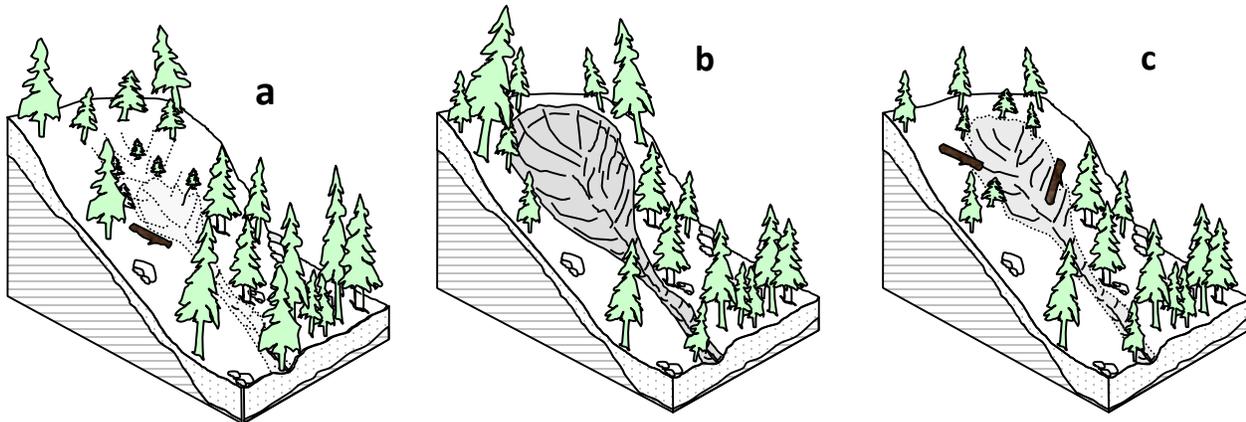


Figure 109a-e. Evolution of a bedrock hollow following a landslide (adapted from Dietrich et al., 1988; Drawing by Jack Powell, DNR, 2004).

The common angle of repose for dry, cohesion-less materials is about 36° (72%) (36 degrees), and saturated soils can become unstable at lower gradients. Thus, slopes steeper than about 35° (70%) (35 degrees) are considered susceptible to shallow debris slides. “Bedrock” hollows are formed on slopes of varying steepness. Hollows with slopes steeper than 70% (approximately 35° degrees) are potentially unstable in well-consolidated materials, but hollows in poorly consolidated materials may be unstable at lower angles. Note: For the purpose of this document, bBedrock hollow slopes are measured on the steepest part of the slope, and generally not along the axis unless the hollow is full (Figure 110).

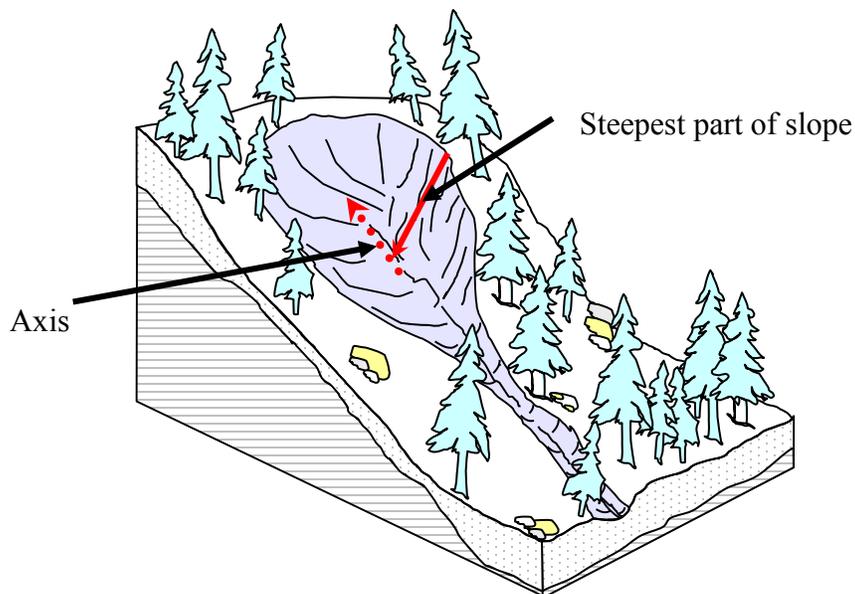


Figure 10-11 Bedrock hollow slopes are measured on the steepest part of the slope generally not along the axis (Drawing: Jack Powell, DNR, 2004).

Vegetation can provide the critical cohesion on marginally stable slopes and removes water from the soil through evapotranspiration. Leaving trees in steep, landslide-prone bedrock hollows helps maintain rooting strength and should reduce the likelihood of landsliding (Figure 4412) (Montgomery et al., 2000). However, wind-throw of the residual trees following harvest can be associated with debris slide or debris flow events. In high wind environments, it is essential

to harvest in a manner that will limit the susceptibility of the residual trees to ~~wind-throw~~windthrow as well as to reduce the potential for landslides (for example leaving wider strips, pruning or topping trees in the strips, or feathering the edges of reserve strips).



Figure 11.12 Example of leave areas protecting unstable slopes (Photo: Venice Goetz, DNR, 2004).

Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. A series of converging bedrock hollows may form the upper part of a convergent headwall (Figure 1213). Convergent headwalls are broadly concave both longitudinally and across the slope, but may contain sharp ridges that separate the bedrock hollows or headwater channels (Figure 13a, b14, and Figure 1415).

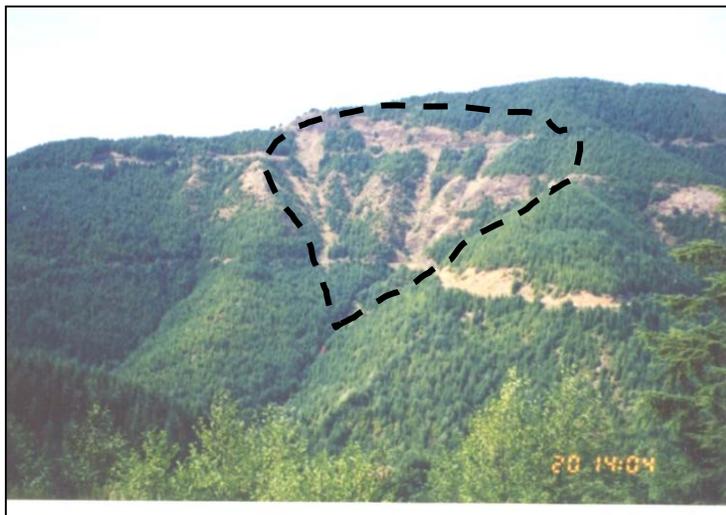


Figure 1213: Convergent headwall example (Photo: Venice Goetz, DNR, 1995).

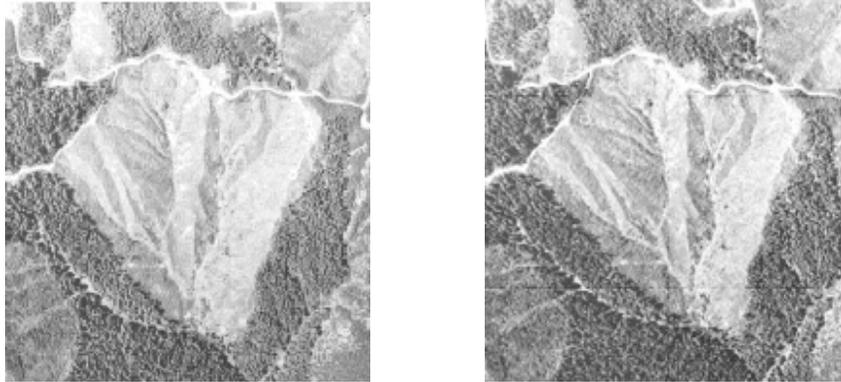


Figure 143a, b- Stereo-pair of a clearcut convergent headwall in Pistol Creek basin, North Fork Calawah River, Washington.

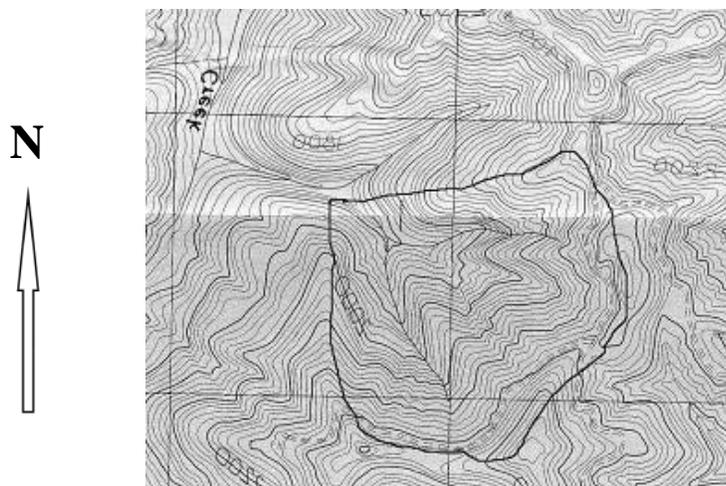


Figure 154. Topographic map and outline of convergent headwall displayed in the stereo-pair of Figure 143a, b14. Scanned from portions of Hunger Mountain and Snider Peak USGS 7.5' quadrangles.

Convergent headwalls generally range from about 30 to 300 acres. Slope gradients are typically steeper than 35° degrees (70%) and may exceed 45° degrees (94%). Unlike bedrock hollows, which exhibit a wide range of gradients, only very steep convergent landforms with an obvious history of landslides are called convergent headwalls. Soils are thin because landslides are frequent in these landforms. History of evacuation and landsliding can be evident by a lack of vegetation or mature trees on the site, or the presence of early seral plant communities such as grasses or red alder. It is the arrangement of bedrock hollows and first-order channels on the landscape that causes a convergent headwall to be a unique mass-wasting feature. The highly convergent shape of the slopes, coupled with thin soils (due to frequent landslides), allows rapid onset of subsurface storm water flow. The mass-wasting response of these landforms to storms, disturbances such as fire, and ~~to~~ forest practices activities is much greater than is observed on other steep hillslopes in the same geologic settings. Convergent headwalls may be also prone to surface erosion from the scars of frequent landslides.

Channel gradients are extremely steep within convergent headwalls, and generally remain so for long distances downstream. Landslides that evolve into debris flows in convergent headwalls

typically deliver debris to larger channels below. Channels that exit the bottoms of headwalls have been formed by repeated debris flows and are efficient at conducting them. Convergent headwalls commonly have debris fans at the base of their slopes.

Inner gorges are canyons created by a combination of stream down-cutting and mass movement on slope walls (Kelsey, 1988). Inner gorges are characterized by steep, straight or concave side-slope walls that commonly have a distinctive break in slope (Figure 165). Debris flows, in part, shape inner gorges by scouring the stream, undercutting side slopes, and/or depositing material within or adjacent to the channel (Figure 176). Inner gorge side-slopes may show evidence of recent landslides, such as obvious landslides, raw ~~un-vegetated~~unvegetated slopes, young, even-aged disturbance vegetation, or areas that are convergent in contour and concave in profile. Because of steep slopes and proximity to water, landslide activity in inner gorges is highly likely to deliver sediment to streams or structures downhill. Exceptions can occur where benches of sufficient size to stop moving material exist along the gorge walls, but these are uncommon.

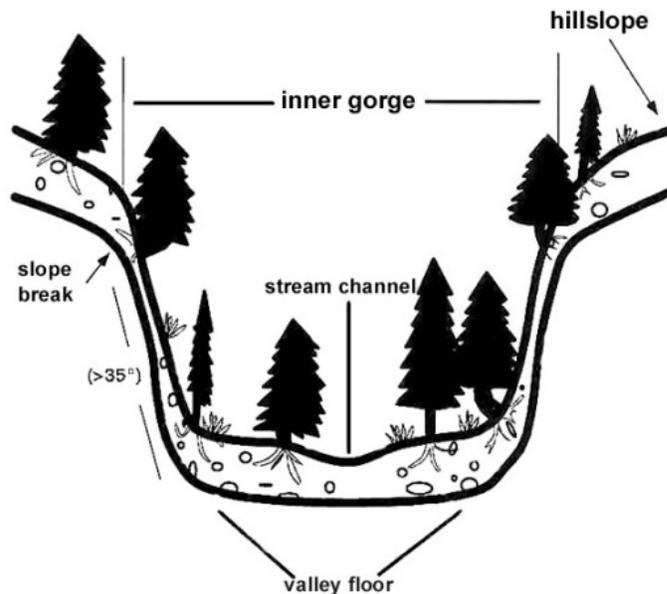


Figure 165. Cross-section of an inner gorge. This view emphasizes the abrupt steepening below the break-in-slope (Drawing: Benda, et al., 1998).



Figure 176- Photograph showing how debris flows help shape features related to inner gorges.

For example, over-steepened canyon wall, U-shaped profile, buried wood, distinctive break-in-slope along margins of inner gorge (Photo: Laura Vaugeois, DNR, 2004).

The geometry of inner gorges varies. Steep inner gorge walls can be continuous for great lengths, as along a highly confined stream that is actively down cutting, but there may also be gentler slopes between steeper ones along valley walls. Inner gorges can be asymmetrical with one side being steeper than the other. Stream-eroded valley sides, which can be V-shaped with distinct slope breaks at the top, commonly do not show evidence of recent landsliding as do inner gorges which tend to be U-shaped. In practice, a minimum vertical height of 10 feet is usually applied to distinguish between inner gorges and slightly incised streams.

The upper boundary of an inner gorge is assumed to be a line along the first break in slope of at least 10° degrees (18%) or the line above which gradients are mostly gentler than 35° degrees (70%) and convex. The delineating break-in-slope occurs where over-steepened slopes related to inner gorge erosion processes intersect slopes formed from normal hillslope erosion processes. While the upper inner gorge boundary is typically distinct, in some places it can be subtle and challenging to discern. Inner gorge slopes tend to be especially unstable at the point where the slope breaks because the abrupt change in gradient causes subsurface water to collect within the soil matrix which can destabilize the soil mass and initiate movement. Just as for all other landforms, inner gorge slopes should be measured along the steepest portion of the slope (see Figure 110).

The steepness of inner gorges is dependent on the underlying materials. In competent bedrock, gradients of 35° degrees (70%) or steeper can be maintained, but soil mantles are sensitive to root-strength loss at these angles. Slope gradients as gentle as about 28° degrees (53%) can be unstable in gorges cut into incompetent bedrock, weathered materials, or unconsolidated deposits.

Erosion along the gorge walls can intercept shallow groundwater forming seeps along the sides of the inner gorge, which promotes continued mass wasting. Root strength along walls and margins of inner gorges has been found to be a factor that limits the rates of mass wasting. Inner gorge areas

can lose root strength when trees blow down. However, downed timber has a buttressing effect providing some slope reinforcement. Effective rooting width of forest trees is approximately the same as the crown width. In some instances where the inner gorge feature is highly unstable it is necessary to maintain trees beyond the slope break. ~~Use of~~ The rooting strength of trees adjacent to the landform ~~for~~ can often provide additional support.

5.45.2 Groundwater Recharge Areas, and the Effects of Groundwater on Landslide Stability of (Glacial) Deep-Seated Landslides

In order to identify and delineate groundwater recharge areas in glacial terrain it is necessary to first identify and delineate glacial deep-seated landslides. Glacial deep-seated landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however, their failure mechanics are similar to deep-seated landslides developed in other materials (Terzaghi, 1951). Deep-seated landslides developed in other materials are also susceptible to forest practices activities in the groundwater recharge area. Consequently, scientific knowledge regarding the dynamics of deep-seated failures can be applied to better understand and manage glacial deep-seated landslides.

Glacial deep-seated landslides occur in glacial terrain and are defined as a landslide feature where most of the slide plane or zone lies within glacial deposits. The depth of the glacial deposits extends below the maximum rooting depth of trees, to depths ranging from tens to hundreds of feet beneath the ground surface. Glacial deep-seated landslide deposits occur in continental or alpine glacial deposits, or a combination of both. The continental glacial deposits in Washington are located in the northern areas of the state (Figure 18a), whereas the alpine glacial deposits (Figure 18b) can be found in mid-to-high elevation mountain ranges (Booth et al., 2003; Booth et al., 1994; Thorsen, R.M., 1980; Barnosky, 1984; Heusser, 1973; Crandall, 1965).

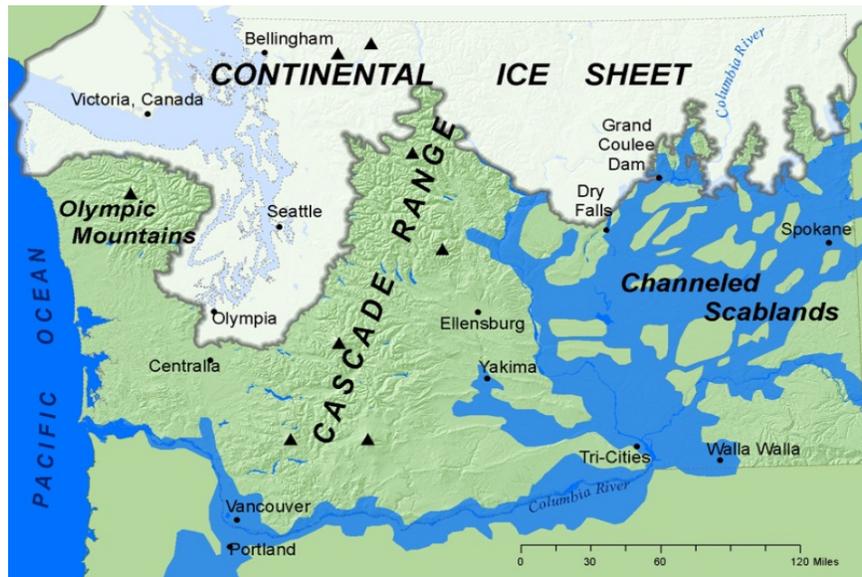


Figure 18a Extent of continental ice sheet in the Pacific Northwest (DNR, 2014).

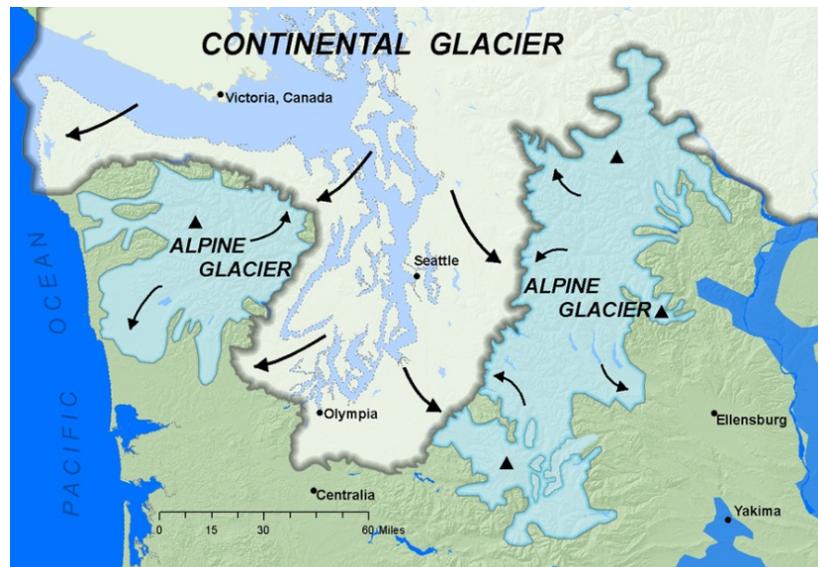


Figure 18b Continental and alpine glaciation in western Washington (DNR, 2014)

Deep-seated landslides in glacial terrain can involve rotational and translational movement, flows or a combination of movement types. Glacial deep-seated landslides can occur in any type of glacial deposit including till, outwash, glaciolacustrine and glaciomarine silt and clay, or a mix containing multiple glacial strata. During interglacial periods, layers of loess, (e.g., windblown silt and clay) and other non-glacial sediments can also be deposited between glacial layers or on the surface of glacial materials and become overlain by deposits from successive glaciations.

Glacial deposits and other earthen materials display a wide range of hydrologic characteristics, including: permeability, which is the rate water moves through a geologic material; and storage capacity, which is the amount of water released or taken into storage per unit area of geologic material for a given change in hydraulic head (See Appendix F for hydraulic properties of various soils):

- Glacial till is comprised of unsorted and non-stratified glacial materials that can range in size from clay to boulders that was generally over run by glacial ice during periods when the ice was advancing. Glacial till generally has low permeability and low water storage capacity;
- Glacial outwash typically contains sorted and stratified sediments deposited by water flowing from glacial ice either during the advance or retreat of the glacier and have higher permeability and higher water storage capacity than glacial till;
- Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes; and,
- Glaciomarine deposits which are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

Glaciomarine and glaciolacustrine deposits typically have low permeability and low storage capacity like glacial till.

Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 19). The hydrologic budget is the amount of ground water present and is calculated based on precipitation (rain and snow), interception of precipitation by vegetation, evapotranspiration, surface storage, surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic

budget that infiltrates into the subsurface below the root zone. The groundwater component is composed of water within the unsaturated, or vadose zone, and the saturated zone.

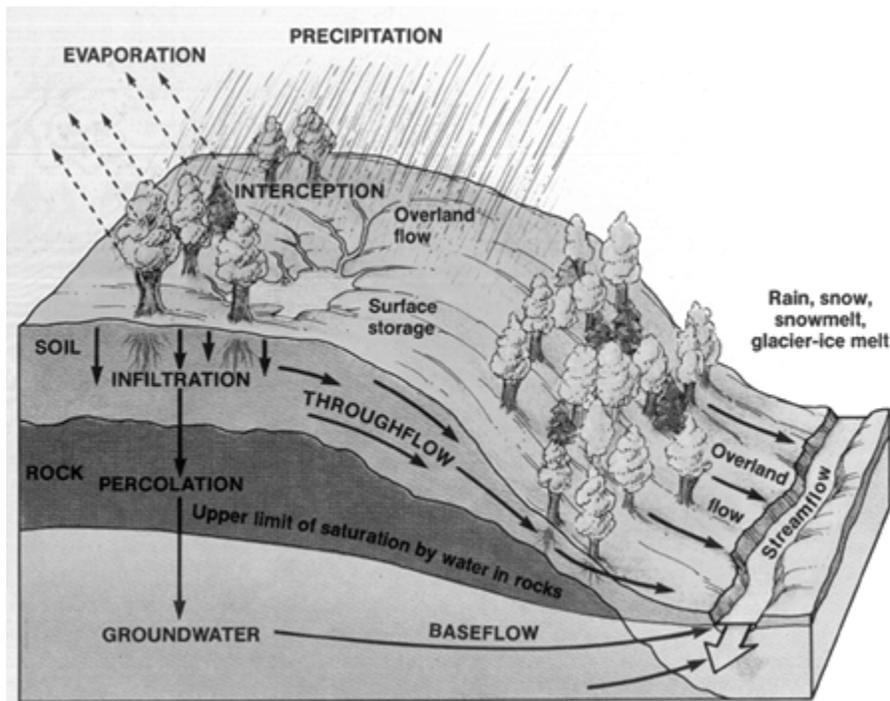


Figure 19 Hydrologic budget of a hillslope (University of Colorado).

Groundwater recharge to a glacial deep-seated landslide can present in several ways. Groundwater recharge may originate from adjacent non-glacial materials that flows into glacial sediments, or runoff from upland non-glacial materials and contribute groundwater recharge within glacial sediments. A contributing component of groundwater recharge can also be surface flow.

5.2.1 Groundwater Flow

Groundwater recharge areas of deep-seated slides are located in the lands up-slope that can contribute subsurface water to the landslide. In some cases this can include upslope portions of the landslide itself. Cemented soil horizons, fine-grained soils, and/or the presence of glacial till can be factors controlling the infiltration and flow of groundwater (Bauer and Mastin, 1997; Vaccaro et al., 1998). Groundwater flows originating in upland areas are discharged as springs, streams, and other surface water features at lower elevations. The amount of the recharge area that contributes groundwater to a glacial deep-seated landslide constitutes that landslide's groundwater recharge area and includes the landslide itself.

Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area (Bauer and Mastin, 1997; Vaccaro et al., 1998). Groundwater perching and the characteristics of the overlying groundwater recharge area can be important factors in a deep-seated failure, especially for landslides in glacial sand and other unconsolidated sequences deposits that overlie fine-grained glacial-lake clay deposits or till (Figure 1920). This is a common configuration of the glacial deposits in much of the northern half of western Washington (e.g., landslides in Seattle (Gerstel and others et al., 1997) and in the Stillaguamish River valley (Benda and others et al., 1988)), but this type of landslide also occurs in alpine glacial deposits in

southwest Washington, far from the mountain front maximum extent of continental glaciation. Groundwater filtering downflowing through porous-permeable sand layers is trapped-perched above the poorly-less permeable clay or till. During storm and following precipitation events, the sand above the clay becomes saturated creating a buoyant effect and lowering cohesion in the sand, both of which weaken the contact between the clay and sand. This in turn may causes the overlying mass to slide along the sand/clay contact. A key predictive observation is noting common predictor of perched groundwater is the presence of a horizontal line of springs (groundwater refluxing discharge) or a line of vegetation at the contact point between the permeable and less permeable layers. Land uses such as poorly planned ditches or large scale, even aged harvesting that alter the timing or volumes of groundwater recharge in the slide zone can start or accelerate landslide movement.

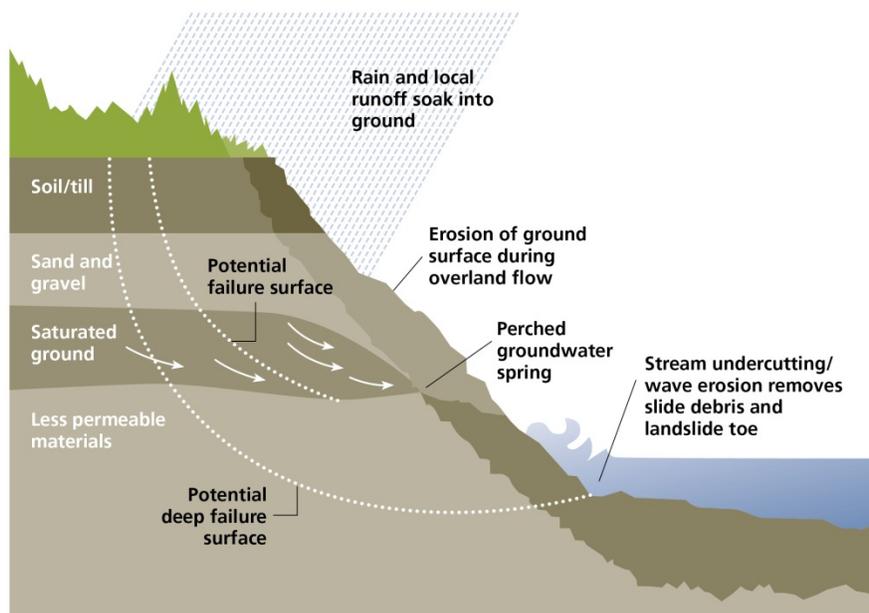
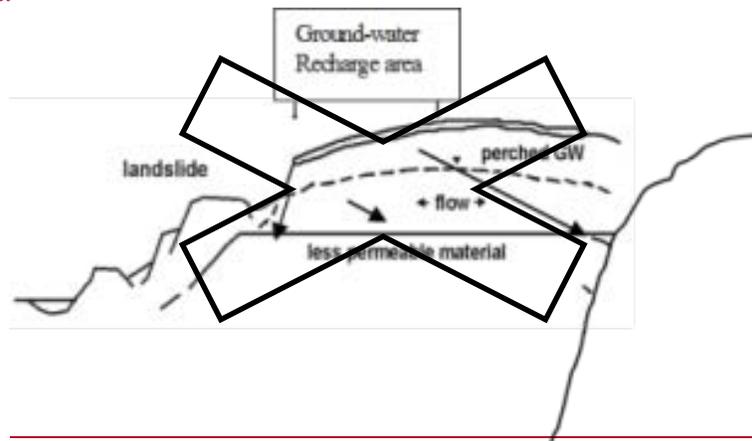


Figure 4920- Diagram illustrating failure surface resulting from groundwater recharge area for a glacial deep-seated landslide (DNR, 2014).

A classic example of a geologic setting where glacial deep-seated landslides are common is in the Puget Sound lowlands where the Esperance Sand or Vashon advance outwash, overlies the Lawton

Clay. In this setting, groundwater recharge from precipitation infiltrates downward within the hillslope until it encounters the relatively impermeable Lawton Clay. Because the water cannot infiltrate into the Lawton Clay at the same rate at which it is supplied from above, the water table rises vertically above the clay surface. The elevated water table increases the pressure within the Esperance Sand and forms a hydraulic gradient which causes water to flow horizontally along the sand-clay contact, resulting in springs where this contact is exposed at the surface (Tubbs, 1974).

5.2.2 Effects of Groundwater on Slope Stability

Saturation of the pore spaces within sediments reduces grain to grain contact which reduces the effective strength of materials. This phenomenon of soil saturation reduces the effective strength of the soil which in turn reduces the stability of a slope comprised of saturated sediments. Because of the likelihood of subsurface water flow along and within perching layers in glacial strata, certain forest practice activities proposed within recharge areas for glacial deep-seated landslides may be classified “Class IV-special” under the forest practices rules per WAC 222-16-050(1)(d) and require further investigation and documentation prepared by a qualified expert. Therefore, it is important to characterize groundwater recharge areas and local stratigraphy in terms of an evaluation of the potential for changes in the water balance due to forest practices activities and an assessment of the degree to which a potential hydrologic change can be effectively delivered to a glacial deep-seated landslide. In the absence of other information, The first order approximation of the recharge area is assumed to be equivalent to the surface basin (topographically defined) basin directly above and including the active landslide. A more refined estimate of the spatial extent of a groundwater recharge area can also be interpreted from field observation of soil profiles, geologic structure, stratigraphy, well logs of wells or boreholes, or large-scale and geologic maps. Additional information regarding delineating and assessing the groundwater recharge areas is included in Part 6.3 and Part 7.2.

5.3 Toes of Deep-Seated Landslides

The toes of deep-seated landslides are a rule-identified forest practices regulatory landform. In this context, “deep-seated landslide toes” means the down slope toe edges, not the entire toe area of displacement material (see Figure 1723). Landslides that have toe edges adjacent to streams have a high potential for delivery of sediment and wood to streams through natural processes. In such situations, streams can undercut the landslide toes and promote movement. Such over-steepened toes of deep-seated landslides can also be sensitive to changes caused by harvest and road construction. The road shown in Figure 21 may have removed a portion of the toe, causing re-activation of the landslide. Resulting instability can take the form of shallow landslides, small-scale slumping, or reactivation of parts or the whole of a deep-seated landslide. Because deep-seated landslides are usually in weak materials (further weakened by previous movement), an angle of 33 degrees (65%) is the threshold value used on the potentially unstable toe edges and the determinate factor in regard to whether a proposed forest practices activity is on a rule-identified landform. Regardless of the surface expression of the toe, it is best to avoid disrupting the balance of the landslide mass by cutting into or removing material from the toe area.

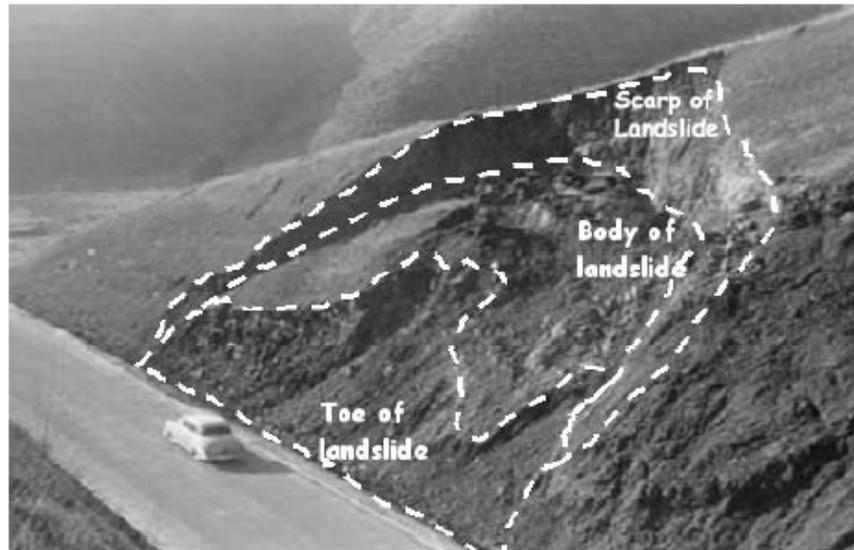


Figure 21 Deep-seated landslide showing the head scarp, side-scarps, body, and toe. Some of the toe has been removed in building and maintaining the highway (adapted from USGS photo).

5.55.4 Outer Edges of Meander Bends

Streams can create unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (Figure 2022) (Schuster and Wieczorek, 2002). The outer edges of meander bends are susceptible to ~~deep-seated landsliding and~~ shallow landsliding, including debris avalanching and small-scale slumping, ~~and deep-seated landsliding~~. The outer edges of meander bends may be protected by the riparian management zone (RMZ) or channel migration zone (CMZ) rules if the slopes are not particularly high and are contained within the riparian leave areas or within the CMZ (see Board Manual Section 2). As with other situations of overlapping forest practices rules, the harvest unit layout should reflect the extent of the greater of the protections.

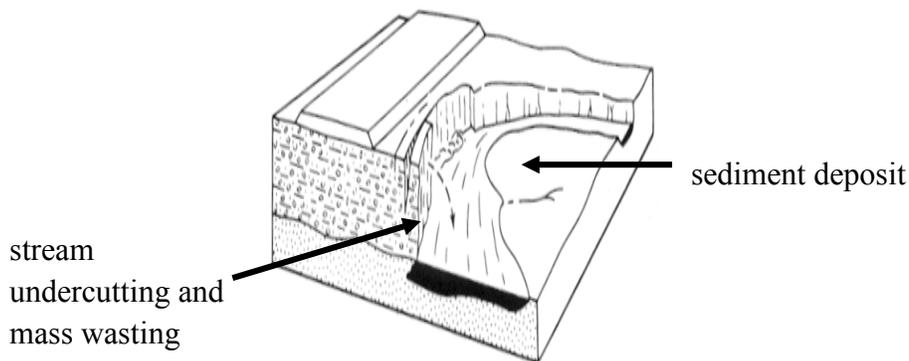


Figure 2022- Outer edge of a meander bend showing mass wasting on the outside of the bend of the bend and deposition on the inside of the bend (adapted from Varnes, 1978).

5.5 Additional Features and Landforms Indicating Potential Slope Instability

Apart from the rule-identified landforms described above, there are other slope indicators that can point to instability. When the feature or landform indicates the presence of slope instability which

cumulatively indicates the presence of unstable slopes, the area can be considered a rule-identified landform. A proposed forest practices activity in this situation may be classed as a “Class IV-Special” if there is potential to damage a public resource or threaten public safety.

Relatively large and recent topographic indicators can be observed on air photos, topographic maps and LiDAR images, but the identification of smaller and older indicators requires careful field observation. In addition to the landforms above, other Topographic, hydrologic and vegetational indicators of slope instability or active movement may include:

(a) ~~T~~Topographic and hydrologic indicators

- Bbare or raw, exposed, ~~un-vegetated~~unvegetated soil on the faces of steep slopes. This condition may mark the location of a debris flow or the headwall or side wall of a slide.
- Benched surfaces, especially below crescent-shaped headwalls, indicative of a rotational slide
- Hummocky topography at the base of steep slopes. This may mark the accumulation zone (runout area) for a flow or slide.
- Bboulder piles
- Hhummocky or benched surfaces, especially below crescent-shaped headwalls
- Ffresh deposits of rock, soil, or other debris at the base of a slope
- ~~ponding of water in irregular depressions or undrained swampy areas on the hillslope above the valley floor~~
- Tension cracks in the surface (across or along slopes, or in roads). Tension cracks may mark the location of an incipient headwall scarp or a minor scarp within the body of an existing slide.
- Pressure ridges typically occur in the body or toe of the slide and may be associated with hummocky topography.
- Intact sections (blocks) having localized horst and graben topography
- Transverse ridges and radial cracks on landslide displacement material
- ~~seepage lines or springs and soil piping~~
- ~~deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)~~
- Stratigraphic indicators, including disconformities, offset contacts, and overturned sections
- Back tilted surfaces from rotation within the slide
- Multiple scarps in a downward direction
- Side scarps, shear margins or lateral scarps
- Displaced surface features like roads, railroads, foundations, and fence lines

Hydrologic indicators

- Pponding of water in irregular depressions in undrained swampy or poorly drained areas on the hillslope above the valley floor. These conditions are often associated with hummocky topography which can be signature of landslide activity.
- Sseepage lines or spring and soil groundwater piping. These conditions often mark the contact between high permeability and low permeability soils.
- Sag ponds (ponded water in a tension crack or low depressions on a landslide body)
- Deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)
- Chaotic drainage patterns as a result of landslide activity.

(b) Vegetational indicators

- Jack-strawed, back-rotated, or leaning trees and stumps. These are typically indicative of active or recently active landslides.
- Trees with curved based and vertical upper boles may indicate slope movement stabilizing over time.
- Bowed, kinked, or pistol-butted trees. These are typically indicative of soil creep, but may indicate incipient land sliding particularly if other indicators are present.
- Split trees and split old growth stumps. These may be associated with tension cracks.
- Water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes. These conditions may indicate the presence of groundwater seeps and associated hydrogeologic conditions.
- Other patterns of disturbed vegetation. Changes in stand composition (early seral stage or lack of mature trees within a hillslope) or small grouping of alder in a conifer-dominated forest may indicate recent or historic slope failure.

No one of these single indicators necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

Additional information about landslide processes, unstable landforms techniques for hazard assessment, and the effects of forest practices management practices on unstable terrain landforms is available in “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest” by the British Columbia Ministry of Forests (Chatwin et al., 1994); Hillslope Stability and Land Use (Sidle et al., 1985); and Landslides, Processes, Prediction and Land Use (Sidle and Ochiai, 2006).

5.5.1 Deep-Seated Landslides

Deep-seated landslides are those in which the slide plane or zone of movement is well below the maximum rooting depth of forest trees (generally greater than 10 feet or 3 meters). Deep-seated landslides may extend to hundreds of feet in depth, often including and may involve underlying bedrock. Deep-seated landslides can occur almost anywhere on a hillslope where geologic and hydrologic conditions are conducive to failure. and They can be as large as several miles across or as small as a fraction of an acre.

The larger ones Deep-seated landslides can usually be identified from topographic maps, or aerial photographs, LiDAR images, and field observations. Many deep-seated landslides occur in the lower portions of hillslopes and extend directly into stream channels whereas deep-seated landslides those confined to upper slopes may not have the ability to deposit material directly into channels. Deep-seated landslides often are part of large landslide complexes that may be intermittently active for hundreds of years or more (Bovis, 1985; Keefer and Johnson, 1983).

One common triggering mechanism of deep-seated landslides results from the over-steepening of the toe by natural means such as glacial erosion or fluvial undercutting, fault uplift, or by human-caused excavations activities such as excavating for land development (Schuster and Wieczorek, 2002). Initiation of such landslides has also been associated with changes in land use, (Van Beek and van Asch, 2004), increases in groundwater levels (van Asch et al., 2005), and the degradation of material strength through natural processes. Movement can be complex, ranging from slow to rapid, and may include numerous small to large horizontal and vertical displacements variously triggered by one or more failure mechanisms (Roering et al., 2005).

Deep-seated landslides characteristically occur in weak materials such as thinly layered rocks, unconsolidated sediments, deeply weathered bedrock, or rocks with closely spaced fractures. Examples include: clay-rich rocks, such as the Lincoln Creek Formation of west-central Washington (Gerstel and Badger, 2002); thinly layered rocks, such as phyllite in northwest Washington (Kovanen and Slaymaker, 2008); and deeply weathered volcanic rocks ~~that~~ ~~cover~~~~present~~ in the Willapa Hills of southwest Washington (Turner et al., 2010). Deep-seated landslides can also occur where a weak layer or prominent discontinuity is present in otherwise strong rocks, such as ~~clay or sand rich sedimentary~~ interbeds ~~within the~~ basalts ~~of eastern~~ Washington or a fault plane or intersecting joint set (Sidle, 1985). In northwest Washington and on the Olympic Peninsula, deep-seated landslides commonly occur along silt or clay beds that are overlain by sandy units such as glacial deposits (Gerstel et al., 1997).

There are three main parts of a deep-seated landslide: the scarps (head and side), ~~along which marginal streams can develop~~; the body, which is the displaced slide material; and the toe, which also consists of displaced materials. The downslope edge of the toe can become over steepened from stream erosion or from the rotation of the slide mass. A deep-seated landslide may have ~~several of each of these parts~~ ~~one or more of these component parts~~ because small deep-seated landslides can be found nested within larger slides. These three main parts are shown in Figures ~~1723 and 18~~. The head- and side- scarps together form an arcuate or horseshoe shaped feature that represents the surface expression of the rupture plane. The body and toe area ~~are~~ usually display hummocky topography, and the flow path of streams on these landslide sections may be displaced in odd ways due to differential movement of discrete landslide blocks. The parts of deep-seated landslides that are most susceptible to shallow landslides and potential sediment delivery are steep scarps (including marginal stream side slopes) and toe edges.

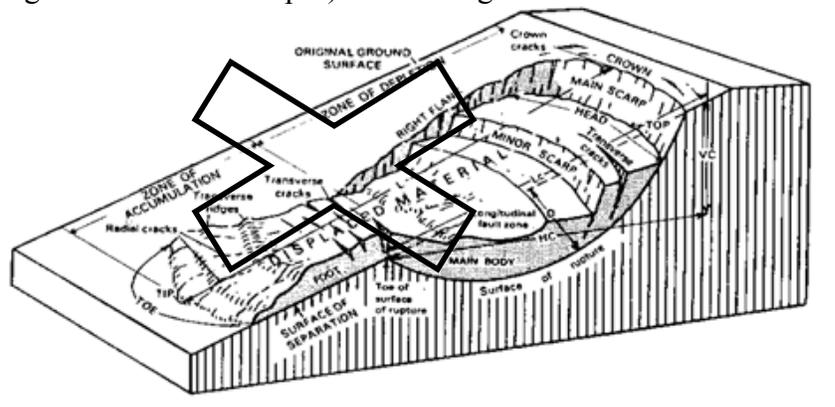


Figure 17. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide. Slow flow (an earthflow) may be found at the toe (Drawing: Varnes, 1978).

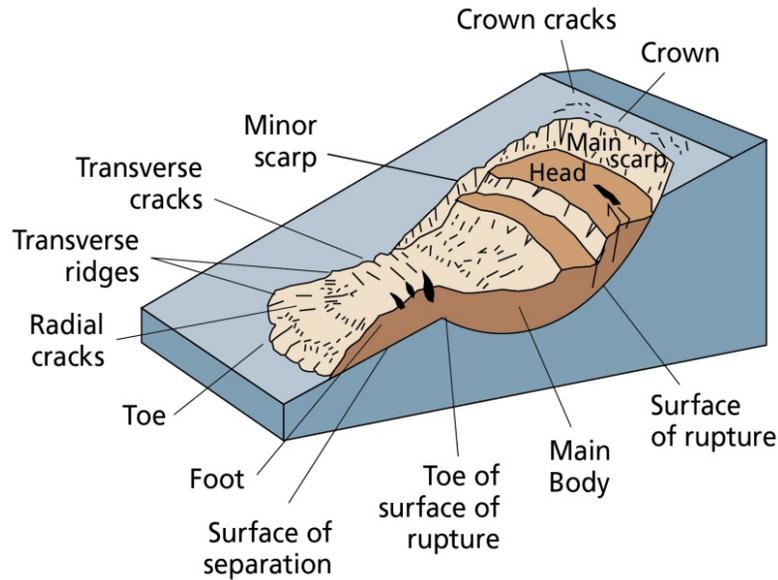


Figure 23. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide (adapted from USGS, 2004).

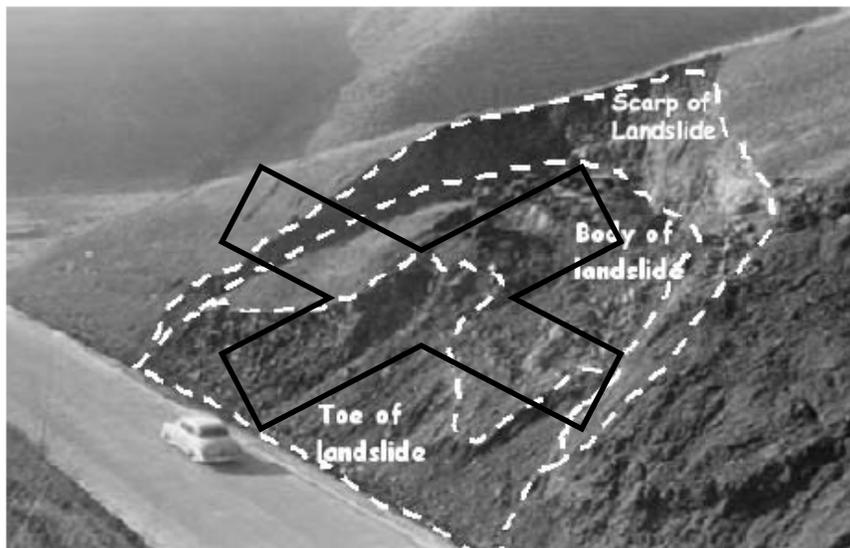


Figure 1823 Deep-seated landslide showing the head scarp, side scarps, body, and toe. Some of the toe has been removed in building and maintaining the highway (adapted from USGS photo).

The sensitivity of any particular landslide to forest practices is highly variable. Deep-seated scarps and toes may be over-steepened and streams draining the ~~displacement~~ displaced material may be subject to debris slide and debris flow initiation in response to harvest or road building. Movement in landslides is usually triggered by accumulations of water at the slide zone, so land-use changes that alter the amount or timing of water delivered to a landslide can start or accelerate movement (Cronin, 1992). Generally, avoiding the following practices will prevent most problems:

~~destabilizing the toe by the removal of removing material during road construction or quarrying which could destabilize the toe; overloading the slopes by dumping spoils on the upper or mid-scarp areas which could overload the slopes, or compacting the soil in these places which could change subsurface hydrology; and directing additional water into the slide from road drainage or drainage capture. The loss of tree canopy interception of moisture and the reduction in evapotranspiration through timber removal on areas up-gradient of the slide may also initiate movement of the slide (van Asch, et al., 2009).~~

~~Part 6.3 provides methods for describing and delineating groundwater recharge areas for deep-seated landslides in glacial sediments.~~

~~PART 6. HOW TO IDENTIFY POTENTIALLY UNSTABLE LANDFORMS AND MATERIALS REGIONAL LISTS~~

~~The Regional (Unstable) Landform Identification Project (RLIP) is a result of the Forests and Fish Report and is being conducted statewide at this time. The purpose of the RLIP is to note and validate region-specific unstable landforms that are not included in the present forest practices rules so that known unstable landforms are not overlooked during the forest practices application process. The final products will be in the form of short reports (validations) and maps that describe (generally and specifically) and locate these regional unstable landforms. This information is intended to be used as a screening tool for forest practices applications and may be eventually included in the forest practices rules and this Board Manual Section.~~

~~When planning timber harvest and construction activities, general practitioners (landowners, foresters, engineers and other field staff) need to determine whether potentially unstable slopes and landforms exist on or around the site of their proposed activities.¹ If so, a qualified expert may be needed to perform additional analysis.~~

~~The assessment typically includes the following components:~~

- ~~1. The general practitioner assesses the project sites for potentially unstable slopes and landforms through:
 - ~~• initial office screening (Part 6.1.1); and~~
 - ~~• field assessment and review (Part 6.2.1).~~~~
- ~~2. If desired by the landowner or required by rule, a qualified expert conducts a geotechnical assessment through:
 - ~~• office review (Part 6.1.2);~~
 - ~~• field review (Part 6.2.2);~~
 - ~~• landslide/landform activity assessment (Part 7.1);~~
 - ~~• water budget and slope stability modeling assessments (Part 7.2);~~
 - ~~• slope stability sensitivity assessment (Part 7.3);~~
 - ~~• deliverability assessment (Part 7.4);~~
 - ~~• summary of findings, results, and conclusions (Part 7.5); and~~
 - ~~• geotechnical reports (Part 8).~~~~

¹ In this context, potentially unstable slopes and landforms that exist “around” a proposed timber harvest or construction activity are those that could possibly be influenced by, or be caused to move due to, the harvest or construction activity.

The elements and recommended sequence of the assessment are generally as follows (modified from Turner and Schuster, 1996):

1. Preliminary fact-finding to answer: What actions does the proposed forest practices activities include (e.g., partial cut, clear cut, road building, stream crossing)? In which landslide province (Part 2.4) are the proposed forest practices activities located and what are the hydrogeologic conditions and types of landforms expected to be present? Are any site-specific resources available for review, such as previously completed geotechnical reports or watershed analysis reports?
2. Office review of geologic maps, topographic maps, aerial photographs, LiDAR, and other information identified during the preliminary fact-finding phase.
3. Field review to observe the site, confirm office review findings and identify unstable and potentially unstable landforms that were not recognized during the office review. The field review may also involve hydrogeologic mapping.
4. Data analysis and assessment regarding the potential for landslide activity that could result from the proposed forest practices activity, and the potential for delivery of sediment to public resources or threats to public safety.

6.1 Office Review Process for the General Practitioner and the Qualified Expert

An office review refers to the initial screening of a selected site using available, remotely sensed information and previously prepared materials or documents (e.g., reports, studies, field data, and analyses). The term “remote sensing” generally refers to information that can be acquired for a particular site or physical feature without visiting the site or collecting data in the field.

A typical office review utilizes all accessible, site-specific and regional remote sensing data to help identify, delineate, and interpret potentially unstable slopes and landforms (e.g., aerial imagery, LiDAR (Light Detection and Ranging), GIS-based model predictions of earth surface attributes derived from digital, high-resolution topographic data). In addition, it is helpful to utilize existing documents and databases (e.g., maps, geotechnical reports and studies, published and unpublished scientific literature, landslide inventories, local and regional databases containing meteorologic, hydrologic, and geologic information) to screen sites for potential slope stability concerns, identify natural resource and public safety considerations, and make a determination regarding next steps in the site assessment. Please see appendices A through F for data sources, and 6.1.3 and 6.1.4 for information regarding remote sensing tools and topographic data.

6.1.1 General Practitioner’s Office Review

It is recommended that the initial office review and screening be conducted by a general practitioner to achieve:

1. identification of potential and existing areas of slope instability within or around the proposed activities;
2. delineation of unstable landforms using descriptions provided in Part 5;
3. location of areas of public resource sensitivity or public safety exposures in the vicinity of the planned operation that could be adversely affected by mass wasting processes; and
4. development of a plan for assessing the landforms in the field.

The information resulting from the general practitioner’s office review will be useful for completing the FPA and providing information on the supplemental slope-stability form if it is required.

Summary of Procedures. The office review process generally includes compiling and evaluating available maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. This initial screening is supplemented with general practitioner’s knowledge about site-

specific conditions and with publicly available documents that might identify site-specific slope stability concerns or place the site in a broader landscape context with regard to potentially unstable landforms and processes (i.e., watershed analyses conducted under chapter 222-22 WAC; see Appendix D). Information sources are available to the user online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. Additional sources of imagery, data, maps, reports, and other documents are listed in appendices A through F.

Relevant maps typically include surface topography and its derivatives (e.g., slope class maps), hydrology (e.g., streams and water types), geology and soils (e.g., rock units, soil types), landslides (landslide inventories and hazard zonation), and information needed to identify public safety exposures (e.g., road networks, parcel boundaries with existing building structure information). Imagery includes aerial photography and LiDAR-derived hillshade images available on public websites and referenced in Appendix B. GIS with map display and analysis capabilities (e.g., ESRI ArcGIS) provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis; however, an initial screening can be performed manually without such tools if they are unavailable to the general practitioner (i.e., by inspecting each map or image separately). Various county websites also offer online interactive GIS information for maps and imagery products (see Appendix A). Follow-up field assessments are needed to verify results of the initial screening because not all features can be identified during the office review. It is helpful to create a site map for field use showing areas of potential slope stability concerns, natural resource sensitivities, and public safety exposures within or around the proposed operation.

Outcome. The initial office screening process aids the general practitioner in targeting portions of the proposed harvest and construction area that may need further assessment in the field. The office screening may not identify all potential unstable landforms, particularly if features are too small or subtle to be identified from available maps and imagery. For example, the general practitioner might not be able to identify the full extent of a groundwater recharge area from topographic maps, or to detect landslides under a mature forest canopy if using aerial photography exclusively. A field assessment is typically conducted while the general practitioner is performing reconnaissance and marking (flagging) the boundaries of the proposed harvest and construction area; see Part 6.2 for guidance on conducting field reviews. The general practitioner might also elect to have a more thorough office review conducted by a qualified expert.

6.1.2 Qualified Expert's Office Review

An assessment by a qualified expert is needed when an assessment of potentially unstable slopes is beyond a general practitioner's expertise, or when activities are proposed on rule-identified landforms, including groundwater recharge areas. The qualified expert's objective is to develop a preliminary geotechnical assessment of landform characteristics and landslide potential prior to initiating field work, so that subsequent field investigations are capable of verifying initial interpretations. The geotechnical office review is generally more in-depth than a general practitioner-conducted initial screening and applies professional expertise in engineering geology, hydrogeology, geomorphology, and associated fields to detect and interpret landscape processes.

Depending on the site specific conditions and the proposed forest practices activities, the qualified expert typically:

1. screens the site with available data in order to identify physical indicators of past, existing, and potential landslide activities, noting their spatial and temporal distributions;
2. delineates on preliminary maps the identified features and associated potentially unstable landforms;
3. formulates initial hypotheses regarding landslide and landform behavior and failure mechanisms, to be evaluated further in the field; and
4. determines the type and level of field investigation needed to verify preliminary landslide interpretations, develop cause-effect relationships, and assess any potential for material delivery and potential adverse impacts to natural resources and threats to public safety.

Summary of Procedures. The geotechnical office review is performed as the initial office screening for compiling and evaluating available information. Most qualified experts have GIS capabilities, are experienced in using remote sensing and modeling tools, and can provide feedback on proposed forest practices activities in relation to their potential for affecting slope instability. The office review typically precedes a field review whose objectives usually include assessing the accuracy, limitations, and uncertainties of remotely sensed information and previously prepared materials assembled during the office review, as well as adjusting any preliminary interpretations of site characteristics or physical feature based on these data sources. The qualified expert determines the nature of the office review and the appropriate combination of assembled information based on the project objectives, requirements, and desired level of confidence in assessment products.

Outcome. The geotechnical office review typically leads to a field review, especially where unstable slopes and landforms are suspected or known and verification is required. Office review findings are included in the report written by the qualified expert. Interpretations based solely on remote sensing data should not be used as substitutes for site-specific field assessments carried out by qualified experts. From the office review, the expert might determine that no unstable slopes or landforms are present, or such features are present and the landowner agrees to exclude these areas from forest operations.

6.1.3 Remote Sensing Tools Available for Office Reviews

Common sources of remotely sensed information used in identifying, delineating, and interpreting landforms can be grouped broadly in the following categories: (1) aircraft- or satellite- based earth imagery and photogrammetry; and (2) LiDAR and high-resolution topographic data. Previously prepared materials or documents often incorporate field and remotely sensed data; these sources include maps and surveys, technical reports and other published/unpublished literature, and physical databases. Appendices A through E list the most common data sources in each category. Among the available remote sensing technologies, LiDAR has proven to be a valuable source of topographic data with distinct advantages over traditional analytical methods (e.g., aerial photo interpretation) for mapping landslides and interpreting landform characteristics (e.g., Haugerud et al., 2003; Burns and Madin, 2009; Roering et al., 2013; Tarolli, 2014). Consequently, LiDAR capabilities and applications are discussed in more detail below.

New remote sensing techniques for terrain characterization are being developed at a rapid pace, due in part to the expanding availability of publicly acquired, high-resolution topographic data (e.g., LiDAR). For example, major advances in deep-seated landslide characterization methods are combining high-resolution LiDAR data with other remotely sensed information and developing quantitative LiDAR analysis techniques to map and quantify landslide movement (Tarolli, 2014). Examples include using LiDAR-derived Digital Elevation Models (DEM) and Digital Terrain

Models (DTM) with: (1) radar data and historical aerial photographs to quantify deep-seated landslide displacement and sediment transport (Roering et al., 2009; Handwerger et al., 2013; Scheingross et al., 2013); (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux (Mackey and Roering, 2011); and, (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows (e.g., Ardizzone et al., 2007; Booth et al., 2009; Burns and Madin, 2009; Tarolli et al., 2012; Van Den Eeckhaut et al., 2012); and, (4) subsurface investigations (Travelletti and Malet, 2012). Such innovative approaches likely will continue to emerge as more sophisticated high-resolution surface and subsurface technologies are developed. It is the task of qualified experts to seek out, evaluate, and apply new remote sensing methods as they become available.

6.1.4 LiDAR and High-Resolution Topographic Data

It is beneficial for general practitioners and qualified experts to obtain high-resolution topographic maps, most commonly hillshade and slope maps, derived from LiDAR.

The process to create high-resolution data begins with airborne LiDAR. LiDAR is a remote sensing technique that involves scanning the earth's surface with an aircraft-mounted laser in order to generate a three-dimensional topographic model (Carter et al., 2001). During a LiDAR acquisition flight, the aircraft's trajectory and orientation are recorded with Global Positioning System (GPS) measurements and the aircraft's inertial measurement unit, respectively. Throughout the flight, the laser sends thousands of pulses per second in a sweeping pattern beneath the aircraft. Energy from a single pulse is commonly reflected by multiple objects within the laser's footprint at ground level, such as the branches of a tree and the bare ground below, generating multiple returns. The first returns are commonly referred to as "highest hit" or "top surface" points and are used to measure the elevations of vegetation and buildings, while the last returns are commonly referred to as "bare earth" points and undergo additional processing to create a model of the earth's ground surface.

To generate a DEM, the aircraft trajectory and orientation measurements are combined with the laser orientation and travel time data to create a geo-referenced point cloud representing the location of each reflected pulse. These irregularly spaced points are commonly interpolated to a regularly spaced grid with horizontal spacing on the order of 1 meter to create a high resolution digital elevation model. Bare earth digital elevation models undergo additional filtering to identify ground returns from the last return point cloud data (for a review of filtering techniques, see Liu, 2008). These bare earth DEMs are most commonly used for interpreting and mapping deep-seated landslide features, especially in forested terrain where vegetation would normally obscure diagnostic ground features (Van Den Eeckhaut et al., 2007).

Hillshade and slope maps derived from bare earth LiDAR DEMs are the most common LiDAR products used to identify deep-seated landslides. A hillshade map is created by simulating sunlight shining on the topographic surface at a specified angle, while a slope map is the magnitude of the topographic gradient, estimated by differencing the elevations of adjacent points in the DEM. Hillshade maps tend to have less contrast on slopes facing the incident sun angle and more contrast on slopes facing away from the incident sun angle, either of which can obscure topographic features. It is therefore recommended to analyze several hillshade maps generated with different sun angles or employ methods such as those described in Burns and Madin (2009) for minimizing illumination and topographic shadowing effects (i.e., multi-directional oblique-weighted hillshade

algorithm). Additional derivative maps such as topographic curvature, surface roughness, and elevation contours can also be useful to identify deep-seated landslide features. Contours should be generated with spacing similar to the LiDAR data resolution and/or the scale of the geomorphic features of interest.

Key topographic features revealing deep-seated landslides and other landform that are visible in LiDAR-derived maps, but might not be visible in other remote sensing data, are similar to those observed in visual indicators. Hummocky topography, benched surfaces, tension cracks, scarps, block and graben features, pressure or transverse ridges, and irregular drainage patterns are often visible, but only when the scale of the feature is larger than the resolution of the LiDAR data. The difference in screening for and depicting potentially unstable features between high and low-resolution LiDAR data can be seen in Figures 24 (b) and (e and f). In Figure 24 (f), a hillshade map derived from 3-foot LiDAR data is shown which allows the user to approximately delineate the landslide's main scarp, body, and toe, whereas such features may not be recognized using lower resolution quality (i.e., 30-meter resolution).

LiDAR hillshades can be used to delineate and interpret deep-seated, and with lesser certainty ~~but~~ ~~not~~ shallow, landslides, although some depositional surfaces (for example debris fans) can be identified. Various measures of surface roughness are commonly used to recognize and quantify deep-seated landslide morphology in landslide mapping studies (McKean and Roering, 2004; Glenn et al., 2006; Booth et al., 2009; Berti et al., 2013). Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005, 2007), and Haugerud (2014).

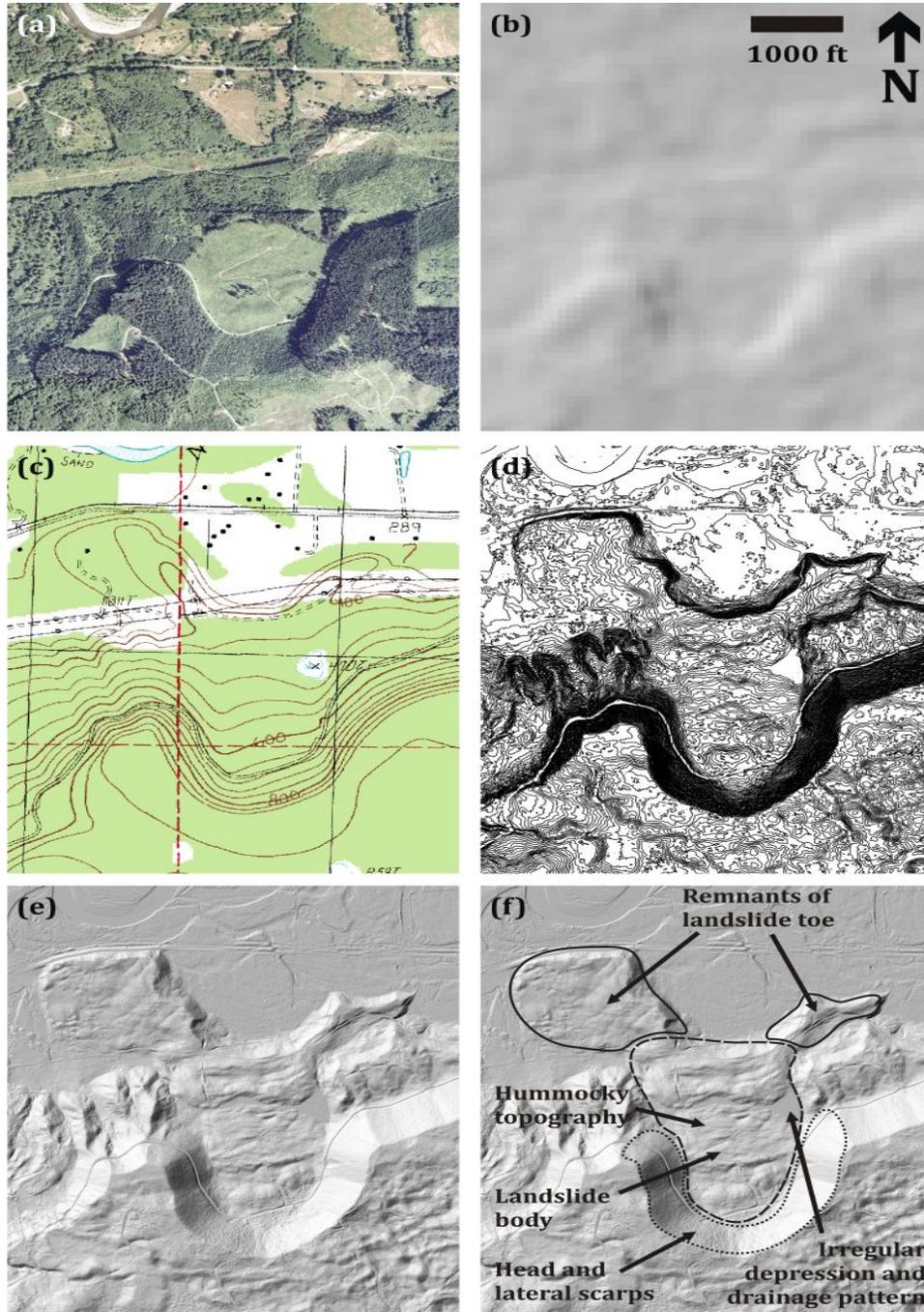


Figure 24 Example of a dormant glacial deep-seated landslide as seen in different types of remotely sensed data and in varying resolution quality: (a) Digital Orthophoto Quadrangle, (b) hillshade map derived from 30-meter resolution ASTER Global Digital Elevation Model, (c) topographic map, (d) 6-foot contour map derived from 3-foot resolution airborne LiDAR, (e) hillshade map derived from 3-foot resolution airborne LiDAR, and (f) annotated version of (e) (Adam Booth, 2014, Portland State University).

Repeat LiDAR acquisitions of a site are becoming more common. This allows the qualified expert to review more than a single LiDAR data set to interpret deep-seated landslide morphology; instead

they can measure topographic changes related to slope instability with pairs of LiDAR scenes (Corsini et al., 2007; Delong et al., 2012; Daehne and Corsini, 2013). Vertical changes can be measured by differencing LiDAR-derived DEMs, while manual or automated tracking of features visible on hillshade or slope maps between scenes can be used to estimate horizontal displacements. Note that many active deep-seated landslides move at rates that may be undetectable given the uncertainties in the LiDAR data, so this technique is most helpful for relatively large topographic changes, typically on the order of several meters (Burns et al., 2010). Care should be taken to precisely align the repeat LiDAR DEMs.

6.2 Field Assessment Process for the General Practitioner and the Qualified Expert

The purpose of the field assessment is to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review. While the office review can provide important information and a starting point, on-site observation of geomorphic features on the ground surface is essential for identifying potentially unstable landforms.

The field assessment performed by the general practitioner determines the presence or absence of potentially unstable slopes and landforms. If such features are located and forest practices are proposed on these features, the landowner may retain a qualified expert to perform additional geotechnical reviews.

6.2.1 General Practitioner's Field Assessment

The objective of the field assessment conducted by a general practitioner is to determine the presence or absence of unstable slopes and landforms, using definitions of the landform types and guidance provided in this Board Manual section. In addition to assessing the potential unstable areas identified in the initial office screening, the general practitioner surveys the operations area for any landforms missed in the office review. The general practitioner typically carries out this assessment while laying out the proposed forest practices activities (e.g., marking unit boundaries, establishing riparian management zones, laying out road systems). See Qualified Expert's Field Assessment for Groundwater Recharge Areas (Part 6.3.2) for information on conducting field reviews on groundwater recharge systems and Additional Features and Landforms Indicating Potential Slope Instability (Part 5.5) for discussions on landform features that may indicate slope instability. When the field assessment indicates complex geological features are present or the scenario is beyond the general practitioner's expertise, the landowner may wish to have a qualified expert complete a further assessment.

Outcomes. Common results of the general practitioner-conducted field assessment generally include:

1. The finding, documented in the slope stability sections of the FPA, that the assessment did not identify any potentially unstable slopes or landforms within or around the planned area for the forest practices activities, and the office/field review process is assumed complete; or
2. The finding that potentially unstable slopes and landforms exist within or around the planned operations area and the landowner completes and attaches the appropriate slope stability sections to the FPA along with any additional required information DNR may have requested; or
3. The general practitioner identifies potentially unstable areas within or around to the operations area, and proposes to conduct timber harvest or construction activities on them. The landowner may retain a qualified expert (see Washington State Department of

Department of Natural Resources (DNR) website for list of qualified experts) to conduct a geotechnical office and field reviews, and prepare a geotechnical report, as required by WAC 222-10-030. The landowner submits the FPA and includes the geotechnical report or additional information completed by the qualified expert to inform the FPA.

6.2.2 Qualified Expert's Office and Field Assessments

When it is determined an analysis needs to be conducted by a qualified expert, the objectives of the geotechnical field review are to:

1. verify the presence or absence of unstable slopes and landforms identified in office reviews and/or identify those that were missed due to insufficient remote sensing data coverage or resolution;
2. refine preliminary maps constructed during office reviews;
3. confirm or refute initial hypotheses regarding landslide behavior, failure mechanisms, and level of activity;
4. solidify understanding of cause-effect relationships;
5. assess relative potentials for material delivery associated with the proposed forest practices to areas of resource sensitivity and threats to public safety;
6. evaluate levels of confidence in office and field findings; and
7. write a geotechnical report summarizing review findings, conclusions, and recommendations (see Part 8 for information required in a geotechnical report).

Summary of Procedures. The qualified expert determines the nature of the field review required to meet the objectives stated above. Depending on the analyst's level of confidence in potentially unstable landform identifications, delineations, and interpretations for any given site, the field assessment might range from qualitative to more quantitative in nature. An example of a qualitative assessment would be one in which the qualified expert collects visual observations and photos of geological features and other site indicators at identified locations (i.e., GPS waypoints) and summarizes those observations in a geotechnical report, as a means for substantiating landform and process interpretations. A more quantitative investigation might include such data collection techniques as topographic surveying for measuring landslide surfaces (i.e., needed for slope stability modeling), soil sampling to test material properties, and subsurface sampling that is especially important in analyzing the depths, materials, and hydrology of deep-seated landslides. Field work needed to complete the review can take one or more days, and the qualified expert might be asked to return to the field for an interdisciplinary team meetings if required by DNR.

It is recommended that the field assessment performed by a qualified expert include the preparation of a site-specific geologic map, because the scope of work associated with most published geologic maps is insufficient to identify small-scale unstable landforms that could have a significant effect on the proposed forest activity. The purpose of geologic mapping is to document surface conditions and provide a basis for the interpretation of subsurface conditions. Ideally the geologic map should be prepared on a scale of 1:10,000 or less using high-resolution LiDAR-generated topography. If high-resolution LiDAR is not available, base maps can consist of U.S. Geological Survey 7.5-Minute topographic maps, DNR forest practices activity maps, or aerial photographs.

A geologic map should ideally include the location, elevation, and altitude of all geologic contacts between permeable and non-permeable soils, although such data collection is not feasible or necessary in all situations. Particular emphasis should be placed on the contact between high

permeability soils and underlying low permeability soils or bedrock and the location of groundwater seeps or springs, especially where deep-seated landslide activity is suspected or encountered. If an unstable or potentially unstable landform is present, the location of pertinent components and effects of the landform should be identified on the map.

Geologic field data collection, analysis, and map compilation are undergoing a revolution in methods, largely precipitated by GPS and GIS-equipped mobile computers (Whitmeyer et.al, 2010; U.S. Geological Survey, 2008; Edmondo, 2002). To be fully effective, geologic reports prepared for FPAs should include GPS locations of landforms and other relevant features within accuracy sufficient for others to identify the landforms in the field. It is also effective to include photographs of significant landforms, or their components should also be photographed if they can be fully captured with ground-based photography. It is important to note indicators of potential slope instability or active movement during the field review. These include topographic, hydrologic, and vegetation indicators as described in Part 5.5.

Outcomes. Common results of a qualified expert geotechnical field assessment include determinations that:

1. The potentially unstable landforms identified in the field assessment do not meet the definitions of the rule-identified landforms (Part 5). The qualified expert reports to the landowner that no potentially unstable landforms are present and the slope stability assessment is assumed complete; or
2. Potentially unstable landforms within or around the operations area have minimal potential for material delivery to areas of resource sensitivity and/or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings, as outlined in WAC 222-10-030(1), and the slope stability assessment is complete; or
3. Unstable landforms within or around the operations area have the potential for material delivery to areas of natural resource sensitivity or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings to be included with the FPA. In most cases, this scenario would be fall under a Class 4IV-Special definition in WAC 222-16-050(1) and require the landowner to submit a SEPA checklist or Environmental Impact Statement.

6.3 Qualified Expert's Office Review and Field Assessment for Groundwater Recharge Areas

When a glacial deep-seated landslide is determined to exist on or around the proposed harvest or construction activities, the area adjacent to the glacial deep-seated landslide needs to be assessed by a qualified expert to determine if a ground water recharge area exists. The recharge, occurrence, and movement of groundwater through water-bearing units (aquifers) and confining units that inhibit groundwater movement can have an effect on slope stability. Hydrogeologic frameworks, which define the groundwater recharge environment and the subsurface environment in which groundwater occurs, have been developed from mapped geologic units, drillers logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000). Groundwater movement is important to understand at smaller local scales associated with the area related to landslides and forest practices in proximity.

The groundwater recharge area for glacial deep-seated landslides is a rule-identified landform. The technical methods used to identify groundwater recharge areas in glacial deep-seated landslides are no different than those for other (e.g., non-glacial) deep-seated landslides.

The recommended first step in delineating the groundwater recharge area is to evaluate its topographic relationship to the landslide. When uncertainties remain as to the accuracy of the area boundary, further investigations and analysis should be performed. This further analysis will provide necessary information DNR uses to review the proposed activity. If an in-depth investigation is performed, the information provided by the qualified expert in their geotechnical report is used by DNR to determine the FPA classification and other decisions based on the applicant's proposed activity. The following discussions and Part 7 will aid the qualified expert in determining next steps if further investigation are needed.

6.3.1 Qualified Expert's Office Review for Groundwater Recharge Areas

When a qualified expert performs an office review of information for evaluating the area contributing groundwater recharge to a landslide, it is recommended that the surrounding topography, land cover and vegetation, soils, and the distribution of hydrogeologic units are reviewed. Time scales of groundwater movement from areas of recharge to discharge may vary over several orders of magnitude, depending on the hydraulic characteristics of the hydrogeologic units, which include water bearing and non-water-bearing rocks and sediments (aquifers) and confining units, respectively.

In a simplified hydrogeologic setting in a humid environment, the groundwater table forms a subdued replica of surface topography with groundwater flow from high-altitude areas of recharge to low-altitude areas of discharge (Freeze and Cherry, 1979). The surficial contributing area may be delineated from DEMs derived from high-resolution LiDAR, if available, or alternately the lower resolution U.S. Geological Survey topographic quadrangles. This analysis provides a first-order approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.

The land cover of the recharge area also influences the spatial extent and magnitude of groundwater recharge. The type and distribution of vegetation affect the amount of precipitation that is intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may also influence groundwater recharge. Remotely-sensed land cover data is available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's National Land Cover Database. In addition, land cover data is available for Washington State through the DNR Forest Resource Inventory System.

Geologic maps provide a basis for delineating the areal extent, orientation, stratigraphic relations, and thickness of rocks and sediments that influence the occurrence and movement of groundwater. The U.S. Geological Survey, DNR, and others have published geologic maps at scales of at least 1:100,000 across Washington and locally at larger scales (1:24,000). Well logs and geotechnical borings may supplement geologic mapping by describing the vertical extent of rocks and sediments and providing information about grain size distributions, sorting, and other physical properties that may influence the hydraulic characteristics of hydrogeologic units. The Washington State Department of Ecology (Department of Ecology) maintains a searchable database of well logs for Washington State, however subsurface data will generally be confined to developed areas and information may be lacking in the forested environment. Hydrogeologic frameworks have been developed from mapped geologic units, drillers logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000) to local scales for sites across Washington State. Hydrogeologic reports are available from sources such as the U.S. Geological Survey and the Department of Ecology.

6.3.2 Qualified Expert's Field Assessment for Groundwater Recharge Areas

A groundwater recharge area of a deep-seated landslide is the area up-gradient of a landslide that can contribute water to the landslide. In simple terms, the groundwater recharge area is the topographic area or hillslope area that is at a higher elevation and capable of delivering water into the landslide.

Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types; therefore, field inspection of the initial groundwater recharge area map will be necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation.

Typically once a landslide has been mapped, an initial designation of the topographic groundwater recharge area is a straightforward task that can be performed on a detailed topographic map of the area. Topography developed from high resolution DEM generated from LiDAR is preferred as the most accurate tool available for mapping surface topography. Figure 25a shows the approximate groundwater recharge area for a landslide based on upslope topographical delineation. Line A corresponds to a cross section showing approximate stratigraphy (Figure 25b) through the groundwater recharge area and landslide body.

After the initial designation by the qualified expert of the groundwater recharge area, a field assessment should be conducted in order to determine if the initial designation accurately reflects the recharge area topography up-gradient of the landslide. Depending on the available topographic data for the site in question, examination of the boundaries of the mapped groundwater recharge area will be necessary to ensure the hillslope morphology displayed by the DEM is accurate. It is helpful to obtain GPS waypoints collected in the field along the topographic boundaries of the groundwater recharge area.

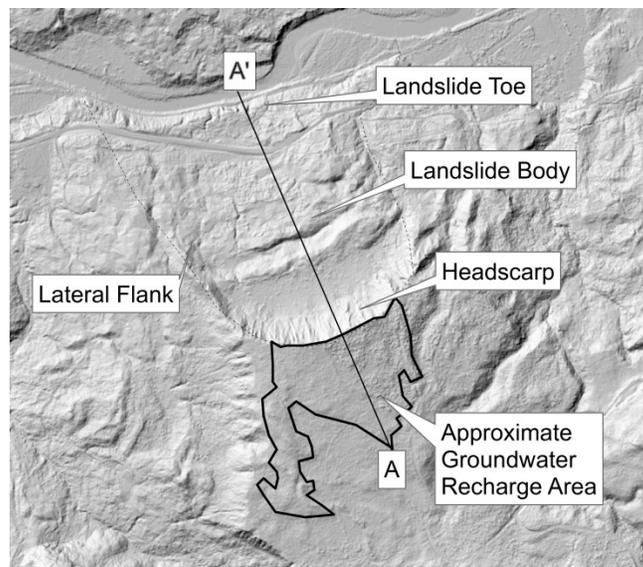


Figure 25a Glacial deep-seated landslide. The black-lined polygon is an approximate upslope contributing groundwater recharge. (DNR, 2014)

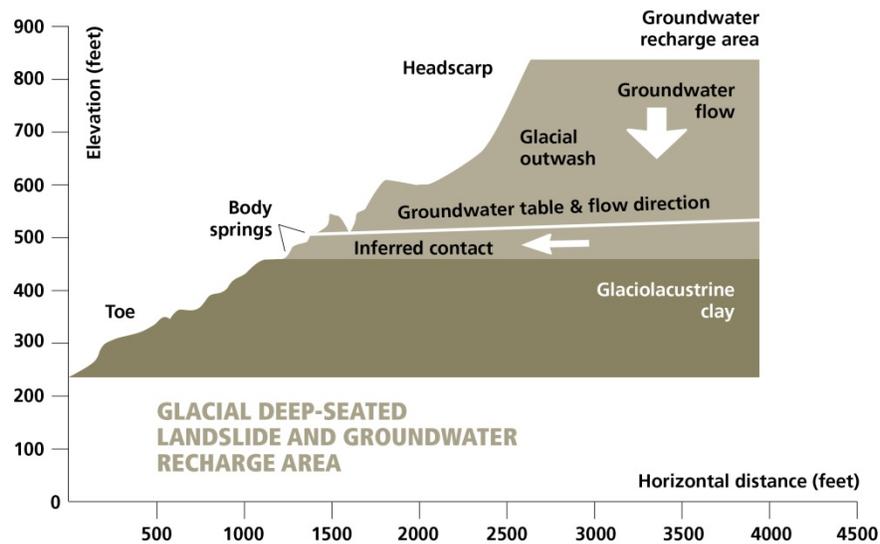


Figure 25b Hillslope cross-section derived from 2-meter DEM of a glacial deep-seated landslide showing groundwater recharge area, geologic units and generalized groundwater flow paths (DNR, 2014)

When the qualified expert has identified the groundwater recharge area, the area should be inspected and any surface water drainage features indicating surface water may be directed into the landslide area should be mapped. Stream drainages on or adjacent to the deep-seated landslide should also be identified, mapped, and assessed for the potential to contribute water to the recharge area and landslide.

During field assessment it is important to examine the characteristics of the surface materials within the groundwater recharge area and document that the soil types and subsurface geologic units are consistent with those mapped for the location of interest. In some cases, published soil and geologic data in forested areas may be mapped on a scale far less detailed for specific areas.

Mapping the stratigraphic units that compose the hillslope (i.e., the distribution of geologic units or horizons with depth below the groundwater recharge area) should be done in order to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide. Subsurface investigations may be needed to adequately determine geologic units where mapping cannot be accurately accomplished by surface data alone.

Exposures of strata within the groundwater recharge area may be examined in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps at the top of the landslide. The distribution of geologic units with increasing depth below the surface may also be available from well drillers logs or other subsurface information such as geologic mapping and reports.

Excavation of test pits, driving soil probes and well-points, drilling monitoring wells or using other geophysical techniques such as seismic or electric resistivity methods should be considered in order to accurately characterize and reduce uncertainties of the subsurface conditions of the groundwater

recharge area, and where topographic indicators are uncertain. See Part 6.4 for further discussion on quantitative field review methods.

Often landslide failure planes are co-incident with subsurface aquitards such as silt or clay beds that form elevated groundwater tables within hillslopes. Understanding the morphology and orientation of these aquitards can help inform the spatial extent of the groundwater recharge area beyond the surface topographic expression of the hillslope up-gradient of a landslide.

Human activities such as construction of road networks and installation of drain fields can direct surface and groundwater towards or away from deep-seated landslides and/or contribute relatively large volumes of water within a groundwater recharge area. The location of such infrastructure should be mapped and evaluated with respect to possible water volumes likely to be contributed to a landslide.

6.4 Quantitative Field Assessment Methods for Qualified Expert's Subsurface Investigations

If an unstable or potentially unstable landform with a potential to deliver sediment to public resources or threaten public safety is identified during the office review and field assessment, additional field analysis by a qualified expert may be needed to more quantitatively assess the hazard. This is generally accomplished with a subsurface investigation. The subsurface investigation should be designed to gather data necessary to evaluate the landslide in accordance with the evapotranspiration, recharge, groundwater flow, and slope stability modeling (see Part 7).

The selection of exploration methods should be based on the study objectives, size of the landslide area, geologic and hydrogeologic conditions, surface conditions and site access, and limitations of budget and time. Subsurface exploration to assess landslides is generally described by McGuffey et al. (1996) as summarized in the following paragraphs:

Test Pits. Shallow test pits can be dug by hand with a shovel. Trackhoes or excavators can be used to advance test pits to depths of nearly 20 feet in certain soils. They are useful for exposing subsurface soil and rock conditions for purposes of mapping or logging the underlying conditions, and to identify shallow groundwater elevations and failure planes.

Hand Auger. A hand auger can be used to identify soil types to depths up to nearly 20 feet (in loose soils) but does not provide significant information regarding soil material properties.

Drive Probe. A simple hand probe can be used to estimate soil density and the depth to dense soil. The Williamson Drive Probe (WDP) (Williamson 1994) was developed as an inexpensive and portable alternative for determining soil relative densities and groundwater table elevations. Sections of hardware pipe are coupled and driven into the ground manually with a sliding hammer. The number of blows, in even distance increments, required to drive the probe is used to describe soil conditions. Blow-count data theoretically can be correlated with the Standard Penetration Test (American Society for Testing and Materials, 2014).

Method limitations include manual labor intensity, which can limit the number of holes drilled in a given day. The WDP can also be used to estimate depth to groundwater if

perforated pipe is used. With these many uses and the low cost, the WDP is an effective alternative to other tests which require expensive equipment and are less portable.

Drill Rigs. Borings constitute a common method for collecting geotechnical data. Access limitations can be addressed if logging roads are fortuitously located, or by using track-mounted equipment. In some cases, undisturbed or lightly disturbed soil samples can be collected for quantitative laboratory testing (i.e., direct shear, bulk density, moisture content, etc.). Drill rigs can also be used to install groundwater monitoring wells that contain pressure transducers, and as a conduit for geotechnical instrumentation (i.e., inclinometer, extensometer, etc.).

Geophysical Methods. Surface-based geophysical methods can be an economical method of collecting general subsurface information over large areas of rugged terrain. These include ground penetrating radar, electromagnetic, resistivity, and seismic refraction methods. These techniques can provide information on the location of boundaries between coarse-grained and fine-grained strata and the depth to the water table.

A qualified expert should be present in the field during the completion of a subsurface investigation so that the field activities are properly executed and the desired results can be achieved.

PART 7 DELIVERY LANDSLIDE ACTIVITY ASSESSMENT

When forest practices harvest or construction activities are proposed on or have the potential to influence potentially unstable slopes, it is recommended the qualified expert assess the landslide activity. The landslide activity assessment is an important component of evaluating the landslide hazard and potential risk associated with planned activities. It will also likely contribute to the information a qualified expert will need in preparation of geologic evaluations.

7.1 Landslide Activity

The three components of landslide activity for evaluation during the office and field review process are: (1) the state of activity, (2) distribution of activity, and (3) style of activity (Cruden and Varnes, 1996).

The state of activity refers to the timing of landslide movements and ranges from active (currently moving) to relict (clearly developed in the geomorphic past under different conditions than are currently present). When an active landslide stops moving, it becomes classified as suspended, and if it remains stationary for more than one annual cycle, it becomes inactive. If the conditions that contributed to prior movement are still present even though the landslide is inactive, the landslide is considered dormant because it may become reactivated at a later time. If the conditions promoting failure have naturally changed to promote stability, the landslide is considered abandoned, while if human intervention has protected against future movement the landslide is considered stabilized. Interpretation of vegetation cover, surface morphology, and toe modification by a stream, if present, all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes (Table 2, Keaton and DeGraff, 1996). Although based on a Rocky Mountain-type climate, the framework described by Keaton and DeGraff has been successfully applied in the Pacific Northwest. New vegetation generally begins to colonize a landslide's scarp, lateral flanks, or other areas of disturbed ground once the landslide becomes dormant and progresses to mature vegetation cover according to the local climate. The scarp, flanks, and internal hummocky

morphology of the landslide also tend to become increasingly subdued with time after the landslide becomes dormant, and the internal drainage network of the landslides tends to become more connected and organized. If the toe of the landslide enters a stream, that stream progressively modifies the toe as recorded by terraces and the establishment of a floodplain comparable to reaches unaffected by landslide activity.

The distribution of activity refers to the geometry and spatial pattern of landslide movements and how these patterns may change with time. One key distinction is if the landslide is advancing by extending downslope in the main direction of movement, or retrogressing by extending upslope in the direction opposite movement. A landslide can also widen or narrow in the direction perpendicular to movement, and more generally can be enlarging or diminishing if its total volume is increasing or decreasing.

The main style of landslide activity is defined as the type of movement options shown in Table 1, Landslide Classification. Many landslides involve different styles of landslide activity, and movements should be described as “complex” if they happen in succession, or as “composite” if they happen simultaneously at different parts of the landslide. Many landslides may reactivate repeatedly over time and their movements are noted as “multiple” if the same style of activity affects any previously displaced material, or “successive” if the same style of activity affects previously stable material in the immediate vicinity of the previous landslide.

Table 2. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates (from Keaton and DeGraff, 1996).

<u>Active State</u>	<u>Main Scarp</u>	<u>Lateral Flanks</u>	<u>Internal Morphology</u>	<u>Vegetation</u>	<u>Toes Relationships</u>	<u>Estimated Age (Years)</u>
<u>Active reactivated, or suspended; dormant-historic</u>	<u>Sharp; unvegetated</u>	<u>Sharp; unvegetated streams at edge</u>	<u>Undrained depressions; hummocky topography; angular blocks separated by scarps</u>	<u>Absent or sparse on lateral and internal scarps; trees tilted and/or bent</u>	<u>Main valley Stream pushed by landslide; floodplain covered by debris; lake may be present</u>	<u>< 100 (historic)</u>
<u>Dormant-young</u>	<u>Sharp; partly vegetated</u>	<u>Sharp; partly vegetated; small tributaries to lateral streams</u>	<u>Undrained and drained depressions; hummocky topography; internal cracks vegetated</u>	<u>Younger or different type or density than adjacent terrain; older tree trunks may be bent</u>	<u>Same as for active class but toe may be modified by modern stream</u>	<u>100 to 5,000 (Late Holocene)</u>
<u>Dormant-mature</u>	<u>Smooth; vegetated</u>	<u>Smooth; vegetated; tributaries extend onto body of slide</u>	<u>Smooth, rolling topography; disturbed internal drainage network</u>	<u>Different type or density than adjacent terrain but same age</u>	<u>Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain</u>	<u>5,000 to 10,000 (Early Holocene)</u>
<u>Dormant-old or relict</u>	<u>Dissected; vegetated</u>	<u>Vague lateral margins; no lateral drainage</u>	<u>Smooth, undulating topography; normal stream pattern</u>	<u>Same age, type, and density as adjacent terrain</u>	<u>Terraces cut into slide debris; uniform modern floodplain</u>	<u>> 10,000 (Late Pleistocene)</u>

Decision flow chart

When a qualified expert needs to determine the potential for delivery for inclusion in a geotechnical report, it is suggested that the following decision flowchart be applied. The flowchart provides a guide for assessing the risk associated with landslides. Generally, the pathway outlined in the chart is defined by the level of landslide activity and how likely the landslide is to deliver sediment to public resources. The decision pathway uses a glacial deep-seated landslide and associated groundwater recharge area as an example for how a qualified expert would assess the risk associated with the landform. The same decision pathway may be used for other types of deep-seated landslides.

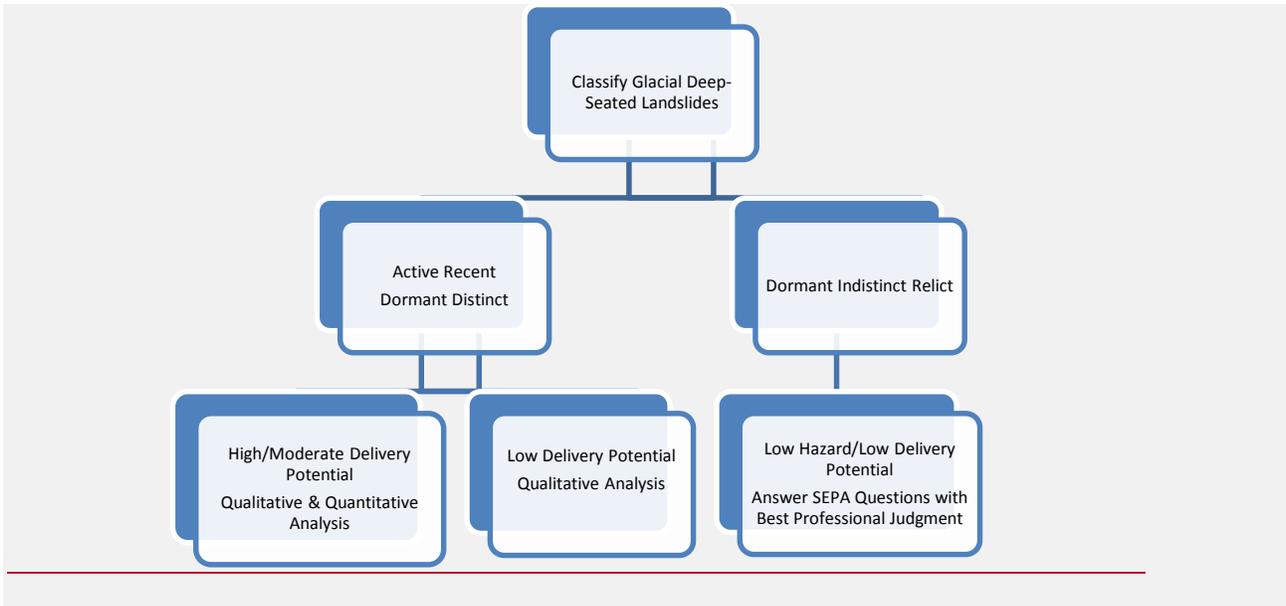


Figure 26 Decision pathway for implementing qualified expert investigations of groundwater recharge area harvests for glacial deep-seated landslides (DNR, 2001).

1. Identify and map glacial deep-seated landslides and associated groundwater recharge areas.
2. Classify landslides using the Landslide Hazard Zonation (LHZ) protocol (modified from Keaton and DeGraff, 1996) for deep-seated landslides as:
 - a. active;
 - b. dormant/distinct;
 - c. dormant/indistinct; or
 - d. relict.
3. Calculate areas for the mapped glacial deep-seated landslide and the associated groundwater recharge area.
4. Evaluate delivery potential if landslide were to move for:
 - a. public safety (houses, roads, etc.);
 - b. public resources (water quality and fish habitat).
5. If the landslide is relict or dormant/indistinct, and has low delivery potential, additional analysis may not be necessary. Documentation of this analysis may be provided by a letter, memo or other appropriate form. If required, answer the SEPA checklist questions (WAC 222-10-030) using best professional judgment of the landslide hazard.
6. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge area and evidence of landslide movement from aerial photographs, LiDAR and other

screening methods. SEPA checklist questions should be answered with qualitative information and best professional judgment.

7. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (6), if appropriate, perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. SEPA checklist questions should be answered with quantitative information from modeling exercises.
8. Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

7.2 Water Budget and Hydrologic Contribution to Slope Stability

To further inform the landslide activity assessment involving groundwater recharge, it is recommended that the qualified expert evaluate the water budget. The water budget of a groundwater/surface-water system describes the input, movement, storage, and output of water from a hydrologic system. Water enters a hydrologic system through precipitation in the form of rainfall and snowmelt. Some of this water is intercepted by vegetation and evaporates before reaching the ground or sublimates from the snowpack. Water that reaches the ground may run off directly as surface flow or shallow, sub-surface runoff, or evaporate from the soil, or transpire through vegetation foliage. Water that percolates below the root zone and reaches the water table is considered to be groundwater recharge. Groundwater moves from areas of high hydraulic head to areas of low hydraulic head where it leaves the groundwater-flow system through wells, springs, streams, wetlands, and other points of groundwater discharge. The occurrence and movement of groundwater through the subsurface depends on the hydraulic properties of subsurface material as well as the distribution of groundwater recharge.

The following discussions of evapotranspiration and groundwater flow may aid the qualified expert during the landslide activity assessment involving a groundwater recharge area. Such assessments and modeling should be considered when uncertainties remain regarding landslide movement or when the risk for damage to public resources or threats to public safety are elevated. These further assessments for calculating water influence to a deep-seated landslide may be necessary when proposed activities have indicated an increase in the potential for contributing movement to potentially unstable slope or landform.

7.2.1 Modeling Evapotranspiration

Modeling evapotranspiration is a data intensive exercise that requires regional and/or site-specific information regarding precipitation types and rates, wind speed, relative humidity, temperature, solar energy, and plant community stand characteristics (Jassal et al., 2009). The goal of evapotranspiration modeling is to derive estimates of the potential increase in water available to the groundwater recharge area from changes in energy balances, wind speeds, and plant community characteristics (i.e., aerodynamic roughness) after forest harvest.

Effects of evapotranspiration on the soil water budget can be partitioned as follows: (1) canopy interception of rainfall or snow and subsequent evaporation loss to the atmosphere; (2) transpiration of infiltrated water to meet the physiological demands of vegetation; (3) evaporation from the soil or litter surface. Different vegetation covers have different balances of these fundamental water loss processes. The effects of evaporation on soil water budgets are relatively small compared with canopy evapotranspiration and interception (Bosch and Hewlett, 1982).

Transpiration is the dominant process by which soil moisture in densely vegetated terrain is converted to water vapor. Transpiration involves the adsorption of soil water by plant roots, the translocation of the water through the plant and release of water vapor through stomatal openings in the foliage. Transpiration rates depend on availability of solar energy and soil moisture as well as vegetation characteristics, including vegetation type (e.g., conifer or deciduous), stand density, height and age, rooting depth, leaf area index, leaf conductance, albedo of the foliage, and canopy structure. Rates of transpiration are similar for different vegetation types if water is freely available (Campbell, 1986).

Transpiration is typically quantified using Soil-Vegetation-Atmosphere Transfer (SVAT) models where the movement of water from the soil through the plant to the atmosphere is represented by several resistances in series: (1) the integrated soil-root system; (2) the stem; (3) the branch; and (4) the effective stomatal resistance. Eddy correlation techniques are commonly used to estimate transpiration fluxes (Hanks and Ashcroft, 1980).

Interception by vegetation cover controls both the amount and timing of precipitation reaching the soil surface. The interception capacity of vegetation types is important because intercepted water has a high surface area to volume ratio that promotes efficient evaporation by convection. Intercepted rainfall is mostly stored on the surface of foliage and stems, while intercepted snowfall bridges between gaps in tree crowns facilitating an accumulation of snow over large surface areas of the canopy. Interception and subsequent evaporation of water from vegetation cover is particularly significant in coniferous forests (Link et al., 2004); losses (both snow and rain) from these dense canopies can account for up to 30 percent to 50 percent of gross annual precipitation (Dingman, 1994). Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10 percent to 30 percent. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21 percent to 35 percent, based on canopy characteristics and climate conditions. Hanell (2011) reported hydrologic modeling (DHSVM; Wigmosta, Njssena and Stork, 2002) that predicts a 27 percent decrease in evapotranspiration resulting from forest conversion to shrub for a site on the western Olympic Peninsula, Washington.

The proportion of rainfall intercepted by forest canopies is inversely related to both antecedent wetness and rainfall intensity. Gentle, short-duration rainfall may be almost totally intercepted, while interception may account for as little as 5 percent of precipitation during intense winter storms (Ramirez and Senarath, 2000).

Approaches for estimating changes in evapotranspiration typically involve some combination of the Penman-Monteith model for calculating the canopy resistance, the Bowen ratio energy balance technique to estimate evaporation from plant surfaces, and the Priestly-Taylor formula to estimate evaporation from the soil surface. Reviews and demonstrations of these techniques can be found in Avery and Fritschen, 1971; Fritschen, 1975; Ziemer, 1979, Hanks and Ashcroft, 1980; Campbell, 1986; Simpson, 2000; Martin et al., 1997; and Sias, 2003.

7.2.2 Groundwater Recharge and Groundwater Flow Modeling

Groundwater recharge is difficult for the qualified expert to measure directly, but several empirical and numerical methods exist for estimating recharge within the surface-water, unsaturated zone, and saturated zone, including physical, tracer, and numerical-modeling techniques (Scanlon et al., 2002). Recharge is commonly estimated by calculating the residual component of the water budget

whereby recharge equals the difference between precipitation and the sum of losses through evapotranspiration, surface runoff, and shallow groundwater flow. The accuracy of recharge estimated through this method is limited by the large uncertainties inherent in the estimating components of the water budget such as evapotranspiration, which is typically large in magnitude relative to groundwater recharge. Examples of numerical models capable of estimating recharge based on a water budget include the Deep Percolation Model (Bauer and Vaccaro, 1987), Precipitation Runoff Modeling System (Leavesley et al., 1983), and the Variable Infiltration Capacity Model (Liang et al., 1994). Once the spatial distribution of groundwater recharge is estimated, the movement of groundwater within the subsurface may be modeled using groundwater-flow models. The movement of groundwater from areas of recharge may be modeled using groundwater flow models such as MODFLOW (Harbaugh et al., 2000). Groundwater-flow models are based on a hydrogeologic framework that incorporates the hydraulic properties of geologic materials and their stratigraphic relations. Groundwater models are calibrated using hydrologic data including groundwater levels within major water-bearing hydrogeologic units and can be used to characterize the movement of groundwater from areas of recharge to areas of discharge.

7.3 Computational Slope Stability Assessment Methods

Qualitative methods for the qualified expert to assess slope stability are summarized in Parts 6.2 and 5.5. Quantitative assessments of slope stability, performed by the qualified expert, may be necessary to characterize slope failure potential at a given site, as well as to evaluate potential impacts to natural resources and public safety associated with proposed forest practice activities. This quantitative assessment most often entails a two-dimensional, limit-equilibrium analysis method, but other methods may be necessary under certain conditions. Limit-equilibrium analysis calculates a factor of safety for sliding along a critical failure surface, which is expressed as a ratio of the shear strength of the earthen material resisting slope failure to the shear stresses driving instability. Relative stability is defined by a factor of safety exceeding a value of one. Computation of the most critical failure surface is an iterative process generally supported by commercially available or public-domain software (e.g., LISA, DLISA, STABL, SLOPE-W).

Development of a 2D model for analysis requires the following input information to define an initial state of stability:

- An engineering geologic section through the slope of concern (generally cut through the steepest portion of the slope) showing the thickness and position of each engineering geologic unit. The topographic surface profile can be field-surveyed or derived remotely from DEM topographic data whereas the subsurface failure plane geometry might need to be interpolated between known or hypothesized points (i.e., the locations at which the failure plane intersects the ground surface) in the absence of field data acquired from boreholes or with other geotechnical methods;
- Location/elevation of groundwater regimes along this critical section; and
- Saturated and unsaturated unit weights and shear strength of each engineering geologic unit.

The potential effects of the proposed forest practices activities on slope stability can then be evaluated by modifying the initial model with the expected condition based on the proposed activities, such as placement of fill for road construction or elevating groundwater levels (pressures) due to forest canopy removal. Limit-equilibrium models also allow the analyst to reconstruct pre-failure slope conditions of existing landslides by varying the input parameters (e.g., surface topography, engineering geologic unity properties, failure plane geometries, groundwater table

elevations) such that the reconstructed original slope fails. These exercises are useful for evaluating reasonable strength parameters of subsurface materials, likely failure plane geometries, and groundwater table elevations in the absence of real data or field indications. Two-dimensional models also can be used to evaluate downslope material impacts to natural resources and threats to public safety, as well as upslope impacts in situations where retrogressive failure mechanisms are suspected. Turner and Schuster (1996), as well as many other references, provide more details on the process and methodologies for performing limit-equilibrium stability analyses, including method assumptions and limitations. All of the above steps require considerable engineering geologic/geotechnical data (e.g., subsurface, instrumentation, laboratory) and expertise to achieve an accurate and meaningful representation of the actual conditions at the site.

7.4 Delivery Assessment

Landslides occur naturally in forested basins and are an important process in the delivery of wood and gravel to streams. Wood and gravel play important roles in creating stream diversity that is essential for fish use as habitat and spawning grounds. In the past, landslides as a result of forest practices activities have created a catastrophic regime that has contributed to the threatened and endangered status of certain species, as well as endangering human life in some instances.

The forest practices rules apply where there is *potential* for sediment and debris to ~~be delivered~~ to a public resource or threatens public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety should be ~~considered~~ re-evaluated. Many factors are part of that ~~consideration~~ evaluation, including ~~the~~:

- Proximity to a public resource or safety concern;
- Nature of the geologic material involved;
- Initial failure volume of a landslide, the runout distance of a landslide, and landscape geometry;
- Landslide type of failure mechanism;
- Slope of channel conditions; and
- Observed deformation characteristics of nearby landslides with comparable geologic/geomorphic attributes.

It is difficult to prescribe guidelines for delivery distances because each situation has a special combination of process and topography. Deep-seated landslides can move anywhere from a few inches to a few miles depending on the friction of the slip plane, the forces pulling the landslides down, and the shear strength resisting those forces. Larger landslides are more likely to be able to move great distances at gentle gradients, but they are also less likely to be significantly affected by forest practices activities.

Because many factors can influence landslide mobility and debris runout, it is not practical to provide generalized prescriptive guidelines to predict delivery for a broad range of conditions. An evaluation of deliverability should, in many cases, require a field assessment, an inquiry of historic landslide activity and behavior, and the application of experienced judgment in landslide processes and mobility.

Timber harvest and road building can cause shallow landslides on steep slopes. Travel distances for such landslides depend on the amount of water contained in or entrained by them. Considering that rain, snowmelt, or some other ~~extreme~~ water inputs trigger the ~~vast~~ majority of landslides in the

Pacific Northwest, it should be noted that almost all landslides contain some amount of water that tends to mobilize the soil or rock. Debris slides that do not reach streams (i.e., do not absorb large volumes of additional water) usually deposit their debris on the hillslope, and are typically unable to move far across large areas of flat ground. However, since most landslides occur during storm conditions, a large proportion of debris slides do reach flowing channels and create the opportunity to entrain enough water to become debris flows. These flows are quite mobile, and can travel great distances in steep or moderate gradient channels.

When channel gradients drop below 12° degrees (20%), debris flows no longer scour and generally begin to slow down. On slopes gentler than about 3- to 4° degrees (5- to 7%) debris flows commonly start losing to lose their momentum and the solids entrained in them (rock, soil, organic material) tend to settle out. Travel distance of a debris flow once it reaches a low-gradient surface is a function of its volume and viscosity. The solid volume of a debris slide or flow deposit is a function of soil depth, distance traveled down the hillslope, and the gradient of the traveled path. The proportion of water is the main control on viscosity. Field or empirical evidence should be used for determining the runout distance.

Even if the main mass of a landslide or debris flow comes to rest without reaching a public resource, there is the possibility that secondary effects may occur. Bare ground exposed by mass movement and disturbed piles of landslide debris can be chronic sources of fine sediment to streams until stabilized by revegetation. If flowing water (seepage, overland flow, or small streams) can entrain significant volumes of fine sediment from such surfaces, the possibility of secondary delivery must be evaluated, along with the likelihood of impact by the initial movement event itself.

To assess the potential for delivery and estimate runout distance, analysts can evaluate the history of landslide runout in the region, use field observations, and/or use geometric relationships appropriate from the scientific literature. In any situation where the potential for delivery is questionable, it is best to have a geotechnical qualified expert examine the situation and evaluate the likelihood of delivery. If forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource, a geotechnical report written by a qualified expert is required.

7.5 Synthesis of Results Prior to Preparation of Geologic Evaluations

This step is generally reserved for qualified experts when preparing geologic evaluations. The following questions and recommendations are provided to guide the qualified expert in their synthesis and can be useful when preparing a geologic evaluation (see Part 8 for geotechnical report guidelines):

1. What are the project objectives (e.g., timber harvest unit evaluation, road construction or abandonment, landslide mitigation)?
2. Which types of unstable slopes and landforms have been identified (see Part 5)?
3. What are their spatial and temporal distributions (see Part 5)?
4. Which office and field methods were used to identify and delineate unstable slopes and landforms (see Part 6)?
5. Based on an analysis of available information (see Parts 7.1, 7.2, 7.3), what is the geotechnical interpretation of physical processes governing unstable slope/landform movement, mechanics, and chronologies of each identified feature?

6. What are the project limitations (e.g., quantity or quality of technical information, site access, project timeframe) that might influence the accuracy and precision of identifying, delineating, and interpreting unstable slopes and landforms?
7. What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identifying, delineating, and interpreting of unstable slopes and landforms?
8. What is the potential for material delivery from each identified unstable slope and landform to areas of public resource sensitivity or public safety (see Parts 7.4)?
9. What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
10. What level of confidence is placed in the identification, delineation, and interpretation of unstable slopes and landforms? How does the confidence level impact any recommendations provided by the qualified expert for unstable slope management and/or mitigation?

Documentation of the project analysis may include annotated images (e.g., LiDAR-derived hillshades, aerial photos), geologic or topographic profiles, maps, sketches, results of subsurface investigations, summaries of computational or simulation modeling, summaries of available (i.e., previously published) information and remotely sensed or field-derived data and text to explain the concrete evidence and logical train-of-thought for the conclusions and recommendations that will be presented in the geotechnical report.

It is recommended field observation and sampling locations used in project analysis be displayed on a map in the geotechnical report. Descriptive, photo, or data-sampling observation points should be geo-referenced (i.e., with GPS waypoints). Mapped GPS track locations for field traverses also are recommended, so that it is clear which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced.

Models, such as those for slope stability and sensitivity (see Parts 7.2 and 7.3) may be used to support analyses of unstable slope and landform characteristics and mechanics. If models are used, the results should not be incorporated in report findings without an adequate assessment and clear statement of their assumptions, limitations, and alignment with existing information (e.g., field data). For example, a modeled reconstruction of landslide failure-plane geometry based on one borehole or drive probe sample would likely be misleading and could result in spurious conclusions.

It is recommended that the analytical methods and processes used to identify, delineate, and interpret unstable slopes and landforms be described in the geotechnical report, along with information sources, data processing techniques, and the meaning and limitations of analysis results. Geotechnical reports should describe all assumptions regarding input parameters or variables, such as groundwater surface elevation estimates employed in stability sensitivity analyses, as well as the reasoning for their use. Geotechnical reports also should include an assessment of the sensitivity of the analytical method or model results to parameter variability. This is especially true where only a range of parameter values are available, or where input values are extrapolated or estimated from other locations or databases.

The report conclusions should document the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the assessment, including office reviews and field assessment, qualitative information and data analyses, geo- and

hydro- technical modeling, and evaluation of material deliverability. Report conclusions might also describe the suitability of the site for the proposed activity clearly state the likely direct and indirect effects of the proposed activity on the geologic environment as well as the likely direct and indirect effects of geologic processes on the proposed activity. Conclusions should be substantiated by the presented evidence, and the logical thought process established in the analysis and synthesis process.

It is helpful to provide a concise statement of confidence in and limitations of the slope stability analysis and its conclusions. Confidence levels are influenced by many factors, including project complexity and objectives, site characteristics (e.g., acreage and accessibility), project timeframes, quantity and quality of available information (e.g., reports, databases) and remotely sensed data, accuracy and precision of field observations and collected data, and the rigor of available analytical methods and models. A discussion of the primary limiting factors assists the landowner and report reviewer in evaluating the potential natural resource, public safety, and liability risks associated with implementing a project.

The geotechnical report might include recommendations regarding additional work needed to supplement the qualified expert report, including but not limited to monitoring by the landowner or their designated qualified expert of geologic conditions (e.g., groundwater, slope movement) and review of plans and specifications. The qualified expert also might be asked by the landowner to provide or evaluate possible mitigation measures for destabilized slopes or landforms.

PART 8. GEOTECHNICAL REPORTS

When harvesting or building roads on potentially unstable slopes a geotechnical report is required to explain how the proposed forest practices ~~isare~~ likely to affect slope stability, delivery ~~sediment and debris~~ to public resources, ~~orand~~ threaten public safety. If the FPA is classed as a "Class IV-Special", tThe applicant must also submit to DNR a SEPA checklist and additional information as described in WAC 222-10-030. The Ggeotechnical reports must be prepared by a qualified experts and the report must meet the requirements ~~as~~ described in WAC 222-10-030(~~51~~).

Effective July 1, 2002, qualified experts must be licensed with Washington's Geologist Licensing Board. For more information on the geologist licensing process, refer to WAC 308-15-010 through 308-15-150, or visit the Geology Board's web site at (www.dol.wa.gov/business/geologist). The education and field experience on forestlands will still be required, in addition to the appropriate geologist license.

In addition to the considerations described in Part 7.5, Tthe following elements should be included in geotechnical reports ~~submitted-prepared~~ by qualified experts:

- (a) *Prepare an introductory section.* This section should describe the qualified expert's qualifications ~~of the expert to ensure he/she meets the aforementioned requirements~~. It should also reference the ~~forest practices application~~FPA number if previously submitted, ~~the~~ landowner(s) and operator(s) names, and a brief description of ~~field trip(s)~~site observations to the area, including dates, relevant weather conditions, and the locations visited. Geographic coordinates (latitude and longitude, GPS waypoints of observation locations) are helpful for reviewers for locating the sites with certainty.
- (b) *Describe the geographic, geologic, and the soil conditions of the area in and around the application site.* ~~This section is to provide reviewers with general background information related to the application site.~~ Include a legal description of the proposal area, the county in

which it is located, and aswhere appropriate, the distance and direction from the nearest municipality, local landmarks, and named water bodies. Provide elevations and aspect. Describe the underlying parent materials, including their origin (i.e., glacial versus bedrock); the name(s) of any rock formations and their associated characteristics; and geologic structure relevant to slope stability. Describe the soils and rocks on site based on existing mapping, field observations, and any available local information. Describe soil and rock texture, depth, and drainage characteristics typically using standard soil and rock classification systems (e.g. Unified Soil Classification System (USCS), American Association of State Highway and Transportation Officials (AASHTO) and Rock Mass Rating, Bieniawski, 1989).

- (c) *Describe the potentially unstable landforms within and around of the site.* Include a general description of the topographic conditions of the site. It may be appropriate to provide GPS coordinates for locations of site observations and other important features such as borings, trenches, and outcrops. Specifically identify the potentially unstable landforms located in the area (i.e., those defined in WAC 222-16-050 (1)(d)(i)), in addition to any other relevant landforms on or around the site. Describe in detail the gradient, form (shape), and approximate size of each potentially unstable landform. Include a description of the dominant mass wasting processes associated with each identified landform, as well as detailed observations of past slope movement and indicators of instability. Assign a unique alphabetic and/or numeric identifier label to each landform on a detailed site map of a scale sufficient to illustrate site landforms and features. Where the proposal involves operations on or in the groundwater recharge area of a glacial deep-seated landslide(s), specifically discuss the probable direct and indirect impacts to groundwater levels and those impacts to the stability of the deep-seated landslide(s).
- (d) *Analyze the possibility that the proposed forest practice will cause or contribute to movement on the potentially unstable slopes.* Explain the proposed forest management activities on and adjacent to the potentially unstable landforms. Clearly illustrate the locations of these activities on the site map, and describe the nature of the activities in the text. Discuss in detail the likelihood that the proposed activities will result in slope movement (separate activities may warrant separate evaluations of movement potential). The scope of analysis should be commensurate with the level of resource and/or public risk. Include a discussion of both direct and indirect effects expected over both the short- and long-term. For proposals involving operations on or in the groundwater recharge area of a glacial deep-seated landslide, conduct an assessment of the effects of past forest practices on slide/slope movement. Explicitly state the basis for conclusions regarding slope movement. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or slope stability model output. Input parameters, model assumptions, and methods should be fully substantiated within the report.
- (e) *Assess the likelihood of delivery of sediment and/or debris to any public resources, or to a location and in a waymanner that would threaten public safety, should slope movement occur.* Include an evaluation of the potential for sediment and/or debris delivery to public resources or areas where public safety could be threatened. Discuss the likely magnitude of an event, if ~~it~~ occurred were to occur. Separate landforms may warrant separate evaluations of delivery and magnitude. Explicitly state the basis for conclusions regarding delivery. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or landslide runout model results, which should have

site-specific data. Input parameters, model assumptions, and methods using best available data should be fully substantiated within the report.

- (f) *Suggest possible mitigation measures to address the identified hazards and risks.* Describe any modifications necessary to mitigate the possibility of slope movement and delivery due to the proposed activities. If no such modifications are necessary, describe the factors inherent to the site or proposed operation that might reduce or eliminate the potential for slope movement or delivery. For example, an intact riparian buffer down slope from a potentially unstable landform may serve to intercept or filter landslide sediment and debris before reaching the stream. Discuss the risks associated with the proposed activities relative to other alternatives, if applicable.

The report should be as detailed as necessary to answer these and any other relevant questions. In particular, examination of aerial photographs (preferably taken over many years), LiDAR-derived products, and other screening tools would be appropriate to evaluate the stability characteristics of the area and the effects of roads or previous logging on the subject or similar sites. Field observations will usually be necessary to define the local geology, landforms, etc. Quantitative estimates of site stability produced using SHALSTAB, XSTABL, or other slope-stability models may be useful.

GLOSSARY

- Aquifer** Saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.
- Aquitard** A less permeable bed in a stratigraphic sequence.
- Confined aquifer** An aquifer that is confined between two aquitards. Confined aquifers occur at depth.
- Debris avalanche** The very rapid and usually sudden sliding and flowage of incoherent, unsorted mixtures of soil and weathered bedrock.
- Discontinuity** Sudden or rapid change with depth in one or more of the physical properties of the materials constituting the earth.
- Drift** A general term for material such as boulders, till, gravel, sand, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice. Generally used to describe glacial deposits of the Pleistocene Epoch.
- Drillers log** The brief notations included as part of a driller's tour report, that describes the gross characteristics of the well cutting noted by the drilling crew. It is useful only if a detailed sample log is not available. Drillers logs may also include information on groundwater elevation.
- Earthflow** A slow flow of earth lubricated by water, occurring as either a low-angle terrace flow or a somewhat steeper but slow hillside flow.
- Engineering geology** Performance of geological service or work including but not limited to consultation, investigation, evaluation, planning, geological mapping, and inspection of geological work, and the responsible supervision thereof, the performance of which is related to public welfare or the safeguarding of life, health, property, and the environment, and includes the commonly recognized practices of construction geology, environmental geology, and urban geology.
- Evapotranspiration** A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Commonly designated by the symbols (E_t) in equations.
- Factor of safety** The ratio of the resistant force acting on the sliding surface to the driving force acting on the potential slide mass. When the factor of safety is greater than 1, the slope is stable; when the factor of safety is less than 1, the slope is unstable.

- Glacial outwash** Sediment deposited by meltwater streams beyond a glacier, typically sorted and stratified sand and gravel.
- Graben** A block, generally long compared to its width, that has been downthrown along faults relative to the rocks on either side.
- Groundwater** Subsurface water that occurs in soils and geologic formations. Encompasses subsurface formations that are fully saturated and near-surface, unsaturated, soil-moisture regimes that have an important influence on many geologic processes.
- Groundwater Recharge area** That portion of a drainage basin in which the net saturated flow of groundwater recharge is the process by which water is absorbed and is added to the zone of saturation, either directly into a formation, or indirectly by way of another formation. Also, the quantity of water that is added to the zone of saturation. The rule definition for groundwater recharge areas for glacial deep-seated landslides is found in WAC 222-16-010.
- Glacial terrace** Relatively flat, horizontal, or gently inclined surfaces, sometimes long and narrow, which are bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side formed by glacial processes.
- Glaciolacustrine** Pertaining to, derived from, or deposited in glacial lakes; deposits and landforms composed of suspended material brought by meltwater streams flowing into lakes.
- Glaciomarine** Pertaining to sediments which originated in glaciated areas and have been transported to an ocean's environment by glacial meltwater.
- Glacial till** Non-sorted, non-stratified sediment carried or deposited by a glacier.
- Hydrogeology** The science that involves the study of the occurrence, circulation, distribution, chemistry, remediation, or quality of water or its role as a natural agent that causes changes in the earth, and the investigation and collection of data concerning waters in the atmosphere or on the surface or in the interior of the earth, including data regarding the interaction of water with other gases, solids, or fluids.
- Hydraulic head** Combined measure of the elevation and the water pressure at a point in an aquifer which represents the total energy of the water; since ground water moves in the direction of lower hydraulic head (i.e., toward lower energy), and hydraulic head is a measure of water pressure, ground water can and often does flow uphill.
- Hydrologic budget** An accounting of the inflow to, outflow from, and storage in a hydrologic unit such as a drainage basin, aquifer, soil zone or water body. For watersheds, the major input is precipitation; major output is stream flow.

<u>Lahar</u>	<u>A mudflow composed chiefly of volcaniclastic materials on the flanks of a volcano.</u>
<u>Resistivity method</u>	<u>A geophysical method that observes the electric potential and current distribution at the earth's surface intended to detect subsurface variation in resistivity which may be related to geology, groundwater quality, porosity, etc.</u>
<u>Seismic method</u>	<u>A geophysical method using the generation, reflection, refraction, detection and analysis of seismic waves in the earth to characterize the subsurface.</u>
<u>Soil</u>	<u>An aggregate of solid particles, generally of minerals and rocks that either was transported or was formed by the weathering of rock in place.</u>
<u>Strata</u>	<u>Plural of stratum.</u>
<u>Stratum</u>	<u>A section of a formation that consists throughout of approximately the same material; a stratum may consist of an indefinite number of beds, and a bed may consist of numberless layers; the distinction of bed and layer is not always obvious.</u>
<u>Stratification</u>	<u>A structure produced by the deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and other essentially tabular units.</u>
<u>Unconfined aquifer</u>	<u>Aquifer in which the water table forms the upper boundary. Unconfined aquifers occur near the ground surface.</u>
<u>Vadose zone</u>	<u>Referred to as the unsaturated zone below the land surface and above the zone of saturation, or water table.</u>
<u>Water table</u>	<u>The surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric. The location of this surface is revealed by the level at which water stands in a shallow well open along its length and penetrating the surficial deposits just deeply enough to encounter standing water at the bottom.</u>

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APPENDIX A MAPS AND SURVEYS

Map and survey data resources available to the qualified expert include:

Multi-disciplinary map and survey data resources:

- Washington State Geologic Information Portal – create, save, and print custom digital maps of Washington State or download map data for GIS applications; includes a variety of base layer selections with interactive Geologic Map, Seismic Scenarios Catalog, Natural Hazards, Geothermal Resources, Subsurface Geology Information, and Earth Resource Permit Locations; available on Washington Dept. of Natural Resources (DNR) website;
- Forest Practices Application Review System (FPARS) – interactive online mapping tool with a variety of digital map base layer selections including topography, surface water (streams, water bodies, wetlands), soils, transportation network, forest site class, and potential slope instability (designed for shallow landslide susceptibility mapping only); available on the DNR website;
- County interactive GIS map viewers – create, save, and print custom digital maps with some combination of the following data: topography (LiDAR and/or U.S. Geological Survey (USGS) DEM), surface water, soils, wetlands, sensitive areas, 100-year floodplain designations, transportation net and traffic counts, property ownership and structure location; available online at select county websites (e.g., King County iMAP);
- Washington State Coastal Atlas Map – interactive map utility for shoreline areas with multiple data layers including shoreline geomorphology (coastal slope stability and landforms), biology (plant communities), land and canopy cover, beaches and shoreline modifications, wetlands and estuaries, historic shoreline planforms, assessed waters, and Shoreline Management Act (SMA) designations; see Department of Ecology website.
- DNR surface mining permits

Topographic maps:

- USGS topographic 7.5 minute quadrangle maps; available from a number of government and non-government online vendors and free downloadable websites;
- LiDAR-based topographic maps (LiDAR-derived DEM (LDEM), typically 1- to 3- meter resolution); see Appendix C for LiDAR map and data sources.

Geologic maps:

- Geologic maps, various scales, in print and compiled by DNR, Division of Geology and Earth Resources as Map Series, Open File Reports, Bulletins, and Information Circulars; see most recent “Publications of the Washington Division of Geology and Earth Resources”; this publication and a status map of 7.5 minute quadrangle geologic mapping efforts (USGS STATEMAP program) are available on the DNR website with links to online publications where available;
- Geologic maps, various scales, in- and out-of-print or historic; all sources including dissertations and theses; see catalog of the Washington Geology Library, available through the DNR website with links to online publications where available;
- Geology digital data; small-scale geology coverage in ArcGIS shapefile format, available on DNR website;

- Geologic maps, various scales, available via The National Geologic Map Database (NGMDB; compiled by USGS and Association of American State Geologists; see NGMDB website catalog) and USGS Online Store (paper and digital copies).

Geologic hazards and landslide inventory maps:

- See Washington State Geologic Information Portal, referenced previously;
- Landslide Hazard Zonation (LHZ) Project – mapped existing and potential deep-seated landslides and landforms in select watersheds; hazard classifications provided with supporting documentation for completed projects; available through the DNR website;
- Landslide inventory and Mass Wasting Map Unit (MWMU) maps contained in Watershed Analysis Reports prepared under chapter 222-22 WAC – mapped landslides (including deep-seated and earthflows) for select Watershed Administrative Units (WAU); Adobe pdf versions of DNR-approved Watershed Analysis Reports are available through the DNR website;
- Modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps
- U.S. Forest Service watershed analyses – available from US Forest Service offices for select watersheds; some documents and maps are available online
- Washington State tribal watershed analyses – available from tribal agency offices; some documents and maps are available online;
- Washington State Coastal Atlas Map – slope stability maps developed prior to 1980, based on aerial photography, geologic mapping, USGS topographic quadrangle map, and field observations. Maps have not been updated with landslide data since 1980 but are used currently in land-use planning and in the Department of Ecology interactive Coastal Map tool; read data limitations on Department of Ecology’s website.
- Qualified expert reports on deep-seated landslides in glaciated and non-glaciated terrain, for select timber harvest units or other forest management projects regulated by the Washington Forest Practices Act. Often contain mapped landslides;
- TerrainWorks (NetMap) – provides digital landscape and analysis tools for slopes stability data/analysis and risk assessments.

Soil surveys:

- Natural Resources Conservation Service (NRCS) soil survey maps and data – online soil survey, map and database service; historical soil survey publications (CD or paper copies); NRCS website administered through the U.S. Department of Agriculture;
- Geochemical and mineralogical soil survey map and data – USGS Mineral Resources Program, open-file report available online (Smith et al., 2013) in Adobe pdf;
- National Cooperative Soil Survey Program (NCSS), Washington State – online soil survey data and link for ordering in-print surveys not available electronically; see NRCS website.

APPENDIX B EARTH IMAGERY AND PHOTOGRAMMETRY

The most common sources of imagery for landslide and landform identification, mapping, and photogrammetric analysis include:

- Aerial photography – historic and recent aerial photos produced in color or black and white and taken at various altitudes (typical scales in the 1:12,000 to 1:60,000 range); aerial photos acquired by the U.S. Soil Conservation Service are available in some areas as early as the 1930s. Multiple flight years are required for chronologically reconstructing deep-seated landslide activity and developing time-constrained landslide inventories. Forest landowners typically purchased photos from regional vendors on a 2 to 10 year cycle until recently when other freely acquired imagery became available (e.g., Google Earth, ESRI World Imagery). Stereo-pair photos are highly valued for landslide detection and reconstruction because they allow stereoscopic projection in three dimensions and can display high-quality feature contrast and sharpness;
- Google Earth – map and geographic information program with Earth surface images created by superimposing satellite imagery (DEM data collected by NASA’s Shuttle Radar Topography Mission), aerial photos, and GIS 3D globe. Ortho-rectified, generally 1-meter resolution, 3D images are available for multiple years (Historical Imagery tool), allowing chronologic deep-seated landslide mapping; Google Earth supports desktop and mobile applications, including managing 3D geospatial data. See Google website for download information;
- Bing Maps Aerial View – part of Microsoft web mapping service; overlays topographic base maps with satellite imagery taken every few years. See Microsoft site for download information;
- ESRI World Imagery – ArcGIS online image service utilizing Landsat imagery based on the USGS Global Land Survey datasets and other satellite imagery, with onboard visualization, processing, and analysis tools that allow imagery integration directly into all ArcGIS projects. Requires ArcGIS capability; see ESRI website.
- NAIP (National Agriculture Imagery Program) aerial imagery – ortho-rectified, generally 1-meter resolution earth surface images taken annually during peak growing season (“leaf-on”), acquired by digital sensors as a four color-band product that can be viewed as a natural color or color infrared image. The latter are particularly useful for vegetation analysis. Data available to the public via the USDA Geospatial Data Gateway and free APFO viewing software, as well as through ESRI for ArcGIS applications; see USDA Farm Service Agency website;
- Washington State Coastal Atlas Map and Photos – oblique shoreline photos spanning years 1976-2007; part of an interactive map tool; see Department of Ecology’s website.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) Archive of downloadable aerial photos.

APPENDIX C SOURCES FOR LIDAR DATA

Sources for viewing and downloading airborne LiDAR of Washington State include the following (URLs may change without notice):

- King County iMAP: Interactive mapping tool
(<http://www.kingcounty.gov/operations/GIS/Maps/iMAP.aspx>) – Displays shaded relief maps derived from LiDAR data at locations where it is available. LiDAR data have been filtered to remove vegetation and manmade structures and can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- National Oceanic and Atmospheric Administration Digital Coast
(<http://csc.noaa.gov/digitalcoast/>) – Archive of downloadable LiDAR data focused on coasts, rivers, and lowlands. Options for downloading point cloud, gridded, or contour data that require geographic information system software such as ArcGIS to view and analyze.
- National Science Foundation Open Topography facility
(<http://www.opentopography.org/index.php>) – Archive of downloadable LiDAR data collected the National Center for Airborne Laser Mapping (NCALM) for research projects funded by the National Science Foundation. Options for downloading point cloud or gridded data for use with geographical information system software, or LiDAR derived hillshade and slope maps that can viewed in Google Earth.
- Oregon Lidar Consortium (<http://www.oregongeology.org/sub/projects/olc/>) – Small amount of Washington State data available along the Columbia River. Lidar Data Viewer displays hillshade maps that have been filtered to remove vegetation and manmade structures.
- Puget Sound Lidar Consortium (<http://pugetsoundlidar.ess.washington.edu/>) – Archive of LiDAR data from Western Washington, downloadable as quarter quad tiles. Data format is ArcInfo interchange files and requires geographic information system software to view.
- Snohomish County Landscape Imaging: SnoScape (<http://gis.snoco.org/maps/snoscape/>) – Displays hillshade maps of bare or built topography derived from LiDAR data where it is available. Can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- USGS EarthExplorer (<http://earthexplorer.usgs.gov/>) – Archive of downloadable LiDAR data acquired by the USGS through contracts, partnerships, and purchases from other agencies or private vendors. File format is LAS and requires GIS software for viewing.

APPENDIX D TECHNICAL REPORTS AND RESOURCES

In addition to library and online sources, the following technical reports, published and unpublished papers and searchable databases are available online:

- Catalog of the Washington Geology Library. Searchable database of the Washington Department of Geology Library containing a comprehensive set of dissertations and theses, watershed analyses, environmental impact statements, and refereed/un-refereed publications on state geology; see DNR website with links to online publications where available.
- USGS Open File Reports. Searchable online database containing reports covering deep-seated landslide investigations and related topics; see USGS Online Publications Directory, USGS website.
- Watershed Analysis, Mass Wasting Assessment reports per chapter 222-22 WAC. Adobe pdf versions of DNR-approved reports are available via the DNR website.
- US Forest Service watershed analysis reports. Available from U.S. Forest Service offices for select watersheds; some electronic documents are available online through the U.S. Forest Service website for national forest of interest.
- Interagency watershed analysis reports. Collaborative projects between federal agencies (U.S. Geological Survey, U.S. Forest Service, U.S. Fish and Wildlife Service), tribal agencies, and industry (e.g., Cook and McCalla basins, Salmon River basin, Quinault watershed). Documents available online through the USGS, Washington Water Science Center.
- Washington Soil Atlas. Available as downloadable Adobe pdf file from the Natural Resources Conservation Service website.

APPENDIX E PHYSICAL DATABASES

Meteorological databases:

- National Weather Service (NWS) cooperative weather stations – coordinated by National Oceanic and Atmospheric Administration (NOAA) – database managed by Western Regional Climate Center
- NWS Weather Surveillance Radar – Doppler and NEXRAD
- Remote Automatic Weather Stations (RAWS) – operated by US Forest Service and Bureau of Land Management – database managed by Western Regional Climate Center

Stream-flow gauge database: USGS National Water Information System website

Seismic data: Pacific Northwest Seismic Network (PNSN) – database managed by USGS, University of Washington, and IRIS Consortium in Seattle. Contains records from seismometers located throughout Washington and Oregon; see the PNSN website.

Climate Data for Washington: The availability of climate data is highly variable for the State of Washington. The following sites provide access to most of the available data useful for evapotranspiration modeling (the URLs may change without notice):

- USGS, Washington Water Data - <http://wa.water.usgs.gov/data/>
- National Surface Meteorological Networks - <https://www.eol.ucar.edu/projects/hydrometer/northwest/northwest.html>
- National Weather Service - <http://www.wrh.noaa.gov/sew/observations.php>
- National Climate Data Center - <http://www.ncdc.noaa.gov/>
- University of Washington Atmospheric Sciences - <http://www.atmos.washington.edu/data/>
- Washington State University - <http://weather.wsu.edu/awn.php>
- Community Collaborative Rain, Hail, and Snow Database - <http://www.cocorahs.org/>
- Western Regional Climate Summary for Washington - <http://www.wrcc.dri.edu/summary/climsmwa.html>
- Natural Resource Conservation Service - <http://www.nrcs.usda.gov/wps/portal/nrcs/main/wa/snow/>
- Washington Dept. of Ecology Water Resources - <http://www.ecy.wa.gov/programs/wr/wrhome.html>
- Washington Dept. of Transportation - http://www.wsdot.com/traffic/weather/weatherstation_list.aspx

National Resources Inventory for Washington State: Statistical survey of land use, natural resource conditions and trends in soil, water, and related resources on non-federal lands; see NRCS website.

APPENDIX F HYDROLOGIC PROPERTIES OF SOILS

This adaptation from Koloski et al., 1989, relates geologic materials commonly found in Washington to the descriptive properties of permeability and storage capacity. A generalized explanation of the two terms is presented below, but is not intended to rigorously define either the geologic categories or the geotechnical properties. The information presented in the table is useful to indicate the general range of values for these properties, be considered representative, but is no substitute for site-specific laboratory and field information.

<u>Classification</u>	<u>Permeability (feet per minute)</u>	<u>Storage Capacity</u>
<u>Alluvial (High Energy)</u>	<u>0.01-10</u>	<u>0.1-0.3</u>
<u>Alluvial (Low Energy)</u>	<u>0.0001-0.1</u>	<u>0.05-0.2</u>
<u>Eolian (Loess)</u>	<u>0.001-0.01</u>	<u>0.05-0.1</u>
<u>Glacial Till</u>	<u>0-0.001</u>	<u>0-0.1</u>
<u>Glacial Outwash</u>	<u>0.01-10</u>	<u>0.01-0.3</u>
<u>Glaciolacustrine</u>	<u>0-0.1</u>	<u>0-0.1</u>
<u>Lacustrine (Inorganic)</u>	<u>0.0001-0.1</u>	<u>0.05-0.3</u>
<u>Lacustrine (Organic)</u>	<u>0.0001-1.0</u>	<u>0.05-0.8</u>
<u>Marine (High Energy)</u>	<u>0.001-1.0</u>	<u>0.1-0.3</u>
<u>Marine (Low Energy)</u>	<u>0.0001-0.1</u>	<u>0.05-0.3</u>
<u>Volcanic (Tephra)</u>	<u>0.0001-0.1</u>	<u>0.05-0.2</u>
<u>Volcanic (Lahar)</u>	<u>0.001-0.1</u>	<u>0.05-0.2</u>

Permeability differences reflect variations in gradation between geologic materials. Very high permeability is associated with high-energy alluvial deposits or glacial outwash where coarse, open-work gravel is common. Permeability in these deposits can vary greatly over short horizontal and vertical distances. Extremely low permeability is associated with poorly to moderately sorted materials that are ice-consolidated and contain a substantial fraction of silt and clay.

Storage capacity reflects the volume of void space and the content of silt or clay within a soil deposit. Storage capacity is very small for poorly sorted or ice-consolidated, fine-grained materials such as till and glaciolacustrine deposits.

APPENDIX G ADDITIONAL RESOURCES

The following literature list provides additional resources not directly cited in this Board Manual section. They are listed topically according to the scientific study/research.

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**FINAL VIEW W/O
TRACK/CHANGE**

**Section 16
Guidelines for Evaluating
Potentially Unstable Slopes and Landforms**

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PART 1. INTRODUCTION

Board Manual Section 16 contains guidelines to evaluate potentially unstable slopes and landforms on forest land. Like all Board Manual sections, it does not contain rules or impose requirements. Instead, it is an advisory technical supplement to the forest practices rules, offering approaches for landowners and other forest professionals to achieve complete assessments that will lead to complete Forest Practices Applications (FPAs) and successful proposals.

The intended audience is:

- Landowners, foresters, and company engineers or private consultants who assist in field work; this group is referred to as “general practitioners” in this Board Manual section; and
- Qualified experts, as that term is defined in WAC 222-10-030(5).

The objectives of Section 16 are: 1) to provide general practitioners with tools to better understand the geology and hydrology in the area of a proposed forest practices activity, and to determine when a qualified expert is needed to conduct further geotechnical analysis; and 2) to assist qualified experts with methods to conduct geotechnical investigations and prepare complete geotechnical reports.

The section is composed of eight parts:

- The first five parts contain general background information for all readers on the various landslide types and provinces in Washington State (Part 2), how to measure slope angles (Part 3), how to recognize slope form (Part 4), and how to recognize potentially unstable slopes and landforms for purposes of identifying them in the area of a proposed forest practices activity (Part 5).
- The final three parts contain recommended procedures and resources for conducting reviews and assessments of potentially unstable areas in relation to proposed forest practices. **General practitioners** will find Parts 6.1.1 and 6.2.1 most useful for their office reviews and field assessments. The remainder of Part 6 and all of Parts 7 and 8 are geared toward the work of **qualified experts** to conduct expert-level office reviews and field assessments, and to prepare geotechnical reports.

The section ends with a glossary of terms that may not be familiar to many readers; a list of the references cited throughout the document; and several appendices containing lists of resources that any reader may find informative or useful.

PART 2. OVERVIEW OF LANDSLIDE TYPES AND PROVINCES

Landslides occur naturally in forested basins and are an important process in the delivery of wood and gravel to streams and nearshore environments. Wood and gravel play significant roles in creating stream diversity essential for fish habitat and spawning grounds (e.g., Reeves et al., 1995; Geertsema and Pojar, 2007; Restrepo et al., 2009).

Under past forest practices rules, forest practices-caused landslides contributed to the acceleration of naturally occurring landslide processes (e.g., Swanson et al., 1977; Robinson et al., 1999; Montgomery et al., 2000; Turner et al., 2010) and may have contributed to the threatened and endangered status of certain species (e.g., Sidle et al., 1985; Beechie et al., 2001) as well as endangered human life in some instances (e.g., Oregon Landslides and Public Safety Project Team, 2001). The current rules were developed to protect public resources and prevent threats to public safety. They apply when it is determined that proposed forest practices activities may contribute to the *potential* for sediment and debris to be delivered to a stream, lake, marine water, or other fish and wildlife habitat, domestic water supplies, public capital improvements, or to cause a threat to public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety must be considered. Other factors include initial failure volume, the nature of the landslide, landslide runout distance, and the slope or channel conditions to determine the potential to deliver to a public resource or threaten public safety.

Certain landforms are particularly susceptible to slope instability or indicate past slope instability. Forest practices applications (FPAs) proposing activities on or near these landforms may be classified “Class IV-special” and receive additional environmental review under the State Environmental Policy Act (SEPA). These landforms, commonly referred to as “rule identified landforms”, are listed in WAC 222-16-050(1). They are:

- Inner gorges, convergent headwalls, and bedrock hollows with slopes >70% (35 degrees);
- Toes of deep-seated landslides with slopes >65% (33 degrees);
- Groundwater recharge areas for glacial deep-seated landslides;
- Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; and
- Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes.

“Landslide” is a general term for any downslope movement of rock, unconsolidated sediment, soil, and/or organic matter under the influence of gravity. It also refers to the deposit itself, and slide materials in mountainous terrain typically are separated from more stable underlying material by a zone of weakness variously called the failure zone, plane, or surface.

Landslides can be classified in several ways. The method shown in Part 2.1 describes the type of movement (fall, topple, slide, spread, or flow) and the types of materials involved (rock, soil, earth, or debris). The failure surface can range from roughly planar (called “translational”), to curved (called “rotational” or a combination of failure surface geometries) (Figure 1). Translational failures can also occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes (Robinson et al., 1999; Turner et al., 2010) with little observed rotation or backward tilting of the slide mass. Landslides can be small (a few cubic

yards) or very large (millions of cubic yards). They can range from very fast moving as in free fall, to very slow as in creep. Landslides can come to rest quickly or can continue to move for years or even centuries. Landslides that stop moving, only to be later reactivated are considered dormant slides. A landslide can also permanently cease moving and undergo erosion and revegetation over long periods of geologic time; this is considered a relic slide.

Ground failures resulting in landslides occur when gravitational forces, in combination with soil and other factors, overcome the strength of the soil and rock on a slope. Contributing factors may include:

- The presence of an impermeable stratigraphic layer beneath a permeable stratigraphic layer.
- Saturation by rain on snow events or heavy and/or prolonged rains that can saturate soils and create instability in soil and weakened bedrock.
- Erosion by rivers, glaciers, or ocean waves that over-steepen slopes resulting in removing support from the base of the slopes.
- Ground shaking caused by earthquakes that increases the driving force and weakens the supporting soil structure.
- Volcanic eruptions that produce lahars and instability on the lateral flanks of the volcano.
- Excess weight from accumulation of rain or snow, stockpiling of rock or earth from waste piles, or manmade structures that exert excessive stress on slopes.
- Human activities such as timber harvest and construction activities that disturb soils, weaken or remove the support for slopes, or increase runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.

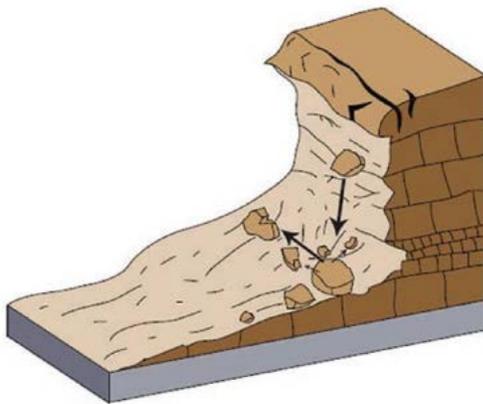
2.1 Landslide Types and Effects

Several classification schemes are used by geologists, engineers, and other professionals to identify and describe landslides. The classification scheme of Varnes (1978), modified by the U.S. Geological Survey (U.S. Geological Survey, 2004), is used for the purposes of this Board Manual section (see Table 1).

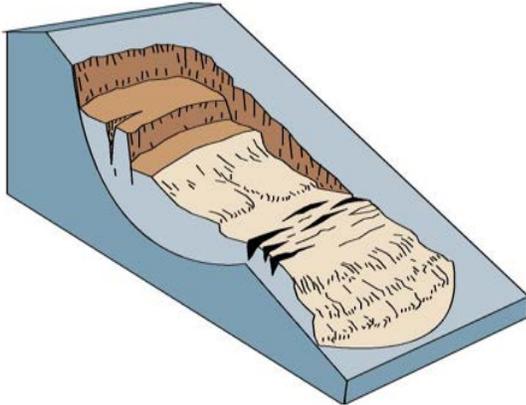
Table 1. Landslide Classification
(modified from U.S. Geological Survey (2004) and Varnes (1978))

Type of Movement		Type of Material		
		Bedrock	Soils	
			Predominately Coarse	Predominately Fine
Falls		Rock Fall	Debris Fall	Earth Fall
Topples		Rock Topple	Debris Topple	Earth Topple
Slides	Rotational	Rock Slide	Debris Slide	Earth Slide
	Translational			
Lateral Spreads		Rock Spread	Debris Spread	Earth Spread
Flows		Rock Flow	Debris Flow	Earth Flow
Complex		Combination of two or more principal types of movement		

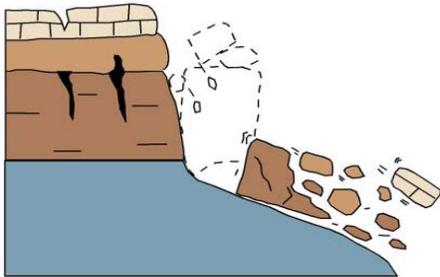
In this scheme, landslides are classified by types of materials and movement. Materials in a landslide mass are either rock or soil (or both) and may also include organic debris. In this context, soil is composed of sand-sized or finer particles and debris is composed of coarser fragments. The types of landslides commonly found in forested areas in Washington include slides, flows, and complex landslides. The types of movement describe the actual internal mechanics of how the landslide mass is displaced: fall, topple, slide, spread, or flow. Thus, landslides are described using two terms that refer respectively to the type of material and method of movement (rockfall, debris flow, and so forth). Landslides may also occur as a complex failure encompassing more than one type of movement (e.g., debris slide - debris flow). Some of the landslide types shown in Table 1 can be further divided into shallow or deep-seated depending on whether the failure plane is above (shallow) or below (deep) the rooting depth of trees. Simplified illustrations of the major types of landslides are shown in Figure 1.



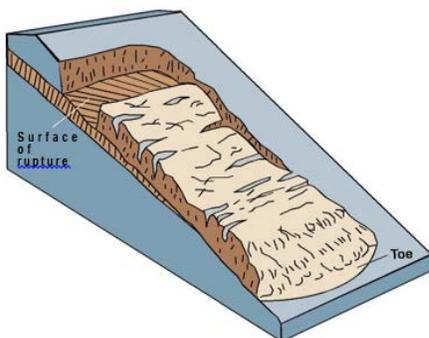
Falls: Falls occur when a mass of rock or soil detach from a steep slope or cliff, often caused by undercutting of the slope. The failure is typically rapid to very rapid. The fallen mass may continue down the slope until the terrain flattens.



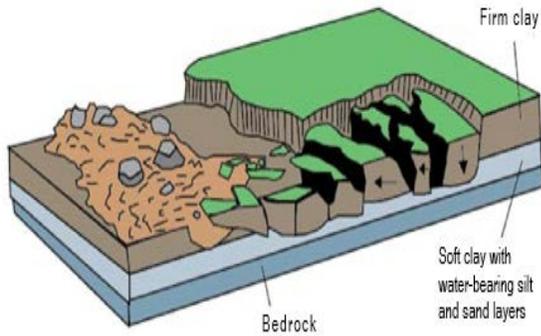
Rotational slides: These are landslides where the surface of rupture is concave-up and the slide movement is rotational about an axis that is parallel to the contour of the slope. Glacial deep-seated landslides can be rotational slides developed in glacial sediments common in the Puget Sound area, but they can also involve more complex types of movement.



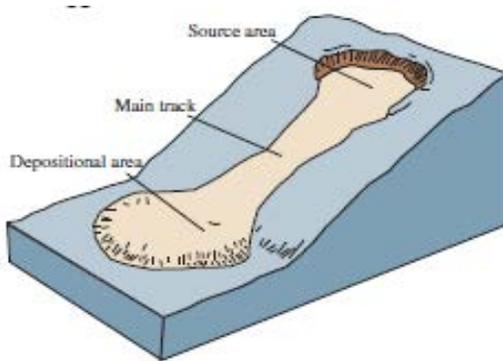
Topples: Landslides where the forward rotation of a mass of rock or soil breaks away or ‘topples’ from the slope. Their failure rates range from extremely slow to extremely fast.



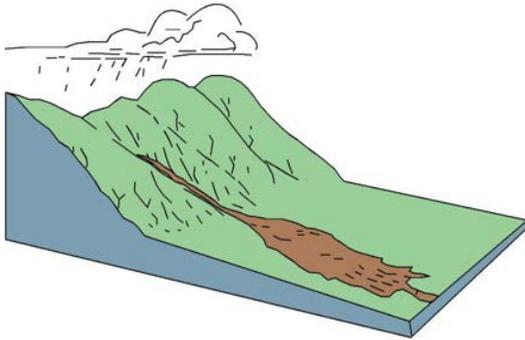
Translational slides: Landslides where the surface of the rupture is roughly planar.



Lateral spreads: Landslides that generally occur on very gentle or level slopes and are caused by subsidence of a fractured mass of cohesive material into softer, often liquefied underlying material.



Earth flows: Landslides consisting of fine-grained soil or clay-bearing weathered bedrock. They can occur on gentle to moderate slopes.



Debris flows: Landslides where loose rock, soil, and organic matter combine with water to form a slurry that flows rapidly downslope.

Figure 1 Illustrations of the major types of landslide movement (all from Highland and Bobrowsky, 2008, except Earth flows from U.S. Geological Survey, 2004).

2.2 Shallow Landslide Types

Shallow landslides are unstable features which typically fail within the vegetation rooting zone and may respond to rainfall events over periods of days to weeks. They occur on a variety of landforms including bedrock hollows, convergent headwalls, inner gorges, toes of deep-seated landslides, the outer edges of meander bends, and in other areas with steep slopes. The amount of water and the materials contained within shallow landslides affect the manner and the distance in which they move.

Debris slides consist of aggregations of coarse soil, rock, and vegetation that lack significant water and move at speeds ranging from very slow to rapid down slope by sliding or rolling forward. The results are irregular hummocky deposits that are typically poorly sorted and non-stratified. Debris slides include those types of landslides also known as shallow rapid, soil slips, and debris avalanches. If debris slides entrain enough water they can become debris flows.

Debris flows are slurries composed of sediment, water, vegetation, and other debris. Solids typically constitute >60% of the volume (Pierson and Scott, 1985). Debris flows usually occur in steep channels as debris becomes charged with water (from soil water or upon entering a stream channel) and liquefies as it breaks up. Channelized debris flows often entrain material and can significantly bulk up in volume during transport. These landslides can travel thousands of feet or miles from the point of initiation, scouring the channel to bedrock in steeper channels. Debris flows commonly slow where the channel makes a sharp bend and stop where the channel slope gradient becomes gentler than about 3 degrees (5%), or the valley bottom becomes wider and allows the flow to spread out. Hyper-concentrated floods may travel greater distances and on shallower slopes than debris flows based on their water content (Iverson and Reid, 1992).

Hyper-concentrated floods are a subset of debris flows containing a mixture of water and sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains, they are commonly caused by the collapse of dams, such as those formed by landslide dams (Figure 2) or debris jams. Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel, and the active floodplain, if present.

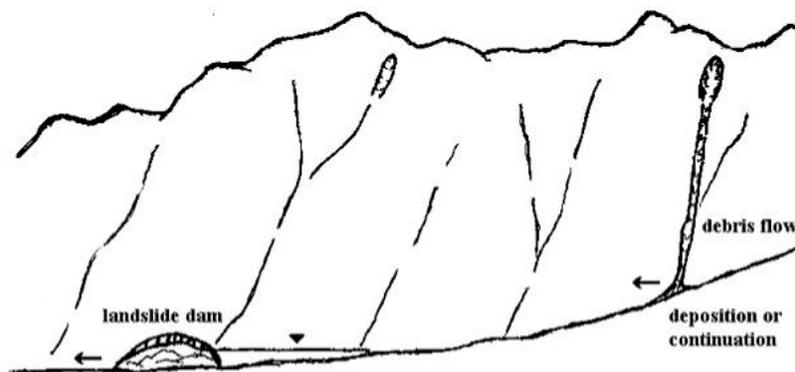


Figure 2 Debris flows, and hyper-concentrated floods

Debris flows and hyper-concentrated floods can occur in any unstable or potentially unstable terrain with susceptible valley geometry. In natural systems, debris flows and hyper-concentrated floods caused by dam-breaks are responsible for moving sediment and woody debris from hillslopes and small channels down into larger streams. But debris flows can also cause damage to streams by scouring channel reaches, disturbing riparian zones, impacting habitat and dumping debris onto salmonid spawning areas. Debris flows can cause elevated turbidity, adversely affect

water quality downstream, pose threats to public safety, and damage roads and structures in their paths (Figure 3).



Figure 3 Road-initiated debris flows in inner gorges, Sygitowicz Creek, Whatcom County (Photo: DNR, 1983).

The debris flows shown in Figure 3 coalesced and, after exiting the confined channel at the base of the mountain, formed a new debris flow spreading across a 1,000-foot wide swath for a distance of 2,000 feet before entering the South Fork Nooksack River. Between the base of the mountain and the river, the debris flow affected (if not severely damaged) a county road, farmyard, house sites, and more than 60 acres of cultivated farm fields.

2.3 Deep-Seated Landslides

Deep-seated landslides are those in which the slide plane or zone of movement is below the maximum rooting depth of forest trees (generally greater than 10 feet or 3 meters), may extend to hundreds of feet in depth, and may involve underlying bedrock. Deep-seated landslides can occur almost anywhere on a hillslope and are usually associated with hydrologic responses in permeable materials overlying less permeable materials. Deep-seated slides may respond to rainfall events over periods of days to weeks, or to weather patterns over months to years or even decades (Washington State Department of Emergency Management, 2013). The larger deep-seated landslides can usually be identified from LiDAR, topographic maps, and aerial photos, whereas the identification of smaller landslides often requires a field inspection and comprehensive inventory maps.

The bodies and toes of deep-seated landslides and earth flows are made up of incoherent collapsed materials that were weakened from previous movement of the materials and therefore may be subject to debris flow initiation. Sediment delivery is common from shallow landslides on steep stream-adjacent toes of deep-seated landslides and from steep side slopes of marginal streams flowing on the bodies of deep-seated landslides. More detailed descriptions of deep-seated landslides are provided in Part 5 (5.3 and 5.5.1).

2.4 Geographic Distribution of Landslides in Washington

Landsliding is a widespread geomorphic process which actively modifies the varied topography and diverse underlying geologic materials present throughout the state. This overview focuses on areas within the state where forest practices activities are prevalent and draws from Thorsen's (1989) organization and discussion by physiographic provinces.

The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by the continental, and to a lesser extent alpine glaciations. Unconsolidated sediments formed by glaciation include thick layers of fine-grained glacial lake sediments (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits. Translational and complex landslides occur within some of the very weak bedrock units exposed within the foothills and lowlands, such as the Chuckanut Formation, Darrington Phyllite, and Puget Group rocks.

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower reaches of the Quinault, Queets, Hoh, and Bogachiel valleys. Large rock slides and rock avalanches are common in the steep upper reaches of Olympic mountain drainages. Translational landslides and large landslide complexes are also abundant in the very weak marine sedimentary rocks (often occurring along inclined bedding surfaces) and mantling residual soils in the western and northwestern portions of the Peninsula, such as the Twin Creek Formation, and the Western Olympic and Hoh Lithic Assemblages (Tabor and Cady, 1978; Badger, 1993). Debris flows and avalanches are often generated in steeper drainages and slopes.

The Willapa Hills of Southwest Washington are comprised primarily of very weak marine sedimentary and volcanic rocks. Because the region has not been glaciated, thick and especially weak residual soils have developed on these rocks. Translational landslides and coalescing landslides forming earthflows are widespread in these weak rocks and overlying soils, such as in the Lincoln Creek Formation (Gerstel and Badger, 2002). Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches (Thorsen, 1989). These deposits are prevalent along the lower Columbia River valley, as well as other areas where colluvial deposits have accumulated on slopes and in drainages underlain by strong and relatively unweathered rock.

The Cascade Range is generally divided on the basis of rock types into northern and southern provinces occurring geographically in the vicinity of Snoqualmie Pass. Strong crystalline rocks intensely scoured by alpine glaciations occur to the north. Weaker volcanic flows, typically pyroclastic and volcanoclastic rocks occur to the south, much of which was beyond the reach of the last continental glaciation. Rockfalls and complex rock slides are dominant in the steep bedrock slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control

large translational failures in the Chumstick and Roslyn Formations (Tabor et al., 1987), the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone (Wegmann, 2003). Shallow landslides generating debris avalanches and flows are common on steep slopes and drainages.

Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides. Rockfalls and rock slides are common from the many steep bedrock exposures in the region. The Blue Mountains in southeastern Washington also have experienced recurring and widespread shallow landsliding and debris flows related to storm events (Harp et al., 1997).

PART 3. MEASUREMENT OF SLOPE ANGLES

The forest practices rules contain specific slopes gradients (degrees and percent) for defining landform descriptions. Part 3 is provided for guidance in determining slope gradients when evaluating the feature on site. Slope gradients are commonly expressed in two different but related ways, as degrees of arc or percent rise to run. It is important to understand the relationships between them.

3.1 Degrees

A circle is divided into 360 degrees of arc. Each degree is further divided into 60 minutes (60'), and each minute into 60 seconds (60"). The quadrant of the circle between a horizontal line and a vertical line comprises 90 degrees of arc (Figure 4a).

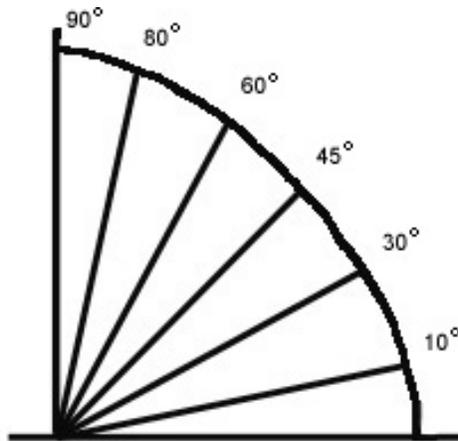


Figure 4a Angles in degrees.

$$a \% = 100 \times \text{rise} / \text{run}$$

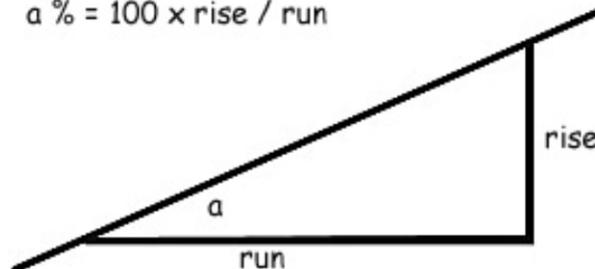


Figure 4b Angles in percent.

3.2 Percent

In Figure 4b, the horizontal distance between two points (distance between the points on a map) is called the run. The vertical distance (difference in elevation) is called the rise. The gradient can be expressed as the ratio of rise divided by run, a fraction that is the tangent of angle α . When multiplied by 100, this fraction is the percent slope.

3.3 Relationship of Degrees to Percent

Because of the differences in the ways they are calculated, each of these two slope measurements is better for certain applications. Because it is more precise at gentle slopes, percent is best for measuring and expressing small angles, such as the gradients of larger streams. But for steeper slopes, the constant angular difference and smaller numbers (an 85 degree slope is 1143%) make degrees more useful.

Figure 5 shows approximate equivalences for gradients expressed in degrees and percent. Note that there is a rough 2:1 ratio in the 30 to 40 degree range (e.g., 35 degrees = 70% slope), but beware - this relationship changes dramatically at gentler and steeper angles.

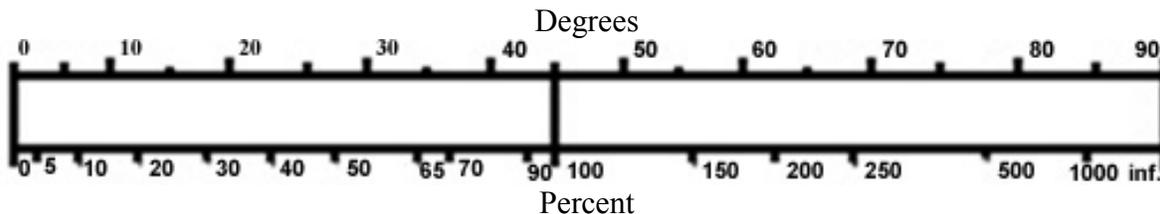


Figure 5 Slope gradients in degrees and percent.

PART 4. SLOPE FORM

Slope shape is an important concept when considering the mechanisms behind shallow landsliding. Understanding and recognizing the differences in slope form is essential to recognizing potentially unstable landforms. There are three major slope forms to be observed when looking across the slope (contour direction): divergent (ridgetop); planar (straight); and convergent (spoon-shaped) (Figure 6a). Landslides can occur on any of these slope forms but divergent slopes tend to be more stable than convergent slopes because water and debris spread out on divergent slopes whereas water and debris concentrate on convergent slopes. Convergent slopes tend to lead into the stream network, encouraging delivery of landslide debris to the stream system. Planar slopes are generally less stable than divergent slopes but more stable than convergent slopes. In the vertical direction, ridgetops are convex areas (bulging outward) and tend to be more stable than planar (straight) mid-slopes and concave areas (sloping inward) (Figure 6b).

Additionally, slope steepness can play a significant role in shallow landsliding. Steeper slopes tend to be less stable. The soil mantle, depending upon its make-up, has a natural angle at which it is relatively stable (natural angle of repose). When hillslopes evolve to be steeper than the natural angle of repose of the soil mantle, the hillslope is less stable and more prone to shallow landslides, especially with the addition of water. The combination of steep slopes and convergent topography has the highest potential for shallow landsliding.

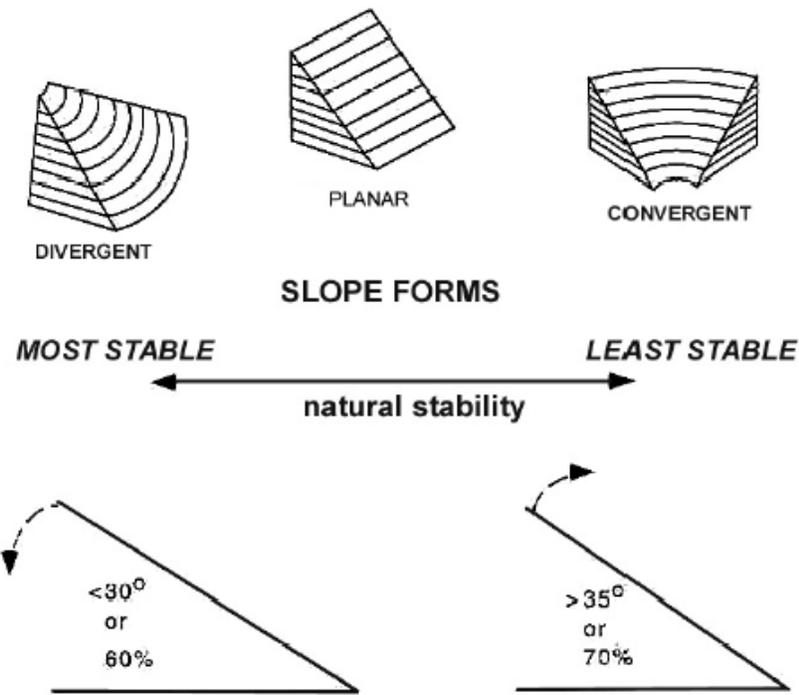


Figure 6a Slope configurations as observed in map view.

Figure 6a shows three major slope forms (divergent, planar, and convergent) and their relative stability. These slope form terms are used in reference to contour (across) directions on a slope. Convergent areas with slope greater than 35 degrees (70%) are the most shallow landslide-prone (Benda et al, 1997/1998).

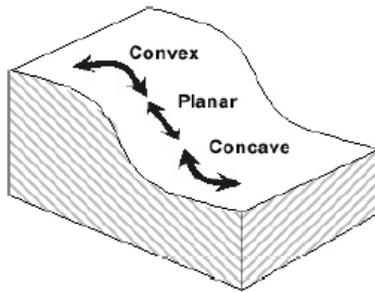


Figure 6b Slope configurations as observed in profile: convex, planar, and concave. These terms are used in reference to up and down directions on a slope (Drawing: Jack Powell, DNR, 2004).

PART 5. CHARACTERISTICS OF UNSTABLE AND POTENTIALLY UNSTABLE SLOPES AND LANDFORMS

This part describes the characteristics of the unstable slopes and landforms listed in WAC 222-16-050(1)(d)(i), commonly referred to as “rule-identified landforms”:

- Inner gorges, convergent headwalls or bedrock hollows with slopes steeper than 35 degrees (>70 percent) (see 5.1);

- Toes of deep-seated landslides with slopes steeper than 33 degrees (>65 percent) (see 5.3);
- Groundwater recharge areas for glacial deep-seated landslides (see 5.2);
- Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (see 5.4); or
- Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes (see 5.5).

Unstable landforms can initially be identified with a combination of topographic and geologic maps, aerial photographs, LiDAR data and a variety of private- and public agency-derived landform screening maps and tools. Field observation is then needed to verify their presence and precisely delineate landform boundaries, gradients, and other characteristics. In addition to the information provided in this part, more information for identifying unstable landforms is offered in Part 6, and tools and resources are listed in appendices A through G.

In most instances, the landform terms described here are also used in the scientific literature. For the purposes of Washington forest practices, the rule-identified landform terms, definitions, and descriptions supersede those used in the scientific literature. Note that all sizes, widths, lengths, and depths are approximate for the following discussion and are not part of the rule-identified landform definitions unless parameters are specifically provided.

5.1 Bedrock Hollows, Convergent Headwalls, Inner Gorges

These three landforms are commonly associated with each other as shown in Figures 7 and 8.

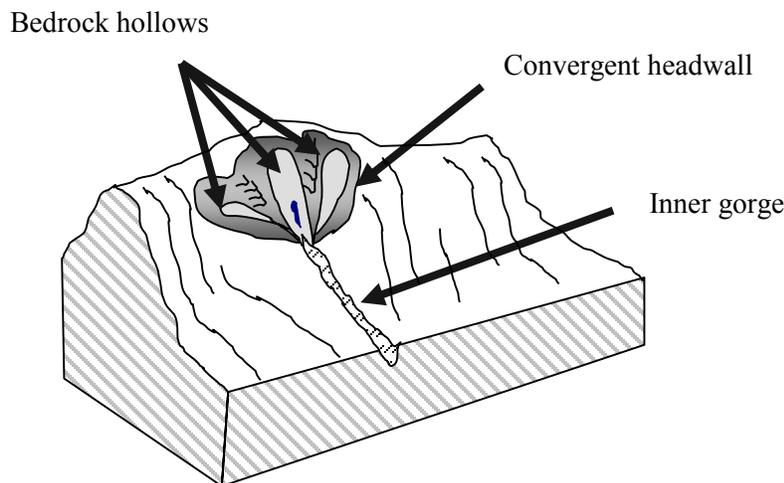


Figure 7 Typical hillslope relationships between bedrock hollows, convergent headwalls, and inner gorges (Drawing: Jack Powell, DNR, 2003).

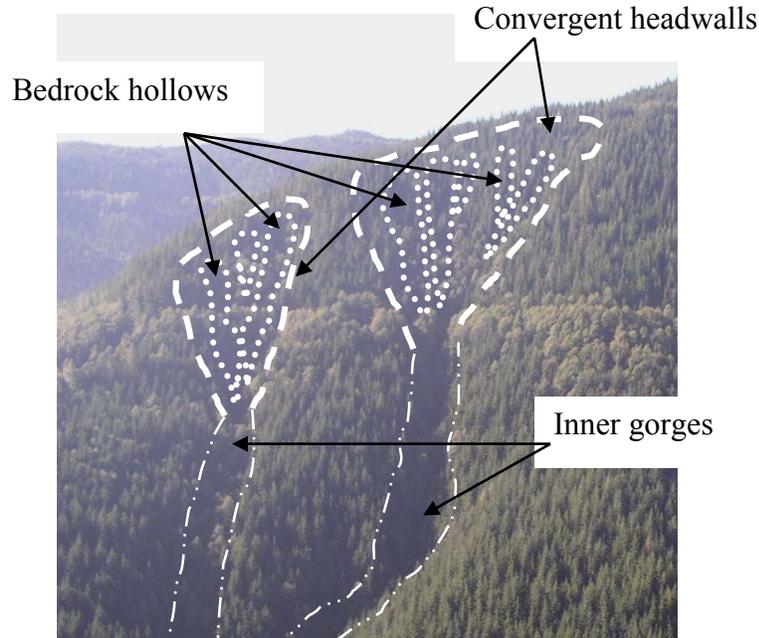


Figure 8 Common hillslope relationship: bedrock hollows in convergent headwalls draining to inner gorges (Photo and drawing: Jack Powell, DNR, 2003).

Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows (Crozier et al., 1990; Dietrich et al., 1986). Not all hollows contain bedrock so the term “bedrock” hollow can be a misnomer. However, the forest practices rules cite these features as “bedrock” hollows so this is the term used in this document. Hollows are commonly spoon-shaped areas of convergent topography with concave profiles on hillslopes. They tend to be oriented linearly up- and down-slope. Their upper ends can extend to the ridge or begin as much as several hundred feet below the ridge line. Most hollows are approximately 75 to 200 feet wide at their apex (but they can also be as narrow as several feet across at the top), and narrow to 30 to 60 feet downhill. Hollows should not be confused with other hillslope depressions such as small valleys, sag areas (closed depressions) on the bodies of large deep-seated landslides, tree windthrow holes (pit and mound topography), or low-gradient swales.

Hollows often form on other landforms such as head scarps and toes of deep-seated landslides. Bedrock hollows can occur singly or in clusters that define a convergent headwall. They commonly drain into inner gorges (Figure 9).

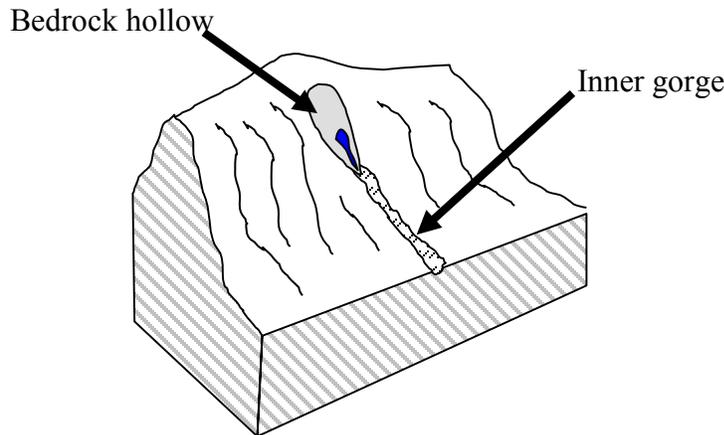


Figure 9 Bedrock hollow and relationship to inner gorges (Drawing: Jack Powell, DNR, 2003).

Hollows usually terminate where distinct channels begin. This is at the point of channel initiation where water emerges from a slope and has carved an actual incision. Steep bedrock hollows typically undergo episodic evacuation of debris by shallow-rapid mass movement (a debris flow), followed by slow refilling with colluvium that takes years or decades. Unless they have recently experienced evacuation by a landslide, hollows are partially or completely filled with colluvial soils that are typically deeper than those on the adjacent spurs and planar slopes. Recently evacuated hollows may have water flowing along their axes, whereas partially evacuated hollows will have springs until they fill with sufficient colluvium to allow water to flow subsurface.

Figure 10 illustrates the evolution of a bedrock hollow. Drawing “a” shows that over a period of tens to hundreds or thousands of years in some places, sediment accumulates in a hollow. When the soil approaches a depth of 3 to 5 feet (1-2 meters), the likelihood of landslides increases. Recurrent landsliding within the hollow slowly erodes bedrock and maintains the form of the hollow (Drawing “b”). After a landslide, bedrock may be exposed (and also seeps or springs) and the risk of additional sliding is often reduced, but not gone. Drawing “c” shows soil from the surrounding hillsides (colluvium) slowly re-filling the hollow. As vegetation and trees establish the site after past failures, the roots help stabilize the soil.

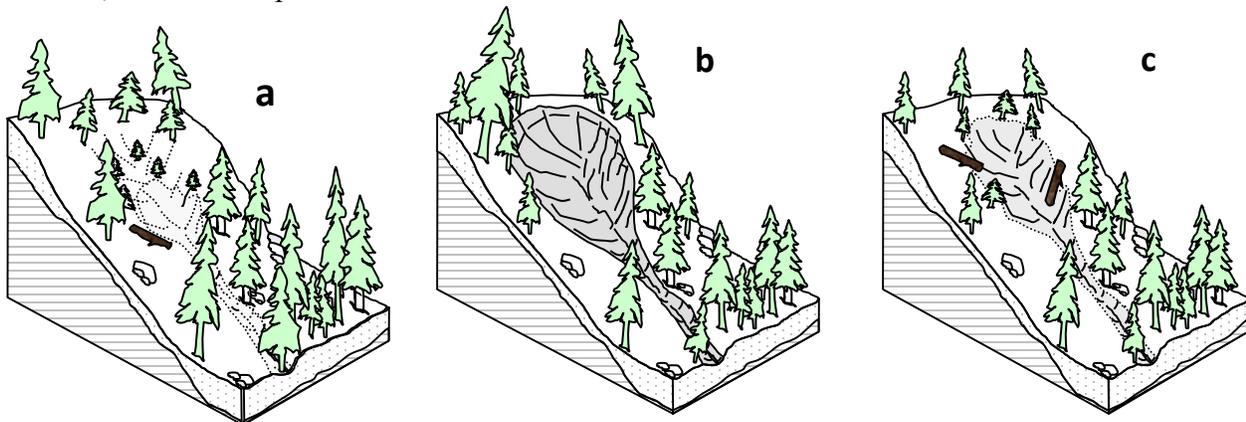


Figure 10 Evolution of a bedrock hollow following a landslide (adapted from Dietrich et al., 1988; (Drawing by Jack Powell, DNR, 2004).

The common angle of repose for dry, cohesion-less materials is about 72% (36 degrees), and saturated soils can become unstable at lower gradients. Thus, slopes steeper than about 70% (35 degrees) are considered susceptible to shallow debris slides. “Bedrock” hollows are formed on slopes of varying steepness. Hollows with slopes steeper than 70% (approximately 35 degrees) are potentially unstable in well-consolidated materials, but hollows in poorly consolidated materials may be unstable at lower angles. *Note: For the purpose of this document, bedrock hollow slopes are measured on the steepest part of the slope, and generally not along the axis unless the hollow is full (Figure 11).*

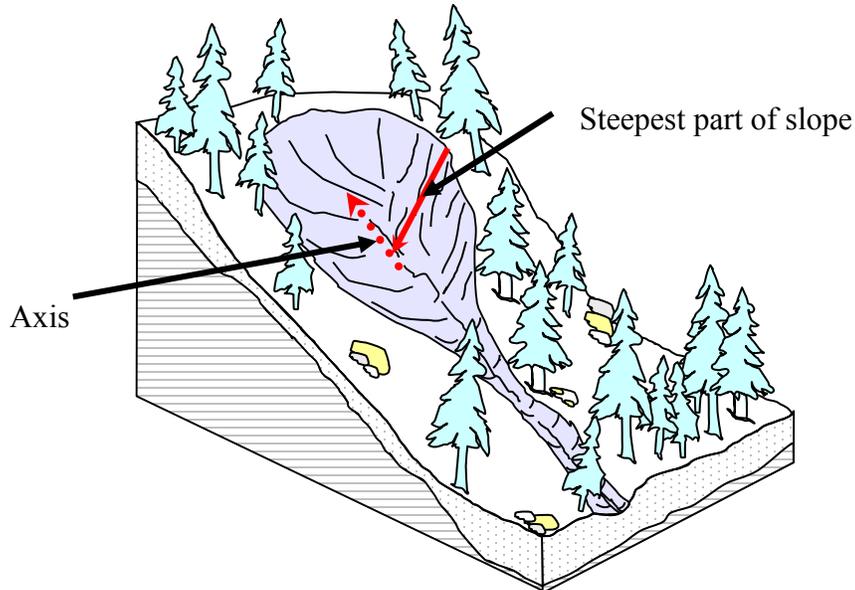


Figure 11 Bedrock hollow slopes are measured on the steepest part of the slope generally not along the axis (Drawing: Jack Powell, DNR, 2004).

Vegetation can provide the critical cohesion on marginally stable slopes and removes water from the soil through evapotranspiration. Leaving trees in steep, landslide-prone bedrock hollows helps maintain rooting strength and should reduce the likelihood of landsliding (Figure 12) (Montgomery et al., 2000). However, windthrow of the residual trees following harvest can be associated with debris slide or debris flow events. In high wind environments, it is essential to harvest in a manner that will limit the susceptibility of the residual trees to windthrow as well as to reduce the potential for landslides (for example leaving wider strips, pruning or topping trees in the strips, or feathering the edges of reserve strips).



Figure 12 Example of leave areas protecting unstable slopes (Photo: Venice Goetz, DNR, 2004).

Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. A series of converging bedrock hollows may form the upper part of a convergent headwall (Figure 13). Convergent headwalls are broadly concave both longitudinally and across the slope, but may contain sharp ridges that separate the bedrock hollows or headwater channels (Figure 14, and Figure 15).

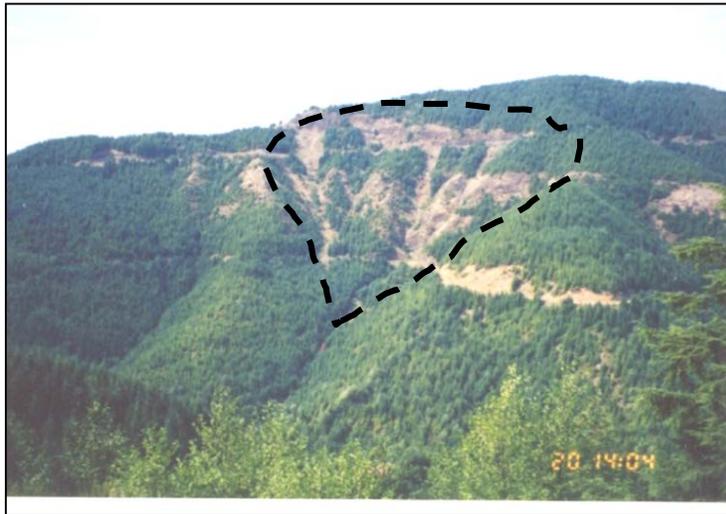


Figure 13 Convergent headwall example (Photo: Venice Goetz, DNR, 1995).

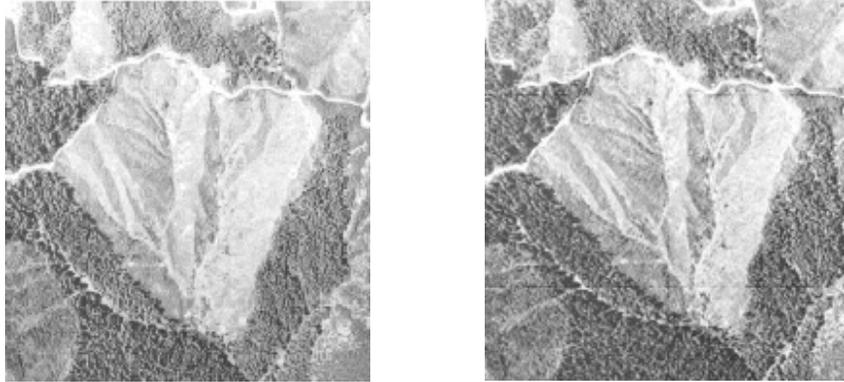


Figure 14a, b Stereo-pair of a clearcut convergent headwall in Pistol Creek basin, North Fork Calawah River, Washington.

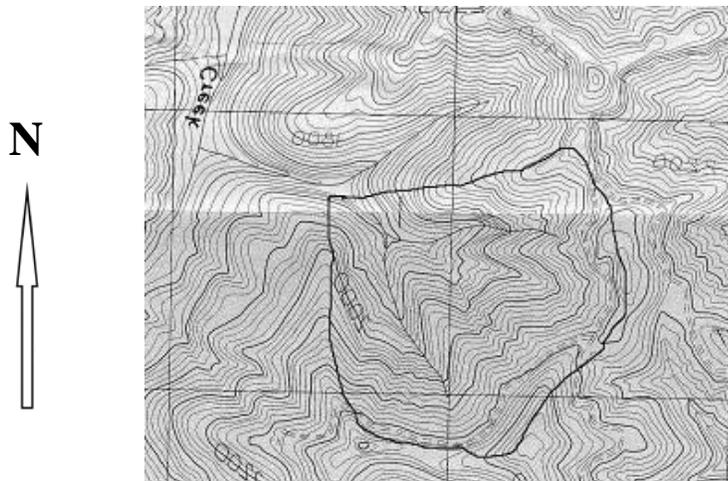


Figure 15 Topographic map and outline of convergent headwall displayed in the stereo-pair of Figure 14. Scanned from portions of Hunger Mountain and Snider Peak USGS 7.5' quadrangles.

Convergent headwalls generally range from about 30 to 300 acres. Slope gradients are typically steeper than 35 degrees (70%) and may exceed 45 degrees (94%). Unlike bedrock hollows, which exhibit a wide range of gradients, only very steep convergent landforms with an obvious history of landslides are called convergent headwalls. Soils are thin because landslides are frequent in these landforms. History of evacuation and landsliding can be evident by a lack of vegetation or mature trees on the site, or the presence of early seral plant communities such as grasses or red alder. It is the arrangement of bedrock hollows and first-order channels on the landscape that causes a convergent headwall to be a unique mass wasting feature. The highly convergent shape of the slopes, coupled with thin soils (due to frequent landslides), allows rapid onset of subsurface storm water flow. The mass wasting response of these landforms to storms, disturbances such as fire, and forest practices activities is much greater than is observed on other steep hillslopes in the same geologic settings. Convergent headwalls may be also prone to surface erosion from the scars of frequent landslides.

Channel gradients are extremely steep within convergent headwalls, and generally remain so for long distances downstream. Landslides that evolve into debris flows in convergent headwalls typically deliver debris to larger channels below. Channels that exit the bottoms of headwalls have

been formed by repeated debris flows and are efficient at conducting them. Convergent headwalls commonly have debris fans at the base of their slopes.

Inner gorges are canyons created by a combination of stream down-cutting and mass movement on slope walls (Kelsey, 1988). Inner gorges are characterized by steep, straight or concave side-slope walls that commonly have a distinctive break in slope (Figure 16). Debris flows, in part, shape inner gorges by scouring the stream, undercutting side slopes, and/or depositing material within or adjacent to the channel (Figure 17). Inner gorge side slopes may show evidence of recent landslides, such as obvious landslides, raw unvegetated slopes, young, even-aged disturbance vegetation, or areas that are convergent in contour and concave in profile. Because of steep slopes and proximity to water, landslide activity in inner gorges is highly likely to deliver sediment to streams or structures downhill. Exceptions can occur where benches of sufficient size to stop moving material exist along the gorge walls, but these are uncommon.

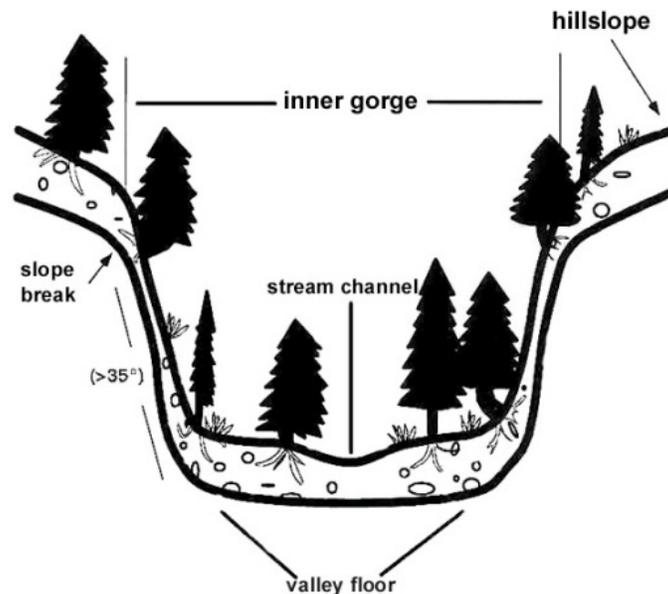


Figure 16 Cross-section of an inner gorge. This view emphasizes the abrupt steepening below the break-in-slope (Drawing: Benda et al., 1998).



Figure 17 Photograph showing how debris flows help shape features related to inner gorges.

For example, over-steepened canyon wall, U-shaped profile, buried wood, distinctive break-in-slope along margins of inner gorge (Photo: Laura Vaugeois, DNR, 2004).

The geometry of inner gorges varies. Steep inner gorge walls can be continuous for great lengths, as along a highly confined stream that is actively down cutting, but there may also be gentler slopes between steeper ones along valley walls. Inner gorges can be asymmetrical with one side being steeper than the other. Stream-eroded valley sides, which can be V-shaped with distinct slope breaks at the top, commonly do not show evidence of recent landsliding as do inner gorges which tend to be U-shaped. In practice, a minimum vertical height of 10 feet is usually applied to distinguish between inner gorges and slightly incised streams.

The upper boundary of an inner gorge is assumed to be a line along the first break in slope of at least 10 degrees (18%) or the line above which gradients are mostly gentler than 35 degrees (70%) and convex. The delineating break-in-slope occurs where over-steepened slopes related to inner gorge erosion processes intersect slopes formed from normal hillslope erosion processes. While the upper inner gorge boundary is typically distinct, in some places it can be subtle and challenging to discern. Inner gorge slopes tend to be especially unstable at the point where the slope breaks because the abrupt change in gradient causes subsurface water to collect within the soil matrix which can destabilize the soil mass and initiate movement. Just as for all other landforms, inner gorge slopes should be measured along the steepest portion of the slope (see Figure 11).

The steepness of inner gorges is dependent on the underlying materials. In competent bedrock, gradients of 35 degrees (70%) or steeper can be maintained, but soil mantles are sensitive to root strength loss at these angles. Slope gradients as gentle as about 28 degrees (53%) can be unstable in gorges cut into incompetent bedrock, weathered materials, or unconsolidated deposits.

Erosion along the gorge walls can intercept shallow groundwater forming seeps along the sides of the inner gorge, which promotes continued mass wasting. Root strength along walls and margins of inner gorges has been found to be a factor that limits the rates of mass wasting. Inner gorge areas can lose root strength when trees blow down. However, downed timber has a buttressing effect providing some slope reinforcement. Effective rooting width of forest trees is approximately the

same as the crown width. In some instances where the inner gorge feature is highly unstable it is necessary to maintain trees beyond the slope break. The rooting strength of trees adjacent to the landform can often provide additional support.

5.2 Groundwater Recharge Areas, and the Effects of Groundwater on Landslide Stability of (Glacial) Deep-Seated Landslides

In order to identify and delineate groundwater recharge areas in glacial terrain it is necessary to first identify and delineate glacial deep-seated landslides. Glacial deep-seated landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however, their failure mechanics are similar to deep-seated landslides developed in other materials (Terzhagi, 1951). Deep-seated landslides developed in other materials are also susceptible to forest practices activities in the groundwater recharge area. Consequently, scientific knowledge regarding the dynamics of deep-seated failures can be applied to better understand and manage glacial deep-seated landslides.

Glacial deep-seated landslides occur in glacial terrain and are defined as a landslide feature where most of the slide plane or zone lies within glacial deposits. The depth of the glacial deposits extends below the maximum rooting depth of trees, to depths ranging from tens to hundreds of feet beneath the ground surface. Glacial deep-seated landslide deposits occur in continental or alpine glacial deposits, or a combination of both. The continental glacial deposits in Washington are located in the northern areas of the state (Figure 18a), whereas the alpine glacial deposits (Figure 18b) can be found in mid-to-high elevation mountain ranges (Booth et al., 2003; Booth et al., 1994; Thorsen, R.M., 1980; Barnosky, 1984; Heusser, 1973; Crandall, 1965).



Figure 18a Extent of continental ice sheet in the Pacific Northwest (DNR, 2014).

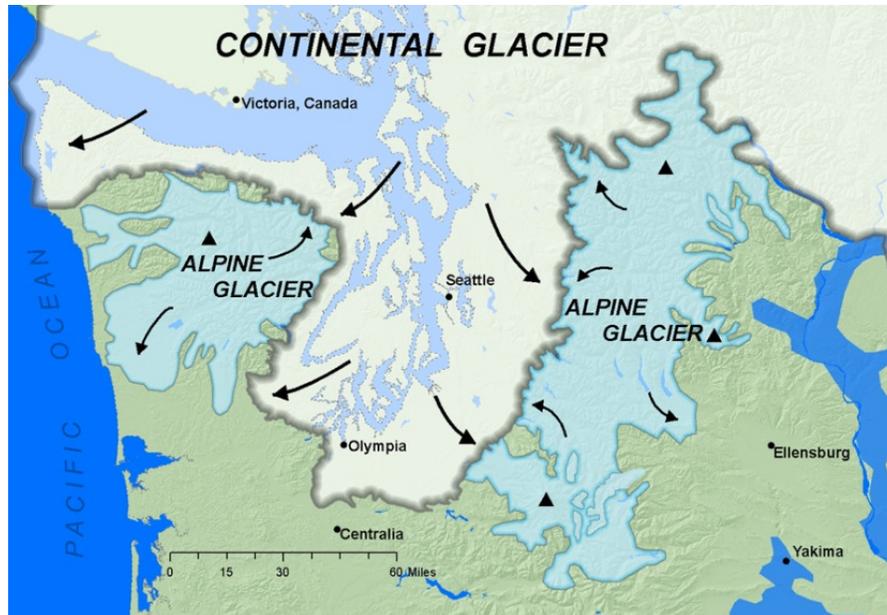


Figure 18b Continental and alpine glaciation in western Washington (DNR, 2014)

Deep-seated landslides in glacial terrain can involve rotational and translational movement, flows or a combination of movement types. Glacial deep-seated landslides can occur in any type of glacial deposit including till, outwash, glaciolacustrine and glaciomarine silt and clay, or a mix containing multiple glacial strata. During interglacial periods, layers of loess, (e.g., windblown silt and clay) and other non-glacial sediments can also be deposited between glacial layers or on the surface of glacial materials and become overlain by deposits from successive glaciations.

Glacial deposits and other earthen materials display a wide range of hydrologic characteristics, including: permeability, which is the rate water moves through a geologic material; and storage capacity, which is the amount of water released or taken into storage per unit area of geologic material for a given change in hydraulic head (See Appendix F for hydraulic properties of various soils):

- Glacial till is comprised of unsorted and non-stratified glacial materials that can range in size from clay to boulders that was generally over run by glacial ice during periods when the ice was advancing. Glacial till generally has low permeability and low water storage capacity;
- Glacial outwash typically contains sorted and stratified sediments deposited by water flowing from glacial ice either during the advance or retreat of the glacier and have higher permeability and higher water storage capacity than glacial till;
- Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes; and,
- Glaciomarine deposits which are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

Glaciomarine and glaciolacustrine deposits typically have low permeability and low storage capacity like glacial till.

Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 19). The hydrologic budget is the amount of ground water present and is calculated based on precipitation (rain and snow), interception of precipitation by vegetation, evapotranspiration, surface storage,

surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic budget that infiltrates into the subsurface below the root zone. The groundwater component is composed of water within the unsaturated, or vadose zone, and the saturated zone.

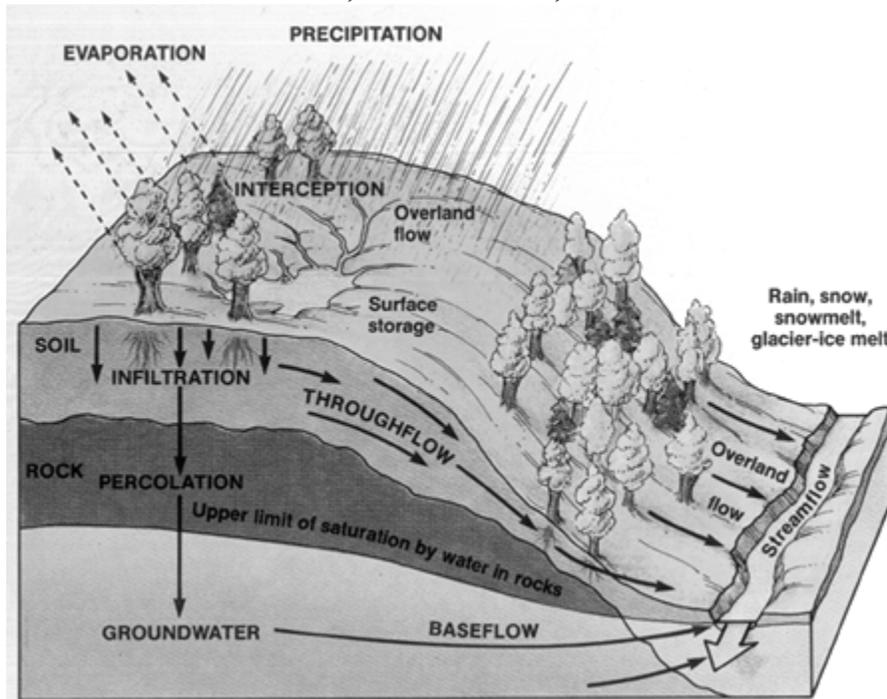


Figure 19 Hydrologic budget of a hillslope (University of Colorado).

Groundwater recharge to a glacial deep-seated landslide can present in several ways. Groundwater recharge may originate from adjacent non-glacial materials that flows into glacial sediments, or runoff from upland non-glacial materials and contribute groundwater recharge within glacial sediments. A contributing component of groundwater recharge can also be surface flow.

5.2.1 Groundwater Flow

Groundwater flows originating in upland areas are discharged as springs, streams, and other surface water features at lower elevations. The amount of the recharge area that contributes groundwater to a glacial deep-seated landslide constitutes that landslide's groundwater recharge area and includes the landslide itself.

Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area (Bauer and Mastin, 1997; Vaccaro et al., 1998). Groundwater perching and the characteristics of the overlying groundwater recharge area can be important factors in a deep-seated failure, especially for landslides in glacial sand and other unconsolidated deposits that overlie fine-grained glacial-lake clay deposits or till (Figure 20). This is a common configuration of the glacial deposits in much of the northern half of western Washington (e.g., landslides in Seattle (Gerstel et al., 1997) and in the Stillaguamish River valley (Benda et al., 1988)), but this type of landslide also occurs in alpine glacial deposits in southwest Washington, far from the maximum extent of continental glaciation. Groundwater flowing through permeable sand layers is perched above the less permeable clay or till. During and following precipitation events, the sand above the clay becomes saturated creating a buoyant effect and lowering cohesion in the sand, both of which weaken the contact between the clay and sand. This in turn may cause the

overlying mass to slide along the sand/clay contact. A common predictor of perched groundwater is the presence of a horizontal line of springs (groundwater discharge) or a line of vegetation at the contact point between the permeable and less permeable layers.

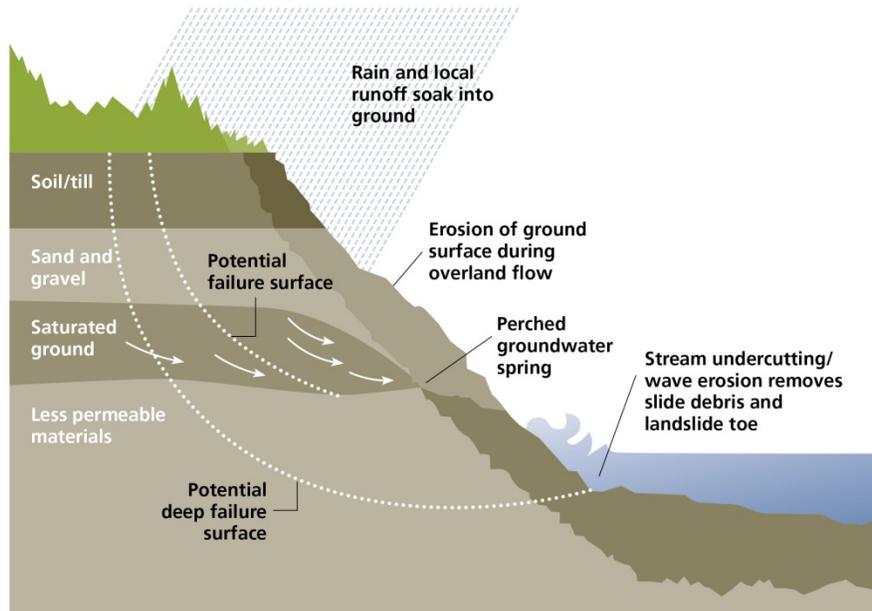


Figure 20 Diagram illustrating failure surface resulting from groundwater recharge to a glacial deep-seated landslide (DNR, 2014).

A classic example of a geologic setting where glacial deep-seated landslides are common is in the Puget Sound lowlands where the Esperance Sand or Vashon advance outwash, overlies the Lawton Clay. In this setting, groundwater recharge from precipitation infiltrates downward within the hillslope until it encounters the relatively impermeable Lawton Clay. Because the water cannot infiltrate into the Lawton Clay at the same rate at which it is supplied from above, the water table rises vertically above the clay surface. The elevated water table increases the pressure within the Esperance Sand and forms a hydraulic gradient which causes water to flow horizontally along the sand-clay contact, resulting in springs where this contact is exposed at the surface (Tubbs, 1974).

5.2.2 Effects of Groundwater on Slope Stability

Saturation of the pore spaces within sediments reduces grain to grain contact which reduces the effective strength of materials. This phenomenon of soil saturation reduces the effective strength of the soil which in turn reduces the stability of a slope comprised of saturated sediments. Because of the likelihood of subsurface water flow along and within perching layers in glacial strata, certain forest practice activities proposed within recharge areas for glacial deep-seated landslides may be classified “Class IV-special” per WAC 222-16-050(1)(d) and require further investigation and documentation prepared by a qualified expert. Therefore, it is important to characterize groundwater recharge areas and stratigraphy in terms of the potential for changes in the water balance due to forest practices activities and the degree to which a potential hydrologic change can be effectively delivered to a glacial deep-seated landslide. The first order approximation of the recharge area is the surface basin (topographically defined) directly above and including the landslide. The spatial extent of a groundwater recharge area can also be interpreted from field observation of soil profiles,

geologic structure, stratigraphy, well logs or boreholes, and geologic maps. Additional information regarding delineating and assessing the groundwater recharge areas is included in Part 6.3 and Part 7.2.

5.3 Toes of Deep-Seated Landslides

Toes of deep-seated landslides are a rule-identified forest practices regulatory landform. In this context, “deep-seated landslide toes” means the down slope toe edges, not the entire toe area of displacement material (see Figure 23). Landslides that have toe edges adjacent to streams have a high potential for delivery of sediment and wood to streams through natural processes. In such situations, streams can undercut the landslide toes and promote movement. Over-steepened toes of deep-seated landslides can also be sensitive to changes caused by harvest and road construction. The road shown in Figure 21 may have removed a portion of the toe, causing re-activation of the landslide. Resulting instability can take the form of shallow landslides, small-scale slumping, or reactivation of parts or the whole of a deep-seated landslide. Because deep-seated landslides are usually in weak materials (further weakened by previous movement), an angle of 33 degrees (65%) is the threshold value used on the potentially unstable toe edges and the determinate factor in regard to whether a proposed forest practices activity is on a rule-identified landform. Regardless of the surface expression of the toe, it is best to avoid disrupting the balance of the landslide mass by cutting into or removing material from the toe area.

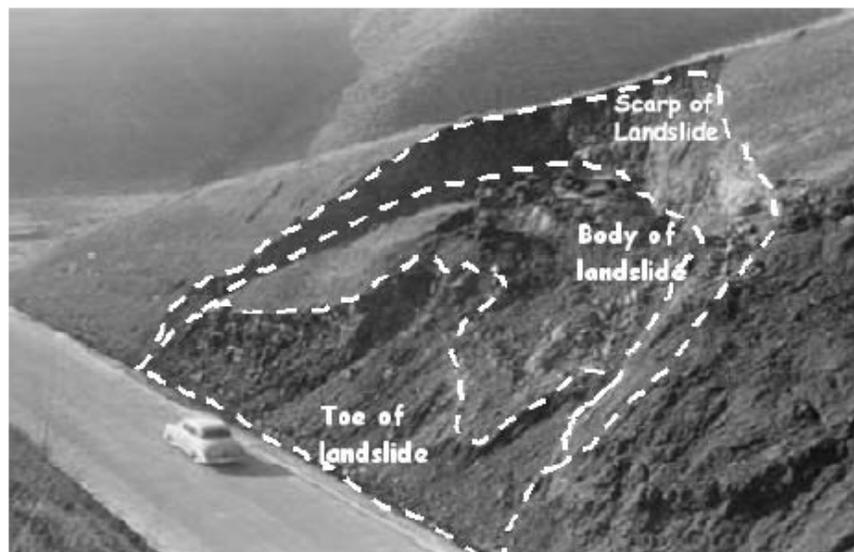


Figure 21 Deep-seated landslide showing the head scarp, side-scarps, body, and toe. Some of the toe has been removed in building and maintaining the highway (adapted from USGS photo).

5.4 Outer Edges of Meander Bends

Streams can create unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (Figure 22) (Schuster and Wieczorek, 2002). The outer edges of meander bends are susceptible to deep-seated and shallow landsliding, including debris avalanching and small-scale slumping. The outer edges of meander bends may be protected by the riparian management zone (RMZ) or channel migration zone (CMZ) rules if the slopes are not particularly high and are contained within the riparian leave areas or within the CMZ

(see Board Manual Section 2). As with other situations of overlapping forest practices rules, the harvest unit layout should reflect the extent of the greater of the protections.

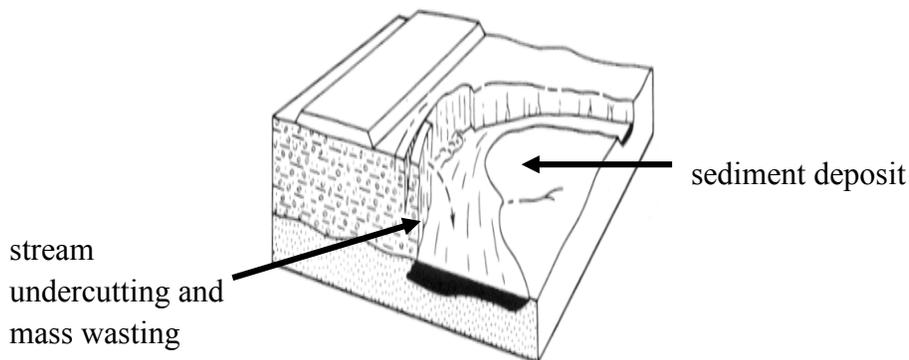


Figure 22 Outer edge of a meander bend showing mass wasting on the outside of the bend and deposition on the inside of the bend (adapted from Varnes, 1978).

5.5 Additional Features and Landforms Indicating Potential Slope Instability

Apart from the rule-identified landforms described above, there are other slope indicators that can point to instability. When the feature or landform indicates the presence of slope instability which cumulatively indicates the presence of unstable slopes, the area can be considered a rule-identified landform. A proposed forest practices activity in this situation may be classed as a “Class IV-Special” if there is potential to damage a public resource or threaten public safety.

Relatively large and recent topographic indicators can be observed on air photos, topographic maps and LiDAR images, but the identification of smaller and older indicators requires careful field observation. Topographic, hydrologic and vegetational indicators of slope instability or active movement may include:

Topographic indicators

- Bare or raw, exposed, unvegetated soil on the faces of steep slopes. This condition may mark the location of a debris flow or the headwall or side wall of a slide.
- Benched surfaces, especially below crescent-shaped headwalls, indicative of a rotational slide
- Hummocky topography at the base of steep slopes. This may mark the accumulation zone (runout area) for a flow or slide.
- Boulder piles
- Hummocky or benched surfaces, especially below crescent-shaped headwalls
- Fresh deposits of rock, soil, or other debris at the base of a slope
- Tension cracks in the surface (across or along slopes, or in roads). Tension cracks may mark the location of an incipient headwall scarp or a minor scarp within the body of an existing slide.
- Pressure ridges typically occur in the body or toe of the slide and may be associated with hummocky topography.
- Intact sections (blocks) having localized horst and graben topography
- Transverse ridges and radial cracks on landslide displacement material
- Stratigraphic indicators, including disconformities, offset contacts, and overturned sections

- Back tilted surfaces from rotation within the slide
- Multiple scarps in a downward direction
- Side scarps, shear margins or lateral scarps
- Displaced surface features like roads, railroads, foundations, and fence lines

Hydrologic indicators

- Ponding of water in irregular depressions in undrained swampy or poorly drained areas on the hillslope above the valley floor. These conditions are often associated with hummocky topography which can be signature of landslide activity.
- Seepage lines or spring and groundwater piping. These conditions often mark the contact between high permeability and low permeability soils.
- Sag ponds (ponded water in a tension crack or low depressions on a landslide body)
- Deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)
- Chaotic drainage patterns as a result of landslide activity.

(Vegetational indicators)

- Jack-strawed, back-rotated, or leaning trees and stumps. These are typically indicative of active or recently active landslides.
- Trees with curved based and vertical upper boles may indicate slope movement stabilizing over time.
- Bowed, kinked, or pistol-butted trees. These are typically indicative of soil creep, but may indicate incipient land sliding particularly if other indicators are present. Split trees and split old growth stumps. These may be associated with tension cracks.
- Water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes. These conditions may indicate the presence of groundwater seeps and associated hydrogeologic conditions.
- Other patterns of disturbed vegetation. Changes in stand composition (early seral stage or lack of mature trees within a hillslope) or small grouping of alder in a conifer-dominated forest may indicate recent or historic slope failure.

No single indicator necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

Additional information about landslide processes, techniques for hazard assessment, and management practices on unstable terrain is available in “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest” by the British Columbia Ministry of Forests (Chatwin et al., 1994); Hillslope Stability and Land Use (Sidle et al., 1985); and Landslides, Processes, Prediction and Land Use (Sidle and Ochiai, 2006).

5.5.1 Deep-Seated Landslides

Deep-seated landslides are those in which the slide plane or zone of movement is below the maximum rooting depth of forest trees (generally greater than 10 feet or 3 meters). Deep-seated landslides may extend to hundreds of feet in depth and may involve underlying bedrock. Deep-seated landslides can occur almost anywhere on a hillslope where geologic and hydrologic conditions are conducive to failure. They can be as large as several miles across or as small as a fraction of an acre.

Deep-seated landslides can be identified from topographic maps, aerial photographs, LiDAR images, and field observations. Many deep-seated landslides occur in the lower portions of hillslopes and extend directly into stream channels whereas those confined to upper slopes may not have the ability to deposit material directly into channels. Deep-seated landslides often are part of large landslide complexes that may be intermittently active for hundreds of years or more (Bovis, 1985; Keefer and Johnson, 1983).

One common triggering mechanism of deep-seated landslides results from the over-steepening of the toe by natural means such as glacial erosion or fluvial undercutting, fault uplift, or by activities such as excavating for land development (Schuster and Wieczorek, 2002). Initiation of such landslides has also been associated with changes in land use (Van Beek and van Asch, 2004), increases in groundwater levels (van Asch et al., 2005), and the degradation of material strength through natural processes. Movement can be complex, ranging from slow to rapid, and may include numerous small to large horizontal and vertical displacements variously triggered by one or more failure mechanisms (Roering et al., 2005).

Deep-seated landslides characteristically occur in weak materials such as thinly layered rocks, unconsolidated sediments, deeply weathered bedrock, or rocks with closely spaced fractures. Examples include: clay-rich rocks, such as the Lincoln Creek Formation of west-central Washington (Gerstel and Badger, 2002); thinly layered rocks, such as phyllite in northwest Washington (Kovanen and Slaymaker, 2008); and deeply weathered volcanic rocks present in the Willapa Hills of southwest Washington (Turner et al., 2010). Deep-seated landslides can also occur where a weak layer or prominent discontinuity is present in otherwise strong rocks, such as sedimentary interbeds within basalts or a fault plane or intersecting joint set (Sidle, 1985). In northwest Washington and on the Olympic Peninsula, deep-seated landslides commonly occur along silt or clay beds that are overlain by sandy units such as glacial deposits (Gerstel et al., 1997).

There are three main parts of a deep-seated landslide: the scarps (head and side); the body, which is the displaced slide material; and the toe, which also consists of displaced materials. The downslope edge of the toe can become over steepened from stream erosion or from the rotation of the slide mass. A deep-seated landslide may have one or more of these component parts because small deep-seated landslides can be found nested within larger slides. These three main parts are shown in Figure 23. The head and side scarps together form an arcuate or horseshoe shaped feature that represents the surface expression of the rupture plane. The body and toe area usually display hummocky topography, and the flow path of streams on these landslide sections may be displaced in odd ways due to differential movement of discrete landslide blocks. The parts of deep-seated landslides that are most susceptible to shallow landslides and potential sediment delivery are steep scarps (including marginal stream side slopes) and toe edges.

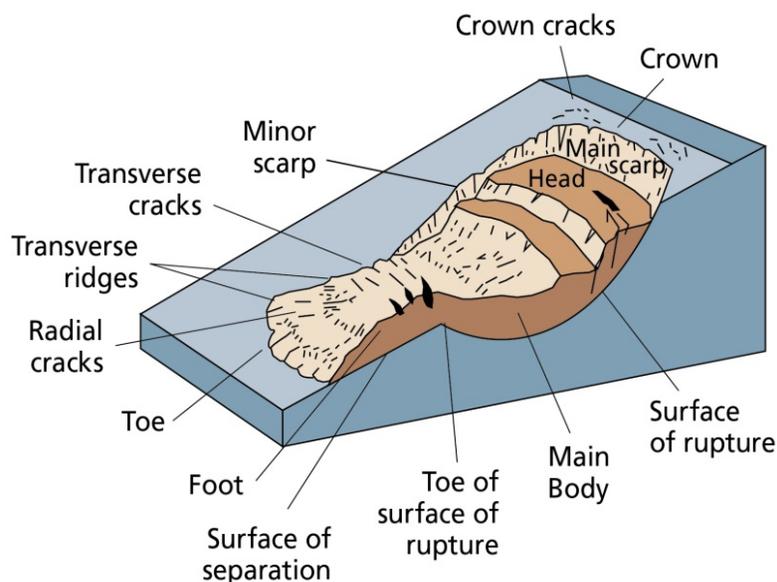


Figure 23. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide (adapted from USGS, 2004).

The sensitivity of any particular landslide to forest practices is highly variable. Deep-seated scarps and toes may be over-steepened and streams draining the displaced material may be subject to debris slide and debris flow initiation in response to harvest or road building. Movement in landslides is usually triggered by accumulations of water at the slide zone, so land use changes that alter the amount or timing of water delivered to a landslide can start or accelerate movement (Cronin, 1992). Generally, avoiding the following practices will prevent most problems: removing material during road construction or quarrying which could destabilize the toe; dumping spoils on the upper or mid-scarp areas which could overload the slopes, or compacting the soil in these places which could change subsurface hydrology; and directing additional water into the slide from road drainage or drainage capture. The loss of tree canopy interception of moisture and the reduction in evapotranspiration through timber removal on areas up-gradient of the slide may also initiate movement of the slide (van Asch, et al., 2009).

Part 6.3 provides methods for describing and delineating groundwater recharge areas for deep-seated landslides in glacial sediments.

PART 6. HOW TO IDENTIFY POTENTIALLY UNSTABLE LANDFORMS

When planning timber harvest and construction activities, general practitioners (landowners, foresters, engineers and other field staff) need to determine whether potentially unstable slopes and landforms exist on or around the site of their proposed activities.¹ If so, a qualified expert may be needed to perform additional analysis.

¹ In this context, potentially unstable slopes and landforms that exist “around” a proposed timber harvest or construction activity are those that could possibly be influenced by, or be caused to move due to, the harvest or construction activity.

The assessment typically includes the following components:

1. The general practitioner assesses the project sites for potentially unstable slopes and landforms through:
 - initial office screening (Part 6.1.1); and
 - field assessment and review (Part 6.2.1).
2. If desired by the landowner or required by rule, a qualified expert conducts a geotechnical assessment through:
 - office review (Part 6.1.2);
 - field review (Part 6.2.2);
 - landslide/landform activity assessment (Part 7.1);
 - water budget and slope stability modeling assessments (Part 7.2);
 - slope stability sensitivity assessment (Part 7.3);
 - deliverability assessment (Part 7.4);
 - summary of findings, results, and conclusions (Part 7.5); and
 - geotechnical reports (Part 8).

The elements and recommended sequence of the assessment are generally as follows (modified from Turner and Schuster, 1996):

1. Preliminary fact-finding to answer: What actions does the proposed forest practices activities include (e.g., partial cut, clear cut, road building, stream crossing)? In which landslide province (Part 2.4) are the proposed forest practices activities located and what are the hydrogeologic conditions and types of landforms expected to be present? Are any site-specific resources available for review, such as previously completed geotechnical reports or watershed analysis reports?
2. Office review of geologic maps, topographic maps, aerial photographs, LiDAR, and other information identified during the preliminary fact-finding phase.
3. Field review to observe the site, confirm office review findings and identify unstable and potentially unstable landforms that were not recognized during the office review. The field review may also involve hydrogeologic mapping.
4. Data analysis and assessment regarding the potential for landslide activity that could result from the proposed forest practices activity, and the potential for delivery of sediment to public resources or threats to public safety.

6.1 Office Review Process for the General Practitioner and the Qualified Expert

An office review refers to the initial screening of a selected site using available, remotely sensed information and previously prepared materials or documents (e.g., reports, studies, field data, and analyses). The term “remote sensing” generally refers to information that can be acquired for a particular site or physical feature without visiting the site or collecting data in the field.

A typical office review utilizes all accessible, site-specific and regional remote sensing data to help identify, delineate, and interpret potentially unstable slopes and landforms (e.g., aerial imagery, LiDAR (Light Detection and Ranging), GIS-based model predictions of earth surface attributes derived from digital, high-resolution topographic data). In addition, it is helpful to utilize existing documents and databases (e.g., maps, geotechnical reports and studies, published and unpublished scientific literature, landslide inventories, local and regional databases containing meteorologic, hydrologic, and geologic information) to screen sites for potential slope stability concerns, identify natural resource and public safety considerations, and make a determination regarding next steps in

the site assessment. Please see appendices A through F for data sources, and 6.1.3 and 6.1.4 for information regarding remote sensing tools and topographic data.

6.1.1 General Practitioner's Office Review

It is recommended that the initial office review and screening be conducted by a general practitioner to achieve:

1. identification of potential and existing areas of slope instability within or around the proposed activities;
2. delineation of unstable landforms using descriptions provided in Part 5;
3. location of areas of public resource sensitivity or public safety exposures in the vicinity of the planned operation that could be adversely affected by mass wasting processes; and
4. development of a plan for assessing the landforms in the field.

The information resulting from the general practitioner's office review will be useful for completing the FPA and providing information on the supplemental slope-stability form if it is required.

Summary of Procedures. The office review process generally includes compiling and evaluating available maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. This initial screening is supplemented with general practitioner's knowledge about site-specific conditions and with publicly available documents that might identify site-specific slope stability concerns or place the site in a broader landscape context with regard to potentially unstable landforms and processes (i.e., watershed analyses conducted under chapter 222-22 WAC; see Appendix D). Information sources are available to the user online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. Additional sources of imagery, data, maps, reports, and other documents are listed in appendices A through F.

Relevant maps typically include surface topography and its derivatives (e.g., slope class maps), hydrology (e.g., streams and water types), geology and soils (e.g., rock units, soil types), landslides (landslide inventories and hazard zonation), and information needed to identify public safety exposures (e.g., road networks, parcel boundaries with existing building structure information). Imagery includes aerial photography and LiDAR-derived hillshade images available on public websites and referenced in Appendix B. GIS with map display and analysis capabilities (e.g., ESRI ArcGIS) provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis; however, an initial screening can be performed manually without such tools if they are unavailable to the general practitioner (i.e., by inspecting each map or image separately). Various county websites also offer online interactive GIS information for maps and imagery products (see Appendix A). Follow-up field assessments are needed to verify results of the initial screening because not all features can be identified during the office review. It is helpful to create a site map for field use showing areas of potential slope stability concerns, natural resource sensitivities, and public safety exposures within or around the proposed operation.

Outcome. The initial office screening process aids the general practitioner in targeting portions of the proposed harvest and construction area that may need further assessment in the field. The office screening may not identify all potential unstable landforms, particularly if features are too small or subtle to be identified from available maps and imagery. For example, the general practitioner might not be able to identify the full extent of a groundwater recharge area from topographic maps, or to detect landslides under a mature forest canopy if using aerial photography exclusively. A field assessment is typically conducted while the general practitioner is performing reconnaissance and

marking (flagging) the boundaries of the proposed harvest and construction area; see Part 6.2 for guidance on conducting field reviews. The general practitioner might also elect to have a more thorough office review conducted by a qualified expert.

6.1.2 Qualified Expert's Office Review

An assessment by a qualified expert is needed when an assessment of potentially unstable slopes is beyond a general practitioner's expertise, or when activities are proposed on rule-identified landforms, including groundwater recharge areas. The qualified expert's objective is to develop a preliminary geotechnical assessment of landform characteristics and landslide potential prior to initiating field work, so that subsequent field investigations are capable of verifying initial interpretations. The geotechnical office review is generally more in-depth than a general practitioner-conducted initial screening and applies professional expertise in engineering geology, hydrogeology, geomorphology, and associated fields to detect and interpret landscape processes.

Depending on the site specific conditions and the proposed forest practices activities, the qualified expert typically:

1. screens the site with available data in order to identify physical indicators of past, existing, and potential landslide activities, noting their spatial and temporal distributions;
2. delineates on preliminary maps the identified features and associated potentially unstable landforms;
3. formulates initial hypotheses regarding landslide and landform behavior and failure mechanisms, to be evaluated further in the field; and
4. determines the type and level of field investigation needed to verify preliminary landslide interpretations, develop cause-effect relationships, and assess any potential for material delivery and potential adverse impacts to natural resources and threats to public safety.

Summary of Procedures. The geotechnical office review is performed as the initial office screening for compiling and evaluating available information. Most qualified experts have GIS capabilities, are experienced in using remote sensing and modeling tools, and can provide feedback on proposed forest practices activities in relation to their potential for affecting slope instability. The office review typically precedes a field review whose objectives usually include assessing the accuracy, limitations, and uncertainties of remotely sensed information and previously prepared materials assembled during the office review, as well as adjusting any preliminary interpretations of site characteristics or physical feature based on these data sources. The qualified expert determines the nature of the office review and the appropriate combination of assembled information based on the project objectives, requirements, and desired level of confidence in assessment products.

Outcome. The geotechnical office review typically leads to a field review, especially where unstable slopes and landforms are suspected or known and verification is required. Office review findings are included in the report written by the qualified expert. Interpretations based solely on remote sensing data should not be used as substitutes for site-specific field assessments carried out by qualified experts. From the office review, the expert might determine that no unstable slopes or landforms are present, or such features are present and the landowner agrees to exclude these areas from forest operations.

6.1.3 Remote Sensing Tools Available for Office Reviews

Common sources of remotely sensed information used in identifying, delineating, and interpreting landforms can be grouped broadly in the following categories: (1) aircraft- or satellite- based earth imagery and photogrammetry; and (2) LiDAR and high-resolution topographic data. Previously prepared materials or documents often incorporate field and remotely sensed data; these sources include maps and surveys, technical reports and other published/unpublished literature, and physical databases. Appendices A through E list the most common data sources in each category. Among the available remote sensing technologies, LiDAR has proven to be a valuable source of topographic data with distinct advantages over traditional analytical methods (e.g., aerial photo interpretation) for mapping landslides and interpreting landform characteristics (e.g., Haugerud et al., 2003; Burns and Madin, 2009; Roering et al., 2013; Tarolli, 2014). Consequently, LiDAR capabilities and applications are discussed in more detail below.

New remote sensing techniques for terrain characterization are being developed at a rapid pace, due in part to the expanding availability of publicly acquired, high-resolution topographic data (e.g., LiDAR). For example, major advances in deep-seated landslide characterization methods are combining high-resolution LiDAR data with other remotely sensed information and developing quantitative LiDAR analysis techniques to map and quantify landslide movement (Tarolli, 2014). Examples include using LiDAR-derived Digital Elevation Models (DEM) and Digital Terrain Models (DTM) with: (1) radar data and historical aerial photographs to quantify deep-seated landslide displacement and sediment transport (Roering et al., 2009; Handwerger et al., 2013; Scheingross et al., 2013); (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux (Mackey and Roering, 2011); and, (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows (e.g., Ardzzone et al., 2007; Booth et al., 2009; Burns and Madin, 2009; Tarolli et al., 2012; Van Den Eeckhaut et al., 2012); and, (4) subsurface investigations (Travelletti and Malet, 2012). Such innovative approaches likely will continue to emerge as more sophisticated high-resolution surface and subsurface technologies are developed. It is the task of qualified experts to seek out, evaluate, and apply new remote sensing methods as they become available.

6.1.4 LiDAR and High-Resolution Topographic Data

It is beneficial for general practitioners and qualified experts to obtain high-resolution topographic maps, most commonly hillshade and slope maps, derived from LiDAR.

The process to create high-resolution data begins with airborne LiDAR. LiDAR is a remote sensing technique that involves scanning the earth's surface with an aircraft-mounted laser in order to generate a three-dimensional topographic model (Carter et al., 2001). During a LiDAR acquisition flight, the aircraft's trajectory and orientation are recorded with Global Positioning System (GPS) measurements and the aircraft's inertial measurement unit, respectively. Throughout the flight, the laser sends thousands of pulses per second in a sweeping pattern beneath the aircraft. Energy from a single pulse is commonly reflected by multiple objects within the laser's footprint at ground level, such as the branches of a tree and the bare ground below, generating multiple returns. The first returns are commonly referred to as "highest hit" or "top surface" points and are used to measure the elevations of vegetation and buildings, while the last returns are commonly referred to as "bare earth" points and undergo additional processing to create a model of the earth's ground surface.

To generate a DEM, the aircraft trajectory and orientation measurements are combined with the laser orientation and travel time data to create a geo-referenced point cloud representing the location of each reflected pulse. These irregularly spaced points are commonly interpolated to a regularly spaced grid with horizontal spacing on the order of 1 meter to create a high resolution digital elevation model. Bare earth digital elevation models undergo additional filtering to identify ground returns from the last return point cloud data (for a review of filtering techniques, see Liu, 2008). These bare earth DEMs are most commonly used for interpreting and mapping deep-seated landslide features, especially in forested terrain where vegetation would normally obscure diagnostic ground features (Van Den Eeckhaut et al., 2007).

Hillshade and slope maps derived from bare earth LiDAR DEMs are the most common LiDAR products used to identify deep-seated landslides. A hillshade map is created by simulating sunlight shining on the topographic surface at a specified angle, while a slope map is the magnitude of the topographic gradient, estimated by differencing the elevations of adjacent points in the DEM. Hillshade maps tend to have less contrast on slopes facing the incident sun angle and more contrast on slopes facing away from the incident sun angle, either of which can obscure topographic features. It is therefore recommended to analyze several hillshade maps generated with different sun angles or employ methods such as those described in Burns and Madin (2009) for minimizing illumination and topographic shadowing effects (i.e., multi-directional oblique-weighted hillshade algorithm). Additional derivative maps such as topographic curvature, surface roughness, and elevation contours can also be useful to identify deep-seated landslide features. Contours should be generated with spacing similar to the LiDAR data resolution and/or the scale of the geomorphic features of interest.

Key topographic features revealing deep-seated landslides and other landforms that are visible in LiDAR-derived maps, but might not be visible in other remote sensing data, are similar to those observed in visual indicators. Hummocky topography, benched surfaces, tension cracks, scarps, block and graben features, pressure or transverse ridges, and irregular drainage patterns are often visible, but only when the scale of the feature is larger than the resolution of the LiDAR data. The difference in screening for and depicting potentially unstable features between high and low-resolution LiDAR data can be seen in Figures 24 (b) and (e and f). In Figure 24 (f), a hillshade map derived from 3-foot LiDAR data is shown which allows the user to approximately delineate the landslide's main scarp, body, and toe, whereas such features may not be recognized using lower resolution quality (i.e., 30-meter resolution).

LiDAR hillshades can be used to delineate and interpret deep-seated, and with lesser certainty shallow landslides, although some depositional surfaces (for example debris fans) can be identified. Various measures of surface roughness are commonly used to recognize and quantify deep-seated landslide morphology in landslide mapping studies (McKean and Roering, 2004; Glenn et al., 2006; Booth et al., 2009; Berti et al., 2013). Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005, 2007), and Haugerud (2014).

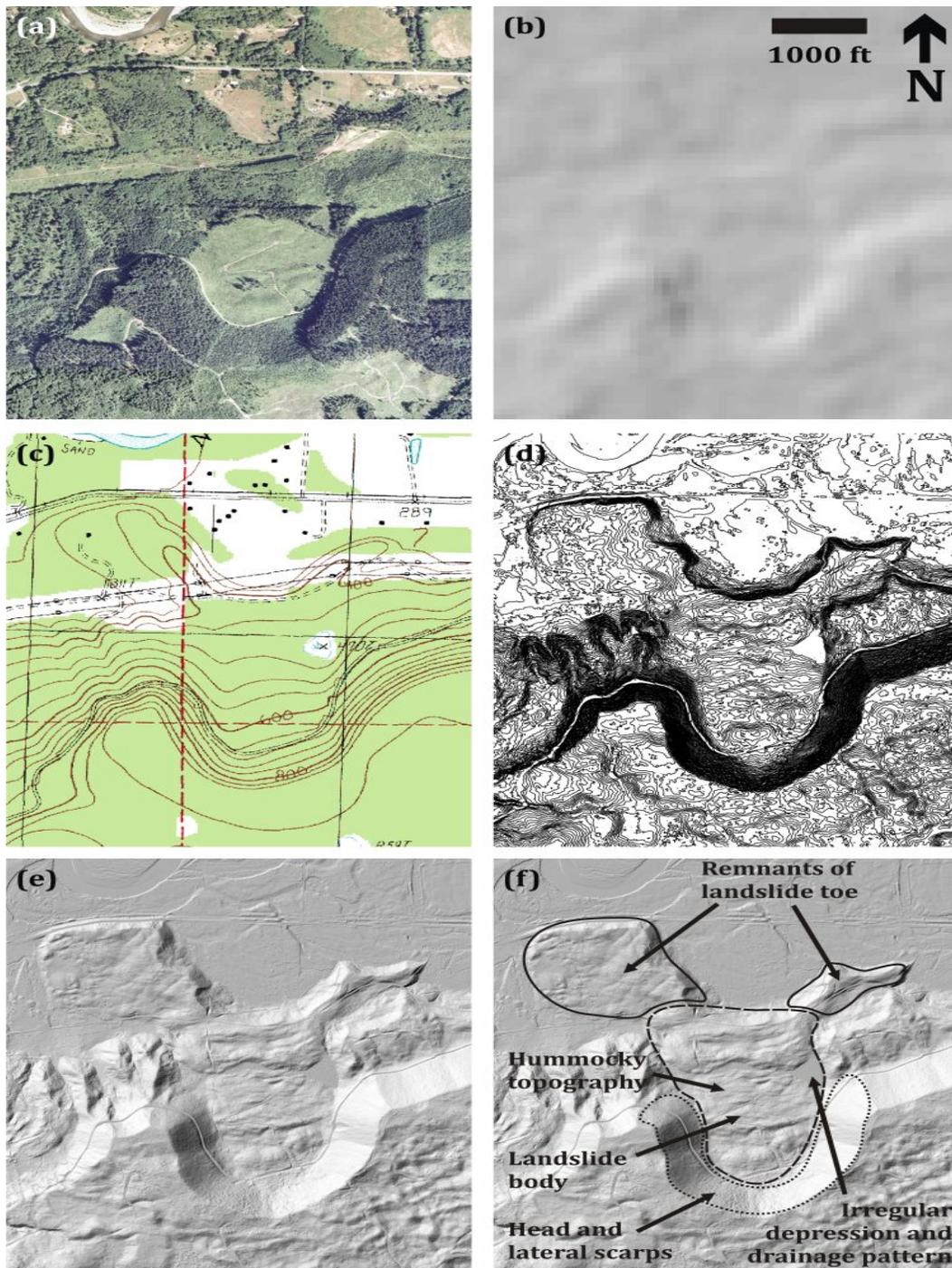


Figure 24 Example of a dormant glacial deep-seated landslide as seen in different types of remotely sensed data and in varying resolution quality:

(a) Digital Orthophoto Quadrangle, (b) hillshade map derived from 30-meter resolution ASTER Global Digital Elevation Model, (c) topographic map, (d) 6-foot contour map derived from 3-foot resolution airborne LiDAR, (e) hillshade map derived from 3-foot resolution airborne LiDAR, and (f) annotated version of (e) (Adam Booth, 2014, Portland State University).

Repeat LiDAR acquisitions of a site are becoming more common. This allows the qualified expert to review more than a single LiDAR data set to interpret deep-seated landslide morphology; instead they can measure topographic changes related to slope instability with pairs of LiDAR scenes (Corsini et al., 2007; DeLong et al., 2012; Daehne and Corsini, 2013). Vertical changes can be measured by differencing LiDAR-derived DEMs, while manual or automated tracking of features visible on hillshade or slope maps between scenes can be used to estimate horizontal displacements. Note that many active deep-seated landslides move at rates that may be undetectable given the uncertainties in the LiDAR data, so this technique is most helpful for relatively large topographic changes, typically on the order of several meters (Burns et al., 2010). Care should be taken to precisely align the repeat LiDAR DEMs.

6.2 Field Assessment Process for the General Practitioner and the Qualified Expert

The purpose of the field assessment is to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review. While the office review can provide important information and a starting point, on-site observation of geomorphic features on the ground surface is essential for identifying potentially unstable landforms.

The field assessment performed by the general practitioner determines the presence or absence of potentially unstable slopes and landforms. If such features are located and forest practices are proposed on these features, the landowner may retain a qualified expert to perform additional geotechnical reviews.

6.2.1 General Practitioner's Field Assessment

The objective of the field assessment conducted by a general practitioner is to determine the presence or absence of unstable slopes and landforms, using definitions of the landform types and guidance provided in this Board Manual section. In addition to assessing the potential unstable areas identified in the initial office screening, the general practitioner surveys the operations area for any landforms missed in the office review. The general practitioner typically carries out this assessment while laying out the proposed forest practices activities (e.g., marking unit boundaries, establishing riparian management zones, laying out road systems). See Qualified Expert's Field Assessment for Groundwater Recharge Areas (Part 6.3.2) for information on conducting field reviews on groundwater recharge systems and Additional Features and Landforms Indicating Potential Slope Instability (Part 5.5) for discussions on landform features that may indicate slope instability. When the field assessment indicates complex geological features are present or the scenario is beyond the general practitioner's expertise, the landowner may wish to have a qualified expert complete a further assessment.

Outcomes. Common results of the general practitioner-conducted field assessment generally include:

1. The finding, documented in the slope stability sections of the FPA, that the assessment did not identify any potentially unstable slopes or landforms within or around the planned area for the forest practices activities, and the office/field review process is assumed complete; or
2. The finding that potentially unstable slopes and landforms exist within or around the planned operations area and the landowner completes and attaches the appropriate slope stability sections to the FPA along with any additional required information DNR may have requested; or

3. The general practitioner identifies potentially unstable areas within or around to the operations area, and proposes to conduct timber harvest or construction activities on them. The landowner may retain a qualified expert (see Washington State Department of Department of Natural Resources (DNR) website for list of qualified experts) to conduct geotechnical office and field reviews, and prepare a geotechnical report, as required by WAC 222-10-030. The landowner submits the FPA and includes the geotechnical report or additional information completed by the qualified expert to inform the FPA.

6.2.2 Qualified Expert's Office and Field Assessments

When it is determined an analysis needs to be conducted by a qualified expert, the objectives of the geotechnical field review are to:

1. verify the presence or absence of unstable slopes and landforms identified in office reviews and/or identify those that were missed due to insufficient remote sensing data coverage or resolution;
2. refine preliminary maps constructed during office reviews;
3. confirm or refute initial hypotheses regarding landslide behavior, failure mechanisms, and level of activity;
4. solidify understanding of cause-effect relationships;
5. assess relative potentials for material delivery associated with the proposed forest practices to areas of resource sensitivity and threats to public safety;
6. evaluate levels of confidence in office and field findings; and
7. write a geotechnical report summarizing review findings, conclusions, and recommendations (see Part 8 for information required in a geotechnical report).

Summary of Procedures. The qualified expert determines the nature of the field review required to meet the objectives stated above. Depending on the analyst's level of confidence in potentially unstable landform identifications, delineations, and interpretations for any given site, the field assessment might range from qualitative to more quantitative in nature. An example of a qualitative assessment would be one in which the qualified expert collects visual observations and photos of geological features and other site indicators at identified locations (i.e., GPS waypoints) and summarizes those observations in a geotechnical report, as a means for substantiating landform and process interpretations. A more quantitative investigation might include such data collection techniques as topographic surveying for measuring landslide surfaces (i.e., needed for slope stability modeling), soil sampling to test material properties, and subsurface sampling that is especially important in analyzing the depths, materials, and hydrology of deep-seated landslides. Field work needed to complete the review can take one or more days, and the qualified expert might be asked to return to the field for an interdisciplinary team meetings if required by DNR.

It is recommended that the field assessment performed by a qualified expert include the preparation of a site-specific geologic map, because the scope of work associated with most published geologic maps is insufficient to identify small-scale unstable landforms that could have a significant effect on the proposed forest activity. The purpose of geologic mapping is to document surface conditions and provide a basis for the interpretation of subsurface conditions. Ideally the geologic map should be prepared on a scale of 1:10,000 or less using high-resolution LiDAR-generated topography. If high-resolution LiDAR is not available, base maps can consist of U.S. Geological Survey 7.5-Minute topographic maps, DNR forest practices activity maps, or aerial photographs.

A geologic map should ideally include the location, elevation, and altitude of all geologic contacts between permeable and non-permeable soils, although such data collection is not feasible or necessary in all situations. Particular emphasis should be placed on the contact between high permeability soils and underlying low permeability soils or bedrock and the location of groundwater seeps or springs, especially where deep-seated landslide activity is suspected or encountered. If an unstable or potentially unstable landform is present, the location of pertinent components and effects of the landform should be identified on the map.

Geologic field data collection, analysis, and map compilation are undergoing a revolution in methods, largely precipitated by GPS and GIS-equipped mobile computers (Whitmeyer et.al, 2010; U.S. Geological Survey, 2008; Edmondo, 2002). To be fully effective, geologic reports prepared for FPAs should include GPS locations of landforms and other relevant features within accuracy sufficient for others to identify the landforms in the field. It is also effective to include photographs of significant landforms, or their components should also be photographed if they can be fully captured with ground-based photography. It is important to note indicators of potential slope instability or active movement during the field review. These include topographic, hydrologic, and vegetation indicators as described in Part 5.5.

Outcomes. Common results of a qualified expert geotechnical field assessment include determinations that:

1. The potentially unstable landforms identified in the field assessment do not meet the definitions of the rule-identified landforms (Part 5). The qualified expert reports to the landowner that no potentially unstable landforms are present and the slope stability assessment is assumed complete; or
2. Potentially unstable landforms within or around the operations area have minimal potential for material delivery to areas of resource sensitivity and/or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings, as outlined in WAC 222-10-030(1), and slope stability assessment is complete; or
3. Unstable landforms within or around the operations area have the potential for material delivery to areas of natural resource sensitivity or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings to be included with the FPA. In most cases, this scenario would be fall under a Class IV-Special definition in WAC 222-16-050(1) and require the landowner to submit a SEPA checklist or Environmental Impact Statement.

6.3 Qualified Expert's Office Review and Field Assessment for Groundwater Recharge Areas

When a glacial deep-seated landslide is determined to exist on or around the proposed harvest or construction activities, the area adjacent to the glacial deep-seated landslide needs to be assessed by a qualified expert to determine if a ground water recharge area exists. The recharge, occurrence, and movement of groundwater through water-bearing units (aquifers) and confining units that inhibit groundwater movement can have an effect on slope stability. Hydrogeologic frameworks, which define the groundwater recharge environment and the subsurface environment in which groundwater occurs, have been developed from mapped geologic units, drillers logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000). Groundwater movement is important to understand at smaller local scales associated with the area related to landslides and forest practices in proximity.

The groundwater recharge area for glacial deep-seated landslides is a rule-identified landform. The technical methods used to identify groundwater recharge areas in glacial deep-seated landslides are no different than those for other (e.g., non-glacial) deep-seated landslides.

The recommended first step in delineating the groundwater recharge area is to evaluate its topographic relationship to the landslide. When uncertainties remain as to the accuracy of the area boundary, further investigations and analysis should be performed. This further analysis will provide necessary information DNR uses to review the proposed activity. If an in-depth investigation is performed, the information provided by the qualified expert in their geotechnical report is used by DNR to determine the FPA classification and other decisions based on the applicant's proposed activity. The following discussions and Part 7 will aid the qualified expert in determining next steps if further investigation are needed.

6.3.1 Qualified Expert's Office Review for Groundwater Recharge Areas

When a qualified expert performs an office review of information for evaluating the area contributing groundwater recharge to a landslide, it is recommended that the surrounding topography, land cover and vegetation, soils, and the distribution of hydrogeologic units are reviewed. Time scales of groundwater movement from areas of recharge to discharge may vary over several orders of magnitude, depending on the hydraulic characteristics of the hydrogeologic units, which include water bearing and non-water-bearing rocks and sediments (aquifers) and confining units, respectively.

In a simplified hydrogeologic setting in a humid environment, the groundwater table forms a subdued replica of surface topography with groundwater flow from high-altitude areas of recharge to low-altitude areas of discharge (Freeze and Cherry, 1979). The surficial contributing area may be delineated from DEMs derived from high-resolution LiDAR, if available, or alternately the lower resolution U.S. Geological Survey topographic quadrangles. This analysis provides a first-order approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.

The land cover of the recharge area also influences the spatial extent and magnitude of groundwater recharge. The type and distribution of vegetation affect the amount of precipitation that is intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may also influence groundwater recharge. Remotely-sensed land cover data is available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's National Land Cover Database. In addition, land cover data is available for Washington State through the DNR Forest Resource Inventory System.

Geologic maps provide a basis for delineating the areal extent, orientation, stratigraphic relations, and thickness of rocks and sediments that influence the occurrence and movement of groundwater. The U.S. Geological Survey, DNR, and others have published geologic maps at scales of at least 1:100,000 across Washington and locally at larger scales (1:24,000). Well logs and geotechnical borings may supplement geologic mapping by describing the vertical extent of rocks and sediments and providing information about grain size distributions, sorting, and other physical properties that may influence the hydraulic characteristics of hydrogeologic units. The Washington State Department of Ecology (Department of Ecology) maintains a searchable database of well logs for Washington State, however subsurface data will generally be confined to developed areas and information may be lacking in the forested environment. Hydrogeologic frameworks have been

developed from mapped geologic units, drillers logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000) to local scales for sites across Washington State. Hydrogeologic reports are available from sources such as the U.S. Geological Survey and the Department of Ecology.

6.3.2 Qualified Expert's Field Assessment for Groundwater Recharge Areas

A groundwater recharge area of a deep-seated landslide is the area up-gradient of a landslide that can contribute water to the landslide. In simple terms, the groundwater recharge area is the topographic area or hillslope area that is at a higher elevation and capable of delivering water into the landslide.

Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types; therefore, field inspection of the initial groundwater recharge area map will be necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation.

Typically once a landslide has been mapped, an initial designation of the topographic groundwater recharge area is a straightforward task that can be performed on a detailed topographic map of the area. Topography developed from high resolution DEM generated from LiDAR is preferred as the most accurate tool available for mapping surface topography. Figure 25a shows the approximate groundwater recharge area for a landslide based on upslope topographical delineation. Line A corresponds to a cross section showing approximate stratigraphy (Figure 25b) through the groundwater recharge area and landslide body.

After the initial designation by the qualified expert of the groundwater recharge area, a field assessment should be conducted in order to determine if the initial designation accurately reflects the recharge area topography up-gradient of the landslide. Depending on the available topographic data for the site in question, examination of the boundaries of the mapped groundwater recharge area will be necessary to ensure the hillslope morphology displayed by the DEM is accurate. It is helpful to obtain GPS waypoints collected in the field along the topographic boundaries of the groundwater recharge area.

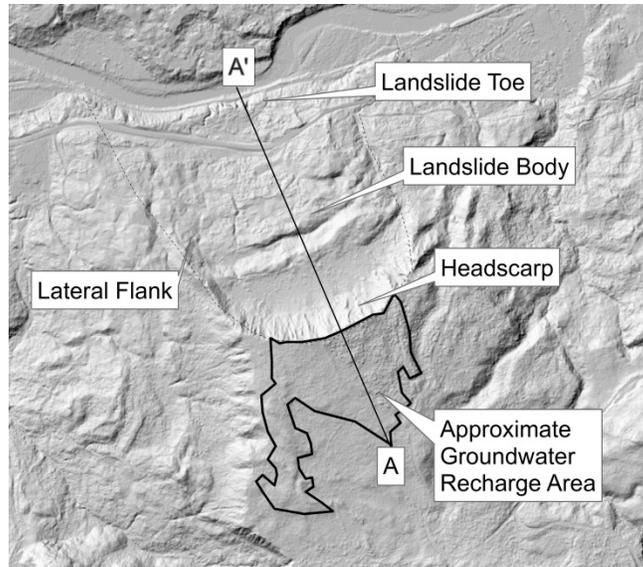


Figure 25a Glacial deep-seated landslide. The black-lined polygon is an approximate upslope contributing groundwater recharge. (DNR, 2014)

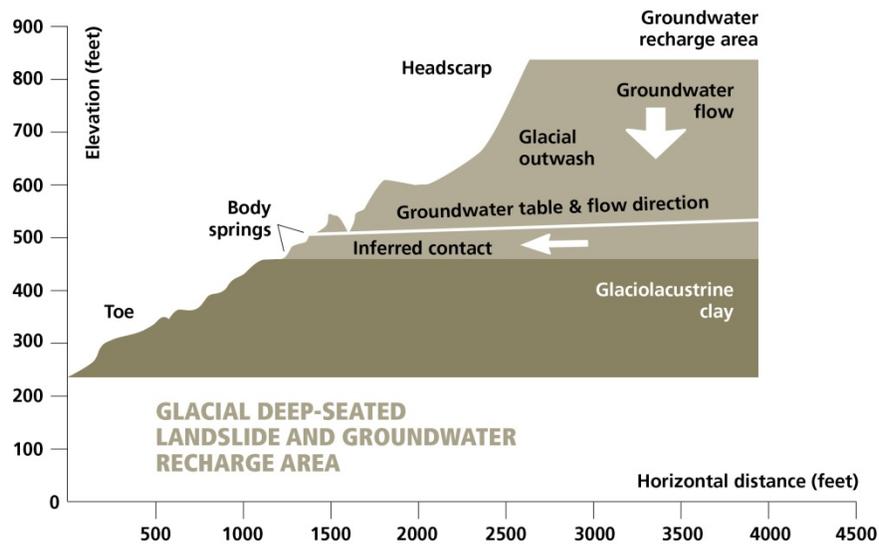


Figure 25b Hillslope cross-section derived from 2-meter DEM of a glacial deep-seated landslide showing groundwater recharge area, geologic units and generalized groundwater flow paths (DNR, 2014)

When the qualified expert has identified the groundwater recharge area, the area should be inspected and any surface water drainage features indicating surface water may be directed into the landslide area should be mapped. Stream drainages on or adjacent to the deep-seated landslide

should also be identified, mapped, and assessed for the potential to contribute water to the recharge area and landslide.

During field assessment it is important to examine the characteristics of the surface materials within the groundwater recharge area and document that the soil types and subsurface geologic units are consistent with those mapped for the location of interest. In some cases, published soil and geologic data in forested areas may be mapped on a scale far less detailed for specific areas.

Mapping the stratigraphic units that compose the hillslope (i.e., the distribution of geologic units or horizons with depth below the groundwater recharge area) should be done in order to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide. Subsurface investigations may be needed to adequately determine geologic units where mapping cannot be accurately accomplished by surface data alone.

Exposures of strata within the groundwater recharge area may be examined in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps at the top of the landslide. The distribution of geologic units with increasing depth below the surface may also be available from well drillers logs or other subsurface information such as geologic mapping and reports.

Excavation of test pits, driving soil probes and well-points, drilling monitoring wells or using other geophysical techniques such as seismic or electric resistivity methods should be considered in order to accurately characterize and reduce uncertainties of the subsurface conditions of the groundwater recharge area, and where topographic indicators are uncertain. See Part 6.4 for further discussion on quantitative field review methods.

Often landslide failure planes are co-incident with subsurface aquitards such as silt or clay beds that form elevated groundwater tables within hillslopes. Understanding the morphology and orientation of these aquitards can help inform the spatial extent of the groundwater recharge area beyond the surface topographic expression of the hillslope up-gradient of a landslide.

Human activities such as construction of road networks and installation of drain fields can direct surface and groundwater towards or away from deep-seated landslides and/or contribute relatively large volumes of water within a groundwater recharge area. The location of such infrastructure should be mapped and evaluated with respect to possible water volumes likely to be contributed to a landslide.

6.4 Quantitative Field Assessment Methods for Qualified Expert's Subsurface Investigations

If an unstable or potentially unstable landform with a potential to deliver sediment to public resources or threaten public safety is identified during the office review and field assessment, additional field analysis by a qualified expert may be needed to more quantitatively assess the hazard. This is generally accomplished with a subsurface investigation. The subsurface investigation should be designed to gather data necessary to evaluate the landslide in accordance with the evapotranspiration, recharge, groundwater flow, and slope stability modeling (see Part 7).

The selection of exploration methods should be based on the study objectives, size of the landslide area, geologic and hydrogeologic conditions, surface conditions and site access, and limitations of

budget and time. Subsurface exploration to assess landslides is generally described by McGuffey et al. (1996) as summarized in the following paragraphs:

Test Pits. Shallow test pits can be dug by hand with a shovel. Trackhoes or excavators can be used to advance test pits to depths of nearly 20 feet in certain soils. They are useful for exposing subsurface soil and rock conditions for purposes of mapping or logging the underlying conditions, and to identify shallow groundwater elevations and failure planes.

Hand Auger. A hand auger can be used to identify soil types to depths up to nearly 20 feet (in loose soils) but does not provide significant information regarding soil material properties.

Drive Probe. A simple hand probe can be used to estimate soil density and the depth to dense soil. The Williamson Drive Probe (WDP) (Williamson 1994) was developed as an inexpensive and portable alternative for determining soil relative densities and groundwater table elevations. Sections of hardware pipe are coupled and driven into the ground manually with a sliding hammer. The number of blows, in even distance increments, required to drive the probe is used to describe soil conditions. Blow-count data theoretically can be correlated with the Standard Penetration Test (American Society for Testing and Materials, 2014).

Method limitations include manual labor intensity, which can limit the number of holes drilled in a given day. The WDP can also be used to estimate depth to groundwater if perforated pipe is used. With these many uses and the low cost, the WDP is an effective alternative to other tests which require expensive equipment and are less portable.

Drill Rigs. Borings constitute a common method for collecting geotechnical data. Access limitations can be addressed if logging roads are fortuitously located, or by using track-mounted equipment. In some cases, undisturbed or lightly disturbed soil samples can be collected for quantitative laboratory testing (i.e., direct shear, bulk density, moisture content, etc.). Drill rigs can also be used to install groundwater monitoring wells that contain pressure transducers, and as a conduit for geotechnical instrumentation (i.e., inclinometer, extensometer, etc.).

Geophysical Methods. Surface-based geophysical methods can be an economical method of collecting general subsurface information over large areas of rugged terrain. These include ground penetrating radar, electromagnetic, resistivity, and seismic refraction methods. These techniques can provide information on the location of boundaries between coarse-grained and fine-grained strata and the depth to the water table.

A qualified expert should be present in the field during the completion of a subsurface investigation so that the field activities are properly executed and the desired results can be achieved.

PART 7 LANDSLIDE ACTIVITY ASSESSMENT

When forest practices harvest or construction activities are proposed on or have the potential to influence potentially unstable slopes, it is recommended the qualified expert assess the landslide activity. The landslide activity assessment is an important component of evaluating the landslide hazard and potential risk associated with planned activities. It will also likely contribute to the information a qualified expert will need in preparation of geologic evaluations.

7.1 Landslide Activity

The three components of landslide activity for evaluation during the office and field review process are: (1) the state of activity, (2) distribution of activity, and (3) style of activity (Cruden and Varnes, 1996).

The state of activity refers to the timing of landslide movements and ranges from active (currently moving) to relict (clearly developed in the geomorphic past under different conditions than are currently present). When an active landslide stops moving, it becomes classified as suspended, and if it remains stationary for more than one annual cycle, it becomes inactive. If the conditions that contributed to prior movement are still present even though the landslide is inactive, the landslide is considered dormant because it may become reactivated at a later time. If the conditions promoting failure have naturally changed to promote stability, the landslide is considered abandoned, while if human intervention has protected against future movement the landslide is considered stabilized. Interpretation of vegetation cover, surface morphology, and toe modification by a stream, if present, all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes (Table 2, Keaton and DeGraff, 1996). Although based on a Rocky Mountain-type climate, the framework described by Keaton and DeGraff has been successfully applied in the Pacific Northwest. New vegetation generally begins to colonize a landslide's scarp, lateral flanks, or other areas of disturbed ground once the landslide becomes dormant and progresses to mature vegetation cover according to the local climate. The scarp, flanks, and internal hummocky morphology of the landslide also tend to become increasingly subdued with time after the landslide becomes dormant, and the internal drainage network of the landslides tends to become more connected and organized. If the toe of the landslide enters a stream, that stream progressively modifies the toe as recorded by terraces and the establishment of a floodplain comparable to reaches unaffected by landslide activity.

The distribution of activity refers to the geometry and spatial pattern of landslide movements and how these patterns may change with time. One key distinction is if the landslide is advancing by extending downslope in the main direction of movement, or retrogressing by extending upslope in the direction opposite movement. A landslide can also widen or narrow in the direction perpendicular to movement, and more generally can be enlarging or diminishing if its total volume is increasing or decreasing.

The main style of landslide activity is defined as the type of movement options shown in Table 1, Landslide Classification. Many landslides involve different styles of landslide activity, and movements should be described as "complex" if they happen in succession, or as "composite" if they happen simultaneously at different parts of the landslide. Many landslides may reactivate repeatedly over time and their movements are noted as "multiple" if the same style of activity affects any previously displaced material, or "successive" if the same style of activity affects previously stable material in the immediate vicinity of the previous landslide.

Table 2. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates (from Keaton and DeGraff, 1996).

Active State	Main Scarp	Lateral Flanks	Internal Morphology	Vegetation	Toes Relationships	Estimated Age (Years)
Active reactivated, or suspended; dormant-historic	Sharp; unvegetated	Sharp; unvegetated streams at edge	Undrained depressions; hummocky topography; angular blocks separated by scarps	Absent or sparse on lateral and internal scarps; trees tilted and/or bent	Main valley Stream pushed by landslide; floodplain covered by debris; lake may be present	< 100 (historic)
Dormant-young	Sharp; partly vegetated	Sharp; partly vegetated; small tributaries to lateral streams	Undrained and drained depressions; hummocky topography; internal cracks vegetated	Younger or different type or density than adjacent terrain; older tree trunks may be bent	Same as for active class but toe may be modified by modern stream	100 to 5,000 (Late Holocene)
Dormant-mature	Smooth; vegetated	Smooth; vegetated; tributaries extend onto body of slide	Smooth, rolling topography; disturbed internal drainage network	Different type or density than adjacent terrain but same age	Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain	5,000 to 10,000 (Early Holocene)
Dormant-old or relict	Dissected; vegetated	Vague lateral margins; no lateral drainage	Smooth, undulating topography; normal stream pattern	Same age, type, and density as adjacent terrain	Terraces cut into slide debris; uniform modern floodplain	> 10,000 (Late Pleistocene)

Decision flow chart

When a qualified expert needs to determine the potential for delivery for inclusion in a geotechnical report, it is suggested that the following decision flowchart be applied. The flowchart provides a guide for assessing the risk associated with landslides. Generally, the pathway outlined in the chart is defined by the level of landslide activity and how likely the landslide is to deliver sediment to public resources. The decision pathway uses a glacial deep-seated landslide and associated groundwater recharge area as an example for how a qualified expert would assess the risk associated with the landform. The same decision pathway may be used for other types of deep-seated landslides.

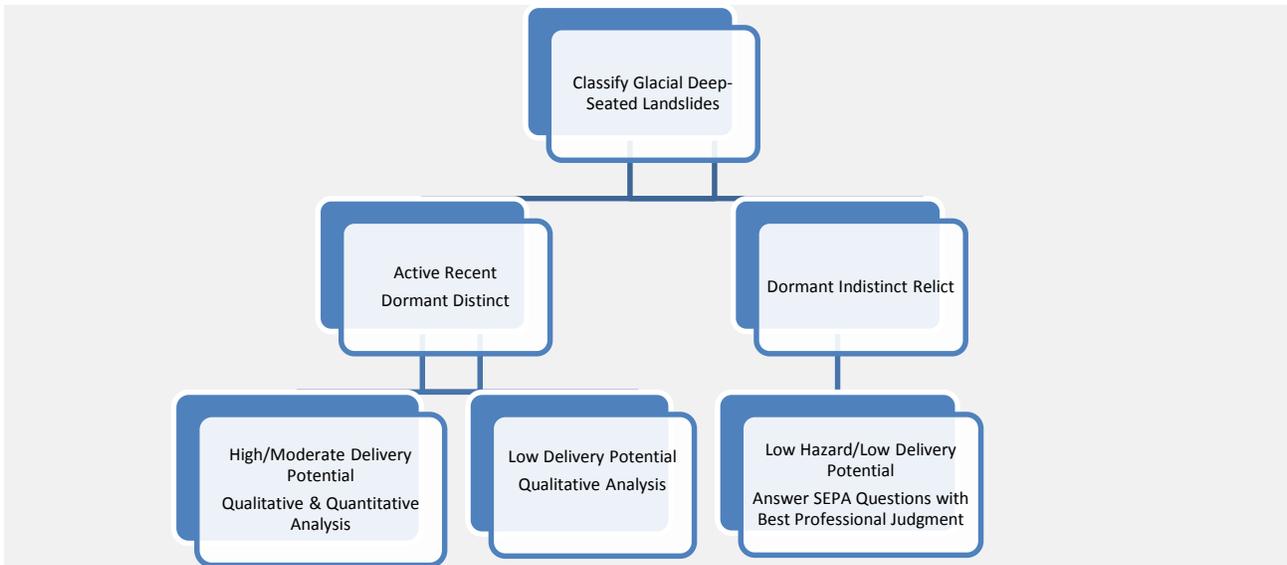


Figure 26 Decision pathway for implementing qualified expert investigations of groundwater recharge area harvests for glacial deep-seated landslides (DNR, 2001).

1. Identify and map glacial deep-seated landslides and associated groundwater recharge areas.
2. Classify landslides using the Landslide Hazard Zonation (LHZ) protocol (modified from Keaton and DeGraff, 1996) for deep-seated landslides as:
 - a. active;
 - b. dormant/distinct;
 - c. dormant/indistinct; or
 - d. relict.
3. Calculate areas for the mapped glacial deep-seated landslide and the associate groundwater recharge area.
4. Evaluate delivery potential if landslide were to move for:
 - a. public safety (houses, roads, etc.);
 - b. public resources (water quality and fish habitat).
5. If the landslide is relict or dormant/indistinct, and has low delivery potential, additional analysis may not be necessary. Documentation of this analysis may be provided by a letter, memo or other appropriate form. If required, answer the SEPA checklist questions (WAC 222-10-030) using best professional judgment of the landslide hazard.
6. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge area and evidence of landslide movement from aerial photographs, LiDAR and other screening methods. SEPA checklist questions should be answered with qualitative information and best professional judgment.
7. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (6), if appropriate, perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. SEPA checklist questions should be answered with quantitative information from modeling exercises.
8. Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

7.2 Water Budget and Hydrologic Contribution to Slope Stability

To further inform the landslide activity assessment involving groundwater recharge, it is recommended that the qualified expert evaluate the water budget. The water budget of a groundwater/surface-water system describes the input, movement, storage, and output of water from a hydrologic system. Water enters a hydrologic system through precipitation in the form of rainfall and snowmelt. Some of this water is intercepted by vegetation and evaporates before reaching the ground or sublimates from the snowpack. Water that reaches the ground may run off directly as surface flow or shallow, sub-surface runoff, or evaporate from the soil, or transpire through vegetation foliage. Water that percolates below the root zone and reaches the water table is considered to be groundwater recharge. Groundwater moves from areas of high hydraulic head to areas of low hydraulic head where it leaves the groundwater-flow system through wells, springs, streams, wetlands, and other points of groundwater discharge. The occurrence and movement of groundwater through the subsurface depends on the hydraulic properties of subsurface material as well as the distribution of groundwater recharge.

The following discussions of evapotranspiration and groundwater flow may aid the qualified expert during the landslide activity assessment involving a groundwater recharge area. Such assessments and modeling should be considered when uncertainties remain regarding landslide movement or when the risk for damage to public resources or threats to public safety are elevated. These further assessments for calculating water influence to a deep-seated landslide may be necessary when proposed activities have indicated an increase in the potential for contributing movement to potentially unstable slope or landform.

7.2.1 Modeling Evapotranspiration

Modeling evapotranspiration is a data intensive exercise that requires regional and/or site-specific information regarding precipitation types and rates, wind speed, relative humidity, temperature, solar energy, and plant community stand characteristics (Jassal et al., 2009). The goal of evapotranspiration modeling is to derive estimates of the potential increase in water available to the groundwater recharge area from changes in energy balances, wind speeds, and plant community characteristics (i.e., aerodynamic roughness) after forest harvest.

Effects of evapotranspiration on the soil water budget can be partitioned as follows: (1) canopy interception of rainfall or snow and subsequent evaporation loss to the atmosphere; (2) transpiration of infiltrated water to meet the physiological demands of vegetation; (3) evaporation from the soil or litter surface. Different vegetation covers have different balances of these fundamental water loss processes. The effects of evaporation on soil water budgets are relatively small compared with canopy evapotranspiration and interception (Bosch and Hewlett, 1982).

Transpiration is the dominant process by which soil moisture in densely vegetated terrain is converted to water vapor. Transpiration involves the adsorption of soil water by plant roots, the translocation of the water through the plant and release of water vapor through stomatal openings in the foliage. Transpiration rates depend on availability of solar energy and soil moisture as well as vegetation characteristics, including vegetation type (e.g., conifer or deciduous), stand density, height and age, rooting depth, leaf area index, leaf conductance, albedo of the foliage, and canopy structure. Rates of transpiration are similar for different vegetation types if water is freely available (Campbell, 1986).

Transpiration is typically quantified using Soil-Vegetation-Atmosphere Transfer (SVAT) models where the movement of water from the soil through the plant to the atmosphere is represented by several resistances in series: (1) the integrated soil-root system; (2) the stem; (3) the branch; and (4) the effective stomatal resistance. Eddy correlation techniques are commonly used to estimate transpiration fluxes (Hanks and Ashcroft, 1980).

Interception by vegetation cover controls both the amount and timing of precipitation reaching the soil surface. The interception capacity of vegetation types is important because intercepted water has a high surface area to volume ratio that promotes efficient evaporation by convection. Intercepted rainfall is mostly stored on the surface of foliage and stems, while intercepted snowfall bridges between gaps in tree crowns facilitating an accumulation of snow over large surface areas of the canopy. Interception and subsequent evaporation of water from vegetation cover is particularly significant in coniferous forests (Link et al., 2004); losses (both snow and rain) from these dense canopies can account for up to 30 percent to 50 percent of gross annual precipitation (Dingman, 1994). Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10 percent to 30 percent. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21 percent to 35 percent, based on canopy characteristics and climate conditions. Hanell (2011) reported hydrologic modeling (DHSVM; Wigmosta, Njssena and Stork, 2002) that predicts a 27 percent decrease in evapotranspiration resulting from forest conversion to shrub for a site on the western Olympic Peninsula, Washington.

The proportion of rainfall intercepted by forest canopies is inversely related to both antecedent wetness and rainfall intensity. Gentle, short-duration rainfall may be almost totally intercepted, while interception may account for as little as 5 percent of precipitation during intense winter storms (Ramirez and Senarath, 2000).

Approaches for estimating changes in evapotranspiration typically involve some combination of the Penman-Monteith model for calculating the canopy resistance, the Bowen ratio energy balance technique to estimate evaporation from plant surfaces, and the Priestly-Taylor formula to estimate evaporation from the soil surface. Reviews and demonstrations of these techniques can be found in Avery and Fritschen, 1971; Fritschen, 1975; Ziemer, 1979, Hanks and Ashcroft, 1980; Campbell, 1986; Simpson, 2000; Martin et al., 1997; and Sias, 2003.

7.2.2 Groundwater Recharge and Groundwater Flow Modeling

Groundwater recharge is difficult for the qualified expert to measure directly, but several empirical and numerical methods exist for estimating recharge within the surface-water, unsaturated zone, and saturated zone, including physical, tracer, and numerical-modeling techniques (Scanlon et al., 2002). Recharge is commonly estimated by calculating the residual component of the water budget whereby recharge equals the difference between precipitation and the sum of losses through evapotranspiration, surface runoff, and shallow groundwater flow. The accuracy of recharge estimated through this method is limited by the large uncertainties inherent in the estimating components of the water budget such as evapotranspiration, which is typically large in magnitude relative to groundwater recharge. Examples of numerical models capable of estimating recharge based on a water budget include the Deep Percolation Model (Bauer and Vaccaro, 1987), Precipitation Runoff Modeling System (Leavesley et al., 1983), and the Variable Infiltration Capacity Model (Liang et al., 1994). Once the spatial distribution of groundwater recharge is estimated, the movement of groundwater within the subsurface may be modeled using groundwater-

flow models. The movement of groundwater from areas of recharge may be modeled using groundwater flow models such as MODFLOW (Harbaugh et al., 2000). Groundwater-flow models are based on a hydrogeologic framework that incorporates the hydraulic properties of geologic materials and their stratigraphic relations. Groundwater models are calibrated using hydrologic data including groundwater levels within major water-bearing hydrogeologic units and can be used to characterize the movement of groundwater from areas of recharge to areas of discharge.

7.3 Computational Slope Stability Assessment Methods

Qualitative methods for the qualified expert to assess slope stability are summarized in Parts 6.2 and 5.5. Quantitative assessments of slope stability, performed by the qualified expert, may be necessary to characterize slope failure potential at a given site, as well as to evaluate potential impacts to natural resources and public safety associated with proposed forest practice activities. This quantitative assessment most often entails a two-dimensional, limit-equilibrium analysis method, but other methods may be necessary under certain conditions. Limit-equilibrium analysis calculates a factor of safety for sliding along a critical failure surface, which is expressed as a ratio of the shear strength of the earthen material resisting slope failure to the shear stresses driving instability. Relative stability is defined by a factor of safety exceeding a value of one. Computation of the most critical failure surface is an iterative process generally supported by commercially available or public-domain software (e.g., LISA, DLISA, STABL, SLOPE-W).

Development of a 2D model for analysis requires the following input information to define an initial state of stability:

- An engineering geologic section through the slope of concern (generally cut through the steepest portion of the slope) showing the thickness and position of each engineering geologic unit. The topographic surface profile can be field-surveyed or derived remotely from DEM topographic data whereas the subsurface failure plane geometry might need to be interpolated between known or hypothesized points (i.e., the locations at which the failure plane intersects the ground surface) in the absence of field data acquired from boreholes or with other geotechnical methods;
- Location/elevation of groundwater regimes along this critical section; and
- Saturated and unsaturated unit weights and shear strength of each engineering geologic unit.

The potential effects of the proposed forest practices activities on slope stability can then be evaluated by modifying the initial model with the expected condition based on the proposed activities, such as placement of fill for road construction or elevating groundwater levels (pressures) due to forest canopy removal. Limit-equilibrium models also allow the analyst to reconstruct pre-failure slope conditions of existing landslides by varying the input parameters (e.g., surface topography, engineering geologic unity properties, failure plane geometries, groundwater table elevations) such that the reconstructed original slope fails. These exercises are useful for evaluating reasonable strength parameters of subsurface materials, likely failure plane geometries, and groundwater table elevations in the absence of real data or field indications. Two-dimensional models also can be used to evaluate downslope material impacts to natural resources and threats to public safety, as well as upslope impacts in situations where retrogressive failure mechanisms are suspected. Turner and Schuster (1996), as well as many other references, provide more details on the process and methodologies for performing limit-equilibrium stability analyses, including method assumptions and limitations. All of the above steps require considerable engineering

geologic/geotechnical data (e.g., subsurface, instrumentation, laboratory) and expertise to achieve an accurate and meaningful representation of the actual conditions at the site.

7.4 Delivery Assessment

The forest practices rules apply where there is *potential* for sediment and debris to deliver to a public resource or threaten public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety should be evaluated. Many factors are part of that evaluation, including:

- Proximity to a public resource or safety concern;
- Nature of the geologic material involved;
- Initial failure volume of a landslide;
- Landslide type of failure mechanism;
- Slope of channel conditions; and
- Observed deformation characteristics of nearby landslides with comparable geologic/geomorphic attributes.

It is difficult to prescribe guidelines for delivery distances because each situation has a special combination of process and topography. Deep-seated landslides can move anywhere from a few inches to a few miles depending on the friction of the slip plane, the forces pulling the landslides down, and the shear strength resisting those forces. Larger landslides are more likely to be able to move great distances at gentle gradients, but they are also less likely to be significantly affected by forest practices activities.

Because many factors can influence landslide mobility and debris runout, it is not practical to provide generalized prescriptive guidelines to predict delivery for a broad range of conditions. An evaluation of deliverability should, in many cases, require a field assessment, an inquiry of historic landslide activity and behavior, and the application of experienced judgment in landslide processes and mobility.

Timber harvest and road building can cause shallow landslides on steep slopes. Travel distances for such landslides depend on the amount of water contained in or entrained by them. Considering that rain, snowmelt, or some other water inputs trigger the majority of landslides in the Pacific Northwest, it should be noted that almost all landslides contain some amount of water that tends to mobilize the soil or rock. Debris slides that do not reach streams (i.e., do not absorb large volumes of additional water) usually deposit their debris on the hillslope, and are typically unable to move far across large areas of flat ground. However, since most landslides occur during storm conditions, a large proportion of debris slides do reach flowing channels and create the opportunity to entrain enough water to become debris flows. These flows are quite mobile and can travel great distances in steep or moderate gradient channels.

When channel gradients drop below 12 degrees (20%), debris flows no longer scour and generally begin to slow down. On slopes gentler than about 3 to 4 degrees (5 to 7%) debris flows commonly start to lose their momentum and the solids entrained in them (rock, soil, organic material) tend to settle out. Travel distance of a debris flow once it reaches a low-gradient surface is a function of its volume and viscosity. The solid volume of a debris slide or flow deposit is a function of soil depth, distance traveled down the hillslope, and the gradient of the traveled path. The proportion of water

is the main control on viscosity. Field or empirical evidence should be used for determining the runout distance.

Even if the main mass of a landslide or debris flow comes to rest without reaching a public resource, there is the possibility that secondary effects may occur. Bare ground exposed by mass movement and disturbed piles of landslide debris can be chronic sources of fine sediment to streams until stabilized by revegetation. If flowing water (seepage, overland flow, or small streams) can entrain significant volumes of fine sediment from such surfaces, the possibility of secondary delivery must be evaluated, along with the likelihood of impact by the initial movement event itself.

To assess the potential for delivery and estimate runout distance, analysts can evaluate the history of landslide runout in the region, use field observations, and/or use geometric relationships appropriate from the scientific literature. In any situation where the potential for delivery is questionable, it is best to have a qualified expert examine the situation and evaluate the likelihood of delivery. If forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource, a geotechnical report written by a qualified expert is required.

7.5 Synthesis of Results Prior to Preparation of Geologic Evaluations

This step is generally reserved for qualified experts when preparing geologic evaluations. The following questions and recommendations are provided to guide the qualified expert in their synthesis and can be useful when preparing a geologic evaluation (see Part 8 for geotechnical report guidelines):

1. What are the project objectives (e.g., timber harvest unit evaluation, road construction or abandonment, landslide mitigation)?
2. Which types of unstable slopes and landforms have been identified (see Part 5)?
3. What are their spatial and temporal distributions (see Part 5)?
4. Which office and field methods were used to identify and delineate unstable slopes and landforms (see Part 6)?
5. Based on an analysis of available information (see Parts 7.1, 7.2, 7.3), what is the geotechnical interpretation of physical processes governing unstable slope/landform movement, mechanics, and chronologies of each identified feature?
6. What are the project limitations (e.g., quantity or quality of technical information, site access, project timeframe) that might influence the accuracy and precision of identifying, delineating, and interpreting unstable slopes and landforms?
7. What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identifying, delineating, and interpreting of unstable slopes and landforms?
8. What is the potential for material delivery from each identified unstable slope and landform to areas of public resource sensitivity or public safety (see Parts 7.4)?
9. What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
10. What level of confidence is placed in the identification, delineation, and interpretation of unstable slopes and landforms? How does the confidence level impact any recommendations provided by the qualified expert for unstable slope management and/or mitigation?

Documentation of the project analysis may include annotated images (e.g., LiDAR-derived hillshades, aerial photos), geologic or topographic profiles, maps, sketches, results of subsurface investigations, summaries of computational or simulation modeling, summaries of available (i.e.,

previously published) information and remotely sensed or field-derived data and text to explain the concrete evidence and logical train-of-thought for the conclusions and recommendations that will be presented in the geotechnical report.

It is recommended field observation and sampling locations used in project analysis be displayed on a map in the geotechnical report. Descriptive, photo, or data-sampling observation points should be geo-referenced (i.e., with GPS waypoints). Mapped GPS track locations for field traverses also are recommended, so that it is clear which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced.

Models, such as those for slope stability and sensitivity (see Parts 7.2 and 7.3) may be used to support analyses of unstable slope and landform characteristics and mechanics. If models are used, the results should not be incorporated in report findings without an adequate assessment and clear statement of their assumptions, limitations, and alignment with existing information (e.g., field data). For example, a modeled reconstruction of landslide failure-plane geometry based on one borehole or drive probe sample would likely be misleading and could result in spurious conclusions.

It is recommended that the analytical methods and processes used to identify, delineate, and interpret unstable slopes and landforms be described in the geotechnical report, along with information sources, data processing techniques, and the meaning and limitations of analysis results. Geotechnical reports should describe all assumptions regarding input parameters or variables, such as groundwater surface elevation estimates employed in stability sensitivity analyses, as well as the reasoning for their use. Geotechnical reports also should include an assessment of the sensitivity of the analytical method or model results to parameter variability. This is especially true where only a range of parameter values are available, or where input values are extrapolated or estimated from other locations or databases.

The report conclusions should document the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the assessment, including office reviews and field assessment, qualitative information and data analyses, geo- and hydro- technical modeling, and evaluation of material deliverability. Report conclusions might also describe the suitability of the site for the proposed activity clearly state the likely direct and indirect effects of the proposed activity on the geologic environment as well as the likely direct and indirect effects of geologic processes on the proposed activity. Conclusions should be substantiated by the presented evidence, and the logical thought process established in the analysis and synthesis process.

It is helpful to provide a concise statement of confidence in and limitations of the slope stability analysis and its conclusions. Confidence levels are influenced by many factors, including project complexity and objectives, site characteristics (e.g., acreage and accessibility), project timeframes, quantity and quality of available information (e.g., reports, databases) and remotely sensed data, accuracy and precision of field observations and collected data, and the rigor of available analytical methods and models. A discussion of the primary limiting factors assists the landowner and report reviewer in evaluating the potential natural resource, public safety, and liability risks associated with implementing a project.

The geotechnical report might include recommendations regarding additional work needed to supplement the qualified expert report, including but not limited to monitoring by the landowner or their designated qualified expert of geologic conditions (e.g., groundwater, slope movement) and review of plans and specifications. The qualified expert also might be asked by the landowner to provide or evaluate possible mitigation measures for destabilized slopes or landforms.

PART 8. GEOTECHNICAL REPORTS

When harvesting or building roads on potentially unstable slopes a geotechnical report is required to explain how the proposed forest practices are likely to affect slope stability, deliver sediment and debris to public resources, or threaten public safety. If the FPA is classed as a “Class IV-Special”, the applicant must also submit to DNR a SEPA checklist and additional information as described in WAC 222-10-030. The geotechnical report must be prepared by a qualified expert and the report must meet the requirements described in WAC 222-10-030(1).

Effective July 1, 2002, qualified experts must be licensed with Washington’s Geologist Licensing Board. For more information on the geologist licensing process, refer to WAC 308-15-010 through 308-15-150, or visit the Geology Board’s web site at (www.dol.wa.gov/business/geologist). The education and field experience on forestlands will still be required, in addition to the appropriate geologist license.

In addition to the considerations described in Part 7.5, the following elements should be included in geotechnical reports prepared by qualified experts:

- (a) *Prepare an introductory section.* This section should describe the qualified expert’s qualifications. It should also reference the FPA number if previously submitted, landowner and operator names, and a brief description of site observations to the area, including dates, relevant weather conditions, and the locations visited. Geographic coordinates (latitude and longitude, GPS waypoints of observation locations) are helpful for reviewers for locating the sites with certainty.
- (b) *Describe the geographic, geologic, and the soil conditions of the area in and around the application site.* Include a legal description of the proposal area, the county in which it is located, and where appropriate the distance and direction from the nearest municipality, local landmarks, and named water bodies. Provide elevations and aspect. Describe the underlying parent materials, including their origin (i.e., glacial versus bedrock); the name(s) of any rock formations and their associated characteristics; and geologic structure relevant to slope stability. Describe soils and rocks on site based on existing mapping, field observations, and any available local information. Describe soil and rock texture, depth, and drainage characteristics typically using standard soil and rock classification systems (e.g. Unified Soil Classification System (USCS), American Association of State Highway and Transportation Officials (AASHTO) and Rock Mass Rating, Bieniawski, 1989).
- (c) *Describe the potentially unstable landforms within and around the site.* Include a general description of the topographic conditions of the site. It may be appropriate to provide GPS coordinates for locations of site observations and other important features such as borings, trenches, and outcrops. Specifically identify the potentially unstable landforms located in the area (i.e., those defined in WAC 222-16-050 (1)(d)(i)), in addition to any other relevant landforms on or around the site. Describe in detail the gradient, form (shape), and approximate size of each potentially unstable landform. Include a description of the dominant mass wasting processes associated with each identified landform, as well as detailed observations of past slope movement and indicators of instability. Assign a unique alphabetic and/or numeric

identifier label to each landform on a detailed site map of a scale sufficient to illustrate site landforms and features. Where the proposal involves operations on or in the groundwater recharge area of a glacial deep-seated landslide, specifically discuss the probable direct and indirect impacts to groundwater levels and those impacts to the stability of the deep-seated landslide.

- (d) *Analyze the possibility that the proposed forest practice will cause or contribute to movement on the potentially unstable slopes.* Explain the proposed forest management activities on and adjacent to the potentially unstable landforms. Clearly illustrate the locations of these activities on the site map, and describe the nature of the activities in the text. Discuss in detail the likelihood that the proposed activities will result in slope movement (separate activities may warrant separate evaluations of movement potential). The scope of analysis should be commensurate with the level of resource and/or public risk. Include a discussion of both direct and indirect effects expected over both the short- and long-term. For proposals involving operations on or in the groundwater recharge area of a glacial deep-seated landslide, conduct an assessment of the effects of past forest practices on slide/slope movement. Explicitly state the basis for conclusions regarding slope movement. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or slope stability model output. Input parameters, model assumptions, and methods should be fully substantiated within the report.
- (e) *Assess the likelihood of delivery of sediment and/or debris to any public resources, or to a location and in a manner that would threaten public safety, should slope movement occur.* Include an evaluation of the potential for sediment and/or debris delivery to public resources or areas where public safety could be threatened. Discuss the likely magnitude of an event, if one were to occur. Separate landforms may warrant separate evaluations of delivery and magnitude. Explicitly state the basis for conclusions regarding delivery. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or landslide runout model results, which should have site-specific data. Input parameters, model assumptions, and methods using best available data should be fully substantiated within the report.
- (f) *Suggest possible mitigation measures to address the identified hazards and risks.* Describe any modifications necessary to mitigate the possibility of slope movement and delivery due to the proposed activities. If no such modifications are necessary, describe the factors inherent to the site or proposed operation that might reduce or eliminate the potential for slope movement or delivery. For example, an intact riparian buffer down slope from a potentially unstable landform may serve to intercept or filter landslide sediment and debris before reaching the stream. Discuss the risks associated with the proposed activities relative to other alternatives, if applicable.

The report should be as detailed as necessary to answer these and any other relevant questions. In particular, examination of aerial photographs (preferably taken over many years), LiDAR-derived products, and other screening tools would be appropriate to evaluate the stability characteristics of the area and the effects of roads or previous logging on the subject or similar sites. Field observations will usually be necessary to define the local geology, landforms, etc. Quantitative estimates of site stability produced using SHALSTAB, XSTABL, or other slope-stability models may be useful.

GLOSSARY

Aquifer	Saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.
Aquitard	A less permeable bed in a stratigraphic sequence.
Confined aquifer	An aquifer that is confined between two aquitards. Confined aquifers occur at depth.
Debris avalanche	The very rapid and usually sudden sliding and flowage of incoherent, unsorted mixtures of soil and weathered bedrock.
Discontinuity	Sudden or rapid change with depth in one or more of the physical properties of the materials constituting the earth.
Drift	A general term for material such as boulders, till, gravel, sand, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice. Generally used to describe glacial deposits of the Pleistocene Epoch.
Drillers log	The brief notations included as part of a driller's tour report, that describes the gross characteristics of the well cutting noted by the drilling crew. It is useful only if a detailed sample log is not available. Drillers logs may also include information on groundwater elevation.
Earthflow	A slow flow of earth lubricated by water, occurring as either a low-angle terrace flow or a somewhat steeper but slow hillside flow.
Engineering geology	Performance of geological service or work including but not limited to consultation, investigation, evaluation, planning, geological mapping, and inspection of geological work, and the responsible supervision thereof, the performance of which is related to public welfare or the safeguarding of life, health, property, and the environment, and includes the commonly recognized practices of construction geology, environmental geology, and urban geology.
Evapotranspiration	A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Commonly designated by the symbols (E_t) in equations.
Factor of safety	The ratio of the resistant force acting on the sliding surface to the driving force acting on the potential slide mass. When the factor of safety is greater than 1, the slope is stable; when the factor of safety is less than 1, the slope is unstable.
Glacial outwash	Sediment deposited by meltwater streams beyond a glacier, typically sorted and stratified sand and gravel.

Graben	A block, generally long compared to its width, that has been downthrown along faults relative to the rocks on either side.
Groundwater	Subsurface water that occurs in soils and geologic formations. Encompasses subsurface formations that are fully saturated and near-surface, unsaturated, soil-moisture regimes that have an important influence on many geologic processes.
Groundwater Recharge area	That portion of a drainage basin in which the net saturated flow of groundwater recharge is the process by which water is absorbed and is added to the zone of saturation, either directly into a formation, or indirectly by way of another formation. Also, the quantity of water that is added to the zone of saturation. The rule definition for groundwater recharge areas for glacial deep-seated landslides is found in WAC 222-16-010.
Glacial terrace	Relatively flat, horizontal, or gently inclined surfaces, sometimes long and narrow, which are bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side formed by glacial processes.
Glaciolacustrine	Pertaining to, derived from, or deposited in glacial lakes; deposits and landforms composed of suspended material brought by meltwater streams flowing into lakes.
Glaciomarine	Pertaining to sediments which originated in glaciated areas and have been transported to an ocean's environment by glacial meltwater.
Glacial till	Non-sorted, non-stratified sediment carried or deposited by a glacier.
Hydrogeology	The science that involves the study of the occurrence, circulation, distribution, chemistry, remediation, or quality of water or its role as a natural agent that causes changes in the earth, and the investigation and collection of data concerning waters in the atmosphere or on the surface or in the interior of the earth, including data regarding the interaction of water with other gases, solids, or fluids.
Hydraulic head	Combined measure of the elevation and the water pressure at a point in an aquifer which represents the total energy of the water; since ground water moves in the direction of lower hydraulic head (i.e., toward lower energy), and hydraulic head is a measure of water pressure, ground water can and often does flow uphill.
Hydrologic budget	An accounting of the inflow to, outflow from, and storage in a hydrologic unit such as a drainage basin, aquifer, soil zone or water body. For watersheds, the major input is precipitation; major output is stream flow.
Lahar	A mudflow composed chiefly of volcanoclastic materials on the flanks of a volcano.

Resistivity method	A geophysical method that observes the electric potential and current distribution at the earth's surface intended to detect subsurface variation in resistivity which may be related to geology, groundwater quality, porosity, etc.
Seismic method	A geophysical method using the generation, reflection, refraction, detection and analysis of seismic waves in the earth to characterize the subsurface.
Soil	An aggregate of solid particles, generally of minerals and rocks that either was transported or was formed by the weathering of rock in place.
Strata	Plural of stratum.
Stratum	A section of a formation that consists throughout of approximately the same material; a stratum may consist of an indefinite number of beds, and a bed may consist of numberless layers; the distinction of bed and layer is not always obvious.
Stratification	A structure produced by the deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and other essentially tabular units.
Unconfined aquifer	Aquifer in which the water table forms the upper boundary. Unconfined aquifers occur near the ground surface.
Vadose zone	Referred to as the unsaturated zone below the land surface and above the zone of saturation, or water table.
Water table	The surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric. The location of this surface is revealed by the level at which water stands in a shallow well open along its length and penetrating the surficial deposits just deeply enough to encounter standing water at the bottom.

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APPENDIX A MAPS AND SURVEYS

Map and survey data resources available to the qualified expert include:

Multi-disciplinary map and survey data resources:

- Washington State Geologic Information Portal – create, save, and print custom digital maps of Washington State or download map data for GIS applications; includes a variety of base layer selections with interactive Geologic Map, Seismic Scenarios Catalog, Natural Hazards, Geothermal Resources, Subsurface Geology Information, and Earth Resource Permit Locations; available on Washington Dept. of Natural Resources (DNR) website;
- Forest Practices Application Review System (FPARS) – interactive online mapping tool with a variety of digital map base layer selections including topography, surface water (streams, water bodies, wetlands), soils, transportation network, forest site class, and potential slope instability (designed for shallow landslide susceptibility mapping only); available on the DNR website;
- County interactive GIS map viewers – create, save, and print custom digital maps with some combination of the following data: topography (LiDAR and/or U.S. Geological Survey (USGS) DEM), surface water, soils, wetlands, sensitive areas, 100-year floodplain designations, transportation net and traffic counts, property ownership and structure location; available online at select county websites (e.g., King County iMAP);
- Washington State Coastal Atlas Map – interactive map utility for shoreline areas with multiple data layers including shoreline geomorphology (coastal slope stability and landforms), biology (plant communities), land and canopy cover, beaches and shoreline modifications, wetlands and estuaries, historic shoreline planforms, assessed waters, and Shoreline Management Act (SMA) designations; see Department of Ecology website.
- DNR surface mining permits

Topographic maps:

- USGS topographic 7.5 minute quadrangle maps; available from a number of government and non-government online vendors and free downloadable websites;
- LiDAR-based topographic maps (LiDAR-derived DEM (LDEM), typically 1- to 3- meter resolution); see Appendix C for LiDAR map and data sources.

Geologic maps:

- Geologic maps, various scales, in print and compiled by DNR, Division of Geology and Earth Resources as Map Series, Open File Reports, Bulletins, and Information Circulars; see most recent “Publications of the Washington Division of Geology and Earth Resources”; this publication and a status map of 7.5 minute quadrangle geologic mapping efforts (USGS STATEMAP program) are available on the DNR website with links to online publications where available;
- Geologic maps, various scales, in- and out-of-print or historic; all sources including dissertations and theses; see catalog of the Washington Geology Library, available through the DNR website with links to online publications where available;
- Geology digital data; small-scale geology coverage in ArcGIS shapefile format, available on DNR website;

- Geologic maps, various scales, available via The National Geologic Map Database (NGMDB; compiled by USGS and Association of American State Geologists; see NGMDB website catalog) and USGS Online Store (paper and digital copies).

Geologic hazards and landslide inventory maps:

- See Washington State Geologic Information Portal, referenced previously;
- Landslide Hazard Zonation (LHZ) Project – mapped existing and potential deep-seated landslides and landforms in select watersheds; hazard classifications provided with supporting documentation for completed projects; available through the DNR website;
- Landslide inventory and Mass Wasting Map Unit (MWMU) maps contained in Watershed Analysis Reports prepared under chapter 222-22 WAC – mapped landslides (including deep-seated and earthflows) for select Watershed Administrative Units (WAU); Adobe pdf versions of DNR-approved Watershed Analysis Reports are available through the DNR website;
- Modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps
- U.S. Forest Service watershed analyses – available from US Forest Service offices for select watersheds; some documents and maps are available online
- Washington State tribal watershed analyses – available from tribal agency offices; some documents and maps are available online;
- Washington State Coastal Atlas Map – slope stability maps developed prior to 1980, based on aerial photography, geologic mapping, USGS topographic quadrangle map, and field observations. Maps have not been updated with landslide data since 1980 but are used currently in land-use planning and in the Department of Ecology interactive Coastal Map tool; read data limitations on Department of Ecology’s website.
- Qualified expert reports on deep-seated landslides in glaciated and non-glaciated terrain, for select timber harvest units or other forest management projects regulated by the Washington Forest Practices Act. Often contain mapped landslides;
- TerrainWorks (NetMap) – provides digital landscape and analysis tools for slopes stability data/analysis and risk assessments.

Soil surveys:

- Natural Resources Conservation Service (NRCS) soil survey maps and data – online soil survey, map and database service; historical soil survey publications (CD or paper copies); NRCS website administered through the U.S. Department of Agriculture;
- Geochemical and mineralogical soil survey map and data – USGS Mineral Resources Program, open-file report available online (Smith et al., 2013) in Adobe pdf;
- National Cooperative Soil Survey Program (NCSS), Washington State – online soil survey data and link for ordering in-print surveys not available electronically; see NRCS website.

APPENDIX B EARTH IMAGERY AND PHOTOGRAMMETRY

The most common sources of imagery for landslide and landform identification, mapping, and photogrammetric analysis include:

- Aerial photography – historic and recent aerial photos produced in color or black and white and taken at various altitudes (typical scales in the 1:12,000 to 1:60,000 range); aerial photos acquired by the U.S. Soil Conservation Service are available in some areas as early as the 1930s. Multiple flight years are required for chronologically reconstructing deep-seated landslide activity and developing time-constrained landslide inventories. Forest landowners typically purchased photos from regional vendors on a 2 to 10 year cycle until recently when other freely acquired imagery became available (e.g., Google Earth, ESRI World Imagery). Stereo-pair photos are highly valued for landslide detection and reconstruction because they allow stereoscopic projection in three dimensions and can display high-quality feature contrast and sharpness;
- Google Earth – map and geographic information program with Earth surface images created by superimposing satellite imagery (DEM data collected by NASA’s Shuttle Radar Topography Mission), aerial photos, and GIS 3D globe. Ortho-rectified, generally 1-meter resolution, 3D images are available for multiple years (Historical Imagery tool), allowing chronologic deep-seated landslide mapping; Google Earth supports desktop and mobile applications, including managing 3D geospatial data. See Google website for download information;
- Bing Maps Aerial View – part of Microsoft web mapping service; overlays topographic base maps with satellite imagery taken every few years. See Microsoft site for download information;
- ESRI World Imagery – ArcGIS online image service utilizing Landsat imagery based on the USGS Global Land Survey datasets and other satellite imagery, with onboard visualization, processing, and analysis tools that allow imagery integration directly into all ArcGIS projects. Requires ArcGIS capability; see ESRI website.
- NAIP (National Agriculture Imagery Program) aerial imagery – ortho-rectified, generally 1-meter resolution earth surface images taken annually during peak growing season (“leaf-on”), acquired by digital sensors as a four color-band product that can be viewed as a natural color or color infrared image. The latter are particularly useful for vegetation analysis. Data available to the public via the USDA Geospatial Data Gateway and free APFO viewing software, as well as through ESRI for ArcGIS applications; see USDA Farm Service Agency website;
- Washington State Coastal Atlas Map and Photos – oblique shoreline photos spanning years 1976-2007; part of an interactive map tool; see Department of Ecology’s website.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) Archive of downloadable aerial photos.

APPENDIX C SOURCES FOR LIDAR DATA

Sources for viewing and downloading airborne LiDAR of Washington State include the following (URLs may change without notice):

- King County iMAP: Interactive mapping tool (<http://www.kingcounty.gov/operations/GIS/Maps/iMAP.aspx>) – Displays shaded relief maps derived from LiDAR data at locations where it is available. LiDAR data have been filtered to remove vegetation and manmade structures and can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- National Oceanic and Atmospheric Administration Digital Coast (<http://csc.noaa.gov/digitalcoast/>) – Archive of downloadable LiDAR data focused on coasts, rivers, and lowlands. Options for downloading point cloud, gridded, or contour data that require geographic information system software such as ArcGIS to view and analyze.
- National Science Foundation Open Topography facility (<http://www.opentopography.org/index.php>) – Archive of downloadable LiDAR data collected the National Center for Airborne Laser Mapping (NCALM) for research projects funded by the National Science Foundation. Options for downloading point cloud or gridded data for use with geographical information system software, or LiDAR derived hillshade and slope maps that can viewed in Google Earth.
- Oregon Lidar Consortium (<http://www.oregongeology.org/sub/projects/olc/>) – Small amount of Washington State data available along the Columbia River. Lidar Data Viewer displays hillshade maps that have been filtered to remove vegetation and manmade structures.
- Puget Sound Lidar Consortium (<http://pugetsoundlidar.ess.washington.edu/>) – Archive of LiDAR data from Western Washington, downloadable as quarter quad tiles. Data format is ArcInfo interchange files and requires geographic information system software to view.
- Snohomish County Landscape Imaging: SnoScape (<http://gis.snoco.org/maps/snoscape/>) – Displays hillshade maps of bare or built topography derived from LiDAR data where it is available. Can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- USGS EarthExplorer (<http://earthexplorer.usgs.gov/>) – Archive of downloadable LiDAR data acquired by the USGS through contracts, partnerships, and purchases from other agencies or private vendors. File format is LAS and requires GIS software for viewing.

APPENDIX D TECHNICAL REPORTS AND RESOURCES

In addition to library and online sources, the following technical reports, published and unpublished papers and searchable databases are available online:

- Catalog of the Washington Geology Library. Searchable database of the Washington Department of Geology Library containing a comprehensive set of dissertations and theses, watershed analyses, environmental impact statements, and refereed/un-refereed publications on state geology; see DNR website with links to online publications where available.
- USGS Open File Reports. Searchable online database containing reports covering deep-seated landslide investigations and related topics; see USGS Online Publications Directory, USGS website.
- Watershed Analysis, Mass Wasting Assessment reports per chapter 222-22 WAC. Adobe pdf versions of DNR-approved reports are available via the DNR website.
- US Forest Service watershed analysis reports. Available from U.S. Forest Service offices for select watersheds; some electronic documents are available online through the U.S. Forest Service website for national forest of interest.
- Interagency watershed analysis reports. Collaborative projects between federal agencies (U.S. Geological Survey, U.S. Forest Service, U.S. Fish and Wildlife Service), tribal agencies, and industry (e.g., Cook and McCalla basins, Salmon River basin, Quinault watershed). Documents available online through the USGS, Washington Water Science Center.
- Washington Soil Atlas. Available as downloadable Adobe pdf file from the Natural Resources Conservation Service website.

APPENDIX E PHYSICAL DATABASES

Meteorological databases:

- National Weather Service (NWS) cooperative weather stations – coordinated by National Oceanic and Atmospheric Administration (NOAA) – database managed by Western Regional Climate Center
- NWS Weather Surveillance Radar – Doppler and NEXRAD
- Remote Automatic Weather Stations (RAWS) – operated by US Forest Service and Bureau of Land Management – database managed by Western Regional Climate Center

Stream-flow gauge database: USGS National Water Information System website

Seismic data: Pacific Northwest Seismic Network (PNSN) – database managed by USGS, University of Washington, and IRIS Consortium in Seattle. Contains records from seismometers located throughout Washington and Oregon; see the PNSN website.

Climate Data for Washington: The availability of climate data is highly variable for the State of Washington. The following sites provide access to most of the available data useful for evapotranspiration modeling (the URLs may change without notice):

- USGS, Washington Water Data - <http://wa.water.usgs.gov/data/>
- National Surface Meteorological Networks - <https://www.eol.ucar.edu/projects/hydrometer/northwest/northwest.html>
- National Weather Service - <http://www.wrh.noaa.gov/sew/observations.php>
- National Climate Data Center - <http://www.ncdc.noaa.gov/>
- University of Washington Atmospheric Sciences - <http://www.atmos.washington.edu/data/>
- Washington State University - <http://weather.wsu.edu/awn.php>
- Community Collaborative Rain, Hail, and Snow Database - <http://www.cocorahs.org/>
- Western Regional Climate Summary for Washington - <http://www.wrcc.dri.edu/summary/climsmwa.html>
- Natural Resource Conservation Service - <http://www.nrcs.usda.gov/wps/portal/nrcs/main/wa/snow/>
- Washington Dept. of Ecology Water Resources - <http://www.ecy.wa.gov/programs/wr/wrhome.html>
- Washington Dept. of Transportation - http://www.wsdot.com/traffic/weather/weatherstation_list.aspx

National Resources Inventory for Washington State: Statistical survey of land use, natural resource conditions and trends in soil, water, and related resources on non-federal lands; see NRCS website.

APPENDIX F HYDROLOGIC PROPERTIES OF SOILS

This adaptation from Koloski et al., 1989, relates geologic materials commonly found in Washington to the descriptive properties of permeability and storage capacity. A generalized explanation of the two terms is presented below, but is not intended to rigorously define either the geologic categories or the geotechnical properties. The information presented in the table is useful to indicate the general range of values for these properties, be considered representative, but is no substitute for site-specific laboratory and field information.

Classification	Permeability (feet per minute)	Storage Capacity
Alluvial (High Energy)	0.01-10	0.1-0.3
Alluvial (Low Energy)	0.0001-0.1	0.05-0.2
Eolian (Loess)	0.001-0.01	0.05-0.1
Glacial Till	0-0.001	0-0.1
Glacial Outwash	0.01-10	0.01-0.3
Glaciolacustrine	0-0.1	0-0.1
Lacustrine (Inorganic)	0.0001-0.1	0.05-0.3
Lacustrine (Organic)	0.0001-1.0	0.05-0.8
Marine (High Energy)	0.001-1.0	0.1-0.3
Marine (Low Energy)	0.0001-0.1	0.05-0.3
Volcanic (Tephra)	0.0001-0.1	0.05-0.2
Volcanic (Lahar)	0.001-0.1	0.05-0.2

Permeability differences reflect variations in gradation between geologic materials. Very high permeability is associated with high-energy alluvial deposits or glacial outwash where coarse, open-work gravel is common. Permeability in these deposits can vary greatly over short horizontal and vertical distances. Extremely low permeability is associated with poorly to moderately sorted materials that are ice-consolidated and contain a substantial fraction of silt and clay.

Storage capacity reflects the volume of void space and the content of silt or clay within a soil deposit. Storage capacity is very small for poorly sorted or ice-consolidated, fine-grained materials such as till and glaciolacustrine deposits.

APPENDIX G ADDITIONAL RESOURCES

The following literature list provides additional resources not directly cited in this Board Manual section. They are listed topically according to the scientific study/research.

Forest Hydrology

Alila, Y. & Beckers, J. (2001). Using numerical modelling to address hydrologic forest management issues in British Columbia. *Hydrological Processes*, 15(18), 3371-3387.

Beaudry, P. G. & Sagar, R.M. (1995). The water balance of a coastal cedar hemlock ecosystem. In: proceedings of the joint meeting of the Canadian Society for Hydrological Sciences and the Canadian Water Resources Association: Mountain Hydrology, Peaks and Valleys in Research and Applications, May 17-19, Vancouver, British Columbia.

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Eckhardt, K., Breuer, L., & Frede, H. G. (2003). Parameter uncertainty and the significance of simulated land use change effects. *Journal of Hydrology*, 273(1), 164-176

Harr, R.D. (1981). Some characteristics and consequences of snowmelt during rainfall in western Oregon. *Journal of Hydrology*, 53, 277-304.

Hudson, R., & Anderson, A. (2006). Russell creek: Summary of research and implications for professional practice. Research Section, Coast Forest Region, BCMOF, Nanaimo, BC. Extension Note EN-022.

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October 8, 2014

Re: Comments on Forest Practice Board Manual Section 16, Guidelines Evaluating Potential Unstable Slopes and Landforms

Dear Mr. Harlon-Meyer and Mr. Engle:

Thank you for the opportunity to comment on the Forest Practice Board Manual Section 16, Guidelines Evaluating Potential Unstable Slopes and Landforms. We realize that there was an enormous amount of work that went into drafting the proposed changes in a very short time period. The DNR staff along with the technical committee should be commended for summarizing the multitudes of information, which was used to provide an overview to the guidance document for both the forester and the qualified expert. It is unfortunate that there was such a short timeframe (approximately one week) to make substantial and well informed comments and for that reason our comments are minimal. We believe, had there been a longer comment period, it would result in a far better guidance manual for this section.

We understand that Board Manual Section 16 is guidance for the Rule under WAC 222 (specifically portions in 222-20-010 and 222-16-050, 051) and our comments are primarily focused on attempting to make the manual as user friendly as possible for offering guidance to identify and evaluate potentially unstable slopes and landforms. We also believe that as written, several of the proposed changes appear to be surpassing its intended guidance as well as extending beyond the direction from the Forest Practice Board (FPB) to respond to deep seated glacial landslides, which raises some concerns.

The draft proposal has a large amount of background information that is very interesting and provides additional specific knowledge about each type of the Rule Identified Landform (RIL) and other geologic forms but makes it difficult to determine the actual guidance and steps that can be taken for evaluating the potentially unstable slopes. A plausible solution may be removing portions of the draft language and placing them in a background and information appendix. This may also help eliminate the concern of Section 16 having an unintended 'creep' that exceeds what was intended at this time.

Based on our attempt to both help make the manual more user friendly for guidance and to eliminate the appearance of 'creep' beyond the direction of the FPB we offer the following suggestions:

1. Create a new Appendix A titled 'Overview and Background'. Move existing appendices down.
2. Move the following to Appendix A:
 - Part 2. pg 4, 5 and 6 EXCEPT keep 2.1 identifying the landforms up until the last paragraph on page 5 and retain the title Potentially Unstable Landforms as Part 2 title.
 - Move pictures (pg 8,9) (Keep sections 2.2 and 2.3)
 - Section 2.4 (pg 12, 13)
 - Part 5 from 3rd paragraph pg 17 ("In most instances, landform terms...) with the last sustenance in 1st paragraph ("Below are descriptions of the types of ...")
 - 5.1
 - 5.2 EXCEPT last paragraph on pg 26 and name it Hydrologic Budget
 - 5.2.1
 - 5.2.2 move 1st two sentences and rename Ground water on Slope Stability
 - 5.56 pg 31, 32, 33 from "Additional information about landslide processes..."

- 6.1.3
- 6.1.4
- 7.1 2nd paragraph (“The state of the activity refers to the timing...”up to the Decision flow chart
- 7.2 and 7.2.1 hard to determine guidance verses information

3. Under Section 6.1 Summary of Procedures - numbering would help identify the steps and in this case the types of maps so that some don't get missed.

4. Section 7.5 there appears to be some inconsistency due to the word “All” starting the paragraph and the word “should’ within the sentence. To be consistent ‘all’ should be removed and after ‘expert in a geotechnical report...’ ad ‘if appropriate’.

Again, we appreciate the work you have been doing on this complex issue and look forward to the continued improvement of the Board Manual.

Sincerely,

Kendra Smith
On Behalf of Skagit County

Ecology comments on the Forest Practices Board Manual 16, dated September 22.

Overall comments

1. The manual does not have a clear audience. It is not written for the lay person or the qualified expert.
2. The manual should be reorganized so that the suggested guidance to landowners is up front in the manual and easy to find. Currently you have to wade through a lot of graduate level science on unstable slopes, before you find out what the suggested compliance path is.
3. The manual should address to some minimal degree the SEPA process and the fact that it can result in a DS in addition to a DNS or MDNS.
4. Description of eastside glacial geology is very weak compared to westside descriptions.
5. Table developed by the TFW Policy technical group on unstable slopes on information sources should be used around page 17.
6. Expand section 2.4 to include a brief overview of the geology of Washington with graphic interpretation to give the reader a context for describing why Washington has landslides. Also 5.42 also needs geologic context as well.

Specific comments

1. Page 4 line 5. suggest replacing "guidance" with "compliance".
2. Page 4, part2, first line. Suggest you reword to "landslides occur naturally in forested basins. The movement of landforms is an important process....".
3. Part 3 of the manual should be eliminated.
4. Page 44, second paragraph. Second sentence should be deleted. GWRA do not exist as an RIL on non-glacial deep-seated slides.
5. 6.4.2. there appears to be some repeat statements in 2nd and 4th paragraphs.
6. Page 46, 1st figure. Concerned that the GWRA is drawn incorrectly.
7. Page 47, third paragraph, 1st line. "study" should be replaced with "landowner".
8. Page 48, geophysical methods. Change "seismic methods" to "seismic refraction methods".

9. Page 49, landslide activity. A table illustrating the different activity levels described would be helpful.
10. Page 49, 1st paragraph. On the Sumas slide, streams occur down the sides of the deep-seated landslide that may contribute to activity, not just at the toe.
11. Page 50, step 1 should add "associated" after "and". Step 3 should simply say "calculate areas for mapped glacial deep-seated landslide and associated GWRAs."
12. Page 50 and 51. The decision pathway does not include how the proposed forest practice factors into process.
13. Page 52, under modeling ET. Would be helpful if you had an illustration of the hydrologic cycle being discussed.
14. Page 54. There are significant changes to the delivery section when this is supposed to be the topic for the 2nd phase of the board manual review.

ANDERSON, PATRICIA (DNR)

From: Millersoils <millersoils@comcast.net>
Sent: Thursday, September 25, 2014 9:43 PM
To: RATCLIFF, MARC (DNR)
Cc: Miller, Dick; miller, ken
Subject: Section 16 draft of BM
Attachments: sec 16,p12.jpg; sec 16,p, 26.msg; sec 16,p35.jpg; sec 16,p50.jpg; sec 16,p56.jpg; sec 16,p57.jpg

Marc, As requested, attached are pages with vague text.

Among these are my two key comments:

1. SLOs will need DNR help in the pre-fpa submission and before they decide to pay a geotech. This help COULD be through the SLO or from an FP forester who at least would provide available LiDar , and geologic hazard and landslide inventory maps.
2. DNR and geotechs need a systematic, quantitative way **to communicate level or degree of "likelihood, hazard, potential, and risk"**. **For example:** 1 to10, L,M,H(5 classes preferred), % certainty...

This section 16 contains much descriptive and technical information , and step-by-step instructions. Tis generally clearly written; professionally presented.///dick miller

mountain and the river the debris flow affected (if not severely damaged) a county road, farmyard, and house sites, and more than 60+ acres of cultivated farm fields.

2.3 Deep-Seated Landslides

~~A more detailed explanation of deep-seated landslides is covered later in this section because deep-seated landslides are also landforms.~~ Regardless of failure mechanism, deep-seated landslides are those in which the slide plane or zone of movement is well below the maximum rooting depth of forest trees (generally greater than ~~three meters (10 feet or three meters)~~) and may extend to hundreds of feet in depth often including bedrock. Deep-seated landslides can occur almost anywhere on a hillslope and are typically commonly associated with hydrologic responses in permeable geologic materials overlying less permeable materials. The larger deep-seated landslides can usually be identified from topographic maps, aerial photos, and LiDAR. The runout from deep-seated landslides can also behave as earth flows depending on the type of material and failure mechanics. Deep-seated landslides developed in glacial sediments are sometimes referred to as "glacial deep-seated landslides." Complex landslides occur when a variety of types of material and movement are present.

~~Certain key areas of deep-seated landslides may be sensitive to forest practices.~~ The bodies and toes of deep-seated landslides and earth flows are made up of incoherent collapsed material weakened from previous movement, and therefore may be subject to debris slide and debris flow initiation in response to harvest or road building. Sediment delivery is common from shallow landslides on steep stream-adjacent toes of deep-seated landslides and steep side-slopes of marginal streams on the bodies of deep-seated landslides is common. More detailed descriptions of deep-seated landslides are covered in Part 5.3 and Part 5.6.

2.4 Geographic Distribution of Landslides in Washington

Landsliding is a widespread geomorphic process, actively modifying the varied topography and diverse underlying geologic materials present throughout the state. This overview focuses on areas within the state where forest practice activities are prevalent and draws from (Horsen's (1989) organization and discussion by (physiographic provinces).

The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by continental, and to a lesser extent, alpine glaciations. Unconsolidated sediments associated with glaciation include thick interlayered packages of fine-grained (glacial lake sediments) (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits. Translational and complex landslides occur within some of the very weak bedrock units exposed within the foothills and lowlands, such as the Chuckanut Formation, Darrington Phyllite, and Puget Group rocks.

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide

former

and glaciomarine silt and clay, and they often involve multiple glacial strata. During interglacial periods, layers of loess, (e.g., windblown silt and clay) and other non-glacial sediments can also be deposited between glacial units or on the surface of glacial materials and become overlain by deposits from successive glaciations. ✓

Glacial deposits and other earth materials display a wide range of hydrologic characteristics (Table 2). Glacial till generally has low permeability, comprises an unsorted and non-stratified glacial material that can range in size from clay to boulders, and is typically deposited and over run during periods when glacial ice is advancing. Glacial outwash contains typically sorted and stratified sediments deposited by water flowing from glacial ice either during the advance of the glacier or during glacial recession. Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes. Glaciomarine deposits are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

define!

Table 2. Hydrologic Properties of Soils (modified from Koloski et al., 1989)

Classification	Permeability (feet per minute)	Storage Capacity
Alluvial (High Energy)	0.01-10	0.1-0.3
Alluvial (Low Energy)	0.0001-1	0.05-0.2
Eolian (Loess)	0.001-0.01	0.05-0.1
Glacial Till	0-0.001	0-0.1
Glacial Outwash	0.01-10	0.01-0.3
Glaciolacustrine	0-0.1	0-0.1
Lacustrine (Inorganic)	0.0001-0.1	0.05-0.3
Lacustrine (Organic)	0.0001-1.0	0.05-0.8
Marine (High Energy)	0.001-1.0	0.1-0.3
Marine (Low Energy)	0.0001-0.1	0.05-0.3
Volcanic (Tephra)	0.0001-0.1	0.05-0.2
Volcanic (Lahar)	0.001-0.1	0.05-0.2

UNITS ??

Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 19). The hydrologic budget includes precipitation (rain and snow), interception by vegetation, evapotranspiration, surface storage, surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic budget that infiltrates into the subsurface below the root zone. The ground water component is composed of water within the unsaturated, or vadose zone, and the saturated zone. ✓

documents and databases (e.g., maps, geotechnical reports and studies, published and unpublished scientific literature, landslide inventories, local and regional databases containing meteorologic, hydrologic, and geologic information) to screen sites for potential slope-stability concerns, identify natural resource and public safety considerations, develop an initial interpretation of potentially unstable landforms presence/absence and landslide types, and make a determination regarding next steps in the site assessment.

Typically, the office review occurs in two steps: (1) an initial office screening conducted by the landowner or designated representative to determine if unstable slopes and landforms might be present that require field assessment, and whether a qualified expert is desired or needed for more extensive site analyses; and (2) a geotechnical office review completed by the qualified expert for suspected unstable slopes and landforms, the outcome of which potentially leads to a qualified expert conducting geotechnical field review.

6.1.1 Initial Office Screening Conducted by a Landowner or Designated Representative

The objective of an initial office review conducted by a landowner or designated representative is to: (1) identify potential or existing areas of slope instability within or adjacent to the harvest operations area; (2) delineate potential unstable landforms using definitions and type descriptions provided in Part 5 of this Board Manual section; (3) locate areas of natural resource sensitivity or public safety exposures in the vicinity of the planned operation that could be adversely affected by mass wasting processes; and (4) develop a plan for assessing potential unstable slopes and landforms in the field. This information is required on forest practices applications (FPAs) and any supplemental slope-stability informational forms required at the time of FPA submission. Designated representatives might include forest engineers, foresters, or qualified experts.

Need
Help
by
DNR
(SLO)

Summary of Procedures The office review process generally includes compiling and evaluating available maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. This initial screening is supplemented with landowner knowledge about site-specific conditions and with publicly available documents that might identify site-specific slope stability concerns or place the site in a broader landscape context with regard to potentially unstable landforms and processes (i.e., watershed analyses conducted under chapter 222-22 WAC; see Appendix D). Information sources are available to the landowner online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. Additional sources of imagery, data, maps, reports, and other documents are listed in Appendices A through E of this Board Manual section.

Relevant maps typically include surface topography and its derivatives (e.g., slope class maps), hydrology (e.g., streams and water types), geology and soils (e.g., rock units, soil types), landslides (landslide inventories and hazard zonation), and information needed to identify public safety exposures (e.g., road networks, parcel boundaries with existing building structure information). Imagery includes aerial photography and LiDAR-derived hillshade images (see Part 6.1.3 for more information) available on public websites and referenced in Appendix B. GIS with map display and analysis capabilities (e.g., ESRI ArcGIS) provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis; however, an initial screening can be performed manually without such tools if they unavailable to the landowner (i.e., by inspecting each map or image separately). Certain counties also offer an online, user-friendly, interactive version of GIS with many of the needed map and imagery products (see Appendix A). A follow-up field assessment is needed to verify results of the initial screening. It is helpful to create a site map, for

<u>Dormant-mature</u>	<u>Smooth: vegetated</u>	<u>Smooth: vegetated; tributaries extend onto body of slide</u>	<u>Smooth, rolling topography; disturbed internal drainage network</u>	<u>Different type or density than adjacent terrain but same age</u>	<u>Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain</u>	<u>5,000 to 10,000 (Early Holocene)</u>
<u>Dormant-old or relict</u>	<u>Dissected: vegetated</u>	<u>Vague lateral margins; no lateral drainage</u>	<u>Smooth, undulating topography; normal stream pattern</u>	<u>Same age, type, and density as adjacent terrain</u>	<u>Terraces cut into slide debris; uniform modern floodplain</u>	<u>> 10,000 (Late Pleistocene)</u>

Decision flow chart

The following decision pathway was developed by the DNR as a guide to the assessing the risk associated with landslides. Generally, the pathway is defined by the level landslide activity and how likely the landslide is to deliver sediment to public resources. The decision pathway uses a glacial deep-seated landslide and associated groundwater recharge area as an example for how a qualified expert would assess the risk associated with the landform. The same decision pathway may be used for other types of deep-seated landslides.

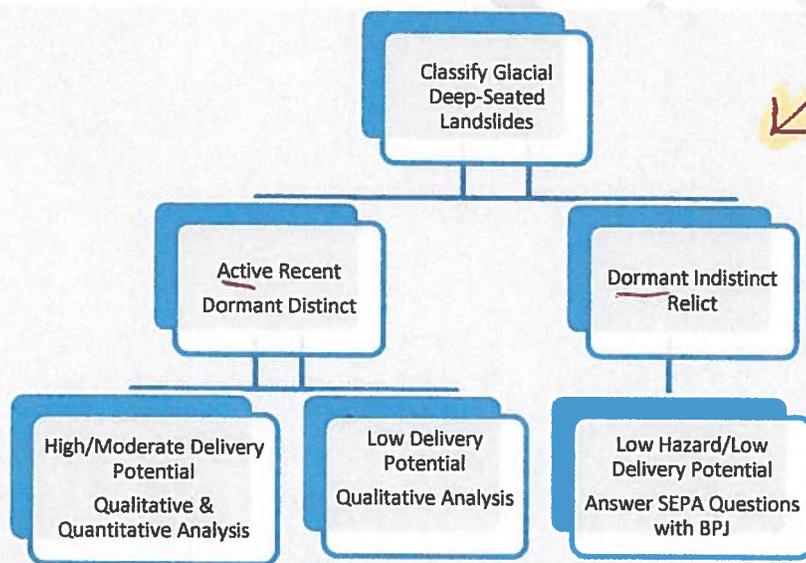


Figure 25 Decision pathway for implementing qualified expert investigations of groundwater Recharge area harvests for glacial deep-seated landslides (DNR Forest Practices Division).

1. Identify and map glacial deep-seated landslides and groundwater recharge areas
2. Classify landslides using the Landslide Hazard Zonation (LHZ) protocol (modified from Keaton and DeGraff, 1996) for deep-seated landslides as:
 - a. active
 - b. dormant/distinct
 - c. dormant/indistinct
 - d. relict
3. Map landslides and related up-gradient groundwater recharge areas and calculate areas.

7. What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identifying, delineating, and interpreting of unstable slopes and landforms?
8. What is the **potential** for material delivery from each identified unstable slope and landform to areas of natural resources sensitivity or public safety (see Parts 7.4)?
9. What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
10. What level of confidence is placed in the identification, delineation, and interpretation of unstable slopes and landforms? How does the confidence level impact any recommendations provided by the qualified expert for unstable slope management and/or mitigation?

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Documentation of the project analysis and synthesis process might take the form annotated images (e.g., LiDAR-derived hillshades, aerial photos), of geologic or topographic profiles, maps, sketches, results of subsurface investigations, summaries of computational or simulation modeling, summaries of available (i.e., previously published) information and remotely sensed or field-derived data and text to explain the concrete evidence and logical train-of-thought for the conclusions and recommendations that will be presented in the geotechnical report. The only conclusions that should be included in the geotechnical report are those that can be substantiated by the presented evidence, and the logical thought process established in the analysis and synthesis process. For instance, interpreted geologic profiles used to evaluate potential groundwater recharge areas should be commensurate with the subsurface information provided in the report and should relate to the proposed project.

Field observation and sampling locations used in project analysis and synthesis should be displayed on a map in the geotechnical report. Descriptive, photo, or data-sampling observation points should be geo-referenced (i.e., with GPS waypoints). Mapped GPS track locations for field traverses also are recommended, so that it is clear which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced.

Models, such as those for slope stability and sensitivity (see Parts 7.2 and 7.3) may be used to support analyses of unstable slope and landform characteristics and mechanics. Model results, however should not be incorporated in report findings without an adequate assessment and clear statement of their assumptions, limitations, and alignment with existing information (e.g., field data). For example, a modeled reconstruction of landslide failure-plane geometry based on one borehole or drive probe sample likely is misleading and could result in spurious conclusions.

The analytical methods used to identify, delineate, and interpret unstable slopes and land forms should be described in the geotechnical report, along with information sources, data processing techniques, and the meaning and limitations of analysis results. Geotechnical reports should describe all assumptions regarding input parameters or variables, such as groundwater surface elevation estimates employed in stability sensitivity analyses, as well as the reasoning for their use. Geotechnical reports also should include an assessment of the sensitivity of the analytical method or model results to parameter variability, especially where only a range of parameter values is available or where input values are extrapolated or estimated from other locations or databases.

The analytical process being used should be described, along with the types of information needed, how data are processed, and the meaning and limitations of potential results. Assumptions such as groundwater levels should be described, including the reasoning for their use. Variability of

parameters should be described along with strength values or other data developed during the synthesis. The results of the analyses for each assumption or variation should be described.

The report conclusions document the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the assessment, including the office and field reviews, qualitative information and data analyses, geo- and hydro-technical modeling, and evaluation of material deliverability. Conclusions should describe the suitability of the site for the proposed activity. Report conclusions also should clearly state the likely direct and indirect effects of the proposed activity or use on the geologic environment as well as the likely direct and indirect effects of geologic processes on the proposed activity.

* The qualified expert should provide a concise statement of confidence in and limitations of the slope stability analysis and its conclusions. Confidence levels are influenced by many factors, including project complexity and objectives, site characteristics (e.g., acreage and accessibility), project timeframes, quantity and quality of available information (e.g., reports, databases) and remotely sensed data, accuracy and precision of field observations and collected data, and the rigor of available analytical methods and models. A discussion of the primary limiting factors assists the landowner and report reviewer in evaluating the potential natural resource, public safety, and liability risks associated with implementing a project.

metrics?

The geotechnical report might include recommendations regarding additional work needed to supplement the qualified expert report, including but not limited to monitoring of geologic conditions (e.g., ground water, slope movement), review of plans and specifications, and construction and/or timber harvest monitoring. The qualified expert also might be asked by the landowner to provide or evaluate possible mitigation measures for destabilized slopes or landforms.

PART 8. GEOTECHNICAL REPORTS

When harvesting or building roads on potentially unstable slopes a geotechnical report is required to explain how the proposed forest practice is likely to affect slope stability, delivery sediment and debris to public resources, and threaten public safety. The applicant must also submit to DNR a State Environment Policy Act (SEPA) checklist and additional information as described in WAC 222-10-030. These Geotechnical reports must be prepared by qualified experts and must meet the requirements as described in WAC 222-10-030(5).

metric

Effective July 1, 2002, qualified experts must be licensed with Washington's Geologist Licensing Board. For more information on the geologist licensing process, refer to WAC 308-15-010 through 308-15-150, or visit the Geology Board's web site at (www.dol.wa.gov/business/geologist). The education and field experience on forestlands will still be required, in addition to the appropriate geologist license.

8.1 Guidelines for Geotechnical Reports

The following elements (a-f) should be included in geotechnical reports submitted by qualified experts:

- (a) *Prepare an introductory section.* This section should describe the expert's qualifications of the expert to ensure he/she meets the aforementioned requirements. It should also reference the forest practices application number (if previously submitted), the landowner(s) and operator(s) names, and a brief description of field trip(s) to the area, including dates, relevant weather

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Science Representative

MEMORANDUM

To: Marc Ratcliff

From: Paul Kennard, Kara Whittaker, and Chris Mendoza for the Forests and Fish Conservation Caucus

Re: Comments on the Revised Board Manual, Section 16

Date: 8 October 2014

OVERVIEW

The Forests and Fish Conservation Caucus supports DNR's effort to improve the Forest Practices Board Manual Section 16 and particularly applauds the decision to include the entire Unstable Slopes and Landforms section in this revision. However, we have serious concerns with several parts pertaining to glacial deep-seated landslides. In this letter, we only comment on these parts of the revised Board Manual.

Below, we start off with summary conclusions, followed by our major comment, and then other points of note—all intended to improve the proposed Board Manual revisions and minimize the risk to public resources and public safety associated with forest practices. We also propose the addition of a Glacial Deep-Seated Landslide Risk Matrix to the revised Board Manual and provide recommended language. The Risk Matrix concept was prompted by discussion with Forest Practices Board members.

Additionally, we are submitting comments (attached in pdf format) of the Board Manual itself. In both documents, we state our comments and we suggest alternate wording where appropriate. This is, in part, because the Conservation Caucus representatives were relegated to an observer role only during meetings of the DNR Expert Panel that crafted this Board Manual draft.

CONCLUSION

The Board Manual fails to provide adequate guidance to meet specific requirements for the implementation of forest practices rules for glacial deep-seated landslides. This is, in part, because the Board Manual is insufficiently directive in stating the need for subsurface information for delineating the ground water recharge areas (GWRA) of glacial deep-seated landslides (GDSLs), modeling groundwater flow, and assessing slope stability.

Additionally, it is impossible to assess landslide run-out volumes or distances without delivery estimation methodologies. This revision provides none. While we understand that the next phase of the Board Manual revision will address this, as it stands, the Board Manual is deficient.

MAJOR POINTS

1. The Board Manual is not sufficiently directive on the need for subsurface information.

Without subsurface information, it is impossible to accurately (1) delineate the groundwater recharge area, (2) assess the slope stability, and (3) quantify the effects of forest practices on a glacial deep-seated landslide with the necessary certainty to protect the public and public resources. Additionally, it is impossible to correctly model groundwater flow, if that analyses method is used.

There are numerous examples (e.g., p. 47) where the Board Manual uses the word “may” in reference to the need for subsurface information, when the words “should” or “must” are needed. We provide comments in the attached pdf on each of these instances.

a. Delineating the GWRA

In the ‘Field Review Assessment for Groundwater Recharge Areas’ (section 6.4.2, p. 45) the Board Manual states that a field inspection is “*necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation.*” The Board Manual additionally asserts the method “*may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.*” Despite this, no additional, directive guidance on specific field methods necessary to accurately delineate the GWRA are given. Rather, the guidance describing subsurface investigation is characterized as optional.

On p. 46, the Board Manual states: “*During field review it is important to examine the characteristics of the surface materials within the groundwater recharge area and document that the soil types and **subsurface** geologic units are consistent with those mapped for the location of interest.*” (Emphasis added). It is an impossible task for a surface investigation to reveal the subsurface controls to the actual GWRA. It is imperative that the Board Manual prescribe other, data-driven methods, including those reliant on detailed subsurface data.

More comments on the need for subsurface data and the limitations of a topographically defined GWRA follow.

b. Slope stability assessment

In section 7.3, ‘Computational Slope Stability Assessment Methods’ (p. 53), the Board Manual directs “*All of the above steps require considerable engineering geologic/geotechnical data (e.g., subsurface, instrumentation, laboratory) and expertise to achieve an accurate and meaningful representation of the actual conditions at the site.*” While the need for additional subsurface data is stated directly here, the overall impression of the Board Manual is that field and office examinations of surficial topographic data are sufficient for GWRA delineation.

c. Ground water modeling

The same considerations apply to section 7.2.2 ‘Groundwater Recharge and Groundwater Flow Modeling’. In Table 2 (p. 26) ranges of values are given for subsurface soil parameters intended for use in delineating the GWRA, modeling groundwater, and assessing landslide stability. However, these parameters vary over several orders of magnitude, up to one million percent (%). A sensitivity analysis using these ranges of model input parameters on ground water modeling or a stability assessment, for example, would show that there is an unacceptable level of uncertainty in the outcome. This supports the idea of the Board Manual providing more specific methods and analyses regarding the collection of site-specific subsurface information for groundwater modeling rather than simply picking from a wide range of values. This direction should be made more explicit in order to avoid high uncertainty in model outputs. The need for sensitivity assessments based on site-specific field data is also mentioned

on p. 56. It is important that this message is consistent throughout the Board Manual and includes site-specific subsurface data.

POINTS OF NOTE

1. Available information

The Board Manual states (p. 4): “*Qualified experts must rely on...a comprehensive review of relevant available information.*” This implies only “available” information is needed and should be corrected to include new information, such as subsurface data, that may not be available at the time of review but could be generated if needed in order to complete a more accurate assessment of site-specific conditions.

2. Forest roads

On p. 5, describing the Rule-identified landforms, the Board Manual lists “... *the influences from potential increases in precipitation available for groundwater recharge from tree removal through forest practice activities.*” The effect of forest roads on the groundwater recharge area is omitted. Forest roads can affect recharge by pirating surface and near subsurface flow from outside the natural GWRA into it and concentrating water within a GWRA.

Later in the Board Manual, contributions to the GWRA from non-glacial geologic units are discussed (p. 27). A road can potentially add to these sources. Please see our comment on this below.

3. Topographic identification of landslides

On p. 12, the Board Manual states: “*The larger deep-seated landslides can usually be identified from topographic maps...*” This implies, correctly, that smaller deep-seated landslides cannot easily be identified using this method. This points to the need for (a) stating that field inspection is required in areas potentially having GDSLs, and (b) the Board Manual to supply better resolution maps of the distribution of deep-seated landslides in Washington State (so a practitioner can tell if the area potentially has a GDSL). Please see comment below.

4. Glacier distribution map

Figures 18a and b (p. 25), depicts the extent of past glaciation in the state. The accompanying description in the text (p. 24) lacks adequate specificity to determine if a particular tract is in an area prone to GDSLs, and the maps lack sufficient resolution for the same purpose. At a minimum, a higher resolution map should be included, that contains both alpine and continental glacier extents (like Figure 18b). Additionally, Figure 18a, with its stated “unknown origin”, should not be used unless its accuracy is verified. We recommend replacing Fig. 18a-b with one statewide figure depicting the “ice limit” (DGER feature) of continental glaciation and the extent of alpine glaciation in the Olympics and Cascades. If a proposed forest practice is within the mapped glacier extent area, the Board Manual should state a field visit is needed to verify the presence or absence of GDSLs.

5. Non-glacial contribution to the GWRA

On page 27, the Board Manual states: “*Groundwater recharge to a glacial deep-seated landslide may originate as recharge to an adjacent non-glacial geologic unit that flows into glacial sediments, or it may run off from upland nonglacial geologic units and recharge within glacial sediments. A component of groundwater recharge can be surface flow.*”

We applaud the inclusion of the non-glacial sources of water. The Board Manual should also explicitly declare that the effect of forest practices on these water sources must be quantified, including surface flow. Please see our earlier comment on forest roads, as they can bring water into the GWRA. We propose language to this effect in the attached pdf.

6. Department of Ecology (DOE) well database

On p. 44-45 of the Board Manual, the DOE searchable well database is mentioned as a source of subsurface hydrogeologic information. In our experience, few to none of these wells are in commercial forests, and in reality their utility for GDSLs is low.

7. Topographic delineation of the groundwater recharge area is insufficient.

On p. 29 and after, the Board Manual states that, as a 1st approximation, the GWRA can be defined topographically.

Page 45, the Board Manual states: “*Figure 24 shows the groundwater recharge area for a landslide based on upslope topographical delineation.*” The figure appears to be the Hazel slide, reversed out, which is confusing and unnecessary. Of more concern, there are no contours on the figure, so it is unclear how the GWRA was derived. Additionally, the GWRA pictured is not consistent with the actual topographically-defined GWRA. Lastly, this is a poor example to suggest delineation of a GWRA solely by topographic means is sufficient.

8. Inappropriate cost (\$) considerations in method selection for conducting subsurface investigations.

On pages 47 and 48 (6.5, ‘Quantitative Field Review Method for Subsurface Investigations’) the Board Manual makes statements regarding landowner’s consideration of “cost and time” when choosing a method for subsurface investigations. This section should be devoted solely to technical recommendations on methods as they directly relate to the quality and quantity of information that each method will provide in order to accurately assess subsurface conditions, and thereby decrease uncertainty, *not* how much money (\$) they will cost. The existing language could be interpreted as suggesting that landowners may choose a “quick and dirty” method (low cost and time saving) even if that method is inadequate for the job at hand – to accurately assess subsurface conditions. Weighing the monetary costs of what landowners are willing to provide for subsurface investigations against the risks to public safety would not be prudent. Rather, providing a table that compares and contrasts specific quantitative field methods regarding their appropriate use / non-use for decreasing uncertainty would be more helpful.

GLACIAL DEEP-SEATED LANDSLIDE RISK MATRIX

Section 6.5 ‘Quantitative Field Review Methods for Subsurface Investigations’ describes a range of geotechnical methods for quantitatively assessing the hazard associated with deep-seated landslides via subsurface investigation. The list of methods described in this section vary widely in the level of certainty of and confidence in the information they can provide, which directly influences the level of risk to public resources or public safety if an inappropriate type of mitigation is prescribed. Hence, we constructed the following draft GDSL Risk Matrix to be added as a new section to the revised Board Manual. Its intent is to provide guidance to DNR for use in FPA classification. We envision a similar matrix can be designed to address similar variability in the level of certainty and confidence among methods presented for delivery assessment in Phase 2 of the Board Manual revision. Then these two matrices can be combined to determine the appropriate level of mitigation for a particular proposal.

(DRAFT) PART X. GLACIAL DEEP-SEATED LANDSLIDE RISK MATRIX

The quality and quantity of information known about the hydrogeologic framework of a glacial deep-seated landslide (GDSL) and its groundwater recharge area (GWRA) are directly related to the certainty and confidence in 1) the likelihood that forest practices will trigger further movement of the GSDL, 2) the likelihood of delivery of sediment and debris to public resources or infrastructure, and 3) the adequacy of proposed mitigation measures. If an inadequate amount and/or poor quality of information is available or sought regarding the investigation and assessment of the hydrogeologic framework of a GDSL and its GWRA, then there will be high uncertainty and hence, low confidence in the product or outcome. Consequently, the likelihood public resources, public safety, and infrastructure will be impacted by forest practices will increase and the adequacy of proposed mitigation measures will decrease (and vice versa). Low certainty and confidence in a geotechnical assessment and/or report can result from project limitations (e.g., quantity or quality of technical information available, inadequate methods, site access, project timeframe) and/or scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that influence the accuracy and precision of identifying, delineating, and interpreting unstable slope and landform initiation and delivery. High certainty and high confidence in a geotechnical assessment depends on an accurate and meaningful representation of actual surface and subsurface site conditions.

The following GDSL Risk Matrix was developed as guidance for DNR on relating the certainty and confidence levels of a range of geotechnical methodologies to the potential risk to public resources or public safety for proper classification of Forest Practices Applications under WAC 222-20-010(9). The appropriate FPA classification will also depend on the potential for the GDSL to deliver sediment or debris to a public resource or threaten public safety (WAC 222-16-050(1)(d)).

Information type	Examples	Limitations/ Specifications	Level of certainty/ confidence	Potential risk to public resources or public safety (mitigation)
Surface topography	30 m or LiDAR DEM, GPS	No geologic or hydrologic data	Low / Low	High (avoid)
Geophysical: shallow	Test pits, hand augers, hand probes	Depth of perched groundwater table may remain unknown	Low / Low	High (avoid)
Geophysical: deep	Ground penetrating radar, electromagnetic, resistivity, and seismic methods	Snapshot in time, regional data source	Low / Low	High (avoid)
		Snapshot in time, site-specific data source	Moderate / Low	Moderate (avoid)
	Drill rig: single sample	Snapshot in time	Low / Low	High (avoid)
Hydrologic	Groundwater monitoring wells	Longitudinal, regional data source	Moderate / Moderate	Moderate (avoid)
		Longitudinal, site-specific data source	High / High	Low (potential to manage)

Conservation Caucus Board Manual Comments
 October 8, 2014

Hydrogeologic modeling	Deep Percolation Model, Precipitation Runoff Modeling System, Variable Infiltration Capacity Model, Limit Equilibrium Analysis	Extrapolated regional data input and/or high margin of error	Moderate / Low	Moderate (avoid)
		Site-specific data input and/or low margin of error	High / High	Low (potential to manage)

In conclusion, the Forests and Fish Conservation Caucus appreciates the opportunity to comment on this important issue. We ask that the identified issues please be addressed before the revised Board Manual is adopted. Please address any questions to our caucus Policy representative, Mary Scurlock (Mary.Scurlock@comcast.net).

Section 16

Guidelines for Evaluating Potentially Unstable Slopes and Landforms

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PART 1. INTRODUCTION

~~This section of the board manual provides guidelines to evaluate potentially unstable slopes and landforms. It can be used to determine if additional information or a detailed environmental statement will be required before the submittal of a forest practices application for timber harvest or the construction of roads, landings, gravel pits, rock quarries, or spoil disposal areas on potentially unstable slopes or landforms that have the potential to deliver sediment or debris to a public resource or have the potential to threaten public safety.~~

~~It begins with an overview of the forest practices rules for potentially unstable slopes, which unstable landforms that are of concern, and the effects of landslides. Also included are important tools and concepts that can be used to determine if slopes are potentially unstable, descriptions of~~

~~rule-identified unstable slopes and landforms, information and guidance on how to identify potentially unstable slope situations, the influence of forest practices activities on slope stability, and how to determine if delivery of material to public resources could occur. If you need to hire a qualified expert, guidelines for the contents of the expert report are listed at the end of this Section. The Forest Practices Board Manual is not a rule.~~ The objective of the manual is to provide guidance pathways which, if followed, meet the requirements for the implementation of forest practices rules. This section of the Board Manual provides guidelines to evaluate potentially unstable slopes and landforms and includes guidance to determine the potential to deliver sediment or debris to a public resource or threaten public safety.

The described processes for analysis in combination with professional judgment will allow the field practitioner and the qualified expert to determine the need for additional geologic analysis and mitigation, or if a detailed geotechnical analysis is required as part of an environmental assessment under the State Environmental Policy Act (SEPA) with a forest practices application (FPA).

This section features an overview of the forest practices rules for potentially unstable slopes, unstable landforms of concern, and the direct and indirect effects of landslides on public resources and public safety. The main body of the manual section includes:

- Tools to be used to determine the potential instability of slopes, descriptions of rule-identified landforms¹ and other unstable or potentially unstable landforms (Part 3 and Part 4);
- How to identify areas with potentially unstable slopes (Part 5);
- How to identify and assess activity level of unstable slopes and landforms (Part 6 and Part 7);
- Guidelines for qualified experts to prepare geotechnical reports (Part 7 and Part 8); and
- The section includes a glossary of terms, a list of references used throughout the document, and appendices listing resources for analysts.

The intended audience is general practitioners (landowners, foresters, engineers) and qualified experts². The goal is to provide information on relevant assessment techniques and certain tasks to be conducted by a qualified expert. It is not intended to be a comprehensive guidance document for the evaluation of unstable or potentially unstable slopes. Qualified experts must rely on personal experience, professional judgment and a comprehensive review of relevant available information.

PART 2. OVERVIEW

~~Landslides occur naturally in forested basins and landform erosion is and are an important process in the delivery of wood and gravel to streams and near shore environments. Wood and gravel play significant roles in creating stream diversity that is essential for fish use as habitat and spawning grounds (e.g., Reeves et al., 1995; Geertsema and Pojar, 2007; Restrepo et al., 2009). In the past, Under past forest practices rules, forest practices-caused landslides have accelerated contributed to~~

¹ "Rule-identified landform" is a commonly used term for the landforms listed in WAC 222-16-050(1). They are listed in Part 2 of this Board Manual section.

² "Qualified expert" is defined in WAC 222-10-030(5).

the acceleration of naturally occurring landslide processes (e.g., Swanson et al., 1977; Robinson et al., 1999; Montgomery et al., 2000; Turner et al., 2010) and may have contributed to the threatened and endangered status of certain species, (e.g., Sidle et al., 1985; Beechie et al., 2001) as well as endangering endangered human life in some instances (e.g., Oregon Landslides and Public Safety Project Team, 2001). The forest practices rules are intended meant to protect public resources and prevent threats to public safety. The rules apply where therewhen it is determined the proposed forest practices activities may contribute to the potential for sediment and debris to be delivered to a stream, lake, marine water or, other fish or and wildlife habitat, domestic water supplies, or public capital improvements, or to cause a threat to public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety is should be considered. Many factors are part of that consideration must be considered including initial failure volume, and the nature of at the landslide, landslide runout distance, and landscape geometry slope or channel conditions to determine the potential to deliver to a public resource or threaten public safety.

2.1 Potentially Unstable Landforms

Certain landforms are particularly susceptible to slope instability or indicate past slope instability. Consequently, Because of this forest practices applications (FPAs) that propose activities on and near these landforms may be classified “Class IV-special” and receive additional environmental review under the State Environmental Policy Act (SEPA). Such rRule-identified unstable landforms that are as described in WAC 222-16-050 and Part 5 of this Ssection include consist of following:

- Inner gorges Bedrock hollows, convergent headwalls, and inner gorges and bedrock hollows with slopes >70% (35° degrees). These landforms are susceptible to shallow landslides including debris flows and earth flows;
- Toes of deep-seated landslides with slopes >65% (33°). This landform is susceptible to re-activated rotational or translational sliding, debris and earth flows and lateral spreads;
- Groundwater recharge areas for glacial deep-seated landslides. This landform is the influences from potential increases in precipitation available for groundwater recharge from tree removal through forest practice activities;
- Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream. These landforms are susceptible to rotational sliding, debris flows, and earth flows;
- And other indication of slope instability. Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes. For example, areas that may contain features indicating the presence of potential slope instability include the bodies of a glacial deep-seated landslides and deep-seated landslides developed in non-glacial materials.

Landslide is a general term for any downslope movement of rock, unconsolidated sediment, soil, and/or organic matter under the influence of gravity. The term also refers to the deposit itself, and slide materials in mountainous terrain typically are separated from more stable underlying material by a zone of weakness variously called the failure zone, plane, or surface. Landslides can be classified in several different ways. The method adopted here (see Part 2.1) is to describe the type of movement (fall, topple, slide, spread, or flow) and the type of material involved (rock, soil, earth, or debris). The failure surface can be roughly planar, in which case

the slide is called “translational”; or curved, in which case it is called “rotational” or a combination of failure surface geometries (Figures 1). Translational failures also can occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes (Robinson et al., 1999; Turner et al., 2010), with little observed rotation or backward tilting of the slide mass. Landslides can be small volumetrically (a few cubic yards) or very large (cubic miles). They can range from very fast moving, as in free fall, to very slow, as in creep. Landslides can come to rest quickly or can continue to move for years or even centuries. Landslides can stop moving only to be later reactivated and are considered dormant slides. A landslide can also permanently cease moving and undergo erosion and revegetation over long periods of geologic time and is considered a relict slide.

Landslides can be grouped into two major categories: deep-seated landslides which fail below the rooting depth of vegetation, or shallow landslides which fail within the vegetation rooting zone. Shallow landslides tend to respond to rainfall events over periods of days or weeks; deep-seated slides may respond to rainfall events over periods of days to weeks, or to weather patterns over months to years or even decades (Washington State Department of Emergency Management, 2013).

Ground failures resulting in landslides occur when gravitational forces, in combination with soil and other factors, overcome the strength of the soil and rock in a slope. Contributing factors can include:

- The presence of an impermeable stratigraphic layer beneath a permeable stratigraphic layer.
- Saturation, by rain on snow events or heavy and/or prolonged rains that can saturate soils and create instability in soil and weakened or weathered bedrock.
- Erosion by rivers, glaciers, or ocean waves that over-steepen slopes or result in removing support from the base of the slopes.
- Ground shaking caused by earthquakes that increase the driving force and weaken the supporting soils structure.
- Volcanic eruptions that produce lahars and instability on the lateral flanks of the volcano.
- Excess weight from accumulation of rain or snow, stockpiling of rock or earth from waste piles, or manmade structures that exert excessive stress on slopes.
- Human activities, such as construction, logging, or road building that disturbs soils and weakens or removes the support for slopes, increases runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.

Landslides are most likely to occur where certain combinations of geologic materials are present, for example, groundwater percolating through porous and permeable sands and gravels and perching on underlying layers of impermeable silt and clay. At this interface, increased groundwater pore pressure can weaken and cause failure of the overlying sand and gravels. This combination is common and widespread in the Puget lowlands. Specifically, glacial outwash sand, locally called the Esperance Sand or Vashon advance outwash, overlies the fine-grained soils, locally called the Lawton Clay or transitional bed, giving rise to over steepened bluffs with benches composed of the perching layer. Similar conditions exist in many bluffs of the greater Puget Sound area (Tubbs, 1974).

2.1 Landslide Types and Effects

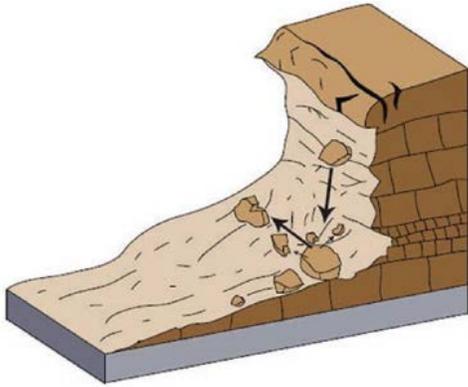
Several classification schemes are used by geologists, engineers and other professionals to identify and describe landslides. The classification scheme of Varnes (1978), modified by the U.S. Geological Survey (U.S. Geological Survey, 2004), is used for the purposes of this Board Manual section (see Table 1).

Table 1. Landslide Classification

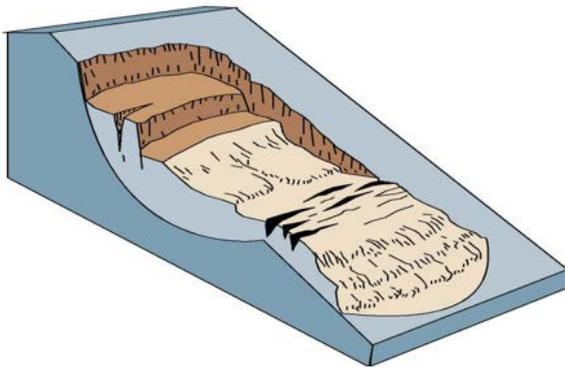
(U.S. Geological Survey (2004), modified from Varnes (1978)).

<u>Type of Movement</u>		<u>Type of Material</u>		
		<u>Bedrock</u>	<u>Soils</u>	
			<u>Predominately Coarse</u>	<u>Predominately Fine</u>
<u>Falls</u>		<u>Rock Fall</u>	<u>Debris Fall</u>	<u>Earth Fall</u>
<u>Topples</u>		<u>Rock Topple</u>	<u>Debris Topple</u>	<u>Earth Topple</u>
<u>Slides</u>	<u>Rotational</u>	<u>Rock Slide</u>	<u>Debris Slide</u>	<u>Earth Slide</u>
	<u>Translational</u>			
<u>Lateral Spreads</u>		<u>Rock Spread</u>	<u>Debris Spread</u>	<u>Earth Spread</u>
<u>Flows</u>		<u>Rock Flow</u>	<u>Debris Flow</u>	<u>Earth Flow</u>
<u>Complex</u>		<u>Combination of two or more principal types of movement</u>		

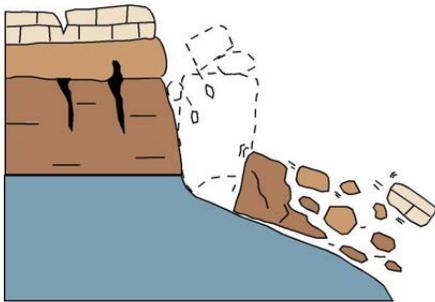
In this scheme landslides are classified by the type of material and the type of movement. Material in a landslide mass is either rock or soil (or both) and may also include organic debris. Soil is described as earth if mainly composed of sand-sized or finer particles and debris if composed of coarser fragments. The types of landslides commonly found in forested areas in Washington include slides, flows, and complex landslides. The type of movement describes the actual internal mechanics of how the landslide mass is displaced: fall, topple, slide, spread, or flow. Thus, landslides are described using two terms that refer respectively to material and movement (rockfall, debris flow, and so forth). Landslides may also occur as a complex failure encompassing more than one type of movement (e.g., debris slide - debris flow). Simplified illustrations of the major types of landslides are presented in Figure 1.



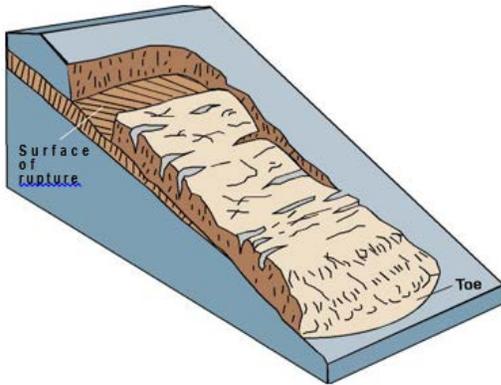
Falls: Falls occur when a mass of rock or soil detach from a steep slope or cliff, often caused by undercutting of the slope. The failure is typically rapid to very rapid. The fallen mass may continue down the slope until the terrain flattens (from Highland and Bobrowsky, 2008).



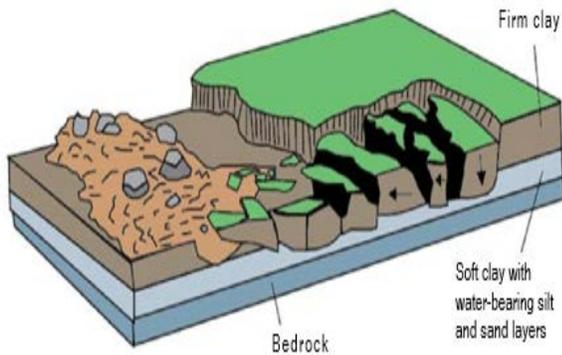
Rotational slides: Landslides on which the surface of rupture is concave-up and the slide movement is rotational about an axis that is parallel to the contour of the slope. Glacial deep-seated landslides can be rotational slides developed in glacial sediments common in the Puget Sound area, but they can also involve more complex types of movement (from Highland and Bobrowsky, 2008).



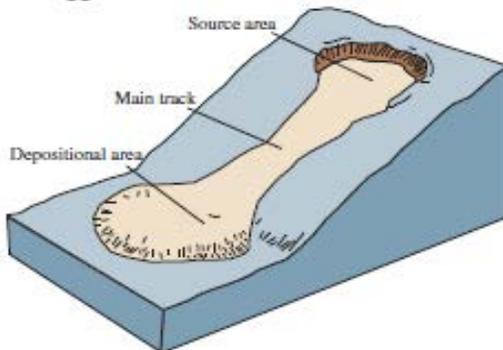
Topples: Topples are the forward rotation out of the slope of a mass of rock or soil. The failure rates range from extremely slow to extremely fast (from Highland and Bobrowsky, 2008).



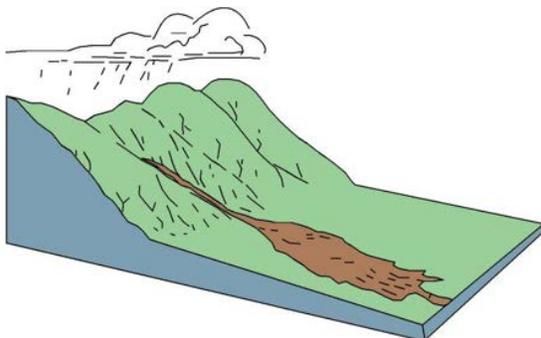
Translational slides: Landslides on which the surface of the rupture is roughly planar (from Highland and Bobrowsky, 2008).



Lateral spreads: Landslide that generally occurs on very gentle or level slopes caused by subsidence of a fractured mass of cohesive material into softer, often liquefied, underlying material (from Highland and Bobrowsky, 2008).



Earth flows: Landslide consisting of fine-grained soil or clay-bearing weathered bedrock. Can occur on gentle to moderate slopes flow (from U.S. Geological Survey, 2004).



Debris flows: Landslide in which loose rock, soil, and organic matter combine with water to form a slurry that flows rapidly downslope (from Highland and Bobrowsky, 2008).

Figure 1 Illustrations of the major types of landslide movement.

Some of the landslide types shown in Table 1 can be further divided into shallow or deep-seated landslides depending on whether the failure plane is above (shallow) or below (deep) the rooting depth of trees.

2.2 Shallow Landslide Types

Shallow landslides typically fail within the vegetation rooting zone and tend to respond to rainfall events over periods of days or weeks. Shallow landslides can occur in bedrock hollows, convergent headwalls, and inner gorges with slopes > 56%, and on toes of deep-seated landslides with slopes > 65%, and, on the outer edges of meander bends, and other areas with steep slopes. There are generally three types of shallow landslides: debris slides, debris flows, and hyper-concentrated floods. They are distinguished from each other by the ratio of water to solids contained in them.

Debris slides consist of aggregations of coarse soil, rock, and vegetation that lack significant water and move at speeds ranging from very slow to rapid down slope by sliding or rolling forward. The results are irregular hummocky deposits that are typically poorly sorted and non-stratified. Debris slides include those types of landslides also known as shallow rapid, soil slips, and debris avalanches. If debris slides entrain enough water they can become debris flows.

Debris flows are slurries composed of sediment, water, vegetation, and other debris. Solids typically constitute >60% of the volume (Pierson and Scott, 1985). Hyper-concentrated floods are a subset of debris flows containing a mixture of water and sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains they are commonly caused by the collapse of dams such as those formed by landslide dams or debris jams (Figure 2). Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel, and the active floodplain if present. Debris flows usually occur in steep channels, as landslide debris becomes charged with water (from soil water, or on entering a stream channel) and liquefies as it breaks up. Channelized debris flows often entrain material and can significantly bulk in volume during transport. These landslides can travel thousands of feet (or even miles) from the point of initiation, scouring the channel to bedrock in steeper channels. Debris flows commonly slow where the channel makes a sharp bend and stop where the channel slope gradient becomes gentler than about 3 degrees, or the valley bottom becomes wider and allows the flow to spread out. Hyper-concentrated floods may travel greater distances and at shallower slopes than debris flows, based on their water content (Iverson, 1992).

~~Hyper-concentrated floods are flowing mixtures of water, sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains, they are commonly caused by the collapse of dams, such as those formed by landslide dams or debris jams (Figure 1). Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-~~

induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel and, if present, the active floodplain.

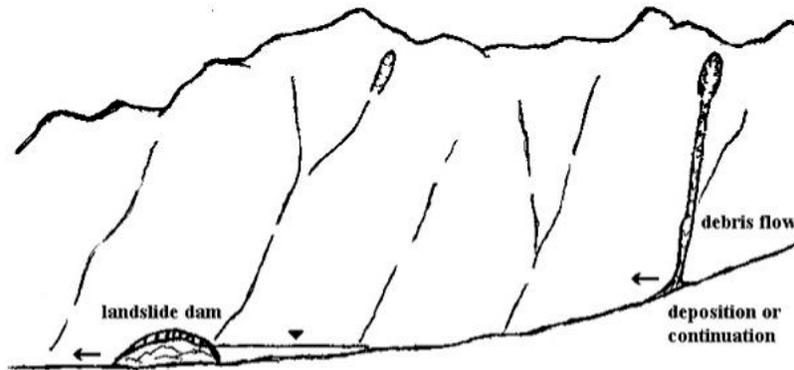


Figure 24. Debris flows, and hyper-concentrated floods

Debris flows and hyper-concentrated floods can occur in any unstable or potentially unstable terrain with susceptible valley geometry. In natural systems, debris flows and hyper-concentrated floods caused by dam-breaks are responsible for moving sediment and woody debris from hillslopes and small channels down into larger streams. But debris flows can also cause damage to streams by scouring channel reaches, disturbing riparian zones, impacting habitat and dumping debris onto salmonid spawning areas. Debris flows can cause elevated turbidity, adversely affect water quality downstream, pose threats to public safety, and damage roads and structures in their paths (Figure 32).



Figure 32. Road-initiated debris flows in inner gorges, Sygitowicz Creek, Whatcom County (Photo: DNR, 1983).

These debris flows shown in Figure 3 coalesced, and after exiting the confined channel at the base of the mountain, formed a new debris flow spreading across a 1,000-foot wide swath for a distance of 2,000 feet before entering the South Fork Nooksack River. Between the base of the

mountain and the river the debris flow affected (if not severely damaged) a county road, farmyard, and house sites, and more than 60+ acres of cultivated farm fields.

2.3 Deep-Seated Landslides

~~A more detailed explanation of deep-seated landslides is covered later in this section because deep-seated landslides are also landforms.~~ Regardless of failure mechanism, deep-seated landslides are those in which the slide plane or zone of movement is well below the maximum rooting depth of forest trees (generally greater than ~~three meters~~ (10 feet or three meters)) and may extend to hundreds of feet in depth often including bedrock. Deep-seated landslides can occur almost anywhere on a hillslope and are typically commonly associated with hydrologic responses in permeable geologic materials overlying less permeable materials. The larger deep-seated landslides can usually be identified from topographic maps, aerial photos, and LiDAR. ~~The runout from deep-seated landslides can also behave as earth flows depending on the type of material and failure mechanics. Deep-seated landslides developed in glacial sediments are sometimes referred to as “glacial deep-seated landslides.” Complex landslides occur when a variety of types of material and movement are present.~~

~~Certain key areas of deep-seated landslides may be sensitive to forest practices.~~ The bodies and toes of deep-seated landslides and earth flows are made up of incoherent collapsed material weakened from previous movement, and therefore may be subject to ~~debris slide and~~ debris flow initiation ~~in response to harvest or road building.~~ Sediment delivery is common from shallow landslides on steep stream-adjacent toes of deep-seated landslides and steep side-slopes of marginal streams on the bodies of deep-seated landslides ~~is common.~~ More detailed descriptions of deep-seated landslides are covered in Part 5.3 and Part 5.6.

2.4 Geographic Distribution of Landslides in Washington

Landsliding is a widespread geomorphic process, actively modifying the varied topography and diverse underlying geologic materials present throughout the state. This overview focuses on areas within the state where forest practice activities are prevalent and draws from Thorsen’s (1989) organization and discussion by physiographic provinces.

The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by continental, and to a lesser extent, alpine glaciations. Unconsolidated sediments associated with glaciation include thick interlayered packages of fine-grained glacial lake sediments (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits. Translational and complex landslides occur within some of the very weak bedrock units exposed within the foothills and lowlands, such as the Chuckanut Formation, Darrington Phyllite, and Puget Group rocks.

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide

complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower reaches of the Quinault, Queets, Hoh, and Bogachiel valleys. Large rock slides and rock avalanches are common in the steep upper reaches of Olympic mountain drainages. Translational landslides and large landslide complexes are also abundant in the very weak marine sedimentary rocks (often occurring along inclined bedding surfaces) and mantling residual soils in the western and northwestern portions of the Peninsula, such as the Twin Creek Formation, and the Western Olympic and Hoh Lithic Assemblages (Tabor and Cady, 1978; Badger, 1993). Debris flows and avalanches are often generated in steeper drainages and slopes.

The Willapa Hills of Southwest Washington are comprised primarily of very weak marine sedimentary and volcanic rocks. Because the region has not been glaciated, thick and especially weak residual soils have developed on these rocks. Translational landslides and coalescing landslides forming earthflows are widespread in these weak rocks and overlying soils, such as in the Lincoln Creek Formation (Gerstel and Badger, 2002). Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches (Thorsen, 1989). These deposits are prevalent along the lower Columbia River valley, as well as other areas where colluvial deposits have accumulated on slopes and in drainages underlain by strong and relatively unweathered rock.

The Cascade Range is generally divided on the basis of rock type into northern and southern portions in the vicinity of Snoqualmie Pass. Predominantly, strong crystalline rocks intensely scoured by alpine glaciations occur to the north. Weaker volcanic flows, pyroclastic and volcanoclastic rocks occupy the south, much of which was beyond the reach of the last continental glaciation. Rockfalls and complex rock slides are dominant in the steep bedrock slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control large translational failures in the Chumstick and Roslyn Formations (Tabor et al, 1987), the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone (Wegmann, 2003). Shallow landslides generating debris avalanches and flows are common on steep slopes and drainages.

Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides. Rockfall and rock slides are common from the many steep bedrock exposures in the region. The Blue Mountains in southeastern Washington also have experienced recurring and widespread shallow landsliding and debris flows related to storm events (Harp et al., 1997).

PART 3. MEASUREMENT OF SLOPE ANGLES

Slope gradients are commonly expressed in two different but related ways, as degrees of arc or percent rise to run. It is important to understand the relationships between them.

3.1 Degrees

A circle is divided into 360° degrees of arc. Each degree is further divided into 60 minutes (60'), and each minute into 60 seconds (60"). The quadrant of the circle between a horizontal line and a vertical line comprises 90° degrees of arc (Figure 43a).

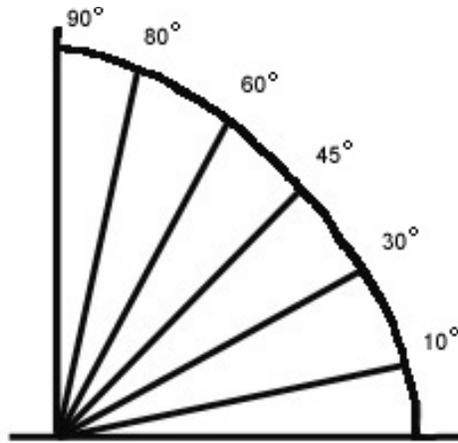


Figure 43a- Angles in degrees.

$$a \% = 100 \times \text{rise} / \text{run}$$

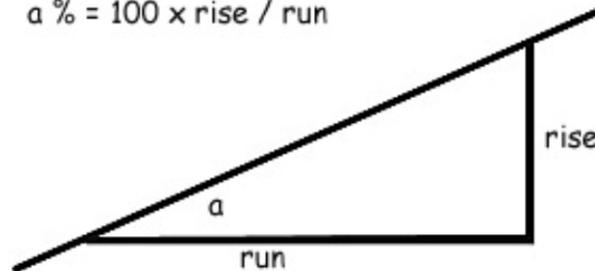


Figure 43b- Angles in percent.

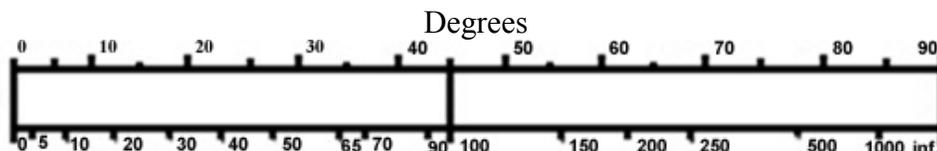
3.2 Percent

In Figure 43b, the horizontal distance between two points (distance between the points on a map) is called the run. The vertical distance (difference in elevation) is called the rise. The gradient can be expressed as the ratio of rise divided by run, a fraction that is the tangent of angle α . When multiplied by 100, this fraction is the percent slope.

3.3 Relationship of Degrees to Percent

Because of the differences in the ways they are calculated, each of these two slope measurements is better for certain applications. Because it is more precise at gentle slopes, percent is best for measuring and expressing small angles, such as the gradients of larger streams. But for steeper slopes, the constant angular difference and smaller numbers (an 85° degree slope is 1143%) make degrees more useful.

Figure 54 shows approximate equivalences for gradients expressed in degrees and percent. Note that there is a rough 2:1 ratio in the 30 to 40° degree range (e.g., 35° degrees = 70% slope), but beware - this relationship changes dramatically at gentler and steeper angles.



Percent

Figure 54. Slope gradients in degrees and percent.

PART 4. SLOPE FORM

Slope shape is an important concept when considering the mechanisms behind shallow landsliding. Understanding and recognizing the differences in slope form is essential key in to recognizing potentially unstable landforms recognition. There are three major slope forms to be observed when looking across the slope (contour direction): divergent (ridgetop); planar (straight); and convergent (spoon-shaped) (Figure 65a). Landslides can occur on any of these slope forms but divergent slopes tend to be more stable than convergent slopes because water and debris spread out on a divergent slopes whereas water and debris concentrate on convergent slopes. Convergent slopes tend to lead into the stream network, encouraging delivery of landslide debris to the stream system. Planar slopes are generally less stable than divergent slopes but more stable than convergent slopes. In the vertical direction, ridgetops are convex areas (bulging outward) and tend to be more stable than planar (straight) mid-slopes and concave areas (sloping inward) (Figure 65b).

Additionally, slope steepness can play a significant role in shallow landsliding. Steeper slopes tend to be less stable. The soil mantle, depending upon its make-up, has a natural angle at which it is relatively stable (natural angle of repose). When hillslopes evolve to be steeper than the natural angle of repose of the soil mantle, the hillslope is less stable and more prone to shallow landslides, especially with the addition of water. The combination of steep slopes and convergent topography has the highest potential for shallow landsliding.

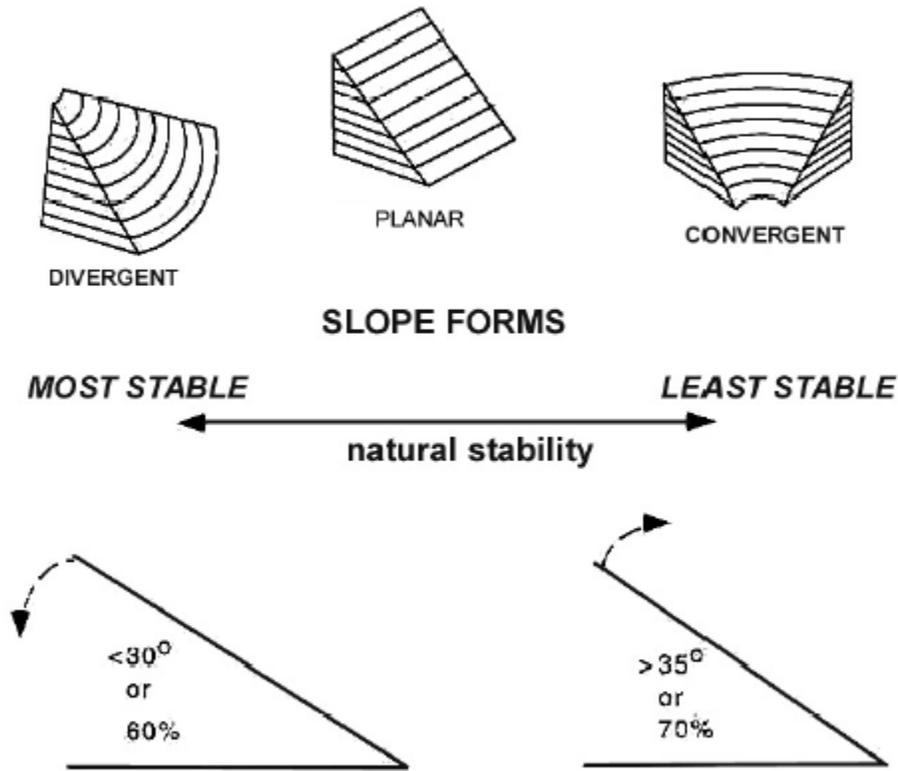


Figure 5a6a- Slope configurations as observed in map view.

This Figure 6a shows three major slope forms (divergent, planar, and convergent) and their relative stability. These slope form terms are used in reference to contour (across) directions on a slope. Convergent areas with slope greater than 35° degrees (70%) are the most shallow landslide-prone (Benda, et al, 1997/8).

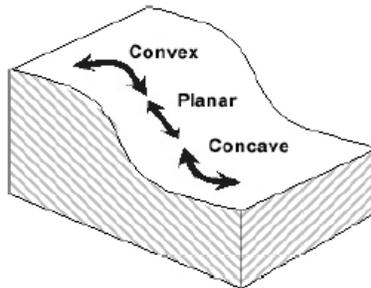


Figure 65b- Slope configurations as observed in profile: convex, planar, and concave. These terms are used in reference to up and down directions on a slope (Drawing: Jack Powell, DNR, 2004).

PART 5. DESCRIPTION IDENTIFICATION AND OVERVIEW OF UNSTABLE AND POTENTIALLY UNSTABLE SLOPES AND LANDFORMS AND PROCESSES

The rule-identified landforms described in Part 5 include bedrock hollows; convergent headwalls; inner gorges with slopes >70% (35° degrees); toes of deep-seated landslides with slopes >65% (33° degrees); groundwater recharge areas for glacial deep-seated landslides; outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; or any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes (WAC 222-16-050 (1)(d)(i)). Below are descriptions of the types of potentially unstable landforms and landslide processes associated with them.

Areas ~~containing of~~ unstable landforms can usually be identified with a combination of topographic and geologic maps, aerial photographs, LiDAR data and a variety of private and public agency-derived landform screening maps and tools, watershed analysis mass wasting map unit (MWMU) maps, landslide hazard maps from the Regional (Unstable) Landform Identification Project (RLIP), Landslide Hazard Zonation Project (LHZ), and modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps. However, field observation is normally required to precisely delineate landform boundaries, gradients, and other characteristics. More details for the identification of unstable land forms are presented in Part 6, and the appendices provide tools and resources available to help in identifying potentially unstable landforms.

In most instances, landform terms described here are also used in the scientific literature. For the purposes of Washington forest practices, the rule-identified landform terms, definitions, and descriptions supersede those used in the scientific literature. Note that all sizes, widths, lengths, and depths are approximate in the following discussion of unstable landforms, and are not part of the rule-identified definitions. Sizes are included to help visualize the landforms.

5.1 Bedrock Hollows, Convergent Headwalls, Inner Gorges

These three landforms are commonly associated with each other as shown in Figures 67 and 78.

Bedrock hollows

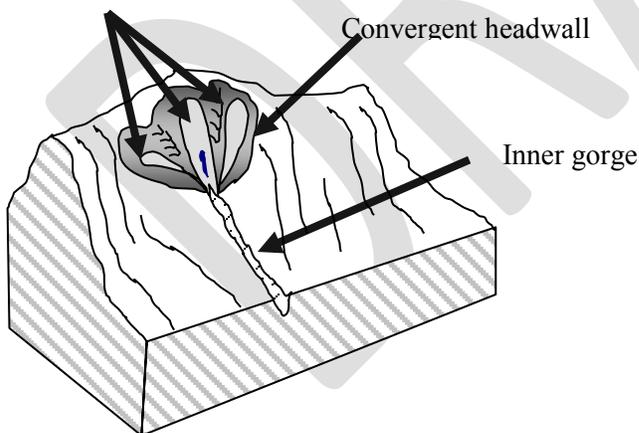


Figure 76. Typical hillslope relationships between bedrock hollows, convergent headwalls, and inner gorges (Drawing: Jack Powell, DNR, 2003).

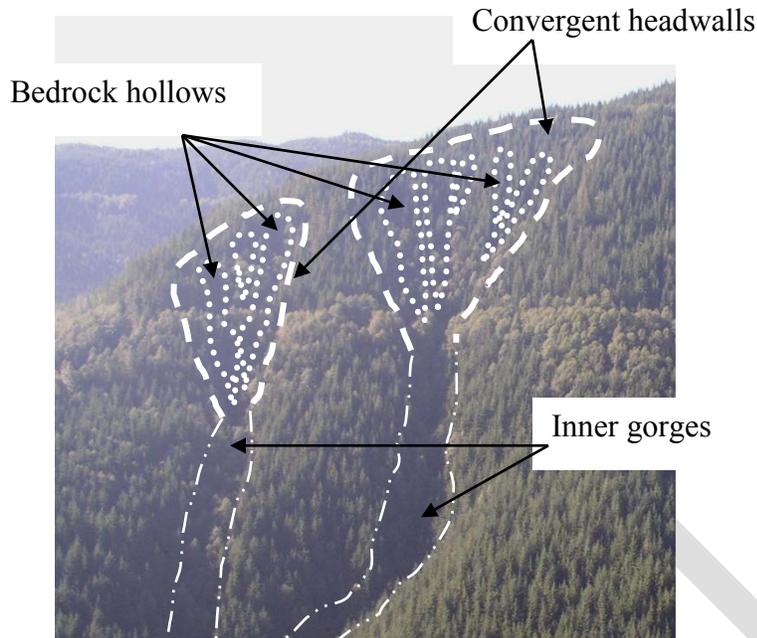


Figure 87. Common hillslope relationship: bedrock hollows in convergent headwalls draining to inner gorges (Photo and drawing: Jack Powell, DNR, 2003).

Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows (Crozier et al., 1990; Dietrich et al., 1987). Not all hollows contain bedrock so the term “bedrock” hollow can be a misnomer. However, the forest practices rules cite these features as “bedrock” hollows so this is the term used in the Board Manual. Hollows are commonly spoon-shaped areas of convergent topography with concave profiles on hillslopes. They tend to be oriented linear up- and down-slope. Their upper ends can extend to the ridge or begin as much as several hundred feet below ridge line. Most hollows are approximately 75 to 200 feet wide at their apex (but they can also be as narrow as several feet across at the top), and narrow to 30 to 60 feet downhill. Hollows should not be confused with other hillslope depressions such as small valleys, sag areas (closed depressions) on the bodies of large deep-seated landslides, tree wind-throw holes (pit and mound topography), or low-gradient swales.

Hollows often form on other landforms such as head scarps and toes of deep-seated landslides. Bedrock hollows can occur singly or in clusters that define a convergent headwall. They commonly drain into inner gorges (Figure 98).

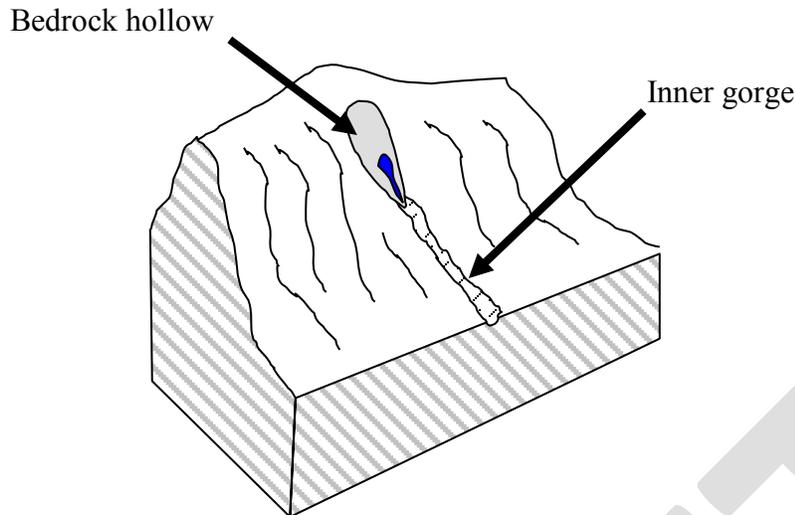


Figure 98. Bedrock hollow and relationship to inner gorge (Drawing: Jack Powell, DNR, 2003).

Hollows usually terminate where distinct channels begin. This is at the point of channel initiation where water emerges from a slope and has carved an actual incision. Steep bedrock hollows typically undergo episodic evacuation of debris by shallow-rapid mass movement (a debris flow), followed by slow refilling with colluvium that takes years or decades. Unless they have recently experienced evacuation by a landslide, hollows are partially or completely filled with colluvial soils that are typically deeper than those on the adjacent spurs and planar slopes. Recently evacuated hollows may have water flowing along their axes whereas partially evacuated hollows will have springs until they fill with sufficient colluvium to allow water to flow subsurface.

Figure 109 illustrates the evolution of a bedrock hollow. Drawing “a” shows that over a period of tens to hundreds or thousands of years in some places, sediment accumulates in a hollow. When the soil approaches a depth of 3 to 5 feet (1-2 meters), the likelihood of landslides increases. Recurrent landsliding within the hollow slowly erodes bedrock and maintains the form of the hollow (Drawing “b”). After a landslide, bedrock is exposed (and also seeps or springs) and the risk of additional sliding is reduced, but not gone. Drawing “c” shows soil from the surrounding hillsides (colluvium) slowly re-filling the hollow. As vegetation and trees establish the site after past failures, their roots help stabilize the soil.

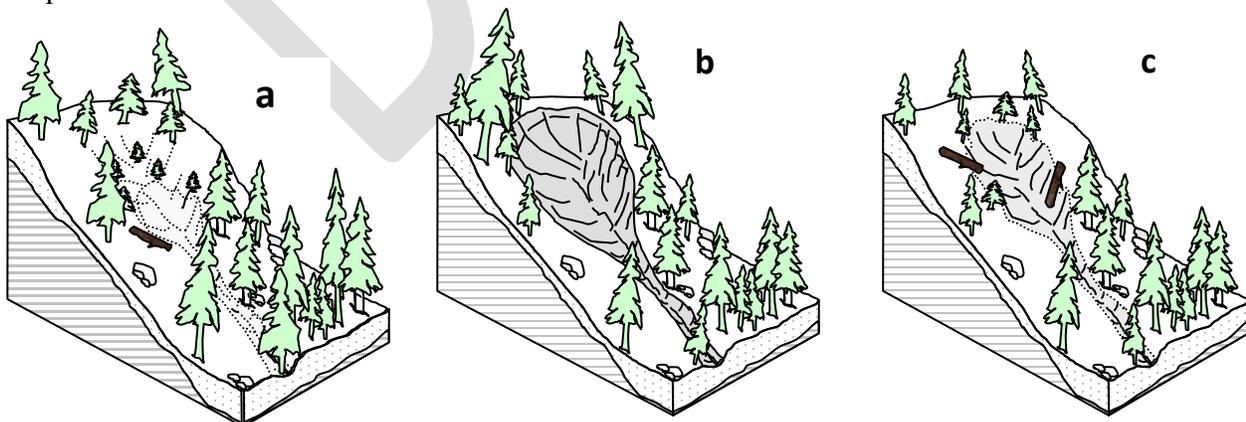


Figure 109a-c: Evolution of a bedrock hollow following a landslide (adapted from Dietrich et al., 1988; Drawing by Jack Powell, DNR, 2004).

The common angle of repose for dry, cohesionless materials is about 36° degrees (72%), and saturated soils can become unstable at lower gradients. Thus, slopes steeper than about 35° degrees (70%) are considered susceptible to shallow debris slides. “Bedrock” hollows are formed on slopes of varying steepness. Hollows with slopes steeper than 70% (approximately 35° degrees) are potentially unstable in well-consolidated materials, but hollows in poorly consolidated materials may be unstable at lower angles. *Note: Bedrock hollow slopes are measured on the steepest part of the slope generally not along the axis unless the hollow is full (Figure 110).*

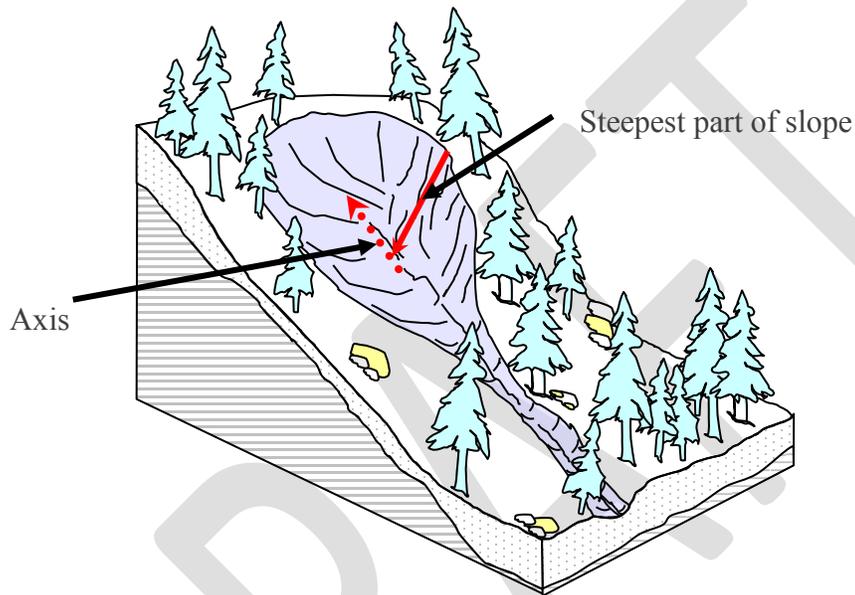


Figure 110: Bedrock hollow slopes are measured on the steepest part of the slope generally not along the axis (Drawing: Jack Powell, DNR, 2004).

Vegetation can provide the critical cohesion on marginally stable slopes and removes water from the soil through evapotranspiration. Leaving trees in steep, landslide-prone bedrock hollows helps maintain rooting strength and should reduce the likelihood of landsliding (Figure 124) (Montgomery et al., 2000). However, wind-throw of the residual trees following harvest can be associated with debris slide or debris flow events. In high wind environments, it is essential to harvest in a manner that will limit the susceptibility of the residual trees to wind-throw as well as to reduce the potential for landslides (for example leaving wider strips, pruning or topping trees in the strips, or feathering the edges of reserve strips).



Figure 121- Example of leave areas protecting unstable slopes (Photo: Venice Goetz, DNR, 2004).

Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. A series of converging bedrock hollows may form the upper part of a convergent headwall (Figure 132). Convergent headwalls are broadly concave both longitudinally and across the slope, but may contain sharp ridges that separate the bedrock hollows or headwater channels (Figure 143a, b, and Figure 154).

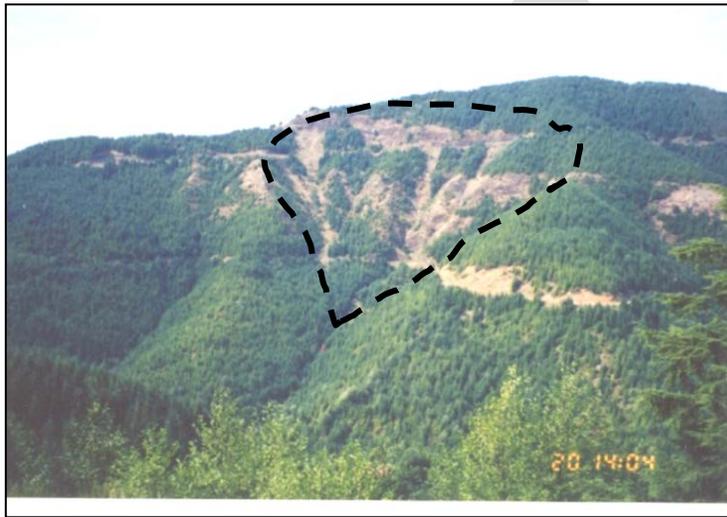


Figure 132- Convergent headwall example (Photo: Venice Goetz, DNR, 1995).

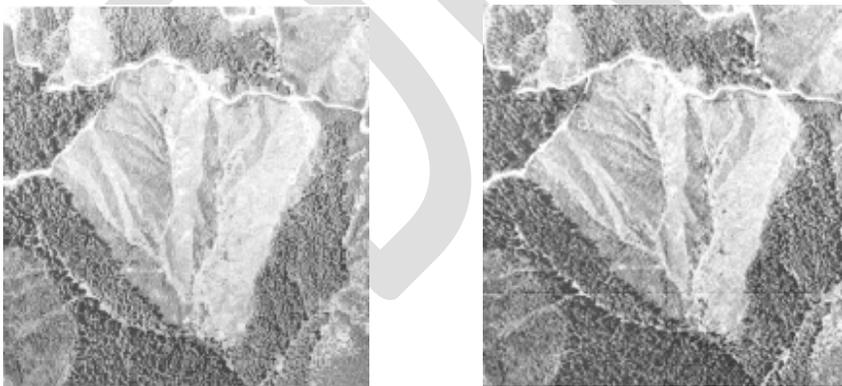


Figure 143a, b- Stereo-pair of a clearcut convergent headwall in Pistol Creek basin, North Fork Calawah River, Washington.

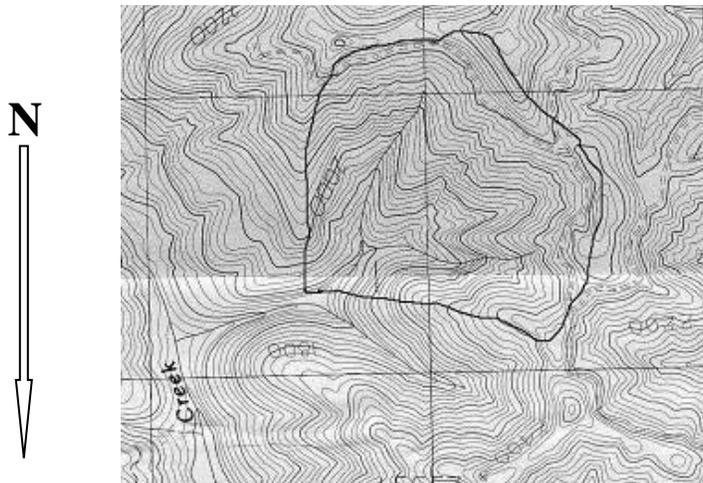


Figure 154. Topographic map and outline of convergent headwall displayed in the stereo-pair of Figure 13a, b. Scanned from portions of Hunger Mountain and Snider Peak USGS 7.5' quadrangles.

Convergent headwalls generally range from about 30 to 300 acres. Slope gradients are typically steeper than 35° degrees (70%) and may exceed 45° degrees (94%). Unlike bedrock hollows, which exhibit a wide range of gradients, only very steep convergent landforms with an obvious history of landslides are called convergent headwalls. Soils are thin because landslides are frequent in these landforms. History of evacuation and landsliding can be evident by a lack of vegetation or mature trees on the site, or the presence of early seral plant communities such as grasses or red alder. It is the arrangement of bedrock hollows and first-order channels on the landscape that causes a convergent headwall to be a unique mass-wasting feature. The highly convergent shape of the slopes, coupled with thin soils (due to frequent landslides), allows rapid onset of subsurface storm water flow. The mass-wasting response of these landforms to storms, disturbances such as fire, and to forest practices activities is much greater than is observed on other steep hillslopes in the same geologic settings. Convergent headwalls may be also prone to surface erosion from the scars of frequent landslides.

Channel gradients are extremely steep within convergent headwalls, and generally remain so for long distances downstream. Landslides that evolve into debris flows in convergent headwalls typically deliver debris to larger channels below. Channels that exit the bottoms of headwalls have been formed by repeated debris flows and are efficient at conducting them. Convergent headwalls commonly have debris fans at the base of their slopes.

Inner gorges are canyons created by a combination of stream down-cutting and mass movement on slope walls (Kelsey, 1988). Inner gorges are characterized by steep, straight or concave side-slope walls that commonly have a distinctive break in slope (Figure 165). Debris flows, in part, shape inner gorges by scouring the stream, undercutting side slopes, and/or depositing material within or adjacent to the channel (Figure 176). Inner gorge side-slopes may show evidence of recent landslides, such as obvious landslides, raw un-vegetated slopes, young, even-aged disturbance vegetation, or areas that are convergent in contour and concave in profile. Because of steep slopes and proximity to water, landslide activity in inner gorges is highly likely to deliver sediment to streams or structures downhill. Exceptions can occur where benches of sufficient size to stop moving material exist along the gorge walls, but these are uncommon.

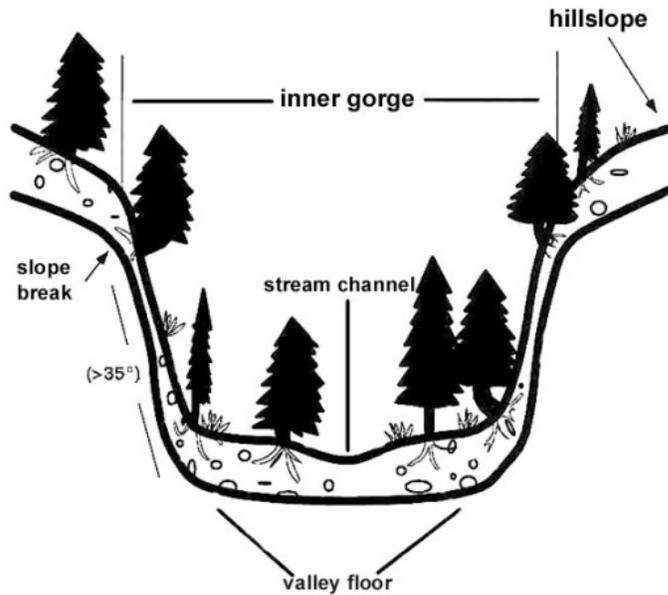


Figure 165. Cross-section of an inner gorge. This view emphasizes the abrupt steepening below the break-in-slope (Drawing: Benda, et al., 1998).



Figure 176. Photograph showing how debris flows help shape features related to inner gorges. (For example, over-steepened canyon wall, U-shaped profile, buried wood, distinctive break in slope along margins of inner gorge (Photo: Laura Vaugeois, DNR, 2004).

The geometry of inner gorges varies. Steep inner gorge walls can be continuous for great lengths, as along a highly confined stream that is actively down cutting, but there may also be gentler slopes between steeper ones along valley walls. Inner gorges can be asymmetrical with one side being steeper than the other. Stream-eroded valley sides, which can be V-shaped with distinct slope breaks at the top, commonly do not show evidence of recent landsliding as do inner gorges which tend to be U-shaped. In practice, a minimum vertical height of 10-feet is usually applied to distinguish between inner gorges and slightly incised streams.

The upper boundary of an inner gorge is assumed to be a line along the first break in slope of at least 10 degrees° or the line above which gradients are mostly gentler than 35 degrees° (70%) and convex. The delineating break-in-slope occurs where over-steepened slopes related to inner gorge erosion processes intersect slopes formed from normal hillslope erosion processes. While the upper inner gorge boundary is typically distinct, in some places it can be subtle and challenging to discern. Inner gorge slopes tend to be especially unstable at the point where the slope breaks because the abrupt change in gradient causes subsurface water to collect within the soil matrix which can destabilize the soil mass and initiate movement. Just as for all other landforms, inner gorge slopes should be measured along the steepest portion of the slope (see Figure 110).

The steepness of inner gorges is dependent on the underlying materials. In competent bedrock, gradients of 35 degrees° (70%) or steeper can be maintained, but soil mantles are sensitive to root-strength loss at these angles. Slope gradients as gentle as about 28 degree° (53%) can be unstable in gorges cut into incompetent bedrock, weathered materials, or unconsolidated deposits.

Erosion along the gorge walls can intercept shallow groundwater forming seeps along the sides of the inner gorge, which promotes continued mass wasting. Root strength along walls and margins of inner gorges has been found to be a factor that limits the rates of mass wasting. Inner gorge areas can lose root strength when trees blow down. However, downed timber has a buttressing effect providing some slope reinforcement. Effective rooting width of forest trees is approximately the same as the crown width. In some instances where the inner gorge feature is highly unstable it is necessary to maintain trees beyond the slope break. Use the rooting strength of trees adjacent to the landform for additional support.

5.42 Groundwater Recharge Areas, and the Effects of Groundwater on Landslide Stability of (Glacial) Deep-Seated Landslides

In order to identify and delineate groundwater recharge areas in glacial terrain it is necessary to first identify and delineate glacial deep-seated landslides. Glacial deep-seated landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however their failure mechanics are similar to deep-seated landslides developed in other materials (Terzhagi, 1951). Deep-seated landslides developed in other materials are also susceptible to forest practice activities in the groundwater recharge area. Consequently, scientific knowledge regarding the dynamics of deep-seated failures can be applied to better understand and manage glacial deep-seated landslides.

Glacial deep-seated landslides occur in glacial terrain and are defined as such where most of the slide plane or zone lies within glacial deposits below the maximum rooting depth of trees, to depths of tens to hundreds of feet beneath the ground surface. Glacial deep-seated landslide deposits occur in continental or alpine glacial deposits, or a combination of both. Continental glacial deposits in Washington are located in the northern areas of the state (Figures 18a and b), whereas alpine glacial deposits can be found in mid-to-high elevation mountain ranges (Booth et al., 2003; Booth et al., 1994; Thorsen, R.M., 1980; Barnosky, 1984; Heusser, 1973; Crandall, 1965).



Figure 18a Extent of continental glaciation in the Pacific Northwest (Origin unknown).

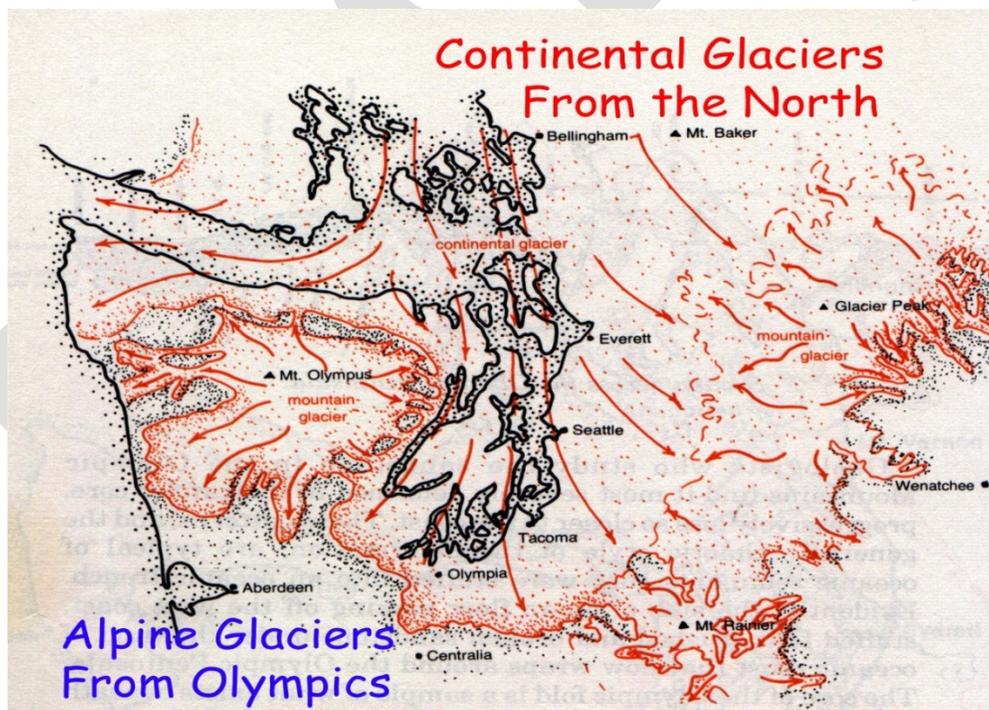


Figure 18b Continental and alpine glaciation in western Washington (Alt, D. D., & Hyndman, D. W., 1984).

Like non-glacial deep-seated landslides, deep-seated landslides in glacial terrain can involve rotational and translational movement, flows or a combination of movement types. Glacial deep-seated landslides can occur in any type of glacial deposit including till, outwash, glaciolacustrine

and glaciomarine silt and clay, and they often involve multiple glacial strata. During interglacial periods, layers of loess, (e.g., windblown silt and clay) and other non-glacial sediments can also be deposited between glacial units or on the surface of glacial materials and become overlain by deposits from successive glaciations.

Glacial deposits and other earth materials display a wide range of hydrologic characteristics (Table 2). Glacial till generally has low permeability, comprises an unsorted and non-stratified glacial material that can range in size from clay to boulders, and is typically deposited and over run during periods when glacial ice is advancing. Glacial outwash contains typically sorted and stratified sediments deposited by water flowing from glacial ice either during the advance of the glacier or during glacial recession. Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes. Glaciomarine deposits are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

Table 2. Hydrologic Properties of Soils (modified from Koloski et al., 1989)

<u>Classification</u>	<u>Permeability (feet per minute)</u>	<u>Storage Capacity</u>
<u>Alluvial (High Energy)</u>	<u>0.01-10</u>	<u>0.1-0.3</u>
<u>Alluvial (Low Energy)</u>	<u>0.0001-1</u>	<u>0.05-0.2</u>
<u>Eolian (Loess)</u>	<u>0.001-0.01</u>	<u>0.05-0.1</u>
<u>Glacial Till</u>	<u>0-0.001</u>	<u>0-0.1</u>
<u>Glacial Outwash</u>	<u>0.01-10</u>	<u>0.01-0.3</u>
<u>Glaciolacustrine</u>	<u>0-0.1</u>	<u>0-0.1</u>
<u>Lacustrine (Inorganic)</u>	<u>0.0001-0.1</u>	<u>0.05-0.3</u>
<u>Lacustrine (Organic)</u>	<u>0.0001-1.0</u>	<u>0.05-0.8</u>
<u>Marine (High Energy)</u>	<u>0.001-1.0</u>	<u>0.1-0.3</u>
<u>Marine (Low Energy)</u>	<u>0.0001-0.1</u>	<u>0.05-0.3</u>
<u>Volcanic (Tephra)</u>	<u>0.0001-0.1</u>	<u>0.05-0.2</u>
<u>Volcanic (Lahar)</u>	<u>0.001-0.1</u>	<u>0.05-0.2</u>

Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 19). The hydrologic budget includes precipitation (rain and snow), interception by vegetation, evapotranspiration, surface storage, surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic budget that infiltrates into the subsurface below the root zone. The ground water component is composed of water within the unsaturated, or vadose zone, and the saturated zone.

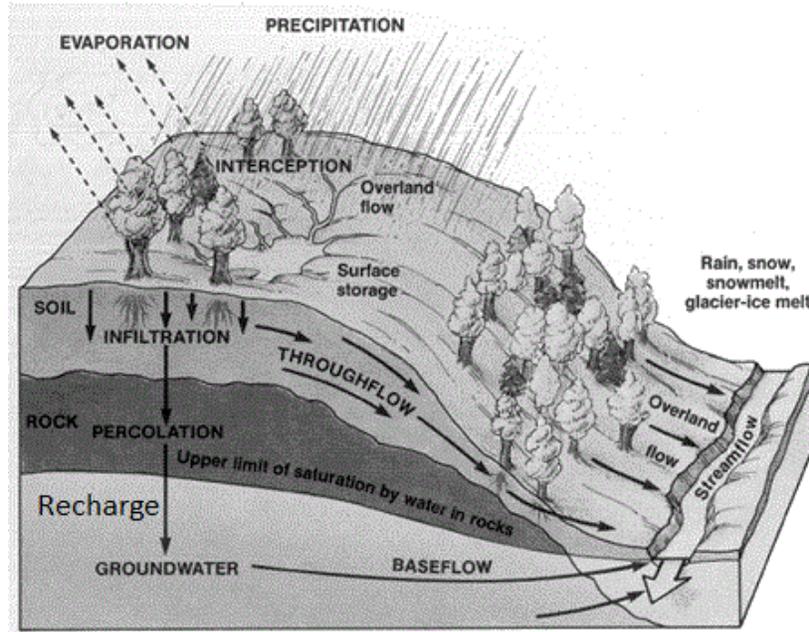


Figure 19 Hydrologic budget of a hillslope (University of Colorado).

Groundwater recharge to a glacial deep-seated landslide may originate as recharge to an adjacent non-glacial geologic unit that flows into glacial sediments, or it may run off from upland non-glacial geologic units and recharge within glacial sediments. A component of groundwater recharge can be surface flow.

5.2.1 Groundwater Flow

Groundwater flows from areas of recharge in upland areas to points of discharge including springs, streams, and other surface water features at lower elevations. The areal extent of recharge that contributes groundwater to a glacial deep-seated landslide constitutes that landslide's groundwater recharge area and includes the landslide itself.

Groundwater recharge areas of deep-seated slides are located in the lands up-slope that can contribute subsurface water to the landslide. In some cases this can include upslope portions of the landslide itself. Cemented soil horizons, fine-grained soils, and/or the presence of glacial till can be factors controlling the infiltration and flow of groundwater (Bauer and Mastin, 1997; Vaccaro et al., 1998). Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area (Bauer and Mastin, 1997; Vaccaro et al., 1998). Groundwater perching and the characteristics of the overlying groundwater recharge area can be important factors in a deep-seated failure, especially for landslides in glacial sand and other unconsolidated sequences that overlie fine-grained glacial-lake clay deposits or till (Figure 1920). This is a common configuration of the glacial deposits in much of the northern half of western Washington (e.g., landslides in Seattle) (Gerstel, and others et al., 1997), and in the Stillaguamish River valley (Benda and others, 1988), but this type of landslide also occurs in alpine glacial deposits in southwest Washington, far from the maximum extent of continental glaciation-mountain front. Groundwater filtering-downflowing through porous-permeable sand layers is trapped-perched above the poorly less permeable clay or till. During and following storm-precipitation events, the sand above the clay becomes saturated creating a buoyant effect and lowering cohesion in the sand, both of which

weaken the contact between the clay and sand. This in turn causes the overlying mass to slide along the sand/clay contact. A key predictive-common predictor of observation is noting perched groundwater is the presence of a horizontal line of springs (groundwater refluxing/discharge) or a line of vegetation at the contact between the permeable and less permeable layers. Land uses such as poorly planned ditches or large-scale, even-aged harvesting that alter the timing or volumes of groundwater recharge in the slide zone can start or accelerate landslide movement.

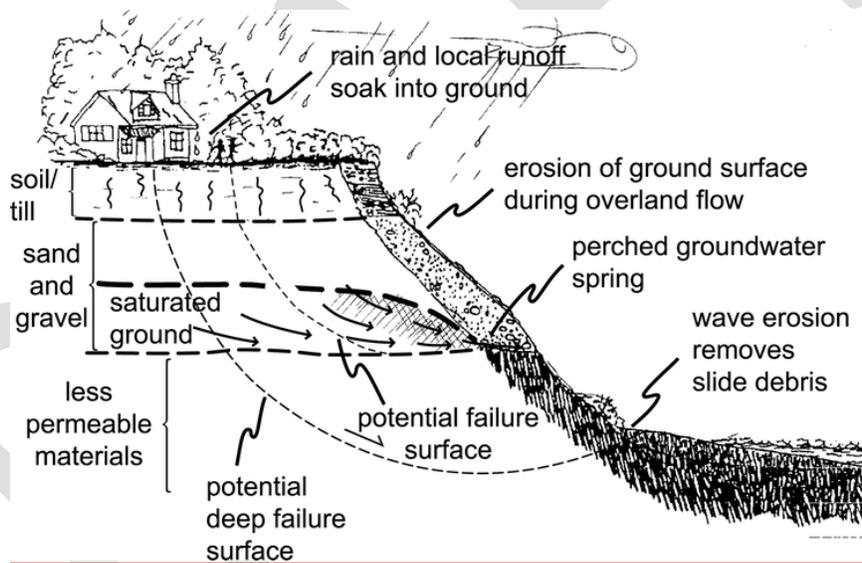
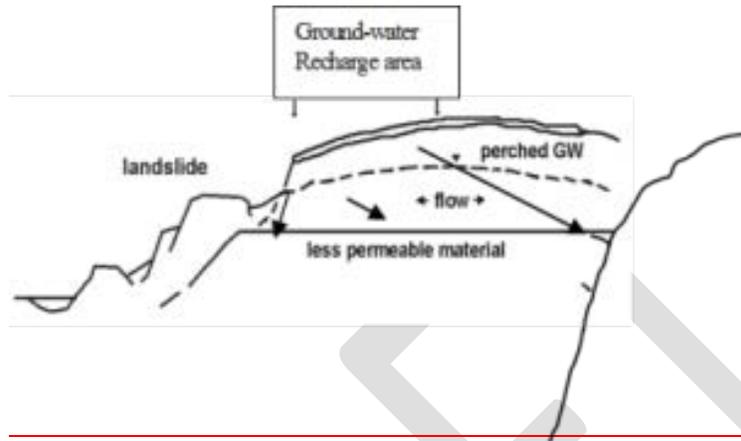


Figure 1920- Diagram illustrating failure surface resulting from groundwater recharge area for a glacial deep-seated landslide (modified from Gerstel et al., 1997).

A classic example of a geologic setting where glacial deep-seated landslides are common is in Puget Sound where the Esperance Sand overlies the Lawton Clay. In this setting, groundwater recharge from precipitation infiltrates downward within the hillslope until it encounters the relatively impermeable Lawton Clay. Because the water cannot infiltrate into the Lawton Clay at the same rate at which it is supplied from above, the water table rises vertically above the clay surface. The elevated water table increases the pressure within the Esperance sand and forms a hydraulic

gradient which causes water to flow horizontally along the sand-clay contact, resulting in springs where this contact is exposed at the surface (Tubbs, 1974).

5.2.2 Effects of Groundwater on Slope Stability

Saturation of the pore spaces within sediments results in pore pressures that act to push the soil particles apart. This phenomenon of soil saturation reduces the effective strength of the soil which in turn reduces the stability of a slope comprised of saturated sediments. Because of the likelihood of subsurface water flow along and within perching layers in glacial strata, recharge areas for glacial deep-seated landslides may be classified “Class IV-special” under WAC 222-16-050(1)(d)the forest practices rules and require further investigation and documentation. Therefore, it is important to characterize groundwater recharge areas and local stratigraphy in terms of an evaluation of the potential for changes in the water balance due to forest practices activities and an assessment of the degree to which a potential hydrologic change can be effectively delivered to a glacial deep-seated landslide. In the absence of other information, The first order approximation of the recharge area is assumed to be equivalent to the surface basin (topographically defined) basin directly above and including the active landslide. A more refined estimate of T the spatial extent of a groundwater recharge area can be also be interpreted from field observation of soil profiles, geologic structure, stratigraphy, well logs of wells or boreholes, or large-scale geologic maps. Additional information regarding delineating and assessing the groundwater recharge areas is included in Part 6.4 and Part 7.2.

5.3 Toes of Deep-Seated Landslides

The toes of deep-seated landslides are a rule identified forest practices regulatory landform. In this context “deep-seated landslide toes” means the down slope toe edges, not the entire toe area of displacement material (see Figure 2247). Landslides that have toe edges adjacent to streams have a high potential for delivery of sediment and wood to streams. In such situations, streams can undercut the landslide toes and promote movement. Such over-steepened toes of deep-seated landslides can also be sensitive to changes caused by harvest and road construction. The road shown in Figure 23 may have removed a portion of the toe, causing failure and re-activation of the landslide. Resulting instability can take the form of shallow landslides, small-scale slumping, or reactivation of parts or the whole of a deep-seated landslide. Because deep-seated landslides are usually in weak materials (further weakened by previous movement), an angle of 33° degrees (65%) is the threshold value used on the potentially unstable toe edges. Regardless of the surface expression of the toe, it is best to avoid disrupting the balance of the landslide mass by cutting into or removing material from the toe area.

5.45 Outer Edges of Meander Bends

Streams can create unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (Figure 219). The outer edges of meander bends are susceptible to deep-seated landsliding and shallow landsliding including debris avalanching and small-scale slumping, and deep-seated landsliding. The outer edges of meander bends may be protected by the riparian management zone (RMZ) or channel migration zone (CMZ) rules if the slopes are not particularly high and are contained within the riparian leave areas or within the CMZ (see Board Manual Section 2). As with other situations of overlapping forest practices rules, the harvest unit layout should reflect the extent of the greater of the protections.

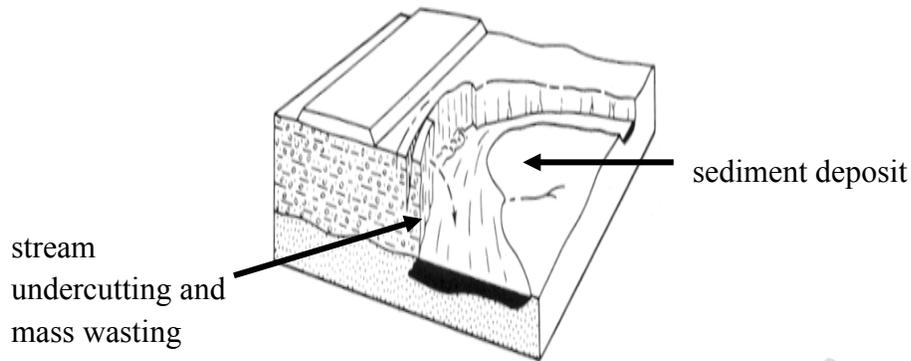


Figure 2021- Outer edge of a meander bend showing mass wasting on the outside of the bend and deposition on the inside (adapted from Varnes, 1978).

5.56 Other Indicators of Slope Instability or Active Movement

Relatively large and recent topographic indicators can be observed on air photos, topographic maps and LiDAR images, but the identification of smaller and older indicators requires careful field observations. In addition to the landforms described above, other topographic, hydrologic and vegetational indicators of slope instability or active movement may include:

(a) Topographic and hydrologic

- bare or raw, exposed, un-vegetated soil on the faces of steep slopes
- boulder piles
- hummocky or benched surfaces, especially below crescent-shaped headwalls
- fresh deposits of rock, soil, or other debris at the base of a slope
- ~~ponding of water in irregular depressions or undrained swampy areas on the hillslope above the valley floor~~
- tension cracks in the surface (across or along slopes, or in roads)
- ~~seepage lines or springs and soil piping~~
- ~~deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)~~
- stratigraphic indicators, including disconformities, offset contacts, and overturned sections
- back tilted surfaces from rotation within the slide.

(b) Hydrologic

- ponding of water in irregular depressions in undrained swampy or poorly drained areas on the hillslope above the valley floor
- seepage lines or spring and soil groundwater piping
- sag ponds (ponded water in a tension crack)
- deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)

(c) Vegetational

- jack-strawed, back-rotated, or leaning trees and stumps
- bowed, kinked, or pistol-butted trees
- split trees and old growth stumps
- water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes
- other patterns of disturbed vegetation or changes in stand composition (early seral stage or lack of mature trees within a hillslope)

No ~~single one of these~~ indicators necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

Additional information about landslide processes, ~~unstable landforms techniques for hazard assessment, and management practices on the effects of forest practices on~~ unstable ~~terrain landforms~~ is available in “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest” by the British Columbia Ministry of Forests ([Chatwin et al., 1994](#)); ~~and Hillslope Stability and Land Use~~ ([Sidle et al., 1985](#)); [Landslides, Processes, Prediction and Land Use \(Sidle and Ochiai, 2006\)](#).

Deep-seated landslides are those in which the slide plane or zone of movement is ~~well~~ below the maximum rooting depth of forest trees (generally greater than 10 feet or 3 meters). Deep-seated landslides may extend to hundreds of feet in depth, ~~often including and may involve underlying~~ bedrock. Deep-seated landslides can occur almost anywhere on a hillslope ~~where geologic and hydrologic conditions are conducive to failure. and~~ They can be as large as several miles across or as small as a fraction of an acre. ~~The larger ones~~ Deep-seated landslides can ~~usually~~ be identified from topographic maps, ~~or~~ aerial photographs, [LiDAR images, and field observations](#). Many deep-seated landslides occur in the lower portions of hillslopes and extend directly into stream channels whereas deep-seated landslides confined to upper slopes may not have the ability to deposit material directly into channels. [Deep-seated landslides often are part of large landslide complexes that may be intermittently active for hundreds of years or more \(Bovis, 1985; Keefer and Johnson, 1983\)](#).

One common triggering mechanism of deep-seated landslides results from the over-steepening of the toe by natural means such as glacial erosion or fluvial undercutting, fault uplift, or [excavating for land development by human-caused excavations](#). Initiation of such landslides has also been associated with changes in land use, increases in groundwater levels, and the degradation of material strength through natural processes. Movement can be complex, ranging from slow to rapid, and may include [numerous](#) small to large [horizontal and vertical](#) displacements [variously triggered by one or more failure mechanisms](#).

Deep-seated landslides characteristically occur in weak materials such as thinly layered rocks, unconsolidated sediments, deeply weathered bedrock, or rocks with closely spaced fractures. Examples include: clay-rich rocks, such as the Lincoln Creek Formation of west-central Washington; thinly layered rocks, such as phyllite in northwest Washington; and deeply weathered volcanic rocks ~~that overpresent in~~ the Willapa Hills of southwest Washington. Deep-seated landslides can also occur where a weak layer or prominent discontinuity is present in otherwise strong rocks, such as ~~clay or sand rich sedimentary~~ interbeds ~~with~~ in the basalts of eastern Washington or a fault plane or intersecting joint set. In northwest Washington and on the Olympic Peninsula, deep-seated landslides commonly occur along silt or clay beds that are overlain by sandy units such as glacial deposits.

There are three main parts of a deep-seated landslide: the scarps (head and side), ~~along which marginal streams can develop~~; the body, which is the displaced slide material; and the toe, which also consists of displaced materials. The downslope edge of the toe can become over steepened from stream erosion or from the rotation of the slide mass. A deep-seated landslide may have [one or more of these component parts several of each of these parts](#) because small deep-seated landslides can be found nested within larger slides. These three main parts are shown in [Figures 22-17 and Figure 23-18](#). The head- and side- scarps together form an arcuate or horseshoe shaped feature that

represents the surface expression of the rupture plane. The body and toe area are usually display hummocky topography, and the flow path of streams on these landslide sections may be displaced in odd ways due to differential movement of discrete landslide blocks. The parts of deep-seated landslides that are most susceptible to shallow landslides and potential sediment delivery are steep scarps (including marginal stream side slopes) and toe edges.

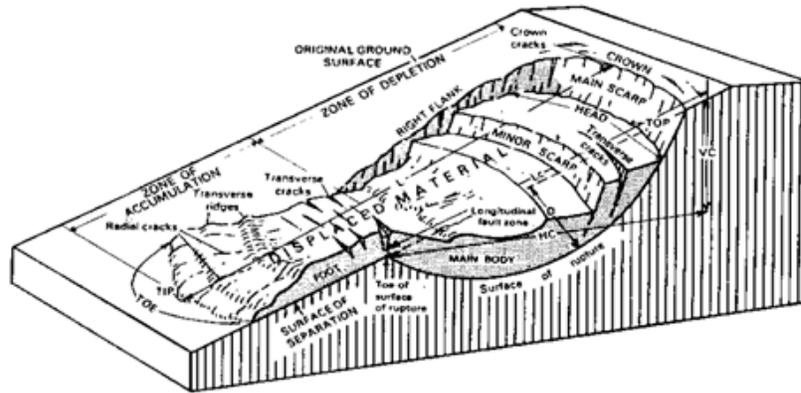


Figure 17. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide. Slow flow (an earthflow) may be found at the toe (Drawing: Varnes, 1978).

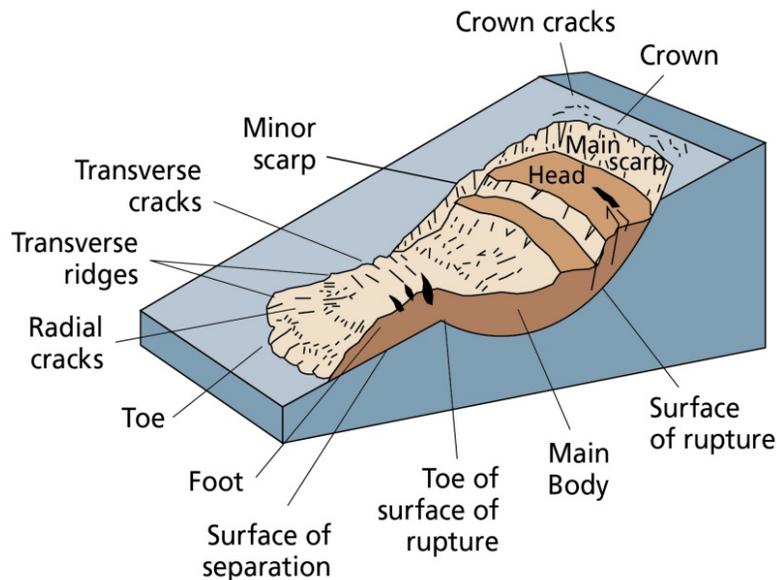


Figure 22. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide (adapted from USGS, 2004).

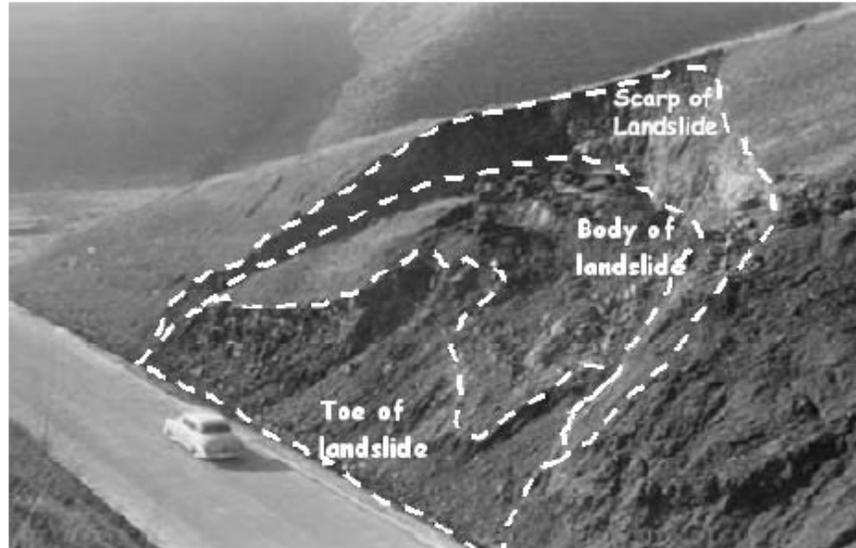


Figure 1823 Deep-seated landslide showing the head scarp, side-scarps, body, and toe. Some of the toe has been removed in building and maintaining the highway (adapted from USGS photo).

The sensitivity of any particular landslide to forest practices is highly variable. Deep-seated scarps and toes may be over-steepened and streams draining the displaced material may be subject to debris slide and debris flow initiation in response to harvest or road building. Movement in landslides is usually triggered by accumulations of water at the slide zone, so land-use changes that alter the amount or timing of water delivered to a landslide can start or accelerate movement (Cronin, 1992). Generally, avoiding the following practices will prevent most problems: destabilizing the toe by the removal of material during road construction or quarrying which could destabilize the toe; overloading the slopes by dumping spoils on the upper or mid-scarp areas which could overload the slopes, or compacting the soil in these places which could change subsurface hydrology; and directing additional water into the slide from road drainage or drainage capture. The loss of tree canopy interception of moisture and the reduction in evapotranspiration through timber removal on areas up gradient of the slide may also initiate movement of the slide (van Asch, et al., 2009).

Parts 5.3 and 6.4 provide methods for describing and delineating groundwater recharge areas for deep-seated landslides in non-glacial sediments.

PART 6 OVERVIEW OF ASSESSMENT FOR POTENTIALLY UNSTABLE SLOPES AND LANDFORMS AND MATERIALS REGIONAL LISTS

~~The Regional (Unstable) Landform Identification Project (RLIP) is a result of the Forests and Fish Report and is being conducted statewide at this time. The purpose of the RLIP is to note and validate region-specific unstable landforms that are not included in the present forest practices rules so that known unstable landforms are not overlooked during the forest practices application process. The final products will be in the form of short reports (validations) and maps that describe (generally and specifically) and locate these regional unstable landforms. This information is intended to be used as a screening tool for forest practices applications and may be eventually included in the forest practices rules and this Board Manual Section.~~

The identification, delineation, and characterization of unstable and potentially unstable landforms should be completed in sequential order, as each step of the review process might uncover new information that could modify assessment methods and findings. General practitioners (landowners, foresters, engineers) typically conduct an initial screening of project sites for potentially unstable slopes and landforms, followed by a more in-depth geotechnical review, if warranted, by a qualified expert.

A typical assessment of unstable slopes and landforms includes following components:

- Assessment conducted by a landowner or designated landowner representative:
 - initial office screening (see Part 6.1.1)
 - field assessment and harvest operations lay-out (Part 6.2.1)
- Geotechnical review conducted by qualified expert (if desired by landowner or required by rule)
 - office review (Part 6.1.2)
 - field review (Part 6.2.2)
 - landslide/landform activity assessment (Part 7.1)
 - water budget and slope stability modeling assessments (Part 7.2)
 - slope stability sensitivity assessment (Part 7.3)
 - deliverability assessment (Part 7.4)
 - summary of findings, results, and recommendations (Part 7.5)
 - qualified expert reports (Part 8)

Elements of the investigation and the order in which they should be completed are generally as follows (modified from Turner and Schuster, 1996):

1. Preliminary fact-finding. What actions does the proposed forest activity include (e.g., partial cut, clear cut, road building, stream crossing)? In which landslide province (Part 2.4) is the proposed forest activity located and what are the hydrogeologic conditions and types of landforms expected to be present? Are any site-specific resources available for review, such as previously completed qualified expert reports or watershed analysis reports?
2. Office review of geologic maps, topographic maps, aerial photographs, LiDAR, and other information identified during the preliminary fact-finding phase.
3. Field review including hydrogeologic mapping and site observations to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review.
4. Data analysis and assessment regarding the potential for landslide activity as a result of the proposed forest practice activity and the potential for delivery of sediment to public resources or threats to public safety.

6.1 Office Review Process

An office review refers to the initial screening of a selected site using available, remotely sensed information and previously prepared materials or documents (e.g., reports, studies, field data and analyses). The term “remote sensing” generally describes information acquired for a particular site or physical phenomenon without making physical contact by, for example, collecting data in the field. A typical office review utilizes all accessible, site-specific and regional remote-sensing data that can be brought to bear on identifying, delineating, and interpreting potentially unstable slopes and landforms (e.g., aerial imagery, LiDAR, GIS-based model predictions of earth surface attributes derived from digital, high-resolution topographic data). In addition, an analyst uses existing

documents and databases (e.g., maps, geotechnical reports and studies, published and unpublished scientific literature, landslide inventories, local and regional databases containing meteorologic, hydrologic, and geologic information) to screen sites for potential slope-stability concerns, identify natural resource and public safety considerations, develop an initial interpretation of potentially unstable landforms presence/absence and landslide types, and make a determination regarding next steps in the site assessment.

Typically, the office review occurs in two steps: (1) an initial office screening conducted by the landowner or designated representative to determine if unstable slopes and landforms might be present that require field assessment, and whether a qualified expert is desired or needed for more extensive site analyses; and (2) a geotechnical office review completed by the qualified expert for suspected unstable slopes and landforms, the outcome of which potentially leads to a qualified expert conducting geotechnical field review.

6.1.1 Initial Office Screening Conducted by a Landowner or Designated Representative

The objective of an initial office review conducted by a landowner or designated representative is to: (1) identify potential or existing areas of slope instability within or adjacent to the harvest operations area; (2) delineate potential unstable landforms using definitions and type descriptions provided in Part 5 of this Board Manual section; (3) locate areas of natural resource sensitivity or public safety exposures in the vicinity of the planned operation that could be adversely affected by mass wasting processes; and (4) develop a plan for assessing potential unstable slopes and landforms in the field. This information is required on forest practices applications (FPAs) and any supplemental slope-stability informational forms required at the time of FPA submission. Designated representatives might include forest engineers, foresters, or qualified experts.

Summary of Procedures The office review process generally includes compiling and evaluating available maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. This initial screening is supplemented with landowner knowledge about site-specific conditions and with publicly available documents that might identify site-specific slope stability concerns or place the site in a broader landscape context with regard to potentially unstable landforms and processes (i.e., watershed analyses conducted under chapter 222-22 WAC; see Appendix D). Information sources are available to the landowner online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. Additional sources of imagery, data, maps, reports, and other documents are listed in Appendices A through E of this Board Manual section.

Relevant maps typically include surface topography and its derivatives (e.g., slope class maps), hydrology (e.g., streams and water types), geology and soils (e.g., rock units, soil types), landslides (landslide inventories and hazard zonation), and information needed to identify public safety exposures (e.g., road networks, parcel boundaries with existing building structure information). Imagery includes aerial photography and LiDAR-derived hillshade images (see Part 6.1.3 for more information) available on public websites and referenced in Appendix B. GIS with map display and analysis capabilities (e.g., ESRI ArcGIS) provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis; however, an initial screening can be performed manually without such tools if they unavailable to the landowner (i.e., by inspecting each map or image separately). Certain counties also offer an online, user-friendly, interactive version of GIS with many of the needed map and imagery products (see Appendix A). A follow-up field assessment is needed to verify results of the initial screening. It is helpful to create a site map, for

field use, showing areas of potential slope stability concerns, natural resource sensitivities, and public safety exposures within or adjacent to the proposed operation.

Outcome The initial office screening aids the landowner in targeting portions of the operations area that need to be assessed in the field for unstable slopes and landforms. Note also that the office screening might not identify all potential unstable landforms, particularly if features are too small or subtle to be identified from available maps and imagery. For example, the landowner might not be able identify the full extent of a groundwater recharge area from topographic maps, or to detect landslides under a mature forest canopy if using aerial photography exclusively. A field assessment typically is conducted by landowners while they are marking (flagging) the boundaries of the operations area. See Part 6.2 for guidance on conducting field reviews. The landowner might also elect to have a more thorough office review conducted by a qualified expert; see Part 6.1.2 for further discussion. Suspected groundwater recharge areas associated with glacial deep-seated landslides should be reviewed by a qualified expert.

6.1.2 Geotechnical Office Review Conducted by a Qualified Expert

The objective of an office review conducted by a qualified expert is to develop a preliminary geotechnical assessment of landform characteristics and landslide potential prior to initiating fieldwork, so that subsequent field investigations are targeted, efficient, and capable of verifying initial interpretations within a reasonable degree of certainty. The geotechnical office review generally is more in-depth than the landowner-conducted initial screening and applies professional expertise in engineering geology, hydrogeology, geomorphology, and associated fields to detection and interpretation of landscape processes. During a geotechnical office review, the qualified expert typically:

1. screens the site with available data in order to identify physical indicators of past, existing, and potential landslide activities, noting their spatial and temporal distributions;
2. delineates on preliminary maps the identified landslide features and associated potentially unstable landforms;
3. formulates initial hypotheses regarding landslide and landform behavior and failure mechanisms, to be evaluated further in the field; and
4. determines the type and level of field investigation needed to verify preliminary landslide interpretations, develop cause-effect relationships, and assess potential for material delivery and potential adverse impacts to natural resources and threats to public safety.

Summary of Procedures The geotechnical office review generally follows the same procedures as the initial office screening for compiling and evaluating available information. Most qualified experts have ArcGIS capabilities, are experienced in using remote-sensing and modeling tools, and can provide feedback on proposed forest practice activities in relation to their potential for affecting slope instability. The office review typically precedes a field review whose objectives usually include assessing the accuracy, limitations, and uncertainties of remotely sensed information and previously prepared materials assembled during the office review, as well as adjusting any preliminary interpretations of site characteristics or physical phenomena based on these data sources. The qualified expert determines the nature of the office review and the appropriate combination of assembled information based on the project objectives, requirements, and desired level of confidence in assessment products.

Outcome The geotechnical office review typically leads to a field review, especially where unstable slopes and landforms are suspected or known and verification is required. Office review findings

are included in the report written by the qualified expert. Note that interpretations based solely on remote-sensing data should not be used as substitutes for site-specific field assessments carried out by qualified experts where such investigations are required by the Forest Practices Act. There might be certain instances, however, where a field review is optional because the qualified expert has a high level of confidence in office review interpretations. For example, the expert might determine that no unstable slopes or landforms are present, or such features are present and the landowner agrees to exclude these areas from forest operations.

6.1.3 Remote-Sensing Tools Available for Office Reviews

Common sources of remotely sensed information used in identifying, delineating, and interpreting potentially unstable slopes and landforms can be grouped broadly in the following categories: (1) aircraft- or satellite- based earth imagery and photogrammetry; and (2) LiDAR (Light Detection and Ranging) and high-resolution topographic data. Previously prepared materials or documents often incorporate field and remotely sensed data; these sources include maps and surveys, technical reports and other published/unpublished literature, and physical databases. Appendices A through E of this Board Manual list the most common data sources in each category. Among the available remote-sensing technologies, LiDAR has proven to be a valuable source of high-resolution topographic data with distinct advantages over traditional analytical methods (e.g., aerial photo interpretation) for mapping landslides and interpreting landform characteristics (e.g., Haugerud et al., 2003; Burns and Madin, 2009; Jaboyedoff et al., 2012; Roering et al., 2013; Tarolli, 2014). Consequently, LiDAR capabilities and applications are discussed in more detail below.

New remote-sensing techniques for terrain characterization are being developed at a rapid pace, due in part to expanding availability of publicly acquired, high-resolution topographic data (e.g., LiDAR). For example, major advances in deep-seated landslide characterization methods are combining high-resolution LiDAR data with other remotely sensed information and developing quantitative LiDAR analysis techniques to map and quantify landslide movement (Tarolli, 2014). Examples include using LiDAR-derived Digital Elevation Models (DEM) and Digital Terrain Models (DTM) with: (1) radar data and historical aerial photographs to quantify deep-seated landslide displacement and sediment transport (Roering et al., 2009; Handwerker et al., 2013; Scheingross et al., 2013); (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux (Mackey and Roering, 2011); and, (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows (e.g., Ardizzone et al., 2007; Booth et al., 2009; Burns and Madin, 2009; Tarolli et al., 2012; Van Den Eeckhaut et al., 2012); and, (4) subsurface investigations (Travelletti and Malet, 2012). Such innovative approaches likely will continue to emerge as more sophisticated high-resolution surface and subsurface technologies are developed. It is the task of qualified experts to seek out, evaluate, and apply new remote-sensing methods as they become available.

6.1.4 LiDAR and High-Resolution Topographic Data

Airborne LiDAR (Light Detection and Ranging) is a remote sensing technique that involves scanning the earth's surface with an aircraft-mounted laser in order to generate a three-dimensional topographic model (Carter et al., 2001). During a LiDAR acquisition flight, the aircraft's trajectory and orientation are recorded with Global Positioning System (GPS) measurements and the aircraft's inertial measurement unit, respectively. Throughout the flight, the laser sends pulses of energy at more than 100,000 pulses per second in a sweeping pattern beneath the aircraft. Energy from a single pulse is commonly reflected by multiple objects within the laser's footprint at ground level,

such as the branches of a tree and the bare ground below, generating multiple returns. The first returns are commonly referred to as “highest hit” or “top surface” points and are used to measure the elevations of vegetation and buildings, while the last returns are commonly referred to as “bare earth” points and undergo additional processing to create a model of the earth’s ground surface.

To generate a digital elevation model (DEM), the aircraft trajectory and orientation measurements are combined with the laser orientation and travel time data to create a georeferenced point cloud representing the location of each reflected pulse. These irregularly spaced points are commonly interpolated to a regularly spaced grid with horizontal spacing on the order of 1 m to create a high resolution digital elevation model. Bare earth digital elevation models undergo additional filtering to identify ground returns from the last return point cloud data (for a review of filtering techniques, see (Liu, 2008). These bare earth DEMs are most commonly used for interpreting and mapping deep-seated landslide features, especially in forested terrain where vegetation would normally obscure diagnostic ground features (Van Den Eeckhaut et al., 2007).

Hillshade and slope maps derived from bare earth LiDAR DEMs are the most common LiDAR products used to identify deep-seated landslides. A hillshade map is created by simulating sunlight shining on the topographic surface at a specified angle, while a slope map is the magnitude of the topographic gradient, estimated by differencing the elevations of adjacent points in the DEM. Hillshade maps tend to have less contrast on slopes facing the incident sun angle and more contrast on slopes facing away from the incident sun angle, either of which can obscure topographic features. It is therefore recommended to analyze several hillshade maps generated with different sun angles or employ methods such as those described in Burns and Madin (2009) for minimizing illumination and topographic shadowing effects (i.e., multi-directional oblique-weighted hillshade algorithm). Additional derivative maps such as topographic curvature, surface roughness, and elevation contours can also be useful to identify deep-seated landslide features. Contours should be generated with spacing similar to the LiDAR data resolution and/or the scale of the geomorphic features of interest.

Key topographic features indicative of deep-seated landslides that are visible in LiDAR-derived maps, but might not be visible in other remote sensing data, are similar to those observed in visual indicators. Hummocky topography, benched surfaces, tension cracks, scarps, block and graben features, shear margins, pressure or transverse ridges, irregular drainage patterns, and displaced surface features are often especially visible, but only when the scale of the feature is larger than the resolution of the LiDAR data. LiDAR hillshades can be used to delineate and interpret deep-seated, but not shallow, landslides, although some depositional surfaces (for example debris fans) can be identified. Various measures of surface roughness are commonly used to recognize and quantify deep-seated landslide morphology in landslide mapping studies (McKean and Roering, 2004; Glen et al., 2006; Booth et al., 2009; Berti et al., 2013). Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005, 2007), and Haugerud (2014).

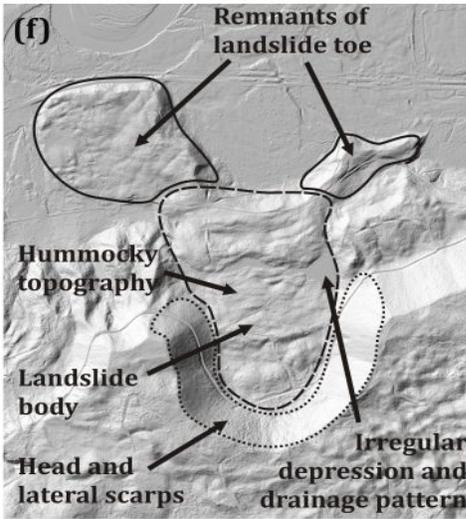
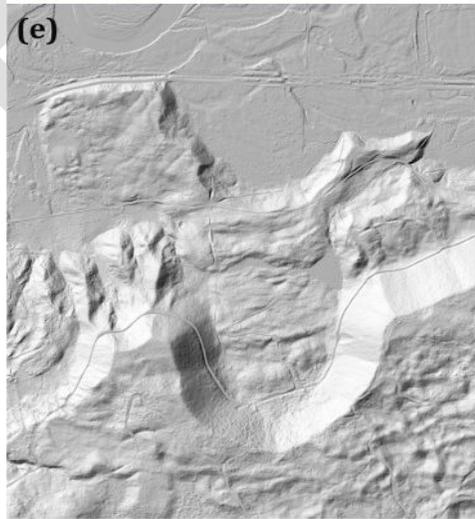
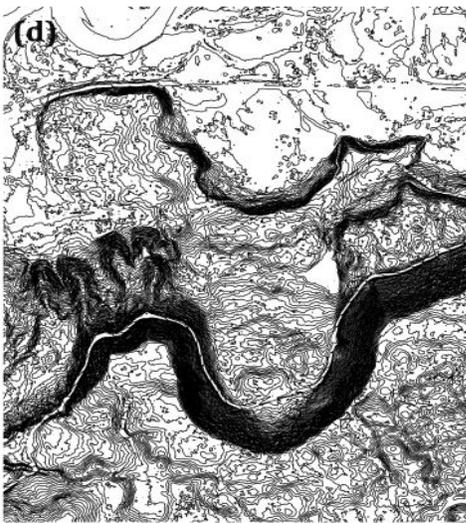
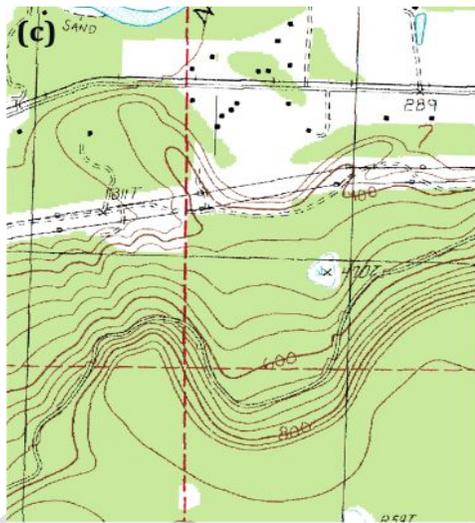
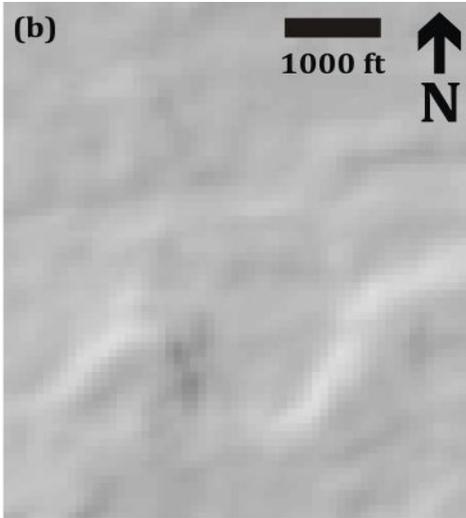


Figure 24 Example of a dormant glacial deep-seated landslide as seen in different types of remotely sensed data: (a) Digital Orthophoto Quadrangle, (b) hillshade map derived from 30-meter resolution ASTER Global Digital Elevation Model, (c) topographic map, (d) 6-foot contour map derived from 3-foot resolution airborne LiDAR, (e) hillshade map derived from 3-foot resolution airborne LiDAR, and (f) annotated version of (e). In (f), the landslide's main scarp, body, and toe are approximately delineated. Subsequent erosion has removed the central part of the landslide toe, hummocky topography is found throughout the body of the landslide, and a sediment-filled depression connected with an irregular drainage pattern is present on the eastern side of the landslide body (Adam Booth, 2014, Portland State University).

Repeat LiDAR acquisitions are becoming more common so that in addition to using a single LiDAR data set to interpret deep-seated landslide morphology, the qualified expert can increasingly measure topographic changes related to slope instability with pairs of LiDAR scenes (Corsini et al., 2007; Delong et al., 2012; Deahne and Corsini, 2013). Vertical changes can be measured by differencing LiDAR-derived DEMs, while manual or automated tracking of features visible on hillshade or slope maps between scenes can be used to estimate horizontal displacements. Note that many active deep-seated landslides move at rates that may be undetectable given the uncertainties in the LiDAR data, so this technique is most helpful for relatively large topographic changes, typically on the order of several meters (Burns et al., 2010). Care should be taken to precisely align the repeat LiDAR DEMs.

6.2 Field Review Process

The purpose of the field review is to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review. While the office review can provide important information, on-site observation of geomorphic features on the ground surface is essential for identifying potentially unstable landforms.

The field review performed by the general practitioner (e.g., landowner, forester, and engineer) confirms the presence or absence of potentially unstable slopes and landforms. If such features are located and forest practices are proposed on these features, the landowner may retain a qualified expert to perform additional geotechnical reviews.

6.2.1 Field Assessment Conducted by a Landowner during Operations Layout

The objective of the field assessment conducted by a landowner or designated representative is to verify the presence or absence of unstable slopes and landforms, using definitions of the landform types and guidance provided in this Board Manual section. In addition to assessing the potential unstable areas identified in the initial office screening, the landowner surveys the operations area for any landforms missed in the office review. The landowner typically carries out this assessment while laying out the forest operations (e.g., marking unit boundaries, establishing riparian management zones).

Summary of Procedures See Field Review Assessment (Part 6.4.2) and Visual Indicators of Slope Instability or Active Movement (Part 6.3) for additional information on conducting field reviews.

Outcomes Common results of landowner-conducted field review include:

1. The landowner does not identify any potentially unstable slopes or landforms within or adjacent to the operations area, the FPA slope stability sections are filled out accordingly, and the office/field review process is complete;
2. The landowner identifies potential unstable slopes and landforms within or adjacent to the operations area. The landowner excludes these areas from this and future planned operations and completes the appropriate FPA slope stability sections similar to (1) and any required additional information.
3. The landowner identifies potentially unstable areas within or adjacent to the operations area, and proposes to conduct forest operations on them. The landowner retains a qualified expert (see Washington State Department of Department of Natural Resources (DNR) website for list of qualified experts) to conduct a geotechnical office review and subsequent field review, and prepare a geotechnical report, as required by WAC 222-10-030. The landowner completes the FPA slope stability sections and includes any additional information.

6.2.2 Geotechnical Field Review Conducted by a Qualified Expert

The objectives of the geotechnical field review conducted by a qualified expert are to: (1) verify the presence or absence of unstable slopes and landforms identified in the geotechnical office review, as well as those that were missed due to insufficient remote-sensing data coverage or resolution; (2) refine preliminary maps constructed during the office review; (3) confirm or refute initial hypotheses regarding landslide behavior, failure mechanisms, and level of activity; (4) solidify understanding of cause-effect relationships; (5) assess relative potentials for material delivery associated with the proposed forest practices to areas of resource sensitivity and threats to public safety; (6) evaluate levels of confidence in office and field findings; and, (6) write a geotechnical report summarizing review findings, conclusions, and recommendations (see Part 8 for guidance on geotechnical report writing).

Summary of Procedures The qualified expert determines the nature of the field review required to meet the objectives stated above subject to DNR's review. Depending on the analyst's level of confidence in potentially unstable landform identifications, delineations, and interpretations for any given site, the field review might range from qualitative to more quantitative in nature. An example of a qualitative review would be one in which the qualified expert collects visual observations and photos of geological features and other site indicators at identified locations (i.e., GPS waypoints) and summarizes those observations in a geotechnical report, as a means for substantiating landform and process interpretations. A more quantitative investigation might include such data collection techniques as topographic surveying for measuring landslide surfaces (i.e., needed for slope stability modeling), soil sampling to test material properties, and subsurface sampling that is especially important in analyzing the depths, materials, and hydrology of deep-seated landslides. Fieldwork needed to complete the review can take one or more days, and the qualified expert might be asked to return to the field for an interdisciplinary team meetings if required by DNR.

The field review performed by a qualified expert should include the preparation of a site-specific geologic map, because the scope of work associated with most published geologic maps is insufficient to identify small-scale unstable landforms that could have a significant effect on the proposed forest activity. The purpose of geologic mapping is to document surface conditions and provide a basis for the interpretation of subsurface conditions. Ideally the geologic map should be prepared on a scale of 1:10,000 or less using high-resolution LiDAR-generated topography. If high-resolution LiDAR is not available base maps can consist of U.S. Geological Survey 7.5-Minute topographic maps, DNR forest practices activity maps, or aerial photographs.

The geologic map should ideally include the location, elevation and attitude of all geologic contacts, although such data collection is not feasible or necessary in all situations. Particular emphasis should be placed on the contact between high permeability soils and underlying low permeability soils or bedrock and the location of groundwater seeps or springs, especially where deep-seated landslide activity is suspected or encountered. If an unstable or potentially unstable landform is present, the location of pertinent components and effects of the landform should be identified on the map, such as headwall and side scarps, tension cracks, drainage patterns, hummocky topography, and run out areas.

Geologic field data collection, analysis, and map compilation are undergoing a revolution in methods, largely precipitated by GPS and GIS-equipped mobile computers (Whitmeyer et.al, 2010; U.S. Geological Survey, 2008; Edmondo, 2002). Geologic reports prepared for FPAs should include GPS locations of landforms and other relevant features with an accuracy sufficient for others to identify the landforms in the field. Significant landforms or their components should also be photographed if their spatial scales are compatible with ground-based photography. Indicators of potential slope instability or active movement should be noted during the field review. These include topographic, hydrologic, and vegetation indicators as described in Part 6.3.

Outcomes Common results of a geotechnical field review include:

1. The qualified expert determines that potentially unstable landforms identified in the office review do not technically meet the definitions provided in this Board Manual section; the qualified expert reports to the landowner that no potentially unstable landforms are present and the slope stability assessment is complete;
2. The qualified expert determines that potentially unstable landforms within or adjacent to the operations area have minimal potential for material delivery to areas of resource sensitivity and/or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings and the slope stability assessment is complete;
3. The qualified expert determines that unstable landforms within or adjacent to the operations area have the potential for material delivery to areas of natural resource sensitivity or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings.

6.3 Visual Indicators of Slope Instability or Active Movement

Topographic indicators are manifested by the land surface. Relatively large and recent topographic indicators can be observed on air photos, topographic maps, and LiDAR images, but the identification of smaller and older indicators requires careful field observations. Topographic indicators for all types of potentially unstable landforms may include:

- Bare or raw, exposed, un-vegetated soil on the faces of steep slopes. This condition may mark the location of a debris flow or the headwall or side wall of a slide.
- Hummocky topography at the base of steep slopes. This may mark the accumulation zone (run out area) for a flow or slide.
- In-filled valleys.
- Benched surfaces, especially below crescent-shaped headwalls, indicative of a rotational slide.

- Fresh deposits of rock, soil, or other debris at the base of a slope.
- Tension cracks in the surface (across or along slopes, or in roads). Tension cracks may mark the location of an incipient headwall scarp or a minor scarp within the body of an existing slide.
- Multiple scarps in a downslope direction.
- Intact sections (blocks) and grabens, translational blocks and grabens.
- Pressure ridges typically occur in the body or toe of the slide and may be associated with hummocky topography.
- Side scarps or shear margins or lateral scarps.
- Transverse ridges.
- Radial cracks.
- Displaced surface features like roads, railroads, foundations, and fence lines.
- Stratigraphic indicators, including disconformities, offset contacts, and overturned sections.
- Back tilted surfaces from rotation within the slide.

Hydrologic indicators result from local hydrogeologic conditions and the interaction of landslides with hydrologic features. Hydrologic indicators may include:

- Chaotic drainage patterns as a result of landslide activity.
- Deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits).
- Seepage lines or springs and ground water piping. These conditions often mark the contact between high permeability and low permeability soils.
- Ponding of water in irregular depressions in undrained or poorly drained areas on the hill slope above the valley floor. These conditions are often associated with hummocky topography which can be signature of landslide activity.
- Sag pond (ponded water in a tension crack).

Vegetation indicators may include:

- Jack-strawed, back-rotated, or leaning trees and stumps. These are typically indicative of active or recently active landslides.
- Bowed, kinked, or pistol-butted trees. These are typically indicative of soil creep, but may indicate incipient land sliding particularly if other indicators are present.
- Split trees and stumps. These may be associated with tension cracks.
- Water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes. These conditions may indicate the presence of groundwater seeps and associated hydrogeologic conditions.
- Uneven age of trees or changes in stand composition. This condition may indicate recent or historical landslide activity. For example, a grove of alder in a conifer-dominated forest may mark the location of a debris flow.

No single indicator necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

6.4 Office and Field Assessment for Groundwater Recharge Areas Conducted by the Qualified Expert

The recharge, occurrence, and movement of groundwater through water-bearing units (aquifers) and confining units that inhibit groundwater movement can have an effect on slope stability. Hydrogeologic frameworks, which define the groundwater-recharge environment and the subsurface environment in which groundwater occurs, have been developed from mapped geologic units, drillers lithostratigraphic logs, and hydrologic data at regional scales such as Puget Sound (Vacarro, 1998, et al.) and the Columbia Plateau (Bauer and Hansen, 2000). Groundwater movement is important to understand at smaller local scales associated with the area related to landslides.

The groundwater recharge area for glacial deep-seated landslides is a rule-identified landform. The technical methods used to identify groundwater recharge areas in glacial deep-seated landslides are no different than those for other (e.g., non-glacial) deep-seated landslides.

6.4.1 Office Review Assessment for Groundwater Recharge Areas

An office review of information for evaluating the area contributing groundwater recharge to a landslide includes reviewing the surrounding topography, land cover and vegetation, soils, and the distribution of hydrogeologic units. Timescales of groundwater movement from areas of recharge to discharge may vary over several orders of magnitude, depending on the hydraulic characteristics of the hydrogeologic units, which include water bearing and non-water-bearing rocks and sediments (aquifers) and confining units, respectively.

In a simplified hydrogeologic setting in a humid environment, the groundwater table forms a subdued replica of surface topography with groundwater flow from high-altitude areas of recharge to low-altitude areas of discharge (Freeze and Cherry, 1979). The surficial contributing area may be delineated from digital elevation models derived from high-resolution LiDAR, if available, or alternately the lower resolution U.S. Geological Survey topographic quadrangles. This analysis provides a first-order approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.

The land cover of the recharge area also influences the spatial extent and magnitude of groundwater recharge. The type and distribution of vegetation affect the amount of precipitation that is intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may also influence groundwater recharge. Remotely sensed land cover data is available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's National Land Cover Database. In addition, land cover data is available for Washington State through the Washington Department of Natural Resources (DNR) Forest Resource Inventory System.

Geologic maps provide a basis for delineating the areal extent, orientation, stratigraphic relations, and thickness of rocks and sediments that influence the occurrence and movement of groundwater. The U.S. Geological Survey, DNR, and others have published geologic maps at scales of at least 1:100,000 across Washington and locally at larger scales (1:24,000). Drillers logs of wells and geotechnical borings may supplement geologic mapping by describing the vertical extent of rocks and sediments and providing information about grain size distributions, sorting, and other physical properties that may influence the hydraulic characteristics of hydrogeologic units. The Washington

State Department of Ecology (Department of Ecology) maintains a searchable database of well logs for Washington State. Hydrogeologic frameworks have been developed from mapped geologic units, drillers lithostratigraphic logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000) to local scales for sites across Washington State. Hydrogeologic reports are available from sources such as the U.S. Geological Survey and Department of Ecology.

6.4.2 Field Review Assessment for Groundwater Recharge Areas

A groundwater recharge area of a deep-seated landslide is the area up-gradient of a landslide that can contribute water to the landslide. In simple terms the groundwater recharge area is the topographic area or hillslope area that is at a higher elevation and capable of delivering water into the landslide.

Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types so field inspection of the initial groundwater recharge area map will be necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation.

Typically once a landslide has been mapped, initial designation of the topographic groundwater recharge area is a straightforward task that can be performed on a detailed topographic map of the area. Topography developed from high resolution digital elevation models (DEMs) generated from LiDAR is preferred. Figure 24 shows the groundwater recharge area for a landslide based on upslope topographical delineation. Line A corresponds to a cross section showing approximate stratigraphy (Figure 24b) through the groundwater recharge area and landslide.

After initial designation of the groundwater recharge area, field review should be conducted in order to determine if the initial designation accurately reflects the recharge area topography up-gradient of the landslide. Depending on the available topographic data for the site in question, examination of the boundaries of the mapped groundwater recharge area will be necessary to ensure the hillslope morphology displayed by the DEM is accurate. If possible it would be optimum to have GPS waypoints collected in the field along the topographic boundaries of the groundwater recharge area.

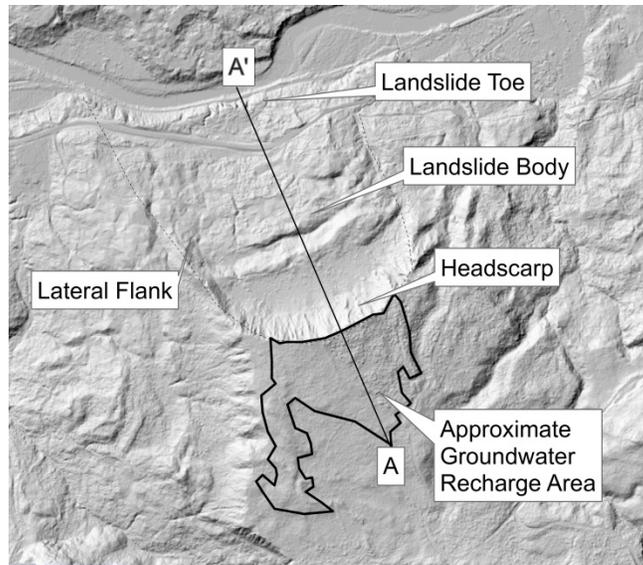


Figure 24a Glacial deep-seated landslide (approximate upslope contributing groundwater recharge area is the black lined polygon) (DNR, 2014).

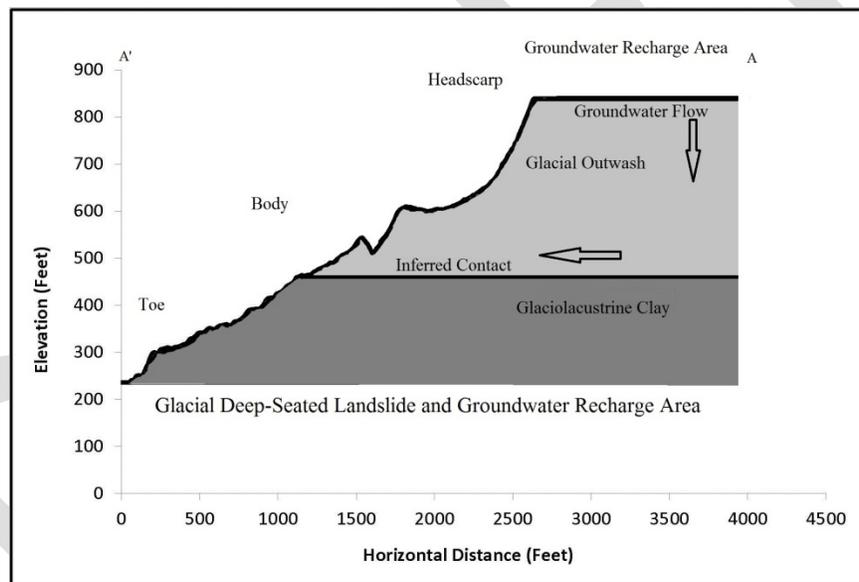


Figure 24b Hillslope cross-section derived from 2-meter DEM of a glacial deep-seated landslide showing groundwater recharge area, geologic units and generalized groundwater flow paths (DNR, 2014)

The groundwater recharge area should be inspected and any surface water drainage features should be mapped that indicate that surface water may be directed into the landslide. Stream drainages on or adjacent to the deep-seated landslide should also be identified, mapped, and assessed for the potential to contribute water to the recharge area and landslide.

During field review it is important to examine the characteristics of the surface materials within the groundwater recharge area and document that the soil types and subsurface geologic units are consistent with those mapped for the location of interest.

Mapping the stratigraphic units that compose the hillslope (i.e., the distribution of geologic units or horizons with depth below the groundwater recharge area) should be done in order to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide.

Exposures of strata within the groundwater recharge area may be examined in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps at the top of the landslide. The distribution of geologic units with increasing depth below the surface may be also be available from well drillers logs or other subsurface information such as geologic mapping and reports.

Excavation of test pits, driving soil probes and well-points, drilling monitoring wells or using other geophysical techniques such as seismic or electric resistivity methods should be considered in order to accurately characterize and reduce uncertainties of the subsurface conditions of the groundwater recharge area and when topographic indicators are uncertain. See Part 6.5 for further discussion on quantitative field review methods.

Often landslide failure planes are co-incident with subsurface aquitards such as silt or clay beds that form elevated groundwater tables within hillslopes. Understanding the morphology of these aquitards can help inform the spatial extent of the groundwater recharge area beyond the surface topographic expression of the hillslope up-gradient of a landslide.

Human-caused activities such as construction of road networks and installation of on-site sewage systems can direct surface and groundwater towards deep-seated landslides and/or contribute relatively large volumes of water within a groundwater recharge area. The location of such infrastructure should be mapped and evaluated with respect to possible water volumes likely to be contributed to a landslide.

6.5 Quantitative Field Review Methods for Subsurface Investigations

If an unstable or potentially unstable landform with a potential to deliver sediment to public resources or threaten public safety is identified during the office and field review, additional field analysis may be needed to more quantitatively assess the hazard. This is generally accomplished with a subsurface investigation.

The subsurface investigation should be designed to gather the data necessary to evaluate the landslide in accordance with the evapotranspiration, recharge, groundwater flow and slope stability modeling when uncertainties related to subsurface conditions exist (see Part 7).

Selection of exploration methods are based on the study objectives, size of the landslide area, geologic and hydrogeologic conditions, surface conditions and site access, and limitations of budget and time. Subsurface exploration to assess landslides is generally described by McGuffey et al. (1996), as summarized in the following paragraphs:

Test Pits. Shallow test pits can be dug by hand with a shovel. Trackhoes or excavators can be used to advance test pits to depths of nearly 20 feet in certain soils. They are useful for exposing subsurface soil and rock conditions for purposes of mapping or logging the underlying conditions, and to identify groundwater elevations and failure planes.

Hand Auger. A hand auger can be used to identify soil types to depths up to nearly twenty feet (in loose soils) but does not provide significant information regarding soil material properties.

Hand Probe. A simple hand probe can be used to estimate soil density and the depth to dense soil. The Williamson Drive Probe (Williamson, 1994) was developed as an inexpensive and portable alternative for determining soil relative densities and groundwater table elevations. Sections of hardware pipe are coupled and driven into the ground manually with a sliding hammer. The number of blows, in even distance increments, required to drive the probe is used to describe soil conditions. Blow-count data theoretically can be correlated with the Standard Penetration Test (SPT; ASTM, 2014).

Method limitations include manual labor intensity, which can limit the number of holes drilled in a given day. The WDP can also be used to estimate depth to ground water if perforated pipe is used. With these many uses and the low cost, the Williamson Drive Probe is an effective alternative to other tests which require expensive equipment and are less portable.

Drill Rigs. Borings constitute a common method for collecting geotechnical data. Accessibility is a common problem in the forested environment, but this problem can be overcome if logging roads are fortuitously located, or by using track-mounted equipment. In some cases, undisturbed or lightly disturbed soil samples can be collected for quantitative laboratory testing (i.e., direct shear, bulk density, moisture content, etc.). Drill rigs can also be used to install groundwater monitoring wells that contain pressure transducers, and as a conduit for geotechnical instrumentation (i.e., inclinometer, extensometer, etc.).

Geophysical Methods. Surface-based geophysical methods can be an economical method of collecting general subsurface information over large areas of rugged terrain. These include ground penetrating radar, electromagnetic, resistivity, and seismic methods. These techniques can provide information on the location of boundaries between coarse-grained and fine-grained strata and the depth to the water table.

A qualified expert should be present in the field during the completion of a subsurface investigation so that the field activities are properly executed and the desired results can be achieved.

PART 7 DELIVERY LANDSLIDE ACTIVITY ASSESSMENT

An assessment of landslide activity is an important component of evaluating landslide hazard. It is recommended that the landslide activity assessment be conducted by a qualified expert.

7.1 Landslide Activity

Three components of landslide activity should be assessed based in the office and field review process: (1) the state of activity, (2) distribution of activity, and (3) style of activity (Cruden and Varnes, 1996).

The state of activity refers to the timing of landslide movements and ranges from active (currently moving) to relict (clearly developed in the geomorphic past under different conditions than are currently present). When an active landslide stops moving, it becomes classified as suspended and if

it remains stationary for more than one annual cycle, it becomes inactive. If the conditions that contributed to prior movement are still present even though the landslide is inactive, the landslide is considered dormant because it may become reactivated at a later time. If the conditions promoting failure have naturally changed to promote stability, the landslide is considered abandoned, while if human intervention has protected against future movement the landslide is considered stabilized. Interpretation of vegetation cover, surface morphology, and toe modification by a stream, if present, all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes (Table 3, Keaton and DeGraff, 1996). Although based on a Rocky Mountain-type climate, the framework described by Keaton and DeGraff has successfully applied in the Pacific Northwest. New vegetation generally begins to colonize a landslide’s scarp, lateral flanks, or other areas of disturbed ground once the landslide becomes dormant and progresses to mature vegetation cover according to the local climate. The scarp, flanks, and internal hummocky morphology of the landslide also tend to become increasingly subdued with time after the landslide becomes dormant, and the internal drainage network of the landslides tends to become more connected and organized. If the toe of the landslide enters a stream, that stream progressively modifies the landslide’s toe as recorded by terraces and the establishment of floodplain comparable to reaches unaffected by landslide activity.

The distribution of activity refers to the geometry and spatial pattern of landslide movements and how these patterns may change with time. One key distinction is if the landslide is advancing by extending downslope in the main direction of movement, or retrogressing by extending upslope in the direction opposite movement. A landslide can also widen or narrow in the direction perpendicular to movement, and more generally can be enlarging or diminishing if its total volume is increasing or decreasing.

The main style of landslide activity is defined as the type of movement options shown in Table 1. Many landslides involve different styles of landslide activity, and movements should be described as complex if they happen in succession, or as composite if they happen simultaneously at different parts of the landslide. Many landslides are also reactivate repeatedly over time and their movements are noted as “multiple” if the same style of activity affects any previously displaced material, or “successive” if the same style of activity affects previously stable material in the immediate vicinity of the previous landslide.

Table 3. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates (from Keaton and DeGraff, 1996).

<u>Active State</u>	<u>Main Scarp</u>	<u>Lateral Flanks</u>	<u>Internal Morphology</u>	<u>Vegetation</u>	<u>Toes Relationships</u>	<u>Estimated Age (Years)</u>
<u>Active reactivated, or suspended; dormant-historic</u>	<u>Sharp; unvegetated</u>	<u>Sharp; unvegetated streams at edge</u>	<u>Undrained depressions; hummocky topography; angular blocks separated by scarps</u>	<u>Absent or sparse on lateral and internal scarps; trees tilted and/or bent</u>	<u>Main valley Stream pushed by landslide; floodplain covered by debris; lake may be present</u>	<u>< 100 (historic)</u>
<u>Dormant-young</u>	<u>Sharp; partly vegetated</u>	<u>Sharp; partly vegetated; small tributaries to lateral streams</u>	<u>Undrained and drained depressions; hummocky topography; internal cracks vegetated</u>	<u>Younger or different type or density than adjacent terrain; older tree trunks may be bent</u>	<u>Same as for active class but toe may be modified by modern stream</u>	<u>100 to 5,000 (Late Holocene)</u>

<u>Dormant-mature</u>	<u>Smooth; vegetated</u>	<u>Smooth; vegetated; tributaries extend onto body of slide</u>	<u>Smooth, rolling topography; disturbed internal drainage network</u>	<u>Different type or density than adjacent terrain but same age</u>	<u>Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain</u>	<u>5,000 to 10,000 (Early Holocene)</u>
<u>Dormant-old or relict</u>	<u>Dissected; vegetated</u>	<u>Vague lateral margins; no lateral drainage</u>	<u>Smooth, undulating topography; normal stream pattern</u>	<u>Same age, type, and density as adjacent terrain</u>	<u>Terraces cut into slide debris; uniform modern floodplain</u>	<u>> 10,000 (Late Pleistocene)</u>

Decision flow chart

The following decision pathway was developed by the DNR as a guide to the assessing the risk associated with landslides. Generally, the pathway is defined by the level landslide activity and how likely the landslide is to deliver sediment to public resources. The decision pathway uses a glacial deep-seated landslide and associated ground water recharge area as an example for how a qualified expert would assess the risk associated with the landform. The same decision pathway may be used for other types of deep-seated landslides.

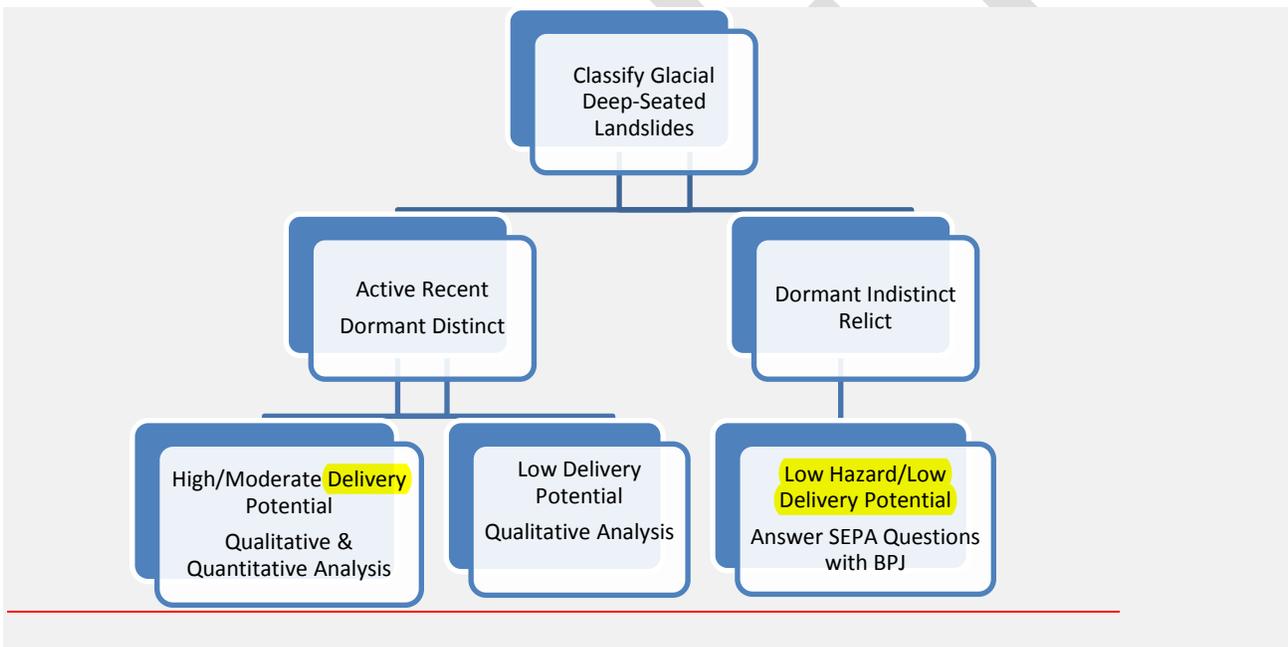


Figure 25 Decision pathway for implementing qualified expert investigations of groundwater Recharge area harvests for glacial deep-seated landslides (DNR Forest Practices Division).

1. Identify and map glacial deep-seated landslides and groundwater recharge areas
2. Classify landslides using the Landslide Hazard Zonation (LHZ) protocol (modified from Keaton and DeGraff, 1996) for deep-seated landslides as:
 - a. active
 - b. dormant/distinct
 - c. dormant/indistinct
 - d. relict
3. Map landslides and related up-gradient groundwater recharge areas and calculate areas.

4. Evaluate delivery potential if landslide were to move for:
 - a. public safety (houses, roads etc);
 - b. public resources (water quality and fish habitat)
5. If the landslide is relict or dormant/indistinct, and has low delivery potential, no additional analysis may be necessary. Answer the State Environmental Policy Act (SEPA) checklist questions using best professional judgment of the landslide hazard.
6. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge and evidence of landslide movement from aerial photographs, LiDAR and other screening methods. Answer SEPA checklist questions with qualitative information and best professional judgment.
7. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (6), perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. Answer SEPA checklist questions with quantitative information from modeling exercises.
8. Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

7.2 Water budget and Hydrologic Contribution to Slope Stability

A water budget of a groundwater/surface-water system describes the input, movement, storage, and output of water from a hydrologic system. Water enters a hydrologic system through precipitation in the form of rainfall and snowmelt. Some of this water is intercepted by vegetation and evaporates before reaching the ground or sublimates from the snowpack. Water that reaches the ground may run off directly as surface flow or shallow, sub-surface runoff, or evaporate from the soil, or transpire through vegetation foliage. Water that percolates below the root zone and reaches the water table is considered to be groundwater recharge. Groundwater moves from areas of recharge of high hydraulic head to areas of low hydraulic head where it leaves the groundwater-flow system through wells, springs, streams, wetlands, and other points of groundwater discharge. The occurrence and movement of groundwater through the subsurface depends on the hydraulic properties of subsurface material as well as the distribution of groundwater recharge.

7.2.1 Modeling Evapotranspiration

Modeling evapotranspiration is a data intensive exercise that requires regional and/or site-specific information regarding precipitation types and rates, wind speed, relative humidity, temperature, solar energy, and plant community stand characteristics.

The goal of evapotranspiration modeling is to derive estimates of the potential increase in water available to the groundwater recharge area from changes in energy balances, wind speeds and plant community characteristics (i.e., aerodynamic roughness) after forest harvest.

Effects of evapotranspiration on the soil water budget can be partitioned as follows: (1) canopy interception of rainfall or snow and subsequent evaporation loss to the atmosphere; (2) transpiration of infiltrated water to meet the physiological demands of vegetation; (3) evaporation from the soil or litter surface. Different vegetation covers have different balances of these fundamental water loss processes. The effects of evaporation on soil water budgets are relatively small compared with canopy evapotranspiration and interception.

Transpiration is the dominant process by which soil moisture in densely vegetated terrain is converted to water vapor. Transpiration involves the adsorption of soil water by plant roots, the translocation of the water through the plant and release of water vapor through stomatal openings in the foliage. Transpiration rates depend on availability of solar energy and soil moisture as well as vegetation characteristics, including vegetation type (e.g., conifer and deciduous), stand density, height and age, rooting depth, leaf area index, leaf conductance, albedo of the foliage, and canopy structure. Rates of transpiration are similar for different vegetation types if water is freely available.

Transpiration is typically quantified using Soil-Vegetation-Atmosphere Transfer (SVAT) models where the movement of water from the soil through the plant to the atmosphere is represented by several resistances in series: (1) the integrated soil-root system; (2) the stem; (3) the branch; and (4) the effective stomatal resistance. Eddy correlation techniques are commonly used to estimate transpiration fluxes.

Interception by vegetation cover controls both the amount and timing of precipitation reaching the soil surface. The interception capacity of vegetation complexes is important because intercepted water has a high surface area to volume ratio that promotes efficient evaporation by convection. Intercepted rainfall is mostly stored on the surface of foliage and stems, while intercepted snowfall bridges between gaps in tree crowns facilitating an accumulation of snow over large surface areas of the canopy. Interception and subsequent evaporation of water from vegetation cover is particularly significant in coniferous forests; losses (both snow and rain) from these dense canopies can account for up to 30% to 50% of gross annual precipitation (Dingman, 1994). Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10% to 30%. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21% to 35%, based on canopy characteristics and climate conditions. Hannel (2011) reported hydrologic modeling (DHSVM; Wigmosta, Njssena and Stork, 2002) that predicts a 27% decrease in evapotranspiration resulting from forest conversion to shrub for a site on the western Olympic Peninsula, Washington.

The proportion of rainfall intercepted by forest canopies is inversely related to both antecedent wetness and rainfall intensity. Gentle, short-duration rainfall may be almost totally intercepted, while interception may account for as little as 5% of precipitation during intense winter storms.

Approaches for estimating changes in evapotranspiration typically involve some combination of the Penman-Monteith model for calculating the canopy resistance, the Bowen ratio energy balance technique to estimate evaporation from plant surfaces, and the Priestly-Taylor formula to estimate evaporation from the soil surface. Reviews and demonstrations of these techniques can be found in Avery and Fritschen, 1971; Fritschen, 1975; Ziemer, 1979, Hanks and Ashcroft, 1980; Campbell, 1986; Simpson, 1999; Martin et al., 1996; and Sias, 2003.

7.2.2 Groundwater Recharge and Groundwater Flow Modeling

Groundwater recharge is difficult to measure directly, but several empirical and numerical methods exist for estimating recharge within the surface-water, unsaturated zone, and saturated zone, including physical, tracer, and numerical-modeling techniques (Scanlon and others, 2002). Recharge is commonly estimated by calculating the residual component of the water budget whereby recharge equals the difference between precipitation and the sum of losses through evapotranspiration, surface runoff, and shallow groundwater flow. The accuracy of recharge estimated through this method is limited by the large uncertainties inherent in the estimating

components of the water budget such as evapotranspiration, which is typically large in magnitude relative to groundwater recharge. Examples of numerical models capable of estimating recharge based on a water budget include the Deep Percolation Model (Vaccaro and Bauer, 1987), Precipitation Runoff Modeling System (Leavesley and others, 1983), and the Variable Infiltration Capacity Model (Liang and others, 1994). Once the spatial distribution of groundwater recharge is estimated, the movement of groundwater within the subsurface may be modeled using groundwater-flow models. The movement of groundwater from areas of recharge may be modeled using groundwater flow models such as MODFLOW (Harbaugh and others, 2000). Groundwater-flow models are based on a hydrogeologic framework that incorporates the hydraulic properties of geologic materials and their stratigraphic relations. Groundwater models are calibrated using hydrologic data including groundwater levels within major water-bearing hydrogeologic units and can be used to characterize the movement of groundwater from areas of recharge to areas of discharge.

7.3 Computational Slope Stability Assessment Methods

Qualitative methods for assessing slope stability are summarized in Parts 6.2 and 6.3. Quantitative assessments of slope stability, performed by the qualified expert, may be necessary to characterize slope failure potential at a given site, as well as to evaluate potential impacts to natural resources and public safety associated with proposed forest practice activities. This quantitative assessment most often entails a two-dimensional, limit-equilibrium analysis method, but other methods may be necessary under certain conditions. Limit-equilibrium analysis calculates a factor of safety for sliding along a critical failure surface, which is expressed as a ratio of the shear strength of the earthen material resisting slope failure to the shear stresses driving instability. Relative stability is defined by a factor of safety exceeding a value of one. Computation of the most critical failure surface is an iterative process generally supported by commercially available or public-domain (e.g., LISA, DLISA, STABL, SLOPE-W) software.

Development of a 2D model for analysis requires the following input information to define an initial state of stability:

- An engineering geologic section through the slope of concern (generally cut through the steepest portion of the slope) showing the thickness and position of each engineering geologic unit; the topographic surface profile can be field-surveyed or derived remotely from digital elevation model (DEM) topographic data whereas the subsurface failure plane geometry might need to be interpolated between known or hypothesized points (i.e., the locations at which the failure plane intersects the ground surface) in the absence of field data acquired from boreholes or with other geotechnical methods;
- Location/elevation of groundwater regimes along this critical section; and
- Saturated and unsaturated unit weights and shear strength of each engineering geologic unit.

The potential effects of the proposed forest practice activities on slope stability can then be evaluated by modifying the initial model with the expected condition based on the proposed activities, such as placement of fill for road construction or elevating groundwater levels (pressures) due to forest canopy removal. Limit-equilibrium models also allow the analyst to reconstruct pre-failure slope conditions of existing landslides by varying the input parameters (e.g., surface topography, engineering geologic unit properties, failure plane geometries, groundwater table elevations) such that the reconstructed original slope fails. These exercises are useful for evaluating

reasonable strength parameters of the units involved likely failure plane geometries or groundwater table elevations in the absence of real data or field indications. Two-dimensional models also can be used to evaluate upslope, as well as downslope, threats to natural resources and public safety in situations where retrogressive failure mechanisms are suspected. Turner and Schuster (1996), as well as many other references, provide more details on the process and methodologies for performing limit-equilibrium stability analyses, including method assumptions and limitations. All of the above steps require considerable engineering geologic/geotechnical data (e.g., subsurface, instrumentation, laboratory) and expertise to achieve an accurate and meaningful representation of the actual conditions at the site.

7.4 DELIVERY-Delivery Assessment

~~Landslides occur naturally in forested basins and are an important process in the delivery of wood and gravel to streams. Wood and gravel play important roles in creating stream diversity that is essential for fish use as habitat and spawning grounds. In the past, landslides as a result of forest practices activities have created a catastrophic regime that has contributed to the threatened and endangered status of certain species, as well as endangering human life in some instances.~~

The forest practices rules apply where there is *potential* for sediment and debris to be delivered to a public resource or threatens public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety ~~should~~ be considered evaluated. Many factors are part of that consideration evaluation, including:

- Proximity to a public resource or safety concern;
- Nature of the geologic material involved;
- ~~the~~ Initial failure volume of a landslide;
- Landslide type of failure mechanism;
- Slope of channel conditions; and
- Observed deformation characteristics of nearby landslides with comparable geologic/geomorphic attributes, the runout distance of a landslide, and landscape geometry.

It is difficult to prescribe guidelines for delivery distances because each situation has a special combination of process and topography. Deep-seated landslides can move anywhere from a few inches to a few miles depending on the friction of the slip plane, the forces pulling the landslides down, and the shear strength resisting those forces. Larger landslides are more likely to be able to move great distances at gentle gradients, but they are also less likely to be significantly affected by forest practices activities.

Because many factors can influence landslide mobility and debris runout, it is not practical to provide generalized prescriptive guidelines to predict delivery for a broad range of conditions. An evaluation of deliverability should, in many cases, require a field review; an inquiry of historic landslide activity and behavior; and the application of experienced judgment in landslide processes and mobility.

Timber harvest and road building can cause shallow landslides on steep slopes. Travel distances for such landslides depend on the amount of water contained in or entrained by them. Considering that rain, snowmelt, or some other ~~extreme~~ water inputs trigger the ~~vast~~ majority of landslides in the Pacific Northwest, it should be noted that almost all landslides contain some amount of water that

tends to mobilize the soil or rock. Debris slides that do not reach streams (i.e., do not absorb large volumes of additional water) usually deposit their debris on the hillslope; and are typically unable to move far across large areas of flat ground. However, since most landslides occur during storm conditions, a large proportion of debris slides do reach flowing channels and create the opportunity to entrain enough water to become debris flows. These flows are quite mobile, and can travel great distances in steep or moderate gradient channels.

When channel gradients drop below 12° degrees (20%), debris flows no longer scour and generally begin to slow down. On slopes gentler than about 3-4° (5-7%) debris flows commonly start losing their momentum and the solids entrained in them (rock, soil, organic material) tend to settle out. Travel distance of a debris flow once it reaches a low-gradient surface is a function of its volume and viscosity. The solid volume of a debris slide or flow deposit is a function of soil depth, distance traveled down the hillslope, and the gradient of the traveled path. The proportion of water is the main control on viscosity. Field or empirical evidence should be used for determining the runout distance.

Even if the main mass of a landslide or debris flow comes to rest without reaching a public resource, there is the possibility that secondary effects may occur. Bare ground exposed by mass movement and disturbed piles of landslide debris can be chronic sources of fine sediment to streams until stabilized by revegetation. If flowing water (seepage, overland flow, or small streams) can entrain significant volumes of fine sediment from such surfaces, the possibility of secondary delivery must be evaluated, along with the likelihood of impact by the initial movement event itself.

To assess the potential for delivery and estimate runout distance, analysts can evaluate the history of landslide runout in the region, use field observations, and/or use geometric relationships appropriate from the scientific literature. In any situation where the potential for delivery is questionable, it is best to have a geotechnical expert examine the situation and evaluate the likelihood of delivery. If forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource, a geotechnical report written by a qualified expert is required.

7.5 Synthesis, Results and Conclusions

All office and field review information gathered for an assessment of unstable slopes and landforms should be synthesized by the qualified expert in a geotechnical report (see Part 10 guidelines), with the following key questions in mind:

1. What are the project objectives (e.g., timber harvest unit evaluation, road construction or abandonment, landslide mitigation)?
2. Which types of unstable slopes and landforms have been identified (see Part 5)?
3. What are their spatial and temporal distributions (see Part 5)?
4. Which office and field methods were used to identify and delineate unstable slopes and landforms (see Part 6)? Have all information sources and methods been cited appropriately in the geotechnical report?
5. Based on an analysis of available information (see Parts 7.1, 7.2, 7.3), what is the geotechnical interpretation of physical processes governing unstable slope/landform movement, mechanics, and chronologies of each identified feature?
6. What are the project limitations (e.g., quantity or quality of technical information, site access, project timeframe) that might influence the accuracy and precision of identifying, delineating, and interpreting unstable slopes and landforms?

7. What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identifying, delineating, and interpreting of unstable slopes and landforms?
8. What is the potential for material delivery from each identified unstable slope and landform to areas of natural resources sensitivity or public safety (see Parts 7.4)?
9. What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
10. What level of confidence is placed in the identification, delineation, and interpretation of unstable slopes and landforms? How does the confidence level impact any recommendations provided by the qualified expert for unstable slope management and/or mitigation?

Documentation of the project analysis and synthesis process might take the form annotated images (e.g., LiDAR-derived hillshades, aerial photos), of geologic or topographic profiles, maps, sketches, results of subsurface investigations, summaries of computational or simulation modeling, summaries of available (i.e., previously published) information and remotely sensed or field-derived data and text to explain the concrete evidence and logical train-of-thought for the conclusions and recommendations that will be presented in the geotechnical report. The only conclusions that should be included in the geotechnical report are those that can be substantiated by the presented evidence, and the logical thought process established in the analysis and synthesis process. For instance, interpreted geologic profiles used to evaluate potential groundwater recharge areas should be commensurate with the subsurface information provided in the report and should relate to the proposed project.

Field observation and sampling locations used in project analysis and synthesis should be displayed on a map in the geotechnical report. Descriptive, photo, or data-sampling observation points should be geo-referenced (i.e., with GPS waypoints). Mapped GPS track locations for field traverses also are recommended, so that it is clear which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced.

Models, such as those for slope stability and sensitivity (see Parts 7.2 and 7.3) may be used to support analyses of unstable slope and landform characteristics and mechanics. Model results, however should not be incorporated in report findings without an adequate assessment and clear statement of their assumptions, limitations, and alignment with existing information (e.g., field data). For example, a modeled reconstruction of landslide failure-plane geometry based on one borehole or drive probe sample likely is misleading and could result in spurious conclusions.

The analytical methods used to identify, delineate, and interpret unstable slopes and land forms should be described in the geotechnical report, along with information sources, data processing techniques, and the meaning and limitations of analysis results. Geotechnical reports should describe all assumptions regarding input parameters or variables, such as groundwater surface elevation estimates employed in stability sensitivity analyses, as well as the reasoning for their use. Geotechnical reports also should include an assessment of the sensitivity of the analytical method or model results to parameter variability, especially where only a range of parameter values is available or where input values are extrapolated or estimated from other locations or databases.

The analytical process being used should be described, along with the types of information needed, how data are processed, and the meaning and limitations of potential results. Assumptions such as groundwater levels should be described, including the reasoning for their use. Variability of

parameters should be described along with strength values or other data developed during the synthesis. The results of the analyses for each assumption or variation should be described.

The report conclusions document the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the assessment, including the office and field reviews, qualitative information and data analyses, geo- and hydro-technical modeling, and evaluation of material deliverability. Conclusions should describe the suitability of the site for the proposed activity. Report conclusions also should clearly state the likely direct and indirect effects of the proposed activity or use on the geologic environment as well as the likely direct and indirect effects of geologic processes on the proposed activity.

The qualified expert should provide a concise statement of confidence in and limitations of the slope stability analysis and its conclusions. Confidence levels are influenced by many factors, including project complexity and objectives, site characteristics (e.g., acreage and accessibility), project timeframes, quantity and quality of available information (e.g., reports, databases) and remotely sensed data, accuracy and precision of field observations and collected data, and the rigor of available analytical methods and models. A discussion of the primary limiting factors assists the landowner and report reviewer in evaluating the potential natural resource, public safety, and liability risks associated with implementing a project.

The geotechnical report might include recommendations regarding additional work needed to supplement the qualified expert report, including but not limited to monitoring of geologic conditions (e.g., ground water, slope movement), review of plans and specifications, and construction and/or timber harvest monitoring. The qualified expert also might be asked by the landowner to provide or evaluate possible mitigation measures for destabilized slopes or landforms.

PART 8. GEOTECHNICAL REPORTS

When harvesting or building roads on potentially unstable slopes a geotechnical report is required to explain how the proposed forest practice is likely to affect slope stability, deliver sediment and debris to public resources, and threaten public safety. The applicant must also submit to DNR a State Environment Policy Act (SEPA) checklist and additional information as described in WAC 222-10-030. These Geotechnical reports must be prepared by qualified experts and must meet the requirements as described in WAC 222-10-030(5).

Effective July 1, 2002, qualified experts must be licensed with Washington's Geologist Licensing Board. For more information on the geologist licensing process, refer to WAC 308-15-010 through 308-15-150, or visit the Geology Board's web site at (www.dol.wa.gov/business/geologist). The education and field experience on forestlands will still be required, in addition to the appropriate geologist license.

8.1 Guidelines for Geotechnical Reports

The following elements (a-f) should be included in geotechnical reports submitted by qualified experts:

- (a) *Prepare an introductory section.* This section should describe the expert's qualifications ~~of the expert to ensure he/she meets the aforementioned requirements~~. It should also reference the forest practices application number (if previously submitted), ~~the~~ landowner(s) and operator(s) names, and a brief description of field trip(s) to the area, including dates, relevant weather

conditions, and the locations visited. Geographic coordinates (latitude and longitude, -GPS waypoints of observation locations should be included so reviewers can find observation locations with certainty.

- (b) *Describe the geographic, geologic, and the soil conditions of the area in and around the application site.* ~~This section is to provide reviewers with general background information related to the application site.~~ Include a legal description of the proposal area, the county in which it is located, and aswhere appropriate, distance and direction from the nearest municipality, local landmarks, and named water bodies. Provide elevations and aspect. Describe the underlying parent materials, including their origin (i.e., glacial versus bedrock); the name(s) of any rock formations and their associated characteristics; and geologic structure relevant to slope stability. Describe ~~the~~ soilss and rocks on site based on existing mapping, field observations, and any available local information. Describe soil and rock texture, depth, and drainage characteristics using standard soil and rock classification systems (e.g. Unified, AASHTO) and (Rock Mass Rating, Bieniawski, 1989).
- (c) *Describe the potentially unstable landforms of the site.* Include a general description of the topographic conditions of the site. Provide GPS coordinates for locations of observations and other important features such as borings, trenches and outcrops. Specifically identify the potentially unstable landforms located in the area (i.e., those defined in WAC 222-16-050 (1)(d)(i)), in addition to any other relevant landforms on or around the site. Describe in detail the gradient, form (shape), and approximate size of each potentially unstable landform. Include a description of the dominant mass wasting processes associated with each identified landform, as well as detailed observations of past slope movement and indicators of instability. Assign a unique alphabetic and/or numeric identifier label to each landform on a detailed site map of a scale sufficient to illustrate site landforms and features. Where the proposal involves operations on or in the groundwater recharge area of a glacial deep-seated landslide(s) specifically discuss the probable direct and indirect impacts to groundwater levels and those impacts to the stability of the deep-seated landslide(s).
- (d) *Analyze the possibility that the proposed forest practice will cause or contribute to movement on the potentially unstable slopes.* Explain the proposed forest management activities on and adjacent to the potentially unstable landforms. Clearly illustrate the locations of these activities on the site map, and describe the nature of the activities in the text. Discuss in detail the likelihood that the proposed activities will result in slope movement (separate activities may warrant separate evaluations of movement potential). The scope of analysis should be commensurate with the level of resource and/or public risk. Include a discussion of both direct and indirect effects expected over both the short- and long-term. For proposals involving operations on or in the groundwater recharge area of a glacial deep-seated landslide, conduct an assessment of the effects of past forest practices on slide/slope movement. Explicitly state the basis for conclusions regarding slope movement. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or slope stability model output. Input parameters, model assumptions, and methods should be fully substantiated within the report.
- (e) *Assess the likelihood of delivery of sediment and/or debris to any public resources, or to a location ~~and in a way~~ that would threaten public safety, should slope movement occur.* Include an evaluation of the potential for sediment and/or debris delivery to public resources or areas where public safety could be threatened. Discuss the likely magnitude of an event, if it occurred.

Separate landforms may warrant separate evaluations of delivery and magnitude. Explicitly state the basis for conclusions regarding delivery. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or landslide runout model results, which should have site specific data.

Input parameters, model assumptions, and methods should be fully substantiated within the report.

- (f) *Suggest possible mitigation measures to address the identified hazards and risks.* Describe any modifications necessary to mitigate the possibility of slope movement and delivery due to the proposed activities. If no such modifications are necessary, describe the factors inherent to the site or proposed operation that might reduce or eliminate the potential for slope movement or delivery. For example, an intact riparian buffer down slope from a potentially unstable landform may serve to intercept or filter landslide sediment and debris before reaching the stream. Discuss the risks associated with the proposed activities relative to other alternatives, if applicable.

The report should be as detailed as necessary to answer these and any other relevant questions. In particular, examination of aerial photographs (preferably taken over many years) would be appropriate to evaluate the stability characteristics of the area and the effects of roads or previous logging on the subject or similar sites. Field observations will usually be necessary to define the local geology, landforms, etc. Quantitative estimates of site stability produced using SHALSTAB, XSTABL, or other slope-stability models may be useful.

GLOSSARY

- Aquiclude** A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.
- Aquifer** Saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.
- Aquitard** A less permeable bed in a stratigraphic sequence.
- Confined aquifer** An aquifer that is confined between two aquitards. Confined aquifers occur at depth.
- Disconformity** Unconformity between parallel strata; for example, strata below not dipping at an angle to those above.
- Discontinuity** Sudden or rapid change with depth in one or more of the physical properties of the materials constituting the earth.
- Drift** Any rock material, such as boulders, till, gravel, sand, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice. Generally used of the glacial deposits of the Pleistocene Epoch.
- Drillers log** A record filled out on tabular form by the chief of a drilling crew of an oil, gas, water, or resource protection well drilling rig. The log shows rock character being drilled, drilling progress, drilling tools used, bit size and type, mud additives used, as well as a description of operations and personnel on duty each tour, along with any other pertinent or unusual event occurring during the drilling operations. Drillers logs may also include information on groundwater elevation.
- Earthflow** A slow flow of earth lubricated by water, occurring as either a low-angle terrace flow or a somewhat steeper but slow hillside flow.
- Engineering geology** Performance of geological service or work including but not limited to consultation, investigation, evaluation, planning, geological mapping, and inspection of geological work, and the responsible supervision thereof, the performance of which is related to public welfare or the safeguarding of life, health, property, and the environment, and includes the commonly recognized practices of construction geology, environmental geology, and urban geology.
- Evapotranspiration** A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Commonly designated by the symbols (E_t) in equations.

<u>Factor of safety</u>	<u>The ratio of the resistant force acting on the sliding surface to the driving force acting on the potential slide mass. When the factor of safety is greater than 1, the slope is stable, when the factor of safety is less than 1, the slope is unstable.</u>
<u>Glacial outwash</u>	<u>Drift deposited by meltwater streams beyond active glacier ice.</u>
<u>Graben</u>	<u>A block, generally long compared to its width, that has been downthrown along faults relative to the rocks on either side.</u>
<u>Groundwater</u>	<u>Subsurface water that occurs in soils and geologic formations. Encompasses subsurface formations that are fully saturated and near-surface, unsaturated, soil-moisture regimes that have an important influence on many geologic processes.</u>
<u>Groundwater Recharge area</u>	<u>That portion of a drainage basin in which the net saturated flow of groundwater Recharge is the process by which water is absorbed and is added to the zone of saturation, either directly into a formation, or indirectly by way of another formation. Also, the quantity of water that is added to the zone of saturation.</u>
<u>Glacial terrace</u>	<u>Relatively flat, horizontal, or gently inclined surfaces, sometimes long and narrow, which are bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side formed by glacial processes.</u>
<u>Glaciolacustrine</u>	<u>Sediments deposits consisting of sorted, predominantly stratified, formations of varying composition, from coarse sands to clays deposited into lakes from glacial meltwater.</u>
<u>Glaciomarine</u>	<u>Sediments which originated in glaciated areas and have been transported to an oceans environment by glacial meltwater.</u>
<u>Glacial till</u>	<u>Non-sorted, non-stratified sediment carried or deposited by a glacier.</u>
<u>Hydrogeology</u>	<u>The science that involves the study of the occurrence, circulation, distribution, chemistry, remediation, or quality of water or its role as a natural agent that causes changes in the earth, and the investigation and collection of data concerning waters in the atmosphere or on the surface or in the interior of the earth, including data regarding the interaction of water with other gases, solids or fluids.</u>
<u>Hydro budget</u>	<u>An accounting of the inflow to, outflow from, and storage in, a hydrologic unit, such as a drainage basin, aquifer, soil zone or water body. For watersheds the major input is precipitation; major output is streamflow.</u>
<u>Piezometer</u>	<u>The basic device for the measurement of hydraulic head. Tube or pipe in which the elevation of a subsurface water level can be determined.</u>

<u>Qualified expert</u>	<u>For the purpose of the section, a person who is licensed with Washington's Geologist Licensing Board as either an engineering geologist or as a hydrogeologist, with three years field experience in the evaluation of relevant land features in forested lands.</u>
<u>Resistivity method</u>	<u>Observation of electric potential and current distribution at the earth's surface intended to detect subsurface variation in resistivity which may be related to geology, groundwater quality, porosity, etc.</u>
<u>Seismic method</u>	<u>A method of geophysical prospecting using the generation, reflection, refraction, detection and analysis of elastic waves in the earth.</u>
<u>Soil</u>	<u>That earth material which has been so modified and acted upon by physical, chemical and biological agents that it will support rooted plants.</u>
<u>Strata</u>	<u>Plural of stratum.</u>
<u>Stratum</u>	<u>A section of a formation that consists throughout of approximately the same material; a stratum may consist of an indefinite number of beds, and a bed may consist of numberless layers; the distinction of bed and layer is not always obvious.</u>
<u>Stratification</u>	<u>A structure produced by the deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and other essentially tabular units.</u>
<u>Unconfined aquifer</u>	<u>Aquifer in which the water table forms the upper boundary. Unconfined aquifers occur near the ground surface.</u>
<u>Vadose zone</u>	<u>Also referred to as the unsaturated zone, it is the layer of the earth surface below the land surface and above of the zone of saturation, or water table.</u>
<u>Water table</u>	<u>The surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric. The location of this surface is revealed by the level at which water stands in a shallow well open along its length and penetrating the surficial deposits just deeply enough to encounter standing water at the bottom.</u>

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Appendix A Maps and Surveys

Map and survey data resources available to the qualified expert include:

Multi-disciplinary map and survey data resources:

- Washington State Geologic Information Portal – create, save, and print custom digital maps of Washington State or download map data for GIS applications; includes a variety of base layer selections with interactive Geologic Map, Seismic Scenarios Catalog, Natural Hazards, Geothermal Resources, Subsurface Geology Information, and Earth Resource Permit Locations; available on WDNR website;
- Forest Practices Application Review System (FPARS) – interactive online mapping tool with a variety of digital map base layer selections including topography, surface water (streams, water bodies, wetlands), soils, transportation network, forest site class, and potential slope instability (designed for shallow landslide susceptibility mapping only); available on WDNR website;
- County interactive GIS map viewers – create, save, and print custom digital maps with some combination of the following data: topography (LiDAR and/or USGS DEM), surface water, soils, wetlands, sensitive areas, 100-year floodplain designations, transportation net and traffic counts, property ownership and structure location; available online at select county websites (e.g., King County iMAP);
- Washington State Coastal Atlas Map – interactive map utility for shoreline areas with multiple data layers including shoreline geomorphology (coastal slope stability and landforms), biology (plant communities), land and canopy cover, beaches and shoreline modifications, wetlands and estuaries, historic shoreline platforms, assessed waters, and Shoreline Management Act (SMA) designations; see Department of Ecology website.
- Washington Department of Natural Resources, Surface Mining Permits and associated geotechnical reports.

Topographic maps:

- USGS topographic 7.5 minute quadrangle maps (10-m resolution DEM preferred); available from a number of government and non-government online vendors and free downloadable websites;
- LiDAR-based topographic maps (LiDAR-derived DEM (LDEM), typically 1- to 3- m resolution); see Appendix C for LiDAR map and data sources.

Geologic maps:

- Geologic maps, various scales, in-print and compiled by DNR, Division of Geology and Earth Resources as Map Series, Open File Reports, Bulletins, and Information Circulars; see most recent “Publications of the Washington Division of Geology and Earth Resources”; this publication and a status map of 7.5 minute quadrangle geologic mapping efforts (USGS STATEMAP program) are available on the DNR website with links to online publications where available;
- Geologic maps, various scales, in- and out-of-print or historic; all sources including dissertations and theses; see Catalog of the Washington Geology Library, available through the DNR website with links to online publications where available;
- Geology digital data; small-scale geology coverage in ArcGIS shapefile format, available on DNR website;

- Geologic maps, various scales, available via The National Geologic Map Database (NGMDB; compiled by USGS and Association of American State Geologists; see NGMDB website catalog) and USGS Online Store (paper and digital copies).

Geologic hazards and landslide inventory maps:

- See Washington State Geologic Information Portal referenced previously;
- Landslide Hazard Zonation (LHZ) Project – mapped existing and potential deep-seated landslides and landforms in select watersheds; hazard classifications provided with supporting documentation for completed projects; available through the DNR website;
- Landslide inventory and Mass Wasting Map Unit (MWMU) maps contained in Watershed Analysis Reports prepared under Chapter 222-22 WAC, Washington Forest Practices Board – mapped landslides (including deep-seated and earthflows) for select Watershed Administrative Units (WAU); Adobe pdf versions of DNR-approved Watershed Analysis Reports are available via the DNR website;
- modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps
- landslide-hazard maps from the Regional (Unstable) Landform Identification Project (RLIP)
- US Forest Service watershed analyses – available from US Forest Service offices for select watersheds; some documents and maps are available online
- Washington State tribal watershed analyses – available from tribal agency offices; some documents and maps are available online;
- Washington State Coastal Atlas Map – slope stability maps developed prior to 1980, based on aerial photography, geologic mapping, USGS topographic quadrangle map, and field observations. Maps have not been updated with landslide data since 1980 but are used currently in land-use planning and in the Department of Ecology interactive Coastal Map tool; read data limitations on Department of Ecology’s website.
- Qualified Expert reports on deep-seated landslides in glaciated and non-glaciated terrain, for select timber harvest units or other forest management projects regulated by the Washington Forest Practices Act. Often contain mapped landslides; available from DNR region offices.

Soil surveys:

- Natural Resources Conservation Service (NRCS) soil survey maps and data – Online Web Soil Survey, map and database service; historical soil survey publications (CD or paper copies); NRCS website administered through the US Department of Agriculture;
- Geochemical and mineralogical soil survey map and data – USGS Mineral Resources Program, open-file report available online (Smith et al., 2013) in Adobe pdf;
- National Cooperative Soil Survey Program (NCSS), Washington State – online soil survey data and link for ordering in-print surveys not available electronically; see NRCS website.

Appendix B Earth Imagery and Photogrammetry

The most common sources of imagery for deep-seated landslide identification, mapping, and photogrammetric analysis include:

- Aerial photography, preferably stereo-pair photos – Historic aerial photos were produced in color or black-and-white depending on the year flown and were taken at various altitudes (typical scales in the 1:12,000 to 1:60,000 range); aerial photos acquired by the US Soil Conservation Service are available in some areas as early as the 1930's. Multiple flight years are required for chronologically reconstructing deep-seated landslide activity and developing time-constrained landslide inventories. Forest landowners typically purchased photos from regional vendors on a 2-10 year cycle until recently, when other freely acquired imagery became available (e.g., Google Earth, ESRI World Imagery). Stereo-pair photos are highly valued for landslide detection and reconstruction because they allow stereoscopic projection in three dimensions and can display high-quality feature contrast and sharpness;
- Google Earth – map and geographic information program with Earth surface images created by superimposing satellite imagery (DEM data collected by NASA's Shuttle Radar Topography Mission (SRTM)), aerial photos, and GIS 3D globe. Ortho-rectified, generally 1-m resolution, 3D images are available for multiple years (Historical Imagery tool), allowing chronologic deep-seated landslide mapping; Google Earth supports desktop and mobile applications, including managing 3D geospatial data. See Google website for download information;
- Bing Maps Aerial View – part of Microsoft web mapping service; overlays topographic base maps with satellite imagery taken every few years. See Microsoft site for download information;
- ESRI World Imagery – ArcGIS online image service utilizing Landsat imagery based on the USGS Global Land Survey (GLS) datasets and other satellite imagery, with onboard visualization, processing, and analysis tools that allow imagery integration directly into all ArcGIS projects. Requires ArcGIS capability; see ESRI website.
- NAIP (National Agriculture Imagery Program) aerial imagery – ortho-rectified, generally 1-m resolution Earth surface images taken annually during peak growing season ("leaf-on"), acquired by digital sensors as a four color-band product that can be viewed as a natural color or color infrared image. The latter are particularly useful for vegetation analysis. Data available to the public via the USDA Geospatial Data Gateway and free APFO viewing software, as well as through ESRI for ArcGIS applications; see USDA Farm Service Agency (FSA) website;
- Washington State Coastal Atlas Map and Photos – oblique shoreline photos spanning years 1976-2007; part of an interactive map tool; see Department of Ecology's website.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) Archive of downloadable aerial photos.

Appendix C Sources for LiDAR Data

Sources for viewing and downloading airborne LiDAR of Washington State include the following (URLs may change without notice):

- King County iMAP: Interactive mapping tool (<http://www.kingcounty.gov/operations/GIS/Maps/iMAP.aspx>) – Displays shaded relief maps derived from LiDAR data at locations where it is available. LiDAR data have been filtered to remove vegetation and manmade structures and can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- National Oceanic and Atmospheric Administration Digital Coast (<http://csc.noaa.gov/digitalcoast/>) – Archive of downloadable LiDAR data focused on coasts, rivers, and lowlands. Options for downloading point cloud, gridded, or contour data that require geographic information system software such as ArcGIS to view and analyze.
- National Science Foundation OpenTopography facility (<http://www.opentopography.org/index.php>) – Archive of downloadable LiDAR data collected the National Center for Airborne Laser Mapping (NCALM) for research projects funded by the National Science Foundation. Options for downloading point cloud or gridded data for use with geographical information system software, or LiDAR derived hillshade and slope maps that can viewed in Google Earth.
- Oregon Lidar Consortium (<http://www.oregongeology.org/sub/projects/olc/>) – Small amount of Washington State data available along the Columbia River. Lidar Data Viewer displays hillshade maps that have been filtered to remove vegetation and manmade structures.
- Puget Sound Lidar Consortium (<http://pugetsoundlidar.ess.washington.edu/>) – Archive of LiDAR data from Western Washington, downloadable as quarter quad tiles. Data format is ArcInfo interchange files and requires geographic information system software to view.
- Snohomish County Landscape Imaging: SnoScape (<http://gis.snoco.org/maps/snoscape/>) – Displays hillshade maps of bare or built topography derived from LiDAR data where it is available. Can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) – Archive of downloadable LiDAR data acquired by the USGS through contracts, partnerships, and purchases from other agencies or private vendors. File format is LAS and requires GIS software for viewing.

Appendix D Technical Reports and Resources

In addition to library and online sources, the following technical reports, published and unpublished papers and searchable databases are available online and at DNR region offices:

- Catalog of the Washington Geology Library. Searchable database of the Washington Department of Geology Library containing a comprehensive set of dissertations and theses, watershed analyses, environmental impact statements, and refereed/un-refereed publications on state geology; see DNR website with links to online publications where available.
- Landslide Hazard Zonation Project (LHZ).
- US Geological Survey Open File Reports. Searchable online database containing reports covering deep-seated landslide investigations and related topics (Haugerud, 2014); see USGS Online Publications Directory, USGS website.
- Watershed Analysis, Mass Wasting Assessment reports per chapter 222-22 WAC, Washington Forest Practices Board. Adobe pdf versions of DNR-approved reports are available via the DNR website.
- US Forest Service watershed analysis reports. Available from US Forest Service offices for select watersheds; some electronic documents are available online via the USFS website for national forest of interest.
- Interagency watershed analysis reports. Collaborative projects between federal agencies (US Geological Survey, US Forest Service, US Fish and Wildlife Service), tribal agencies, and industry (e.g., Cook and McCalla basins, Salmon River basin, Quinault watershed) . Documents available online via US Geological Survey, Washington Water Science Center.
- Washington Soil Atlas. Available as downloadable Adobe pdf file from the Natural Resources Conservation Service website.

Appendix E Physical Databases

- Landslide Hazard Zonation (LHZ) Project;
- Regional Landslide Inventory Project (RLIP)

- National Resources Inventory for Washington State – statistical survey of land use, natural resource conditions and trends in soil, water, and related resources on non-federal lands; see NRCS website;

Meteorological databases –

- National Weather Service (NWS) cooperative weather stations – coordinated by National Oceanic and Atmospheric Administration (NOAA) – database managed by Western Regional Climate Center
- NWS Weather Surveillance Radar – Doppler and NEXRAD -
- Remote Automatic Weather Stations (RAWS) – operated by USFS and BLM – database managed by Western Regional Climate Center

Stream-flow gauge databases – USGS National Water Information System website

Seismic data – Pacific Northwest Seismic Network (PNSN) – database managed by USGS, University of Washington, and IRIS Consortium in Seattle; contains records from seismometers located throughout Washington and Oregon; see PNSN website.

Climate Data for Washington

The availability of climate data is highly variable for the State of Washington. The following sites provide access to most of the available data useful for evapotranspiration modeling (The URLs may change without notice):

- United States Geological Survey Washington Water Data - <http://wa.water.usgs.gov/data/>
- National Surface Meteorological Networks - <https://www.eol.ucar.edu/projects/hydrometer/northwest/northwest.html>
- National Weather Service - <http://www.wrh.noaa.gov/sew/observations.php>
- National Climate Data Center - <http://www.ncdc.noaa.gov/>
- University of Washington Atmospheric Sciences - <http://www.atmos.washington.edu/data/>
- Washington State University - <http://weather.wsu.edu/awn.php>
- Community Collaborative Rain, Hail, and Snow Database - <http://www.cocorahs.org/>
- Western Regional Climate Summary for Washington - <http://www.wrcc.dri.edu/summary/climsmwa.html>
- Natural Resource Conservation Service - <http://www.nrcs.usda.gov/wps/portal/nrcs/main/wa/snow/>
- Washington Dept. of Ecology Water Resources - <http://www.ecy.wa.gov/programs/wr/wrhome.html>
- Washington Dept. of Transportation - http://www.wsdot.com/traffic/weather/weatherstation_list.aspx

Appendix F Additional Resources

Forest Hydrology

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October 8, 2014

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Dear Mr. Ratcliff:

Thank you for this opportunity to comment on the Washington State Department of Natural Resources (“DNR”) proposed changes to Board Manual 16 related to Unstable Slopes. The Washington Forest Protection Association (“WFPA”) is a forestry trade association representing large and small forest landowners and managers of nearly 4 million acres of productive working timberland located in the coastal and inland regions of Washington State. Our members support rural and urban communities through the sustainable growth and harvest of timber and other forest products for U. S. and international markets. WFPA members were founding partners in the Timber Fish and Wildlife table, collaborators in passing the Forest and Fish Law, and continue to be active participants in the Adaptive Management Process. Below, I’ve listed our general comment. I’ve also attached two additional documents: specific comments on the draft manual’s text (Appendix A) and a suggested alternative option in rough draft form (Appendix B).

WFPA has supported the development and approval of the collaborative Mass Wasting strategy approved by the Forest Practices Board (“Board”) at its February meeting. In the aftermath of the tragic landslide in Oso, Washington, the Board directed revision of Board Manual Section 16. The FPA approval process requires extensive site-by-site analysis of each forest practices application. The Board Manual is intended to provide guidance pathways for geotechnical experts, foresters and landowners, which, if followed, meet the requirements for the implementation of forest practices rules. The Board Manual also provides information to FPA reviewers and regulators, and the general public in evaluating unstable slopes and forest practice activities. The Board Manual is not an administrative rule or an exhaustive template for geotechnical reports. The Board Manual is a roadmap that foresters and licensed qualified geotechnical experts use to analyze potential impacts of forest practice activities on unstable slopes by identifying and categorizing unstable slopes, evaluating potential impacts of proposed forest

practices and determining the appropriate forest practice prescription. As such, this guidance is very important for the protection of public safety, the maintenance of public resource, and the viability of the timber industry. The revisions are too important to be done improperly or in haste. To be functional, the guidance must be accurate and effective.

First, we would like to thank the Department staff and the experts tasked with developing this draft. They have done a tremendous job over the past few months. Unfortunately, DNR staff has not had adequate time to refine the draft's language. Likewise, stakeholders have not had adequate time for review of the full document. WFPA has four general concerns about the draft Board Manual. In the accompanying document, we've provided additional specific examples of requested changes. We ask that you take the following concerns into consideration as the process goes forward:

- The extensive Board Manual rewrite goes far beyond the Board's motion.
- There has been lack of sufficient time to fully vet and understand the implications of the draft manual.
- As written, the draft Board Manual may not be useful for foresters, qualified experts and reviewers because it is confusing, unclear and inaccurate in many areas.
- As written, many provisions may trigger legal challenges as administrative rules, not guidance.

I. Extensive rewrite goes far beyond the Board's motion.

On May 13, 2014 the Board approved the following motion and directed staff to: "assemble qualified experts with expertise in ground water recharge on glacial deep seated landslides to review and amend guidance specific to the identification and delineation of ground water recharge areas in Board Manual Section 16, Guidelines for Evaluating Potentially Unstable Slopes and Landforms. In a second phase, amend guidance specific to assessing delivery potential." Examples of material that exceeds the scope of the motion include: significant expansion of the sections dealing with office and field reviews and significant information about non-glacial deep-seated landslides. While all of these sections may be beneficial for future revisions, they do not relate specifically to groundwater recharge areas around glacial deep-seated landslides – the target of the Board motion.

II. Document may not be useful for the intended audience.

Despite the extensive rewrite, the draft document is may not currently be useable for foresters, qualified experts, FPA reviewers and the public. Much of the information in the draft document will be very helpful once it is revised and refined. In Appendix A, we have specifically identified nearly 100 questions, requested changes and reorganization suggestions. The vast majority of these comments are intended to make the Board Manual more readable and useable. Many suggested changes also attempt to clarify what the Board Manual actually requires. Two examples revolve around reports required from qualified experts. First, the draft manual requires a very detailed, expanded list of objectives for field reviews conducted by qualified experts (pages 41-42). Currently, WAC 222-10-030 requires a qualified expert has to (1) describe the potentially unstable landforms in and around the application site and (2) analyze: (a) likelihood of movement or contribution to further movement, (b) likelihood of delivery to public resources or threaten public safety; and (c) possible mitigation. The seven objectives plus creation of a new map and photographs go considerably farther. Those objectives are then are "subject to DNR review" and an ID team. This one paragraph expands DNR's discretion beyond current authority in WAC. The second example involves the geotechnical report itself – the language is incredibly vague when it is required, who decides, and what the standards are. DNR may require a pre-report (page 35), a

field assessment (page 36), an office report (page 36), a written report (page 37), another field visit (page 37, 40), and then presence on site for certain activities (such as an ID team visit, page 41; or a subsurface investigation, page 48). Again, many of these changes may be appropriate after further consideration and refinement of the language, but currently appear to be regulatory requirements absent the appropriate rulemaking process.

III. Lack of sufficient time to fully vet and understand the implications of the draft manual.

The Adaptive Management Process works best when stakeholders have sufficient time and opportunity for review and analysis of Board Manual revision. Although TFW Policy does not have jurisdiction over the “approval” of Board Manuals, stakeholder vetting with a wide range of geotechnical experts, forest engineers, foresters, and reviewers is important to garner understanding from the individuals, agencies and businesses that must implement the Manual’s provisions. Legally, DNR Board Manuals are guidance, not administrative rule, but they are often technically complex. If not drafted carefully, a guidance document can stray over the line to become a de-facto rule which is a violation of the APA and the Adaptive Management Process.

Prudence dictates sufficient time taken to fully vet and understand the document. Draft Board Manual 16 lists an impressive array of technical and scientific documents, extensive directions for utilizing analytical tools, and specific requirements for particular activities. All of this information should be carefully considered before the Board adopts the draft manual. As of this writing, stakeholders have not seen the final document to be sent to the Board. Instead of adopting the Board Manual at the November meeting, we offer two additional courses of action for your consideration: delay approval of the full manual approval for a future meeting, giving adequate time for stakeholder and staff work; or approve an abbreviated addendum to the current Board Manual specifically related to delineating groundwater recharge areas for glacial deep-seated landslides. Such an addendum would be responsive to the May Board motion. Appendix B is a very rough draft for such a document; we believe stakeholders and staff could complete work on an addendum in short order. Approval of an extensive revision could be delayed for a future meeting.

IV. Draft Board Manual maybe considered a rule.

As presented to the stakeholders in the brief review period, the significant revisions to the Board Manual create a risk of legal challenge on three separate grounds. First, the scope and extent of the revisions may be challenged as an unlawful rulemaking, because the revisions result in actions that fall into the APA’s definition of “rule” rather than “guidance.” Second, extensive revisions to the Board Manual addressing unstable slopes should follow the adaptive management process because unstable slopes have long been a CMER priority and the revisions may impact timber industry viability. Significantly, such an extensive revision is well within the objectives of adaptive management to ensure the Board is fully informed before making changes that affect stakeholders in areas of scientific uncertainty and policy discretion. Third, the failure to address natural causes of slope instability could make the revisions arbitrary and capricious. WFPA provides detailed explanations below and in the attached document, and has identified actions the Board and DNR can take to minimize the risk of a legally deficient revision. However, because the remedy for a successful challenge under any of the above grounds would likely be invalidation of the revisions, WFPA urges the Board to carefully evaluate the risks of moving forward against the advantages of ensuring compliance with the legally-required processes and ensuring its decisions are based on sound science and transparent to the public.

(a) To Ensure Compliance with the APA, Revisions to the Board Manual Must Not Change Existing Policies or a Regulatory Program and Must Provide Guidance on Adopted Rule

There are two legal issues related to the revisions to the Board Manual section addressing unstable slopes. First, the revisions proposed to the Board Manual have the potential to be perceived as rulemaking rather than merely providing guidance for implementation of existing rules and statutes. Under RCW 34.05.328(5)(c), unless DNR complies with the Administrative Procedures Act's (APA) rulemaking procedures, it cannot make revisions to the Board Manual that modify the requirements for submitting a forest practices application, interpret a statutory provision the agency administers, establish a standard for approval of a forest practices application, or amend the existing policy for unstable slopes. Second, the timing of the revisions to the Board Manual precedes the revisions to the rules that the Board Manual is interpreting. To avoid being a rule, the Board Manual must be limited to guidance for existing rules.

Currently, the Board is undertaking a rule adoption process related to the DNR's authority to require information for classification of a forest practice. That rulemaking process may have some implications for the Board Manual; to avoid the appearance of rulemaking in the Board Manual, the Board should complete its rule making process before DNR revises the Board Manual providing guidance on the rules.

The role of the Board Manual was recently addressed in *Quinault Indian Nation v. State of Washington, Department of Natural Resources*, PCHB No. 12-118c (Findings of Fact, Conclusions of Law, and Order (Corrected) (April 29, 2014)). There, in Finding of Fact #14, the PCHB stated that the Board Manual is "a technical supplement to the rules" "approved by the Forest Practices Board but not adopted through formal rulemaking". *Id.* at pages 8-9. This decision was appealed to superior court, and reviewed Section 2, which "sets out detailed instructions for determining a CMZ, while allowing for some discretion on the part of the practitioner in making the delineation. Despite the level of detail in the Manual, there is still no cookie cutter approach to a CMZ delineation." *Id.* If challenged, a reviewing court would likely hold the unstable slopes section to the same standard, so long as the Board Manual acts only as a "technical supplement" to the rules. If, however, the Manual is revised to such an extent that it is no longer a supplement to, but is functionally a revision to the rules, a reviewing court would likely invalidate the revisions and find that DNR failed to comply with APA rulemaking requirements.

Any action that constitutes a "rule" must be adopted through formal rulemaking under the Administrative Procedures Act, RCW Ch. 34.05. *City of Vancouver v. State Public Employment Relations Commission*, ___ Wn. App. ___, 2014 WL 1226499 at ¶58 (March 25, 2014). An action can be one of three types of rule under the APA, and a requirement in the Manual not found in the RCW or WAC elevates the Manual to a rule, rather than guidance. *See Association of Washington Business v. State of Washington, Department of Revenue*, 155 Wn.2d 430, 439 ¶11, 120 P.3d 46 (2005) (citing RCW 34.05.328(5)(c)). A **procedural rule** adopts, amends, or repeals "any ... process requirement for making application to an agency for a license or permit". RCW 34.05.328(5)(c)(i). An **interpretive rule** sets forth the agency's interpretation of a statutory provision it administers. RCW 34.05.328(5)(c)(ii). A **significant legislative rule** subjects the violator to penalties or sanctions; establishes, alters, or revokes a qualification or standard for the issuance, suspension, or revocation of a license or permit; or adopts a new, or makes significant amendments to, a policy or regulatory program. RCW 34.05.328(5)(c)(iii). An agency action, whether it is through specified rulemaking or revisions to the Board Manual, may be challenged as rulemaking required to comply with the APA rulemaking procedures if it makes significant changes to an existing policy or regulatory program.

The purpose of requiring agencies to comply with the APA's rulemaking procedures is to "ensure that members of the public can participate meaningfully in the development of agency policy that affects them. When the questioned agency action will affect the public in a general way and where notice to and comment by the affected public seems useful, the action should be regarded as a rule." *Allan v. University of Washington*, 140 Wn.2d 323, 346, 997 P.2d 360 (2000) (in Sanders dissent) (quoting William R. Andersen, *The 1988 Washington Administrative Procedure Act – An Introduction*, 64 Wash. L. Rev. 781, 791 (1989)). To avoid litigation challenging the revisions to the Board Manual as rules subject to the APA's procedural requirements, even if not labeled as such, DNR will need to ensure that the revisions do not meet any of the three categories of rules in the APA.

(b) Inadequate Compliance with the Adaptive Management Process Will Violate the Forest Practices Act

The current forest practices rules and statutes are derived from the Forests & Fish Report, and they rely on "adaptive management" as one of their central tenets. RCW 76.09.370; *see also* WAC 222-12-045 and Board Manual Section 22. Adaptive management "means reliance on scientific methods to test the results of actions taken so that management and related policy can be changed promptly and appropriately." RCW 76.09.020(1). The purpose of adaptive management is to "incorporate best available science and information, include protocols and standards, regular monitoring, a scientific and peer review process, and provide recommendations to the board on proposed changes to forest practices rules to meet timber industry viability and salmon recovery." RCW 76.09.370(7) (emphasis added); WAC 222-08-160, 222-12-045.

After RCW Ch. 76.09 was adopted in 1999, the Board's ability to change the forest practices rules or adopt new rules covering aquatic resources was limited to "changes or new rules consistent with recommendations resulting from the scientifically based adaptive management process established by a rule of the board." RCW 76.09.370(6). The adaptive management process was so critical to the rules that the Legislature only provided two exceptions to this requirement: when a court ordered adoption or modification of the rules or when future state legislation directs the Board to adopt or modify the rules. *Id.*

If provisions of the Board Manual go beyond guidance and require rulemaking, adaptive management may be triggered. Although the adaptive management process does not change the Board's statutory authority to adopt forest practices rules found in RCW 76.09.040(1)(a) and addressed in several cases,¹ it does limit the Board's option to modifying rules relating to aquatic resources to three: (1) follow the adaptive management process, (2) request legislative action, or (3) obtain a court order.

The adaptive management process was carefully and thoughtfully designed to ensure that decisions are based on sound science. The final determination and action by the Board is made only once the Board receives a thorough review by CMER and TFW Policy, and at that point the Board exercises its discretion

¹ *Northwest Ecosystem Alliance v. Washington State Forest Practices Board*, 149 Wn. 2d 67 (2003); *Snohomish County v. State*, 69 Wn. App. 655 (1993); *Plum Creek Timber v. FPAB*, 99 Wn. App. 579 (2000); *Kettle Range Conservation Group v. DNR*, 120 Wn. App. 434 (2003); *Friends of the Columbia Gorge v. FPAB*, 129 Wn. App. 2005; *Northwest Ecosystem Alliance v. Department of Ecology*, 104 Wn. App. 901 (2001); *ALPs v. State Forest Practices Board*, 135 Wn. App. 376 (2006); *ALPs v. DNR*, 102 Wn. App. 1 (1999); *State Owned Forests v. Sutherland*, 124 Wn. App. 400 (2004).

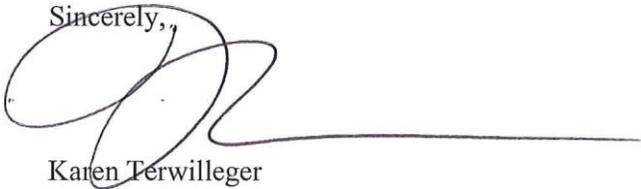
to make a decision. WAC 222-12-045(2)(d)(vii). Where a Board or DNR action proposes to change policy that will impact timber industry viability, water quality, salmon recovery or aquatic species, such as the overhaul of the unstable slope Board Manual section, the Board must provide adequate time for the adaptive management process to provide scientific review, peer review, and recommendations on proposed changes.

(c) Legal Risk from Board Manual Revisions

As presented initially to the stakeholders, the Board Manual exhibits scope creep and inadequately address other forms of natural sources of slope instability, such as precipitation or the undercutting of the toe of the slope. In addition to making the revisions at risk of being found legally deficient, inadequate information has the potential to create a misperception by the public on the impacts of forest practices. From a legal perspective, this creates additional complexity in defending a tort action against the State or a rule challenge which is limited to the record before the agency. If the Board Manual revisions are challenged as rules, to successfully defend an allegation that the modifications were arbitrary and capricious, the agency's record will have to show that DNR considered but rejected adding available scientific literature regarding the myriad other natural causes of slope instability for sound reasons.

Again, we commend DNR staff and their selected experts for the initial work on this Board Manual. Once properly revised and vetted, we believe a new manual will be very helpful and hope that the Board will allow the appropriate time to complete the Board Manual in an efficient, effective manner. WFPA looks forward to working with the Board, DNR, and other TFW partners to finalize revisions.

Sincerely,

A handwritten signature in black ink, consisting of a large, stylized 'K' followed by a horizontal line extending to the right.

Karen Terwillegger

Senior Director for Forest and Environmental Policy

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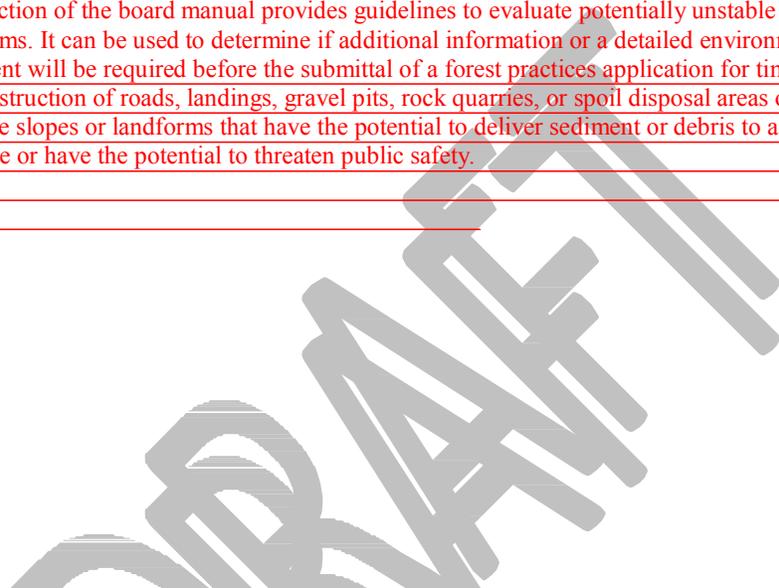
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PART 1. INTRODUCTION

This section of the board manual provides guidelines to evaluate potentially unstable slopes and landforms. It can be used to determine if additional information or a detailed environmental statement will be required before the submittal of a forest practices application for timber harvest or the construction of roads, landings, gravel pits, rock quarries, or spoil disposal areas on potentially unstable slopes or landforms that have the potential to deliver sediment or debris to a public resource or have the potential to threaten public safety.



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~~It begins with an overview of the forest practices rules for potentially unstable slopes, which unstable landforms that are of concern, and the effects of landslides. Also included are important tools and concepts that can be used to determine if slopes are potentially unstable, descriptions of~~

rule-identified unstable slopes and landforms, information and guidance on how to identify potentially unstable slope situations, the influence of forest practices activities on slope stability, and how to determine if delivery of material to public resources could occur. If you need to hire a qualified expert, guidelines for the contents of the expert report are listed at the end of this Section. The Forest Practices Board Manual is not a rule. The objective of the manual is to provide guidance pathways which, if followed, meet the requirements for the implementation of forest practices rules. This section of the Board Manual provides guidelines to evaluate potentially unstable slopes and landforms and includes guidance to determine the potential to deliver sediment or debris to a public resource or threaten public safety. The Manual does not have any independent regulatory authority and it does not establish new environmental regulatory requirements. However, if applicants do not choose to follow this guidance, no presumption of non-compliance is created. If applicants utilize other field methods, default methods listed in the Manual have no presumptive impact or ing the evidentiary value.

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Comment [K1]: The added language provides additional clarification that the manual is not a rule, it is guidance. Inserting this full paragraph at the beginning of each major section might also highlight the non-regulatory nature of the manual.

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The described processes for analysis in combination with professional judgment will allow the field practitioner and the qualified expert to determine the need for additional geologic analysis and mitigation, or if a detailed geotechnical analysis is required as part of an environmental assessment under the State Environmental Policy Act (SEPA) with a forest practices application (FPA).

This section features an overview of the forest practices rules for potentially unstable slopes, unstable landforms of concern, and the direct and indirect effects of landslides on public resources and public safety. The main body of the manual section includes:

- Tools to be used to determine the potential instability of slopes, descriptions of rule-identified landforms¹ and other unstable or potentially unstable landforms (Part 3 and Part 4);
- How to identify areas with potentially unstable slopes (Part 5);
- How to identify and assess activity level of unstable slopes and landforms (Part 6 and Part 7);
- Guidelines for qualified experts to prepare geotechnical reports (Part 7 and Part 8); and
- The section includes a glossary of terms, a list of references used throughout the document, and appendices listing resources for analysts.

The intended audience is general practitioners (landowners, foresters, engineers) and qualified experts². The goal is to provide information on relevant assessment techniques and certain tasks to be conducted by a qualified expert. It is not intended to be a comprehensive guidance document for the evaluation of unstable or potentially unstable slopes. Qualified experts must rely on personal experience, professional judgment and a comprehensive an appropriate review of relevant available information.

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PART 2. OVERVIEW

Landslides occur naturally in forested basins and landform erosion is and are an important process

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in the delivery of wood and gravel to streams and near shore environments. Wood and gravel play significant roles in creating stream diversity ~~that is~~ essential for fish ~~use as~~ habitat and spawning grounds (e.g., Reeves et al., 1995; Geertsema and Pojar, 2007; Restrepo et al., 2009). ~~In the past,~~ Under past forest practices rules, forest practices-caused landslides ~~have accelerated~~ contributed to

¹ "Rule-identified landform" is a commonly used term for the landforms listed in WAC 222-16-050(1). They are listed in Part 2 of this Board Manual section.

² "Qualified expert" is defined in WAC 222-10-030(5).

the acceleration of naturally occurring landslide processes (e.g., Swanson et al., 1977; Robinson et al., 1999; Montgomery et al., 2000; Turner et al., 2010) and may have contributed to the threatened and endangered status of certain species, (e.g., Sidle et al., 1985; Beechie et al., 2001) as well as ~~endangering~~endangered human life in some instances (e.g., Oregon Landslides and Public Safety Project Team, 2001). The forest practices rules are ~~intended meant~~ to protect public resources and prevent threats to public safety. The rules apply ~~where there~~when it is determined the proposed forest practices activities may contribute to the potential for sediment and debris to be delivered to a stream, lake, ~~marine water or~~ other fish ~~or~~and wildlife habitat, domestic water supplies, ~~or~~public capital improvements, or to cause a threat to public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety ~~is~~should be considered. Many factors ~~are part of that consideration must~~ may be considered including initial failure volume, ~~and~~the nature of ~~the~~ landslide, landslide runoff distance, and ~~landscape geometryslope or channel conditions to determine the potential to deliver to a public resource or threaten public safety.~~

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Comment [K3]: The manual is guidance, not rule.
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2.1 Potentially Unstable Landforms

Certain landforms are particularly susceptible to slope instability ~~or indicate past slope~~ instability. ~~Consequently, Because of this~~ forest practices applications (FPAs) that propose activities on ~~and near~~ these landforms may be classified “Class IV-special” and receive additional environmental review under the State Environmental Policy Act (SEPA). ~~Such r~~Rule-identified unstable landforms ~~that are as~~ described in WAC 222-16-050 and Part 5 of this ~~S~~section ~~include consist of~~ following:

Comment [K4]: This language should be consistent with the language in WAC 222-16-050.
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- ~~Inner gorges~~Bedrock hollows, convergent headwalls, ~~and inner gorges~~and bedrock hollows with slopes >70% (35° degrees). These landforms are susceptible to shallow landslides including debris flows and earth flows;
- Toes of deep-seated landslides with slopes >65% (33°). This landform is susceptible to re-activated rotational or translational sliding, debris and earth flows and lateral spreads;
- Groundwater recharge areas for glacial deep-seated landslides. This landform is the influences from potential increases in precipitation available for groundwater recharge from tree removal through forest practice activities;
- Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream. These landforms are susceptible to rotational sliding, debris flows, and earth flows;
- ~~And other indication of slope instability~~Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes. For example, areas that may contain features indicating the presence of potential slope instability include the bodies of a glacial deep-seated landslides and deep-seated landslides developed in non-glacial materials;

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Landslide is a general term for any downslope movement of rock, unconsolidated sediment, soil, and/or organic matter under the influence of gravity. The term also refers to the deposit itself, and slide materials in mountainous terrain typically are separated from more stable underlying material by a zone of weakness variously called the failure zone, plane, or surface. Landslides can be classified in several different ways. The method adopted here (see Part 2.1) is to describe the type of movement (fall, topple, slide, spread, or flow) and the type of material

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involved (rock, soil, earth, or debris). The failure surface can be roughly planar, in which case

the slide is called “translational”; or curved, in which case it is called “rotational” or a combination of failure surface geometries (Figures 1). Translational failures also can occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes (Robinson et al., 1999; Turner et al., 2010), with little observed rotation or backward tilting of the slide mass. Landslides can be small volumetrically (a few cubic yards) or very large (cubic miles). They can range from very fast moving, as in free fall, to very slow, as in creep. Landslides can come to rest quickly or can continue to move for years or even centuries. Landslides can stop moving only to be later reactivated and are considered dormant slides. A landslide can also permanently cease moving and undergo erosion and revegetation over long periods of geologic time and is considered a relict slide.

Landslides can be grouped into two major categories: deep-seated landslides which fail below the rooting depth of vegetation, or shallow landslides which fail within the vegetation rooting zone. Some shallow-rapid failures initiate a little deeper than 3 meters but are not really deep-seated landslides. A common example is road fillslope failures where the road fill is deep, but which evolve into debris flows. Shallow landslides tend to respond to rainfall events over periods of days or weeks; deep-seated slides may respond to rainfall events over periods of days to weeks, or to weather patterns over months to years or even decades (Washington State Department of Emergency Management, 2013).

Ground failures resulting in landslides occur when gravitational forces, in combination with soil and other factors, overcome the strength of the soil and rock in a slope. Contributing factors can may include:

- The presence of an impermeable stratigraphic layer beneath a permeable stratigraphic layer.
- Saturation, by rain on snow events or heavy and/or prolonged rains that can saturate soils and create instability in soil and weakened or weathered bedrock.
- Erosion by rivers, glaciers, or ocean waves that over-steepen slopes or result in removing support from the base of the slopes.
- Ground shaking caused by earthquakes that increase the driving force and weaken the supporting soils structure.
- Volcanic eruptions that produce lahars and instability on the lateral flanks of the volcano.
- Excess weight from accumulation of rain or snow, stockpiling of rock or earth from waste piles, or manmade structures that exert excessive stress on slopes.
- Human activities, such as construction, logging, or road building that disturbs soils and weakens or removes the support for slopes, increases runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.

Landslides are most likely to occur where certain combinations of geologic materials are present, for example, groundwater percolating through porous and permeable sands and gravels and perching on underlying layers of impermeable silt and clay. At this interface, increased groundwater pore pressure can weaken and cause failure of the overlying sand and gravels. This combination is common and widespread in the Puget lowlands. Specifically, glacial outwash sand, locally called the Esperance Sand or Vashon advance outwash, overlies the fine-grained soils, locally called the Lawton Clay or transitional bed, giving rise to over steepened bluffs with benches composed of the perching layer. Similar conditions exist in many bluffs of the greater Puget Sound area (Tubbs,

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Comment [K6]: More descriptive language for describing deep-seated landslides.

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Comment [K8]: Although this statement is not untrue, it does not logically fit with the remainder of this list. This is a permanent environmental condition, whereas the rest of the factors represent a change to the status quo which temporarily or permanently reduces the factor of safety, thus contributing to the occurrence of a landslide.

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Comment [K9]: This should be the first bullet in the list and we need to have language somewhere in the manual that this geomorphic processes appears to be the primary trigger of instability and generation of large, glacial-deep seated landslides. Examples can be provided as well.

Comment [K10]: This is a dubious statement. First, the occurrence of these geologic conditions is fairly narrow in Washington State, let alone in the broader landslide-prone landscape. Second, it is contradicted by the findings of most watershed-scale inventories, notably most of the Watershed Analysis Units.

There are enough landslide-prone geologic units that it is probably not worthwhile to try to itemize. By explicitly calling out one sequence, it creates a misleading focus.

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1974).

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2.1 Landslide Types and Effects

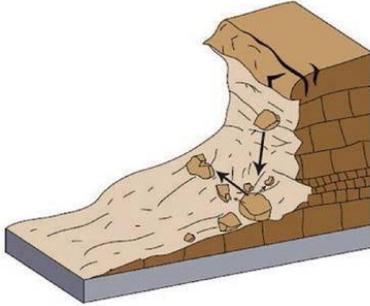
Several classification schemes are used by geologists, engineers and other professionals to identify and describe landslides. The classification scheme of Varnes (1978), modified by the U.S. Geological Survey (U.S. Geological Survey, 2004), is used for the purposes of this Board Manual section (see Table 1).

Table 1. Landslide Classification
(U.S. Geological Survey (2004), modified from Varnes (1978))

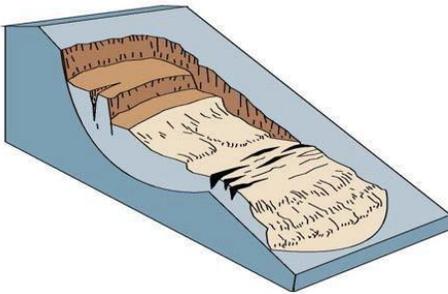
<u>Type of Movement</u>		<u>Type of Material</u>	
		<u>Bedrock</u>	<u>Soils</u>
		<u>Predominately Coarse</u>	<u>Predominately Fine</u>
<u>Falls</u>		<u>Rock Fall</u>	<u>Earth Fall</u>
<u>Topples</u>		<u>Rock Topple</u>	<u>Earth Topple</u>
<u>Slides</u>	<u>Rotational</u>	<u>Rock Slide</u>	<u>Earth Slide</u>
	<u>Translational</u>	<u>Rock Slide</u>	<u>Earth Slide</u>
<u>Lateral Spreads</u>		<u>Rock Spread</u>	<u>Earth Spread</u>
<u>Flows</u>		<u>Rock Flow</u>	<u>Earth Flow</u>
<u>Complex</u>	<u>Combination of two or more principal types of movement</u>		

In this scheme landslides are classified by the type of material and the type of movement. Material in a landslide mass is either rock or soil (or both) and may also include organic debris. Soil is described as earth if mainly composed of sand-sized or finer particles and debris if composed of coarser fragments. The types of landslides commonly found in forested areas in Washington include slides, flows, and complex landslides. The type of movement describes the actual internal mechanics of how the landslide mass is displaced: fall, topple, slide, spread, or flow. Thus, landslides are described using two terms that refer respectively to material and movement (rockfall, debris flow, and so forth). Landslides may also occur as a complex failure encompassing more than one type of movement (e.g., debris slide - debris flow). Simplified illustrations of the major types of landslides are presented in Figure 1.

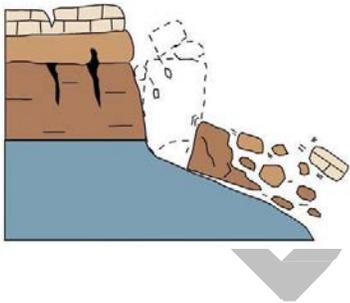
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Falls: Falls occur when a mass of rock or soil detach from a steep slope or cliff, often caused by undercutting of the slope. The failure is typically rapid to very rapid. The fallen mass may continue down the slope until the terrain flattens (from Highland and Bobrowsky, 2008).

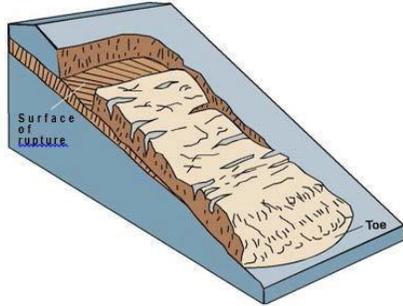


Rotational slides: Landslides on which the surface of rupture is concave-up and the slide movement is rotational about an axis that is parallel to the contour of the slope. Glacial deep-seated landslides can be rotational slides developed in glacial sediments common in the Puget Sound area, but they can also involve more complex types of movement (from Highland and Bobrowsky, 2008).

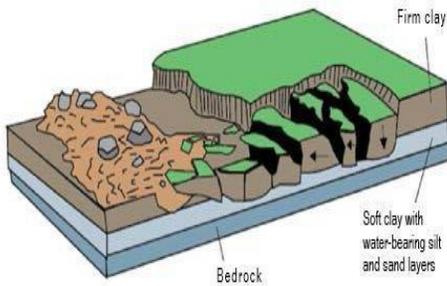


Topples: Topples are the forward rotation out of the slope of a mass of rock or soil. The failure rates range from extremely slow to extremely fast (from Highland and Bobrowsky, 2008).

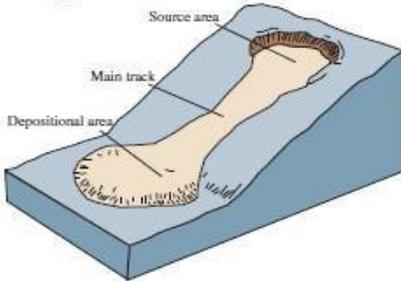
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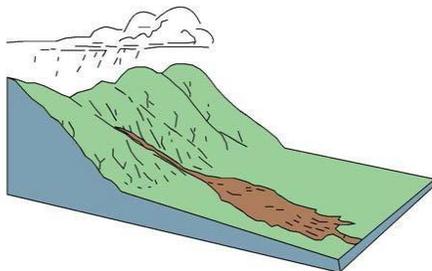
Translational slides: Landslides on which the surface of the rupture is roughly planar (from Highland and Bobrowsky, 2008).



Lateral spreads: Landslide that generally occurs on very gentle or level slopes caused by subsidence of a fractured mass of cohesive material into softer, often liquefied, underlying material (from Highland and Bobrowsky, 2008).



Earth flows: Landslide consisting of fine-grained soil or clay-bearing weathered bedrock. Can occur on gentle to moderate slopes flow (from U.S. Geological Survey, 2004).



Debris flows: Landslide in which loose rock, soil, and organic matter combine with water to form a slurry that flows rapidly downslope (from Highland and Bobrowsky, 2008).

Figure 1 Illustrations of the major types of landslide movement.

Some of the landslide types shown in Table 1 can be further divided into shallow or deep-seated landslides depending on whether the failure plane is above (shallow) or below (deep) the rooting depth of trees.

2.2 Shallow Landslide Types

Shallow landslides typically fail within the vegetation rooting zone and tend to respond to rainfall events over periods of days or weeks. Shallow landslides can occur in bedrock hollows, convergent headwalls, and inner gorges with slopes $>56\%$, and on toes of deep-seated landslides with slopes $>65\%$, and on the outer edges of meander bends, and other areas with steep slopes. There are generally three types of shallow landslides: debris slides, debris flows, and hyper-concentrated floods. They are distinguished from each other by the ratio of water to solids contained in them.

Debris slides consist of aggregations of coarse soil, rock, and vegetation that lack significant water and move at speeds ranging from very slow to rapid down slope by sliding or rolling forward. The results are irregular hummocky deposits that are typically poorly sorted and non-stratified. Debris slides include those types of landslides also known as shallow rapid, soil slips, and debris avalanches. If debris slides entrain enough water they can become debris flows.

Debris flows are slurries composed of sediment, water, vegetation, and other debris. Solids typically constitute $>60\%$ of the volume (Pierson and Scott, 1985). Hyper-concentrated floods are a subset of debris flows containing a mixture of water and sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains they are commonly caused by the collapse of dams such as those formed by landslide dams or debris jams (Figure 2). Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel, and the active floodplain if present. Debris flows usually occur in steep channels, as landslide debris becomes charged with water (from soil water, or on entering a stream channel) and liquefies as it breaks up. Channelized debris flows often entrain material and can significantly bulk in volume during transport. These landslides can travel thousands of feet (or even miles) from the point of initiation, scouring the channel to bedrock in steeper channels. Debris flows commonly slow where the channel makes a sharp bend and stop where the channel slope gradient becomes gentler than about 3 degrees, or the valley bottom becomes wider and allows the flow to spread out. Hyper-concentrated floods may travel greater distances and at shallower slopes than debris flows, based on their water content (Iverson, 1992).

Hyper-concentrated floods are flowing mixtures of water, sediment (dominantly sand-sized), and organic debris with solids that range between 20% and 60% by volume (Pierson and Scott, 1985). In forested mountains, they are commonly caused by the collapse of dams, such as those formed by landslide dams or debris jams (Figure 1). Impounded water and debris released when the dam is breached sends a flood wave down the channel that exceeds the magnitude of normal floods and generally extends beyond the range of influence that has been documented for debris flows (Johnson, 1991). Such hyper-concentrated floods can rise higher than normal rainfall- or snowmelt-

induced flows along relatively confined valley bottoms, driving flood waters, sediment, and wood loads to elevations high above the active channel and, if present, the active floodplain.

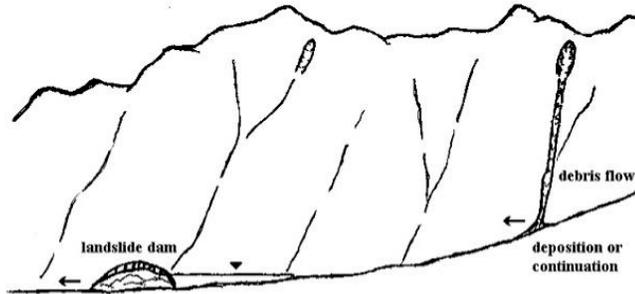


Figure 21- Debris flows, and hyper-concentrated floods

Debris flows and hyper-concentrated floods can occur in any unstable or potentially unstable terrain with susceptible valley geometry. In natural systems, debris flows and hyper-concentrated floods caused by dam-breaks are responsible for moving sediment and woody debris from hillslopes and small channels down into larger streams. But debris flows can also cause damage to streams by scouring channel reaches, disturbing riparian zones, impacting habitat and dumping debris onto salmonid spawning areas. Debris flows can cause elevated turbidity, adversely affect water quality downstream, pose threats to public safety, and damage roads and structures in their paths (Figure 32).



Figure 32- Road-initiated debris flows in inner gorges, Sygitowicz Creek, Whatcom County (Photo: DNR, 1983).

These debris flows shown in Figure 3 coalesced, and after exiting the confined channel at the base of the mountain, formed a new debris flow spreading across a 1,000-foot wide swath for a distance of 2,000 feet before entering the South Fork Nooksack River. Between the base of the

Comment [K11]: DNR has another oblique photo of this same hillside from about 2010, following a second-cycle timber harvest under the current regulatory scheme. This latter photo has been used in presentations by UPSAG (Julie Dieu) and it may also be in the Jack Powell collection. It provides an interesting contrast to this scene where attention to areas of potential instability was a secondary concern.

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mountain and the river the debris flow affected (if not severely damaged) a county road, farmyard, ~~and~~ house sites, and more than 60+ acres of cultivated farm fields.

2.3 Deep-Seated Landslides

~~A more detailed explanation of deep-seated landslides is covered later in this section because deep-seated landslides are also landforms.~~ Regardless of failure mechanism, deep-seated landslides are those in which the slide plane or zone of movement is well below the maximum rooting depth of forest trees (generally greater than ~~three meters~~ (10 feet or three meters)) and may extend to hundreds of feet in depth often including bedrock. Deep-seated landslides can occur almost anywhere on a hillslope and are typically commonly associated with hydrologic responses in permeable geologic materials overlying less permeable materials. The larger deep-seated landslides can usually be identified from topographic maps, aerial photos, and LiDAR. The runout from deep-seated landslides can also behave as earth flows depending on the type of material and failure mechanics. Deep-seated landslides developed in glacial sediments are sometimes referred to as “glacial deep-seated landslides.” Complex landslides occur when a variety of types of material and movement are present.

Certain key areas of deep-seated landslides may be sensitive to forest practices. The bodies and toes of deep-seated landslides and earth flows are made up of incoherent collapsed material weakened from previous movement, and therefore may be subject to debris slide and debris flow initiation in response to harvest or road building. Sediment delivery is common from shallow landslides on steep stream-adjacent toes of deep-seated landslides and steep side-slopes of marginal streams on the bodies of deep-seated landslides is common. More detailed descriptions of deep-seated landslides are covered in Part 5.3 and Part 5.6.

2.4 Geographic Distribution of Landslides in Washington

Landsliding is a widespread geomorphic process, actively modifying the varied topography and diverse underlying geologic materials present throughout the state. This overview focuses on areas within the state where forest practice activities are prevalent and draws from Thorsen’s (1989) organization and discussion by physiographic provinces.

The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by continental, and to a lesser extent, alpine glaciations. Unconsolidated sediments associated with glaciation include thick interlayered packages of fine-grained glacial lake sediments (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits. Translational and complex landslides occur within some of the very weak bedrock units exposed within the foothills and lowlands, such as the Chuckanut Formation, Darrington Phyllite, and Puget Group rocks.

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and

Comment [K12]: It would be appropriate here to have a statement which mirrors the one in Section 2.2 above which itemizes the landforms specifically recognized in the WACs. It would be helpful to include an interpretive statement indicating that only certain areas (i.e. toes) and subcategories of deep seated slides (i.e. glacials) are specifically regulated because empirical evidence and previous study (such as Watershed Analysis) indicates that these are the most sensitive to forest practices.

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Comment [K13]: The guidance should focus on the geomorphic/stratigraphic conditions as originally described for the Hazel site – i.e., permeable glacial with potential groundwater perching zones. Although the rule is “silent” regarding the relevance of deep-seated landsliding in other glacial materials, landslides in till (for example) could be mitigated as other deep-seated landslides with weak materials (i.e., toe RILs or as Category E RILs).

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major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide

complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower reaches of the Quinault, Queets, Hoh, and Bogachiel valleys. Large rock slides and rock avalanches are common in the steep upper reaches of Olympic mountain drainages. Translational landslides and large landslide complexes are also abundant in the very weak marine sedimentary rocks (often occurring along inclined bedding surfaces) and mantling residual soils in the western and northwestern portions of the Peninsula, such as the Twin Creek Formation, and the Western Olympic and Hoh Lithic Assemblages (Tabor and Cady, 1978; Badger, 1993). Debris flows and avalanches are often generated in steeper drainages and slopes.

The Willapa Hills of Southwest Washington are comprised primarily of very weak marine sedimentary and volcanic rocks. While that is true in many areas, but slope stability issues are frequently in areas of thin soils on steep slopes underlain by very competent basalts in the Crescent. Because the region has not been glaciated, thick and especially weak residual soils have developed on these rocks. Translational landslides and coalescing landslides forming earthflows are widespread in these weak rocks and overlying soils, such as in the Lincoln Creek Formation (Gerstel and Badger, 2002). Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches (Thorsen, 1989). These deposits are prevalent along the lower Columbia River valley, as well as other areas where colluvial deposits have accumulated on slopes and in drainages underlain by strong and relatively unweathered rock.

The Cascade Range is generally divided on the basis of rock type into northern and southern portions in the vicinity of Snoqualmie Pass. Predominantly, strong crystalline rocks intensely scoured by alpine glaciations occur to the north. Weaker volcanic flows, pyroclastic and volcaniclastic rocks occupy the south, much of which was beyond the reach of the last continental glaciation. Rockfalls and complex rock slides are dominant in the steep bedrock slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control large translational failures in the Chumstick and Roslyn Formations (Tabor et al., 1987), the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone (Wegmann, 2003). Shallow landslides generating debris avalanches and flows are common on steep slopes and drainages.

Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides. Rockfall and rock slides are common from the many steep bedrock exposures in the region. The Blue Mountains in southeastern Washington also have experienced recurring and widespread shallow landsliding and debris flows related to storm events (Harp et al., 1997).

PART 3. MEASUREMENT OF SLOPE ANGLES

Slope gradients are commonly expressed in two different but related ways, as degrees of arc or percent rise to run. It is important to understand the relationships between them.

3.1 Degrees

A circle is divided into 360° degrees of arc. Each degree is further divided into 60 minutes (60'), and each minute into 60 seconds (60"). The quadrant of the circle between a horizontal line and a vertical line comprises 90° degrees of arc (Figure 43a).

Comment [K14]: These formations are principally located north of I-90 ranging into southern British Columbia, and as such are generally regarded as occurring in the north cascades.

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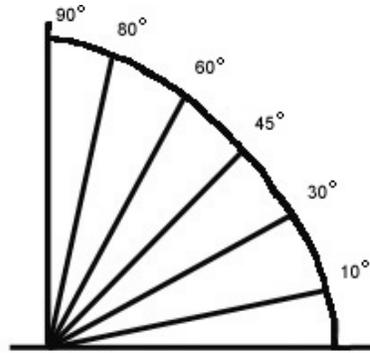


Figure 43a. Angles in degrees.

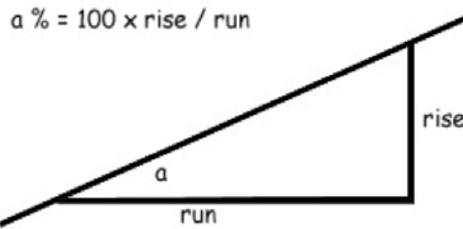


Figure 43b. Angles in percent.

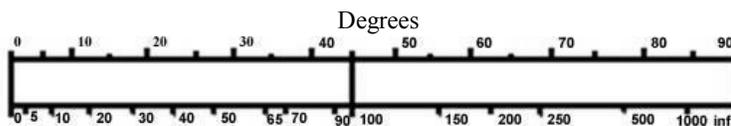
3.2 Percent

In Figure 43b, the horizontal distance between two points (distance between the points on a map) is called the run. The vertical distance (difference in elevation) is called the rise. The gradient can be expressed as the ratio of rise divided by run, a fraction that is the tangent of angle α . When multiplied by 100, this fraction is the percent slope.

3.3 Relationship of Degrees to Percent

Because of the differences in the ways they are calculated, each of these two slope measurements is better for certain applications. Because it is more precise at gentle slopes, percent is best for measuring and expressing small angles, such as the gradients of larger streams. But for steeper slopes, the constant angular difference and smaller numbers (an 85°-degree slope is 1143%) make degrees more useful.

Figure 54 shows approximate equivalences for gradients expressed in degrees and percent. Note that there is a rough 2:1 ratio in the 30 to 40°-degree range (e.g., 35°-degrees = 70% slope), but beware - this relationship changes dramatically at gentler and steeper angles.



Percent

Figure 5.4. Slope gradients in degrees and percent.

PART 4. SLOPE FORM

Slope shape is an important concept when considering the mechanisms behind shallow landsliding. Understanding and recognizing the differences in slope form is essential key in to recognizing potentially unstable landforms recognition. There are three major slope forms to be observed when looking across the slope (contour direction): divergent (ridgetop), planar (straight), and convergent (spoon-shaped) (Figure 6.5a). Landslides can occur on any of these slope forms but divergent slopes tend to be more stable than convergent slopes because water and debris spread out on a divergent slopes whereas water and debris concentrate on convergent slopes. Convergent slopes tend to lead into the stream network, encouraging delivery of landslide debris to the stream system. Planar slopes are generally less stable than divergent slopes but more stable than convergent slopes. In the vertical direction, ridgetops are convex areas (bulging outward) and tend to be more stable than planar (straight) mid-slopes and concave areas (sloping inward) (Figure 6.5b).

Additionally, slope steepness can play a significant role in shallow landsliding. Steeper slopes tend to be less stable. The soil mantle, depending upon its make-up, has a natural angle at which it is relatively stable (natural angle of repose). When hillslopes evolve to be steeper than the natural angle of repose of the soil mantle, the hillslope is less stable and more prone to shallow landslides, especially with the addition of water. The combination of steep slopes and convergent topography has the highest potential for shallow landsliding.

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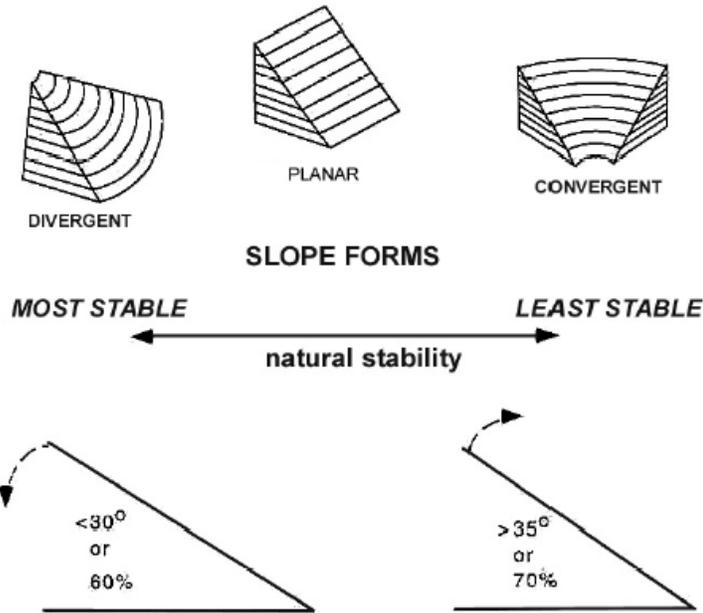


Figure 5a6a- Slope configurations as observed in map view.

This Figure 6a shows three major slope forms (divergent, planar, and convergent) and their relative stability. These slope form terms are used in reference to contour (across) directions on a slope. Convergent areas with slope greater than 35°-degrees (70%) are the most shallow landslide-prone (Benda, et al, 1997/8).

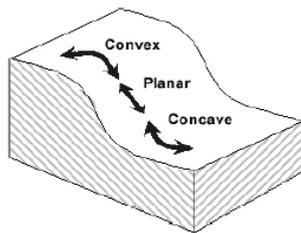


Figure 65b- Slope configurations as observed in profile: convex, planar, and concave. These terms are used in reference to up and down directions on a slope (Drawing: Jack Powell, DNR, 2004).

PART 5. DESCRIPTION IDENTIFICATION AND OVERVIEW OF UNSTABLE AND POTENTIALLY UNSTABLE SLOPES AND LANDFORMS AND PROCESSES

The rule-identified landforms described in Part 5 include bedrock hollows; convergent headwalls; inner gorges with slopes >70% (35°-degrees); toes of deep-seated landslides with slopes >65% (33°-degrees); groundwater recharge areas for glacial deep-seated landslides; outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; or any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes (WAC 222-16-050 (1)(d)(i)). Below are descriptions of the types of potentially unstable landforms and landslide processes associated with them.

Areas containing of potentially unstable landforms can usually be identified with a combination of topographic and geologic maps, aerial photographs, LiDAR data and a variety of private and public agency- derived landform screening maps and tools, watershed analysis mass wasting map unit (MWMU) maps, landslide hazard maps from the Regional (Unstable) Landform Identification Project (RLIP), Landslide Hazard Zonation Project (LHZ), and modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps. However, field observation is normally required to precisely delineate landform boundaries, gradients, and other characteristics. More details for the identification of unstable land forms are presented in Part 6, and the appendices provide tools and resources available to help in identifying potentially unstable landforms.

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In most instances, landform terms described here are also used in the scientific literature. For the purposes of Washington forest practices, the rule-identified landform terms, definitions, and descriptions supersede those used in the scientific literature. Note that all sizes, widths, lengths, and depths are approximate in the following discussion of unstable landforms, and are not part of the rule-identified definitions. Sizes are included to help visualize the landforms.

Comment [K16]: This is not entirely accurate, since two of the landforms enumerated in the WACs all contain a slope threshold.

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5.1 Bedrock Hollows, Convergent Headwalls, Inner Gorges

These three landforms are commonly associated with each other as shown in Figures 67 and 78.

Bedrock hollows

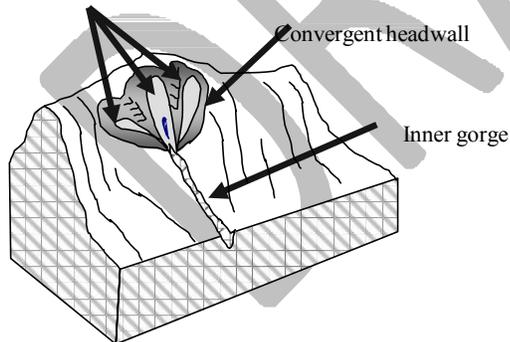


Figure 76- Typical hillslope relationships between bedrock hollows, convergent headwalls, and inner gorges (Drawing: Jack Powell, DNR, 2003).

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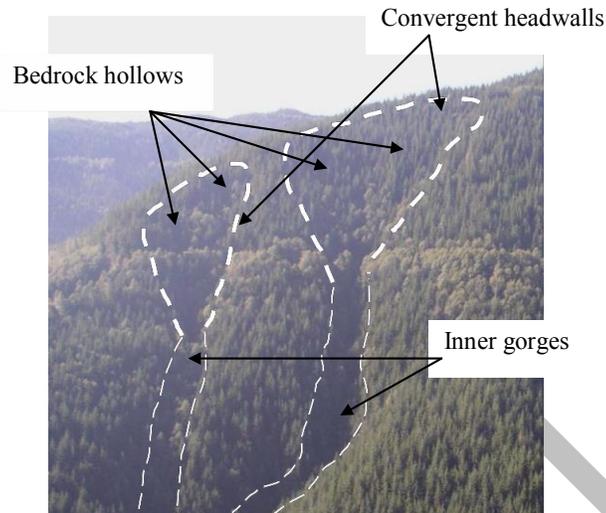


Figure 87. Common hillslope relationship: bedrock hollows in convergent headwalls draining to inner gorges (Photo and drawing: Jack Powell, DNR, 2003).

Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows (Crozier et al., 1990; Dietrich et al., 1987). Not all hollows contain bedrock so the term “bedrock” hollow can be a misnomer. However, the forest practices rules cite these features as “bedrock” hollows so this is the term used in the Board Manual. Hollows are commonly spoon-shaped areas of convergent topography with concave profiles on hillslopes. They tend to be oriented linear up- and down-slope. Their upper ends can extend to the ridge or begin as much as several hundred feet below ridge line. Most hollows are approximately 75 to 200 feet wide at their apex (but they can also be as narrow as several feet across at the top), and narrow to 30 to 60 feet downhill. Hollows should not be confused with other hillslope depressions such as small valleys, sag areas (closed depressions) on the bodies of large deep-seated landslides, tree wind-throw holes (pit and mound topography), or low-gradient swales.

Hollows often form on other landforms such as head scarps and toes of deep-seated landslides. Bedrock hollows can occur singly or in clusters that define a convergent headwall. They commonly drain into inner gorges (Figure 98).

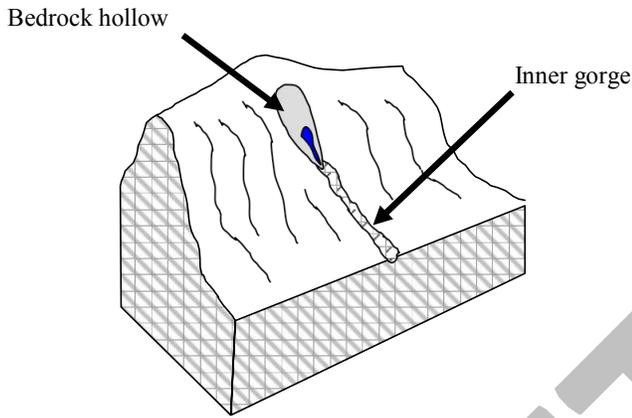


Figure 98—Bedrock hollow and relationship to inner gorges (Drawing: Jack Powell, DNR, 2003).

Hollows usually terminate where distinct channels begin. However, many hollows are not connected to the stream network. This is at the point of channel initiation where water emerges from a slope and has carved an actual incision. Steep bedrock hollows typically undergo episodic evacuation of debris by shallow-rapid mass movement (a debris flow), followed by slow refilling with colluvium that takes years or decades. Unless they have recently experienced evacuation by a landslide, hollows are partially or completely filled with colluvial soils that are typically deeper than those on the adjacent spurs and planar slopes. Recently evacuated hollows may have water flowing along their axes whereas partially evacuated hollows will have springs until they fill with sufficient colluvium to allow water to flow subsurface.

- Comment [K17]: Add clarifying sentence.
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Figure 109 illustrates the evolution of a bedrock hollow. Drawing “a” shows that over a period of tens to hundreds or thousands of years in some places, sediment accumulates in a hollow. When the soil approaches a depth of 3 to 5 feet (1-2 meters), the likelihood of landslides increases. Recurrent landsliding within the hollow slowly erodes bedrock and maintains the form of the hollow (Drawing “b”). After a landslide, bedrock may be exposed (and also seeps or springs) and the risk of additional sliding may be reduced, but not gone. Drawing “c” shows soil from the surrounding hillsides (colluvium) slowly re-filling the hollow. As vegetation and trees establish the site after past failures, their roots help stabilize the soil.

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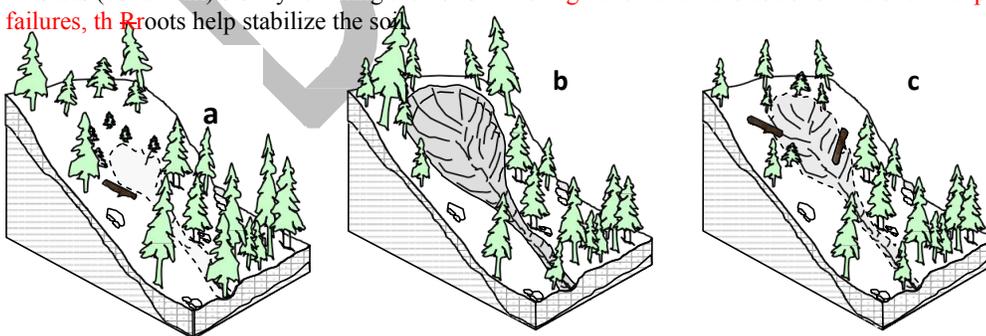


Figure 109a-c. Evolution of a bedrock hollow following a landslide (adapted from Dietrich et al., 1988; (Drawing by Jack Powell, DNR, 2004).

The common angle of repose for dry, cohesionless materials is about 36°-degrees (72%), and saturated soils can become unstable at lower gradients. Thus, slopes steeper than about 35°-degrees (70%) are considered susceptible to shallow debris slides. “Bedrock” hollows are formed on slopes of varying steepness. Hollows with slopes steeper than 70% (approximately 35°-degrees) are potentially unstable in well-consolidated materials, but hollows in poorly consolidated materials may be unstable at lower angles. Note: For purposes of this manual, Bbedrock hollow slopes are measured on the steepest part of the slope generally not along the axis unless the hollow is full (Figure 110).

Comment [K21]: Notes that this guidance for bedrock hollows is specific to the Manual.

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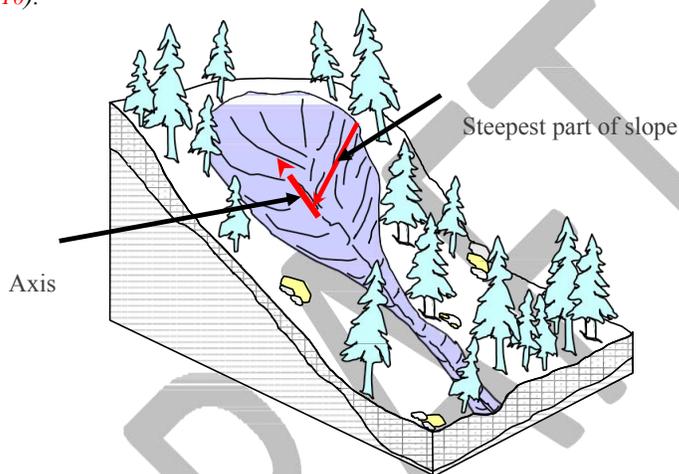


Figure 110. Bedrock hollow slopes are measured on the steepest part of the slope generally not along the axis (Drawing: Jack Powell, DNR, 2004).

Vegetation can provide the critical cohesion on marginally stable slopes and removes water from the soil through evapotranspiration. Leaving trees in steep, landslide-prone bedrock hollows helps maintain rooting strength and should reduce the likelihood of landsliding (Figure 12+)

(Montgomery et al., 2000). However, wind-throw of the residual trees following harvest can be associated with debris slide or debris flow events. In high wind environments, it may be is essential to harvest in a manner that will limit the susceptibility of the residual trees to wind-throw as well as to reduce the potential for landslides (for example leaving wider strips, pruning or topping trees in the strips, or feathering the edges of reserve strips).

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Figure 121- Example of leave areas protecting unstable slopes (Photo: Venice Goetz, DNR, 2004).

Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. A series of converging bedrock hollows may form the upper part of a convergent headwall (Figure 132). Convergent headwalls are broadly concave both longitudinally and across the slope, but may contain sharp ridges that separate the bedrock hollows or headwater channels (Figure 143a, b, and Figure 154).

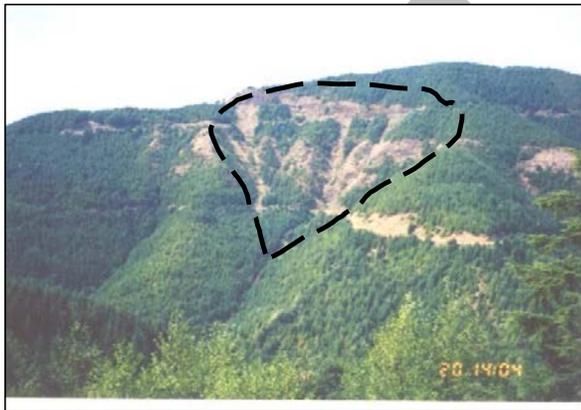


Figure 132- Convergent headwall example (Photo: Venice Goetz, DNR, 1995).

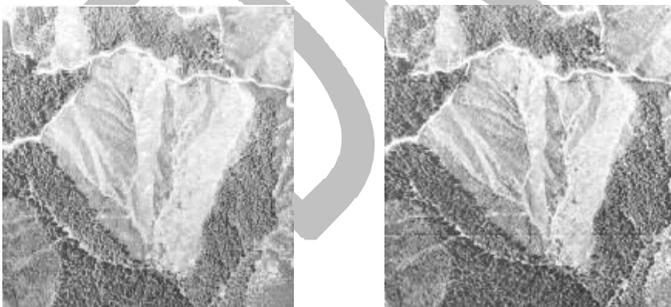


Figure 143a, b- Stereo-pair of a clearcut convergent headwall in Pistol Creek basin, North Fork Calawah River, Washington.

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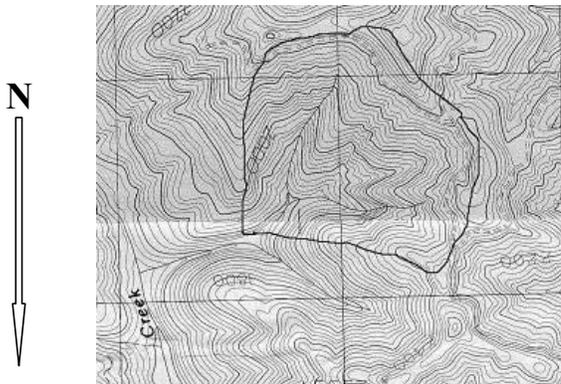


Figure 154. Topographic map and outline of convergent headwall displayed in the stereo-pair of Figure 13a, b. Scanned from portions of Hunger Mountain and Snider Peak USGS 7.5' quadrangles.

Convergent headwalls generally range from about 30 to 300 acres. Slope gradients are typically steeper than 35°-degrees (70%) and may exceed 45°-degrees (94%). Unlike bedrock hollows, which exhibit a wide range of gradients, only very steep convergent landforms with an obvious history of landslides are considered rule-identified called convergent headwalls. Soils are thin because landslides are frequent in these landforms. History of evacuation and landsliding can be evident by a lack of vegetation or mature trees on the site, or the presence of early seral plant communities such as grasses or red alder. It is the arrangement of bedrock hollows and first-order channels on the landscape that causes a convergent headwall to be a unique mass-wasting feature. The highly convergent shape of the slopes, coupled with thin soils (due to frequent landslides), allows rapid onset of subsurface storm water flow. The mass-wasting response of these landforms to storms, disturbances such as fire, and to forest practices activities is much greater than is observed on other steep hillslopes in the same geologic settings. Convergent headwalls may be also prone to surface erosion from the scars of frequent landslides.

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Channel gradients are extremely steep within convergent headwalls, and generally remain so for long distances downstream. Landslides that evolve into debris flows in convergent headwalls typically deliver debris to larger channels below. Channels that exit the bottoms of headwalls have been formed by repeated debris flows and are efficient at conducting them. Convergent headwalls commonly have debris fans at the base of their slopes.

Inner gorges are canyons created by a combination of stream down-cutting and mass movement on slope walls (Kelsey, 1988). Inner gorges are characterized by steep, straight or concave side-slope walls that commonly have a distinctive break in slope (Figure 165). Debris flows, in part, shape inner gorges by scouring the stream, undercutting side slopes, and/or depositing material within or adjacent to the channel (Figure 176). Inner gorge side-slopes may show evidence of recent landslides, such as obvious landslides, raw un-vegetated slopes, young, even-aged disturbance vegetation, or areas that are convergent in contour and concave in profile. Because of steep slopes and proximity to water, landslide activity in inner gorges is highly likely to deliver sediment to streams or structures downhill. Exceptions can occur where benches of sufficient size to stop moving material exist along the gorge walls, but these are uncommon.

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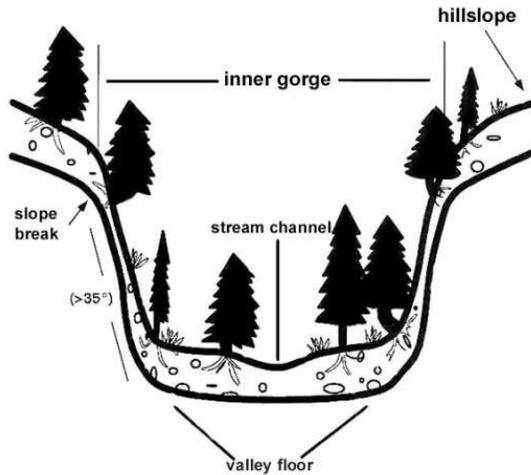


Figure 165. Cross-section of an inner gorge. This view emphasizes the abrupt steepening below the break-in-slope (Drawing: Benda, et al., 1998).



Figure 176. Photograph showing how debris flows help shape features related to inner gorges. (For example, over-steepened canyon wall, U-shaped profile, buried wood, distinctive break in slope along margins of inner gorge (Photo: Laura Vaugeois, DNR, 2004).

The geometry of inner gorges varies. Steep inner gorge walls can be continuous for great lengths, as along a highly confined stream that is actively down cutting, but there may also be gentler slopes between steeper ones along valley walls. Inner gorges can be asymmetrical with one side being steeper than the other. Stream-eroded valley sides, which can be V-shaped with distinct slope breaks at the top, commonly do not show evidence of recent landsliding as do inner gorges which tend to be U-shaped. In practice, a minimum vertical height of 10 feet is usually applied to distinguish between inner gorges and slightly incised streams.

The upper boundary of an inner gorge is assumed to be a line along the first break in slope of at least 10 degrees or the line above which gradients are mostly gentler than 35 degrees (70%) and convex. The delineating break-in-slope occurs where over-steepened slopes related to inner gorge erosion processes intersect slopes formed from normal hillslope erosion processes. While the upper inner gorge boundary is typically distinct, in some places it can be subtle and challenging to discern. Inner gorge slopes tend to be especially unstable at the point where the slope breaks because the abrupt change in gradient causes subsurface water to collect within the soil matrix which can destabilize the soil mass and initiate movement. Just as for all other landforms, inner gorge slopes should be measured along the steepest portion of the slope (see Figure 110).

The steepness of inner gorges is dependent on the underlying materials. In competent bedrock, gradients of 35 degrees (70%) or steeper can be maintained, but soil mantles are sensitive to root-strength loss at these angles. Slope gradients as gentle as about 28 degree (53%) can be unstable in gorges cut into incompetent bedrock, weathered materials, or unconsolidated deposits.

Erosion along the gorge walls can intercept shallow groundwater forming seeps along the sides of the inner gorge, which promotes continued mass wasting. Root strength along walls and margins of inner gorges has been found to be a factor that limits the rates of mass wasting. Inner gorge areas can lose root strength when trees blow down. However, downed timber has a buttressing effect providing some slope reinforcement. Effective rooting width of forest trees is approximately the same as the crown width. In some instances where the inner gorge feature is highly unstable it is necessary to may be possible to improve the stability of the slope by maintaining trees beyond the slope break. Use the rooting strength of trees adjacent to the landform for additional support.

5.42 Groundwater Recharge Areas, and the Effects of Groundwater on Landslide Sstability of (Glacial) Deep-Seated Landslides

In order to identify and delineate groundwater recharge areas in glacial terrain it is necessary to first identify and delineate glacial deep-seated landslides. Glacial deep-seated landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however their failure mechanics are similar to deep-seated landslides developed in other materials (Terzhagi, 1951). Deep-seated landslides developed in other materials are also susceptible to forest practice activities in the groundwater recharge area. Consequently, scientific knowledge regarding the dynamics of deep-seated failures can be applied to better understand and manage glacial deep-seated landslides.

Glacial deep-seated landslides occur in glacial terrain and are defined as such where most of the slide plane or zone lies within glacial deposits below the maximum rooting depth of trees, to depths of tens to hundreds of feet beneath the ground surface. Glacial deep-seated landslide deposits occur in continental or alpine glacial deposits, or a combination of both. Continental glacial deposits in Washington are located in the northern areas of the state (Figures 18a and b), whereas alpine glacial deposits can be found in mid-to-high elevation mountain ranges (Booth et al., 2003; Booth et al., 1994; Thorsen, R.M., 1980; Barnosky, 1984; Heusser, 1973; Crandall, 1965).

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Comment [K26]: More accurate statement.
Comment [K27]: Needs clarification.
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Comment [K28]: This section should follow Section 5.3 below; it appears mis-numbered relative to the index.
Comment [K29]: Although a seminal work in this field, the reference is kind of stale – is there other literature support for making such a broad statement? References to non-glacial deep-seated landslides are out of the scope of the board’s motion. Inclusion in the manual implies that these features are impacted by forest practices and should be regulated as RILs.
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Comment [K30]: This statement requires literature support if it remains in the manual. Most of the Watershed Analyses which contained bedrock deep-seated landslides reached the opposite conclusion – that forest practices have relatively little influence on the stability of these slides. Regardless, it is important to clarify here that the current regulatory scheme distinguishes between glacial and non-glacial deep-seated landslides. Adding non-glacials to the guidance should follow the AMP/CMER scientific assessment process. Adding non-glacials to the RILs legally requires a rule change.
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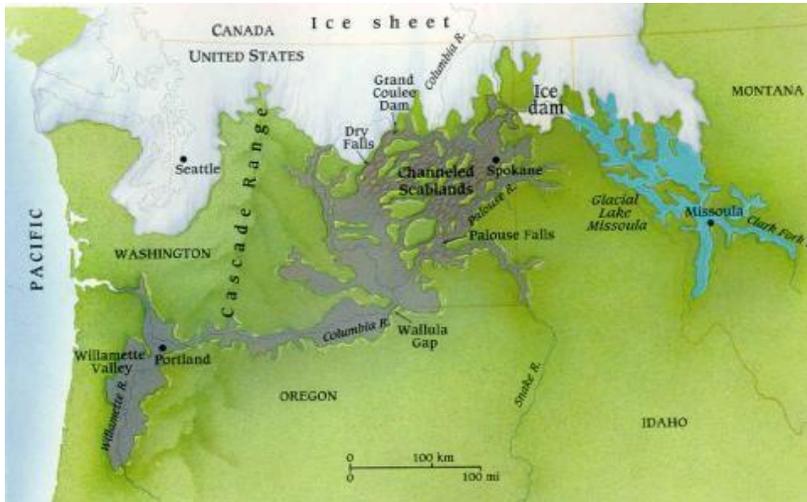


Figure 18a Extent of continental glaciation in the Pacific Northwest (Origin unknown).

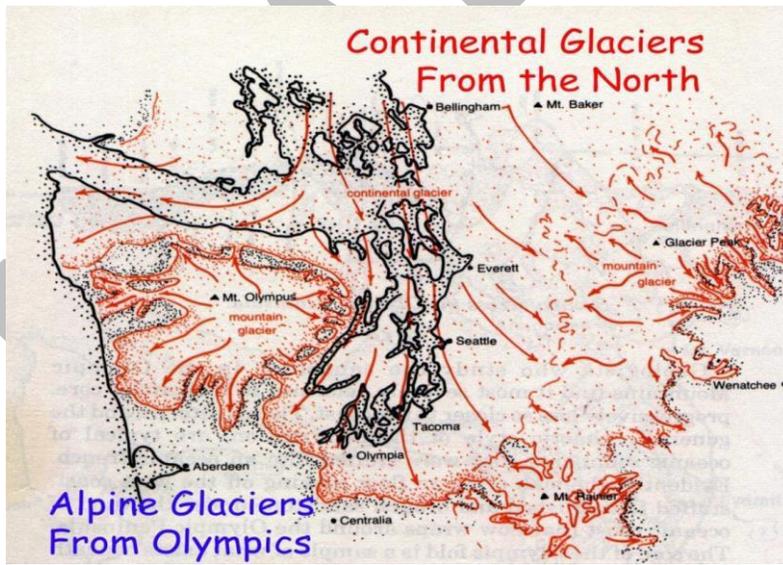


Figure 18b Continental and alpine glaciation in western Washington (Alt, D. D., & Hyndman, D. W., 1984).

Like non-glacial deep-seated landslides, deep-seated landslides in glacial terrain can involve rotational and translational movement, flows or a combination of movement types. Glacial deep-seated landslides can occur in any type of glacial deposit including till, outwash, glaciolacustrine

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and glaciomarine silt and clay, and they often involve multiple glacial strata. During interglacial periods, layers of loess, (e.g., windblown silt and clay) and other non-glacial sediments can also be deposited between glacial units or on the surface of glacial materials and become overlain by deposits from successive glaciations.

Comment [K32]: Is this really faithful to the intent of the rule, the current board manual, and the current interpretation of the DNR science team? The original intent of the GWRA rule was to deal with stratified deposits containing multiple impermeable layers at variable or varying depth.

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Comment [K33]: This section is about glacials.

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Glacial deposits and other earth materials display a wide range of hydrologic characteristics (Table 2). Glacial till generally has low permeability, comprises an unsorted and non-stratified glacial material that can range in size from clay to boulders, and is typically deposited and over run during periods when glacial ice is advancing. Glacial outwash contains typically sorted and stratified sediments deposited by water flowing from glacial ice either during the advance of the glacier or during glacial recession. Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes. Glaciomarine deposits are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

Table 2. Hydrologic Properties of Soils (modified from Koloski et al., 1989)

Classification	Permeability (feet per minute)	Storage Capacity
Alluvial (High Energy)	0.01-10	0.1-0.3
Alluvial (Low Energy)	0.0001-1	0.05-0.2
Eolian (Loess)	0.001-0.01	0.05-0.1
Glacial Till	0-0.001	0-0.1
Glacial Outwash	0.01-10	0.01-0.3
Glaciolacustrine	0-0.1	0-0.1
Lacustrine (Inorganic)	0.0001-0.1	0.05-0.3
Lacustrine (Organic)	0.0001-1.0	0.05-0.8
Marine (High Energy)	0.001-1.0	0.1-0.3
Marine (Low Energy)	0.0001-0.1	0.05-0.3
Volcanic (Tephra)	0.0001-0.1	0.05-0.2
Volcanic (Lahar)	0.001-0.1	0.05-0.2

Comment [K34]: What are the units? This type of information is not useful to the field practitioner – it should be moved to an appendix for QE reference.

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Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 19). The hydrologic budget includes precipitation (rain and snow), interception by vegetation, evapotranspiration, surface storage, surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic budget that infiltrates into the subsurface below the root zone. The ground water component is composed of water within the unsaturated, or vadose zone, and the saturated zone.

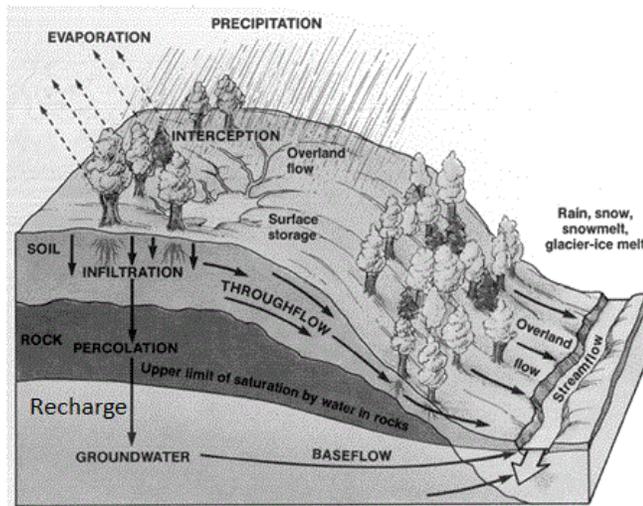


Figure 19 Hydrologic budget of a hillslope (University of Colorado).

Groundwater recharge to a glacial deep-seated landslide may originate as recharge to an adjacent non-glacial geologic unit that flows into glacial sediments, or it may run off from upland non-glacial geologic units and recharge within glacial sediments; in other cases, groundwater in adjacent upslope non-glacial units may infiltrate layers below the failure surface of the glacial deep-seated landslide, thus bypassing the groundwater recharge area. A component of groundwater recharge can be surface flow, but more typically, surface water, such as streams, represents groundwater discharge.

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Comment [K36]: More complete description.

Comment [K37]: During the development of the rule, the bedrock's areas contributions were not included; to imply that recharge originates from adjacent non-glacial geologic units everywhere is a expansion.

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Comment [K38]: The accuracy of this statement seems to depend on the location of the zone of instability within the slide. Further, this sentence is not entirely consistent with Section 5.2.2 below – it probably does not belong here.

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5.2.1 Groundwater Flow

Groundwater flows from areas of recharge in upland areas to points of discharge including springs, streams, and other surface water features at lower elevations. The areal extent of recharge that contributes groundwater to a glacial deep-seated landslide constitutes that landslide's groundwater recharge area and may include the landslide itself.

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Comment [K40]: Specific locations need to be added and appropriate literature cited. Do you mean the southern Cascades from St Helens and Adams?

Groundwater recharge areas of deep-seated slides are located in the lands up-slope that can contribute subsurface water to the landslide. In some cases this can include upslope portions of the landslide itself. Cemented soil horizons, fine-grained soils, and/or the presence of glacial till can be factors controlling the infiltration and flow of groundwater (Bauer and Mastin, 1997; Vaccaro et al., 1998). Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area (Bauer and Mastin, 1997; Vaccaro et al., 1998). Groundwater perching and the characteristics of the overlying groundwater recharge area can be important factors in a deep-seated failure, especially for landslides in glacial sand and other unconsolidated sequences that overlie fine-grained glacial-lake clay deposits or till (Figure 4920). This is a common configuration of the glacial deposits in some locations in much of the northern half of western Washington (e.g., landslides in Seattle) (Gerstel, and others et al., 1997), and in the Stillaguamish River valley (Benda and others, 1988), but this type of landslide also occurs in alpine glacial deposits in southwest Washington, far from the maximum extent of continental glaciation (e.g. SITE LOCATIONS) mountain front. Groundwater filtering down flowing through porous permeable

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| sand layers is ~~trapped-perched~~ above the ~~poorly less~~ permeable clay or till. During ~~and following~~ ~~storm-precipitation~~ events, the sand above the clay becomes saturated creating a buoyant effect and lowering cohesion in the sand, both of which

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weaken the contact between the clay and sand. This in turn ~~may cause~~ causes the overlying mass to slide along the sand/clay contact. A ~~key predictive common predictor of observation is noting perched groundwater is~~ the presence of a horizontal line of springs (groundwater ~~refluxing discharge~~) or a line of ~~hydrophyllic~~ vegetation at the contact between the permeable and less permeable layers. ~~Land uses such as poorly planned ditches or large-scale, even-aged harvesting that alter the timing or volumes of groundwater recharge in the slide zone can start or accelerate landslide movement.~~

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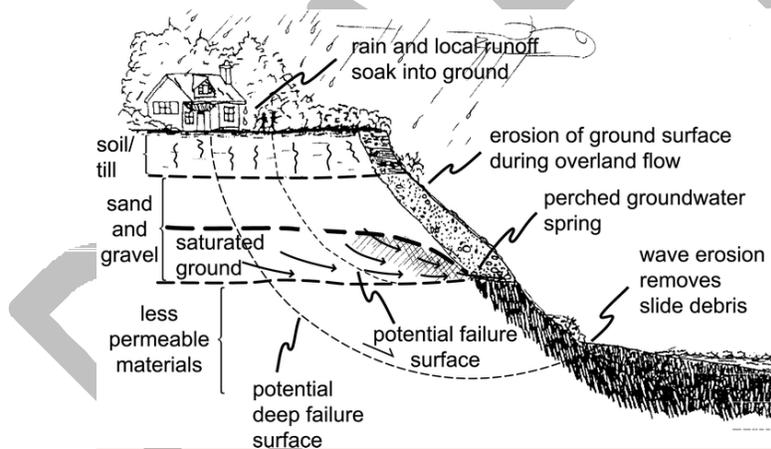
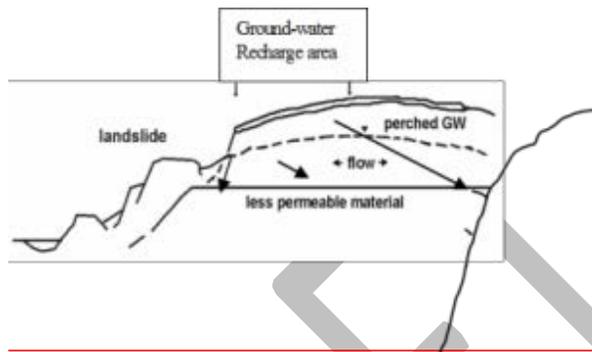


Figure 1920. Diagram illustrating failure surface resulting from groundwater recharge ~~area to~~ for a glacial deep-seated landslide (modified from Gerstel et al., 1997).

A classic example of a geologic setting where glacial deep-seated landslides are common is in Puget Sound where the Esperance Sand overlies the Lawton Clay. In this setting, groundwater recharge from precipitation infiltrates downward within the hillslope until it encounters the relatively impermeable Lawton Clay. Because the water cannot infiltrate into the Lawton Clay at the same rate at which it is supplied from above, the water table rises vertically above the clay surface. The elevated water table increases the pressure within the Esperance sand and forms a hydraulic

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gradient which causes water to flow horizontally along the sand clay contact, resulting in springs where this contact is exposed at the surface (Lubbs, 1974).

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5.2.2 Effects of Groundwater on Slope Stability

Saturation of the pore spaces within sediments results in pore pressures that act to push the soil particles apart. This phenomenon of soil saturation reduces the effective strength of the soil which in turn reduces the stability of a slope comprised of saturated sediments. Because of the likelihood of subsurface water flow along and within perching layers in glacial strata, certain forest practice activities proposed within recharge areas for glacial deep-seated landslides may be classified “Class IV-special” under WAC 222-16-050(1)(d) the forest practices rules and require further investigation and documentation. Once it is determined that the proposed forest practice has the potential to significantly influence the stability of the glacial deep-seated landslide relative to other factors, then the groundwater recharge area is mapped. Therefore, it is important to characterize groundwater recharge areas and local stratigraphy in terms of an evaluation of the potential for changes in the water balance due to forest practices activities and an assessment of the degree to which a potential hydrologic change can be effectively delivered to a glacial deep-seated landslide. In the absence of other information, The first order approximation of the recharge area is assumed to be equivalent to the surface basin (topographically defined) basin directly above and possibly including the active landslide. A more refined estimate of the spatial extent of a groundwater recharge area can be also be interpreted from field observation of soil profiles, geologic structure, stratigraphy, well logs of wells or boreholes, or large-scale geologic maps. Additional information regarding delineating and assessing the groundwater recharge areas is included in Part 6.4 and Part 7.2.

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Comment [K45]: More accurate statement.

Comment [K46]: Before mapping the groundwater recharge area, there should be an analysis about whether the landslide is sensitive to a forest practice and whether it is a glacial or not.

Comment [K47]: See comment in 5.2.1 above. Further, the last three sentences of this section could be deleted because this topic is covered in Section 6.4.

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5.3 Toes of Deep-Seated Landslides

The toes of deep-seated landslides are a rule identified forest practices regulatory landform. In this context “deep-seated landslide toes” means the down slope toe edges, not the entire toe area of displacement material (see Figure 2217). Landslides that have toe edges adjacent to streams have a high potential for delivery of sediment and wood to streams. In such situations, streams can undercut the landslide toes and promote movement. Such over-steepened toes of deep-seated landslides can also be sensitive to changes caused by harvest and road construction. The road shown in Figure 23 may have removed a portion of the toe, causing failure and re-activation of the landslide. Resulting instability can take the form of shallow landslides, small-scale slumping, or reactivation of parts or the whole of a deep-seated landslide. Because deep-seated landslides are usually in weak materials (further weakened by previous movement), an angle of 33° degrees (65%) is the threshold value used on the potentially unstable toe edges. Regardless of the surface expression of the toe, it is best to avoid disrupting the balance of the landslide mass by cutting into or removing material from the toe area.

Comment [K48]: Consider moving above 5.2.

Comment [K49]: This statement is not consistent with the WAC – only toes greater than 65% are listed RILs.

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Comment [K50]: What does this mean – the statement is confusing.

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5.4.5 Outer Edges of Meander Bends

Streams can create unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (Figure 210). The outer edges of meander bends are susceptible to deep-seated landsliding and shallow landsliding including debris avalanching and small-scale slumping, and deep-seated landsliding. The outer edges of meander bends may be protected by the riparian management zone (RMZ) or channel migration zone (CMZ) rules if the slopes are not particularly high and are contained within the riparian leave areas or within the CMZ (see Board Manual Section 2). As with other situations of overlapping forest

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practices rules, the harvest unit layout should reflect the extent of the greater of the protections.

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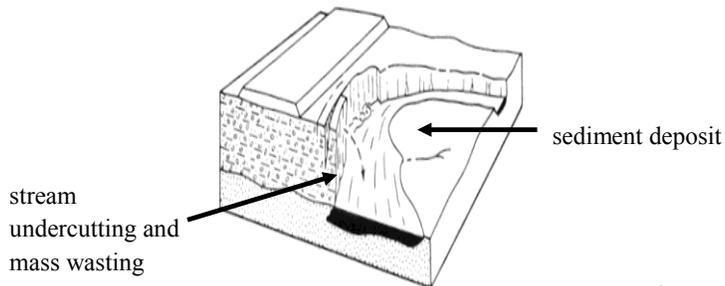


Figure 2021- Outer edge of a meander bend showing mass wasting on the outside of the bend and deposition on the inside (adapted from Varnes, 1978).

5.56 Other Indicators of Slope Instability or Active Movement

Relatively large and recent topographic indicators can be observed on air photos, topographic maps and LiDAR images, but the identification of smaller and older indicators requires careful field observations. In addition to the landforms described above, other topographic, hydrologic and vegetational indicators of slope instability or active movement may include:

(a) Topographic and hydrologic

- bare or raw, exposed, un-vegetated soil on the faces of steep slopes
- boulder piles
- hummocky or benched surfaces, especially below crescent-shaped headwalls
- fresh deposits of rock, soil, or other debris at the base of a slope
- ponding of water in irregular depressions or undrained swampy areas on the hillslope above the valley floor
- tension cracks in the surface (across or along slopes, or in roads)
- seepage lines or springs and soil piping
- deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)
- stratigraphic indicators, including disconformities, offset contacts, and overturned sections
- back tilted surfaces from rotation within the slide.

(b) Hydrologic

- ponding of water in irregular depressions in undrained swampy or poorly drained areas on the hillslope above the valley floor
- seepage lines or spring and soil groundwater piping
- sag ponds (ponded water in a tension crack)
- deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits)

(c) Vegetational

- jack-strawed, back-rotated, or leaning trees and stumps
- bowed, kinked, or pistol-butted trees
- split trees and old growth stumps
- water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes
- other patterns of disturbed vegetation or changes in stand composition (early seral stage or lack of mature trees within a hillslope)

No ~~single one of these~~ indicators necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

Additional information about landslide processes, ~~unstable lanforms techniques for hazard assessment~~, and ~~management practices on the effects of forest practices on~~ unstable ~~terrain landforms~~ is available in “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest” by the British Columbia Ministry of Forests (Chatwin et al., 1994); ~~and Hillslope Stability and Land Use~~ (Sidle et al, 1985); Landslides, Processes, Prediction and Land Use (Sidle and Ochiai, 2006).

Deep-seated landslides are those in which the slide plane or zone of movement is ~~well~~ below the maximum rooting depth of forest trees (generally greater than 10 feet or 3 meters). Deep-seated landslides may extend to hundreds of feet in depth, ~~often including and may involve underlying~~ bedrock. Deep-seated landslides can occur almost anywhere on a hillslope ~~where geologic and hydrologic conditions are conducive to failure.~~ ~~and They~~ can be as large as several miles across or as small as a fraction of an acre. ~~The larger ones~~ Deep-seated landslides can ~~usually~~ be identified from topographic maps, ~~or~~ aerial photographs, LiDAR images, and field observations. Many deep-seated landslides occur in the lower portions of hillslopes and extend directly into stream channels whereas deep-seated landslides confined to upper slopes may not have the ability to deposit material directly into channels. Deep-seated landslides often are part of large landslide complexes that may be intermittently active for hundreds of years or more (Bovis, 1985; Keefer and Johnson, 1983).

One common triggering mechanism of deep-seated landslides results from the over-steepening of the toe by natural means such as glacial erosion or fluvial undercutting, fault uplift, or excavating for land development by human-caused excavations. Initiation of such landslides has also been associated with changes in land use, increases in groundwater levels, and the degradation of material strength through natural processes. Movement can be complex, ranging from slow to rapid, and may include numerous small to large horizontal and vertical displacements variously triggered by one or more failure mechanisms.

Deep-seated landslides characteristically occur in weak materials such as thinly layered rocks, unconsolidated sediments, deeply weathered bedrock, or rocks with closely spaced fractures. Examples include: clay-rich rocks, such as the Lincoln Creek Formation of west-central Washington; thinly layered rocks, such as phyllite in northwest Washington; and deeply weathered volcanic rocks that cover present in the Willapa Hills of southwest Washington. Deep-seated landslides can also occur where a weak layer or prominent discontinuity is present in otherwise strong rocks, such as clay or sand-rich sedimentary interbeds within the basalts of eastern Washington or a fault plane or intersecting joint set. In northwest Washington and on the Olympic Peninsula, deep-seated landslides commonly occur along silt or clay beds that are overlain by sandy units such as glacial deposits.

There are three main parts of a deep-seated landslide: the scarps (head and side), ~~along which marginal streams can develop~~; the body, which is the displaced slide material; and the toe, which also consists of displaced materials. The downslope edge of the toe can become over steepened from stream erosion or from the rotation of the slide mass. A deep-seated landslide may have one or more of these component parts ~~several of each of these parts~~ because small deep-seated landslides can be found nested within larger slides. These three main parts are shown in Figures ~~22+7~~ and Figure 23+8. The head= and side=scarps together form an arcuate or horseshoe shaped feature that

represents the surface expression of the rupture plane. The body and toe area ~~are~~ usually display hummocky topography, and the flow path of streams on these landslide sections may be displaced in odd ways due to differential movement of discrete landslide blocks. The parts of deep-seated landslides that are most susceptible to shallow landslides and potential sediment delivery are steep scarps (including marginal stream side slopes) and toe edges.

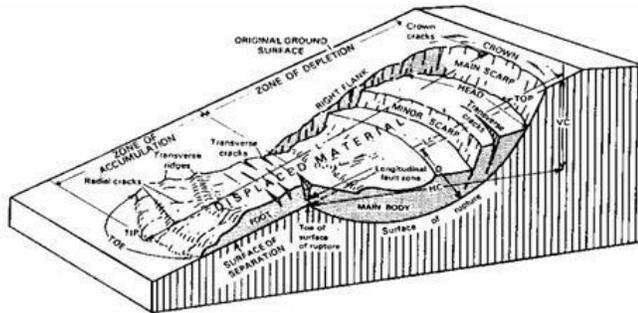


Figure 17. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide. Slow flow (an earthflow) may be found at the toe (Drawing: Varnes, 1978).

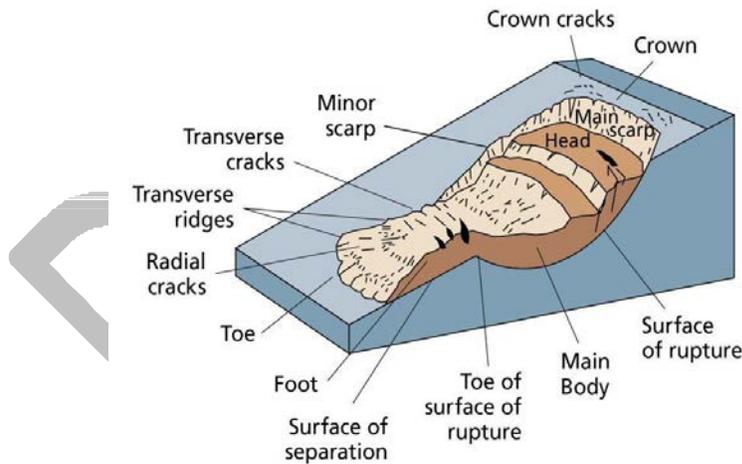


Figure 22. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide (adapted from USGS, 2004).

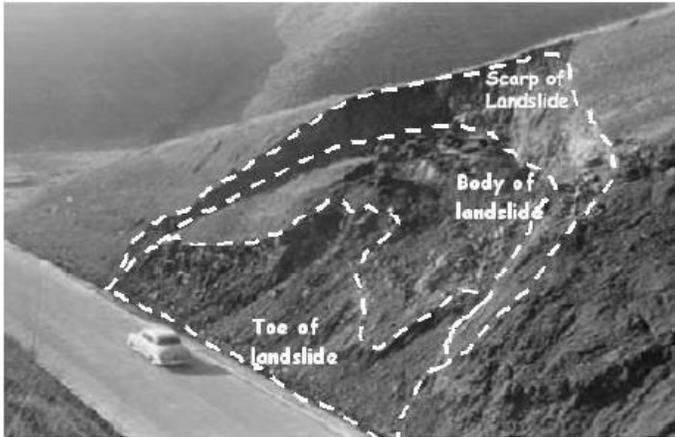


Figure 1823 Deep-seated landslide showing the head scarp, side-scarps, body, and toe. Some of the toe has been removed in building and maintaining the highway (adapted from USGS photo).

The sensitivity of any particular landslide to forest practices is highly variable. Deep-seated scarps and toes may be over-steepened and streams draining the displaced material may be subject to debris slide and debris flow initiation in response to harvest or road building. Movement in landslides is usually triggered by accumulations of water at the slide zone, so land-use changes that alter the amount or timing of water delivered to a landslide can start or accelerate movement (Cronin, 1992). Generally, avoiding the following practices will prevent most problems: destabilizing the toe by the removal of material during road construction or quarrying which could destabilize the toe; overloading the slopes by dumping spoils on the upper or mid-scarp areas which could overload the slopes, or compacting the soil in these places which could change subsurface hydrology; and directing additional water into the slide from road drainage or drainage capture. The loss of tree canopy interception of moisture and the reduction in evapotranspiration through timber removal on areas up gradient of the slide may also initiate movement of the slide (van Asch, et al., 2009).

Parts 5.3 and 6.4 provide methods for describing and delineating groundwater recharge areas for deep-seated landslides in non-glacial sediments.

PART 6 OVERVIEW OF ASSESSMENT FOR POTENTIALLY UNSTABLE SLOPES AND LANDFORMS AND MATERIALS REGIONAL LISTS

The Regional (Unstable) Landform Identification Project (RLIP) is a result of the Forests and Fish Report and is being conducted statewide at this time. The purpose of the RLIP is to note and validate region-specific unstable landforms that are not included in the present forest practices rules so that known unstable landforms are not overlooked during the forest practices application process. The final products will be in the form of short reports (validations) and maps that describe (generally and specifically) and locate these regional unstable landforms. This information is intended to be used as a screening tool for forest practices applications and may be eventually included in the forest practices rules and this Board Manual Section.

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Comment [K51]: The proposed edits significantly change the meaning and should be rejected. The key issues (and problematic practices) are "destabilizing the toe", "overloading the slopes", "compacting the soil", "directing additional water" – not simply constructing roads, quarrying or placing spoils.

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Comment [K52]: Typo? These sections relate to glacial not non-glacial landslides. Further, Section 5.3 appears to be the wrong citation.

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The identification, delineation, and characterization of unstable and potentially unstable landforms should be completed in sequential order as appropriate to address the relevant questions for each site. Each step of the review process might uncover new information that could modify assessment methods and findings. General practitioners (landowners, foresters, engineers) typically conduct an initial screening of project sites for potentially unstable slopes and landforms, followed by a more in-depth geotechnical review, if warranted, by a qualified expert.

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Comment [K53]: The current language implies that every analysis will require every step and ignores the prior knowledge and experience. The suggested language allows flexibility.

A typical assessment of unstable slopes and landforms includes following components:

- Assessment conducted by a landowner or designated landowner representative:
 - initial office screening (see Part 6.1.1)
 - field assessment and harvest operations lay-out (Part 6.2.1)
- Geotechnical review conducted by qualified expert (if desired by landowner or required by rule)
 - office review (Part 6.1.2)
 - field review (Part 6.2.2)
 - landslide/landform activity assessment (Part 7.1)
 - water budget and slope stability modeling assessments (Part 7.2)
 - slope stability sensitivity assessment (Part 7.3)
 - deliverability assessment (Part 7.4)
 - summary of findings, results, and recommendations (Part 7.5)
 - qualified expert reports (Part 8)

Elements of the investigation and the order in which they should be completed are generally as follows (modified from Turner and Schuster, 1996):

1. Preliminary fact-finding. What actions does the proposed forest activity include (e.g., partial cut, clear cut, road building, stream crossing)? In which landslide province (Part 2.4) is the proposed forest activity located and what are the hydrogeologic conditions and types of landforms expected to be present? Are any site-specific resources available for review, such as previously completed qualified expert reports or watershed analysis reports?
2. Office review of geologic maps, topographic maps, aerial photographs, LiDAR, and other information identified during the preliminary fact-finding phase.
3. Field review including hydrogeologic mapping and site observations to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review.
4. Data analysis and assessment regarding the potential for landslide activity as a result of the proposed forest practice activity and the potential for delivery of sediment to public resources or threats to public safety.

6.1 Office Review Process

An office review refers to the initial screening of a selected site using available, remotely sensed information and previously prepared materials or documents (e.g., reports, studies, field data and analyses). The term “remote sensing” generally describes information acquired for a particular site or physical phenomenon without making physical contact by, for example, collecting data in the field. A typical office review utilizes all accessible, site-specific and regional remote-sensing data

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that can be brought to bear on identifying, delineating, and interpreting potentially unstable slopes and landforms (e.g., aerial imagery, LiDAR, GIS-based model predictions of earth surface attributes derived from digital, high-resolution topographic data). In addition, an analyst uses existing

documents and databases (e.g., maps, geotechnical reports and studies, published and unpublished scientific literature, landslide inventories, local and regional databases containing meteorologic, hydrologic, and geologic information) to screen sites for potential slope-stability concerns, identify natural resource and public safety considerations, develop an initial interpretation of potentially unstable landforms presence/absence and landslide types, and make a determination regarding next steps in the site assessment.

Typically, the office review occurs in two steps: (1) an initial office screening conducted by the landowner or **designated** representative to determine if unstable slopes and landforms might be present that require field assessment, and whether a qualified expert is desired or needed for more extensive site analyses; and (2) a geotechnical office review completed by the qualified expert for suspected unstable slopes and landforms, the outcome of which potentially leads to a qualified expert conducting geotechnical field review.

Comment [K54]: Is "designated representative defined? Is it the applicant?

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6.1.1 Initial Office Screening Conducted by a Landowner or Designated Representative

The objective of an initial office review conducted by a landowner or designated representative is to: (1) identify potential or existing areas of slope instability within or adjacent to the harvest operations area; (2) delineate potential unstable landforms using definitions and type descriptions provided in Part 5 of this Board Manual section; (3) locate areas of natural resource sensitivity or public safety exposures in the vicinity of the planned operation that could be adversely affected by mass wasting processes; and (4) develop a plan for assessing potential unstable slopes and landforms in the field. This information is required on forest practices applications (FPAs) and any supplemental slope-stability informational forms required at the time of EPA submission. Designated representatives might include forest engineers, foresters, or qualified experts.

Summary of Procedures. The office review process generally includes compiling and evaluating available maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. This initial screening is supplemented with landowner knowledge about site-specific conditions and with publicly available documents that might identify site-specific slope stability concerns or place the site in a broader landscape context with regard to potentially unstable landforms and processes (i.e., watershed analyses conducted under chapter 222-22 WAC; see Appendix D). Information sources are available to the landowner online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. Additional sources of imagery, data, maps, reports, and other documents are listed in Appendices A through E of this Board Manual section.

Relevant maps typically include surface topography and its derivatives (e.g., slope class maps), hydrology (e.g., streams and water types), geology and soils (e.g., rock units, soil types), landslides (landslide inventories and hazard zonation), and information needed to identify public safety exposures (e.g., road networks, parcel boundaries with existing building structure information). Imagery includes aerial photography and LiDAR-derived hillshade images (see Part 6.1.3 for more information) available on public websites and referenced in Appendix B. GIS with map display and analysis capabilities (e.g., ESRI ArcGIS) provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis; however, an initial screening can be performed manually without such tools if they unavailable to the landowner (i.e., by inspecting each map or image separately). Certain counties also offer an online, user-friendly, interactive version of GIS with many of the needed map and imagery products (see Appendix A). A follow-up field assessment is needed to verify results of the initial screening. It is helpful to create a site map, for

field use, showing areas of potential slope stability concerns, natural resource sensitivities, and public safety exposures within or adjacent to the proposed operation.

Outcome The initial office screening aids the landowner in targeting portions of the operations area that need to be assessed in the field for unstable slopes and landforms. Note also that the office screening might not identify all potential unstable landforms, particularly if features are too small or subtle to be identified from available maps and imagery. For example, the landowner might not be able to identify the full extent of a groundwater recharge area from topographic maps, or to detect landslides under a mature forest canopy if using aerial photography exclusively. A field assessment typically is conducted by landowners while they are marking (flagging) the boundaries of the operations area. See Part 6.2 for guidance on conducting field reviews. The landowner might also elect to have a more thorough office review conducted by a qualified expert; see Part 6.1.2 for further discussion. Suspected groundwater recharge areas associated with glacial deep-seated landslides should be reviewed by a qualified expert.

6.1.2 Geotechnical Office Review Conducted by a Qualified Expert

The objective of an office review conducted by a qualified expert is to develop a preliminary geotechnical assessment of landform characteristics and landslide potential prior to initiating fieldwork, so that subsequent field investigations are targeted, efficient, and capable of verifying initial interpretations within a reasonable degree of certainty. The geotechnical office review generally is more in-depth than the landowner-conducted initial screening and applies professional expertise in engineering geology, hydrogeology, geomorphology, and associated fields to detection and interpretation of landscape processes. Depending on the site specific conditions and the proposed forest practice, during a geotechnical office review, the qualified expert typically may:

1. screens the site with available data in order to identify physical indicators of past, existing, and potential landslide activities, noting their spatial and temporal distributions;
2. delineates on preliminary maps the identified landslide features and associated potentially unstable landforms;
3. formulates initial hypotheses regarding landslide and landform behavior and failure mechanisms, to be evaluated further in the field; and
4. determines the type and level of field investigation needed to verify preliminary landslide interpretations, develop cause-effect relationships, and assess potential for material delivery and potential adverse impacts to natural resources and threats to public safety.

Summary of Procedures The geotechnical office review generally follows the same procedures as the initial office screening for compiling and evaluating available information. Most qualified experts have ArcGIS capabilities, are experienced in using remote-sensing and modeling tools, and can provide feedback on proposed forest practice activities in relation to their potential for affecting slope instability. The office review typically precedes a field review whose objectives usually include assessing the accuracy, limitations, and uncertainties of remotely sensed information and previously prepared materials assembled during the office review, as well as adjusting any preliminary interpretations of site characteristics or physical phenomena based on these data sources. The qualified expert determines the nature of the office review and the appropriate combination of assembled information based on the project objectives, requirements, and desired level of confidence in assessment products.

Outcome The geotechnical office review typically leads to a field review, especially where unstable

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Comment [K55]: This sounds like job security for consultants. The RIL thresholds and descriptions were intended for use by the general practitioner (including regulators) not for QEs. The RILs are precautionary in nature – it is important to keep in mind that not all areas within RILs are unstable (or even potentially unstable) but rather represent a first cut moderate-to-high hazard zone which general practitioners can identify (and possibly avoid) in a repeatable manner. This sentence creates the impression that it is necessary for specialists, not generalists, to perform even the most basic activities in order to adequately implement the rules.

This entire section should be reduced to those specific activities which constitute the professional practice of geology and indicates the limited circumstances (i.e. a Class IV-S or evaluation that delivery to public resources/threats to public safety evaluation) when it is necessary and appropriate to perform (see second paragraph of Section 6.2 below).

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Comment [K56]: The language in this section also implies that a Watershed Analysis level of effort is needed for each harvest unit. The added language is an attempt to scale the review to the relevant issues.

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slopes and landforms are suspected or known and verification is required. Office review findings

are included in the report written by the qualified expert. Note that interpretations based solely on remote-sensing data should not be used as substitutes for site-specific field assessments carried out by qualified experts where such investigations are required by the Forest Practices Act. There might be certain instances, however, where a field review is optional because the qualified expert has a high level of confidence in office review interpretations. For example, the expert might determine that no unstable slopes or landforms are present, or such features are present and the landowner agrees to exclude these areas from forest operations.

6.1.3 Remote-Sensing Tools Available for Office Reviews

Common sources of remotely sensed information used in identifying, delineating, and interpreting potentially unstable slopes and landforms can be grouped broadly in the following categories: (1) aircraft- or satellite- based earth imagery and photogrammetry; and (2) LiDAR (Light Detection and Ranging) and high-resolution topographic data. Previously prepared materials or documents often incorporate field and remotely sensed data; these sources include maps and surveys, technical reports and other published/unpublished literature, and physical databases. Appendices A through E of this Board Manual list the most common data sources in each category. Among the available remote-sensing technologies, LiDAR has proven to be a valuable source of high-resolution topographic data with distinct advantages over traditional analytical methods (e.g., aerial photo interpretation) for mapping landslides and interpreting landform characteristics (e.g., Haugerud et al., 2003; Burns and Madin, 2009; Jaboyedoff et al., 2012; Roering et al., 2013; Tarolli, 2014). Consequently, LiDAR capabilities and applications are discussed in more detail below.

New remote-sensing techniques for terrain characterization are being developed at a rapid pace, due in part to expanding availability of publicly acquired, high-resolution topographic data (e.g., LiDAR). For example, major advances in deep-seated landslide characterization methods are combining high-resolution LiDAR data with other remotely sensed information and developing quantitative LiDAR analysis techniques to map and quantify landslide movement (Tarolli, 2014). Examples include using LiDAR-derived Digital Elevation Models (DEM) and Digital Terrain Models (DTM) with: (1) radar data and historical aerial photographs to quantify deep-seated landslide displacement and sediment transport (Roering et al., 2009; Handwerker et al., 2013; Scheingross et al., 2013); (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux (Mackey and Roering, 2011); and, (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows (e.g., Ardizzone et al., 2007; Booth et al., 2009; Burns and Madin, 2009; Tarolli et al., 2012; Van Den Eeckhaut et al., 2012); and, (4) subsurface investigations (Travelletti and Malet, 2012). Such innovative approaches likely will continue to emerge as more sophisticated high-resolution surface and subsurface technologies are developed. It is the task of qualified experts to seek out, evaluate, and apply new remote-sensing methods as they become available.

6.1.4 LiDAR and High-Resolution Topographic Data

Airborne LiDAR (Light Detection and Ranging) is a remote sensing technique that involves scanning the earth's surface with an aircraft-mounted laser in order to generate a three-dimensional topographic model (Carter et al., 2001). During a LiDAR acquisition flight, the aircraft's trajectory and orientation are recorded with Global Positioning System (GPS) measurements and the aircraft's inertial measurement unit, respectively. Throughout the flight, the laser sends pulses of energy at more than 100,000 pulses per second in a sweeping pattern beneath the aircraft. Energy from a single pulse is commonly reflected by multiple objects within the laser's footprint at ground level.

such as the branches of a tree and the bare ground below, generating multiple returns. The first returns are commonly referred to as “highest hit” or “top surface” points and are used to measure the elevations of vegetation and buildings, while the last returns are commonly referred to as “bare earth” points and undergo additional processing to create a model of the earth’s ground surface.

To generate a digital elevation model (DEM), the aircraft trajectory and orientation measurements are combined with the laser orientation and travel time data to create a georeferenced point cloud representing the location of each reflected pulse. These irregularly spaced points are commonly interpolated to a regularly spaced grid with horizontal spacing on the order of 1 m to create a high resolution digital elevation model. Bare earth digital elevation models undergo additional filtering to identify ground returns from the last return point cloud data (for a review of filtering techniques, see (Liu, 2008). These bare earth DEMs are most commonly used for interpreting and mapping deep-seated landslide features, especially in forested terrain where vegetation would normally obscure diagnostic ground features (Van Den Eeckhaut et al., 2007).

Hillshade and slope maps derived from bare earth LiDAR DEMs are the most common LiDAR products used to identify deep-seated landslides. A hillshade map is created by simulating sunlight shining on the topographic surface at a specified angle, while a slope map is the magnitude of the topographic gradient, estimated by differencing the elevations of adjacent points in the DEM. Hillshade maps tend to have less contrast on slopes facing the incident sun angle and more contrast on slopes facing away from the incident sun angle, either of which can obscure topographic features. It is therefore recommended to analyze several hillshade maps generated with different sun angles or employ methods such as those described in Burns and Madin (2009) for minimizing illumination and topographic shadowing effects (i.e., multi-directional oblique-weighted hillshade algorithm). Additional derivative maps such as topographic curvature, surface roughness, and elevation contours can also be useful to identify deep-seated landslide features. Contours should be generated with spacing similar to the LiDAR data resolution and/or the scale of the geomorphic features of interest.

Key topographic features indicative of deep-seated landslides that are visible in LiDAR-derived maps, but might not be visible in other remote sensing data, are similar to those observed in visual indicators. Hummocky topography, benched surfaces, tension cracks, scarps, block and graben features, shear margins, pressure or transverse ridges, irregular drainage patterns, and displaced surface features are often especially visible, but only when the scale of the feature is larger than the resolution of the LiDAR data. LiDAR hillshades can be used to delineate and interpret deep-seated, but not shallow, landslides, although some depositional surfaces (for example debris fans) can be identified. Various measures of surface roughness are commonly used to recognize and quantify deep-seated landslide morphology in landslide mapping studies (McKean and Roering, 2004; Glen et al., 2006; Booth et al., 2009; Berti et al., 2013). Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005, 2007), and Haugerud (2014).

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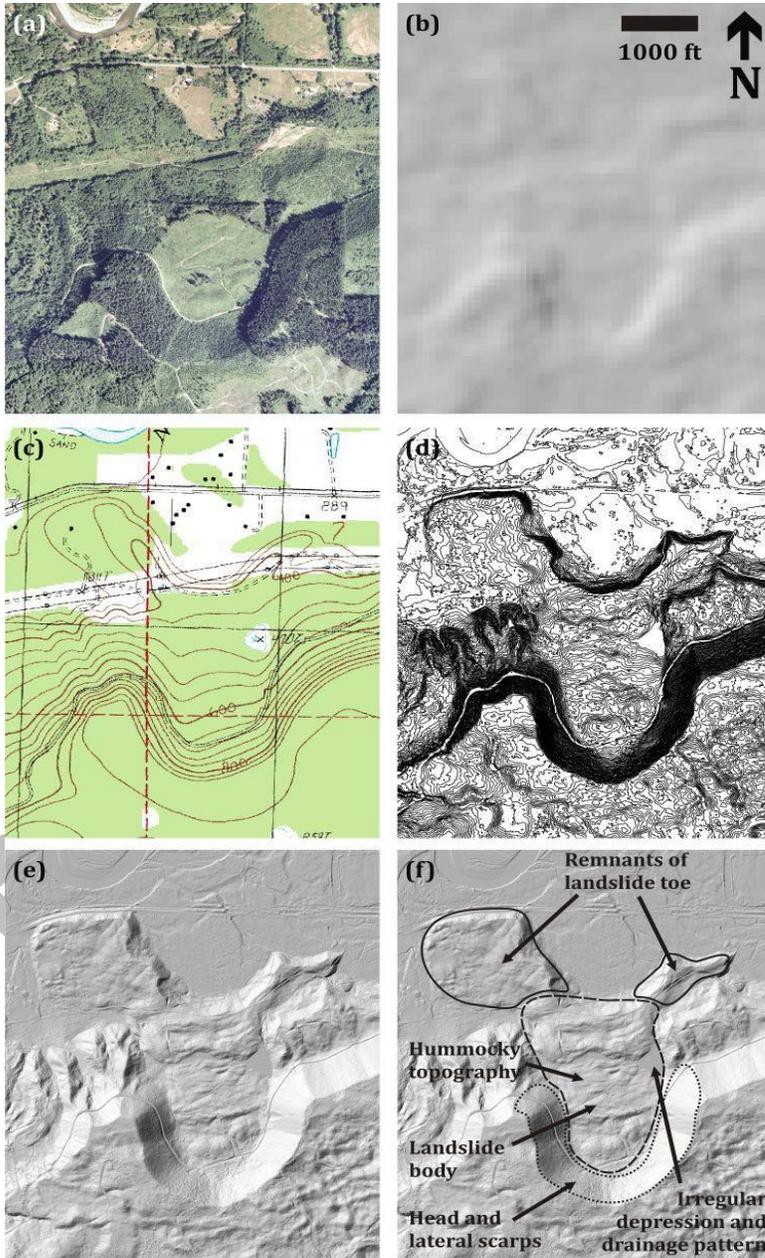


Figure 24 Example of a dormant glacial deep-seated landslide as seen in different types of remotely sensed data: (a) Digital Orthophoto Quadrangle, (b) hillshade map derived from 30-meter resolution ASTER Global Digital Elevation Model, (c) topographic map, (d) 6-foot contour map derived from 3-foot resolution airborne LiDAR, (e) hillshade map derived from 3-foot resolution airborne LiDAR, and (f) annotated version of (e). In (f), the landslide's main scarp, body, and toe are approximately delineated. Subsequent erosion has removed the central part of the landslide toe, hummocky topography is found throughout the body of the landslide, and a sediment-filled depression connected with an irregular drainage pattern is present on the eastern side of the landslide body (Adam Booth, 2014, Portland State University).

Repeat LiDAR acquisitions are becoming more common so that in addition to using a single LiDAR data set to interpret deep-seated landslide morphology, the qualified expert can increasingly measure topographic changes related to slope instability with pairs of LiDAR scenes (Corsini et al., 2007; Delong et al., 2012; Deahne and Corsini, 2013). Vertical changes can be measured by differencing LiDAR-derived DEMs, while manual or automated tracking of features visible on hillshade or slope maps between scenes can be used to estimate horizontal displacements. Note that many active deep-seated landslides move at rates that may be undetectable given the uncertainties in the LiDAR data, so this technique is most helpful for relatively large topographic changes, typically on the order of several meters (Burns et al., 2010). Care should be taken to precisely align the repeat LiDAR DEMs.

6.2 Field Review Process

The purpose of the field review is to confirm the findings of the office review, and to identify unstable and potentially unstable landforms that were not recognized during the office review. While the office review can provide important information, on-site observation of geomorphic features on the ground surface is essential for identifying potentially unstable landforms.

The field review is typically performed by the general practitioner (e.g., landowner, forester, and engineer) and serves to confirm confirms the presence or absence of potentially unstable slopes and landforms. If such features are located and forest practices are proposed on these features, the landowner may retain a qualified expert to perform additional geotechnical reviews.

Comment [K57]: More accurate statement.

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6.2.1 Field Assessment Conducted by a Landowner during Operations Layout

The objective of the field assessment conducted by a landowner or designated representative is to verify the presence or absence of unstable slopes and landforms, using definitions of the landform types and guidance provided in this Board Manual section. In addition to assessing the potential unstable areas identified in the initial office screening, the landowner surveys the operations area for any landforms missed in the office review. The landowner typically carries out this assessment while laying out the proposed forest operations (e.g., marking unit boundaries, establishing riparian management zones).

Comment [K59]: More accurate statement.

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Summary of Procedures See Field Review Assessment (Part 6.4.2) and Visual Indicators of Slope Instability or Active Movement (Part 6.3) for additional information on conducting field reviews.

Outcomes Common results of landowner-conducted field review include:

1. The landowner does not identify any potentially unstable slopes or landforms within or adjacent to the operations area, the FPA slope stability sections are filled out accordingly, and the office/field review process is complete;
2. The landowner identifies potential unstable slopes and landforms within or adjacent to the planned operations area. The landowner excludes these areas from this area of proposed operations and future planned operations and completes the appropriate FPA slope stability sections similar to (1) and any required additional information.
3. The landowner identifies potentially unstable areas within or adjacent to the operations area, and proposes to conduct forest operations on them. The landowner retains a qualified expert (see Washington State Department of Department of Natural Resources (DNR) website for list of qualified experts) to conduct a geotechnical office review and subsequent field review, and prepare a geotechnical report, as required by WAC 222-10-030. The landowner completes the FPA slope stability sections and includes any additional information.

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Comment [K61]: More accurate statement.

6.2.2 Geotechnical Field Review Conducted by a Qualified Expert

The objectives of the geotechnical field review conducted by a qualified expert are to: (1) verify the presence or absence of unstable slopes and landforms identified in the geotechnical office review, in the general practitioner field review, and/or identify as well as those that were missed due to insufficient remote-sensing data coverage or resolution; (2) refine preliminary maps constructed during the office review; (3) confirm or refute initial hypotheses regarding landslide behavior, failure mechanisms, and level of activity; (4) solidify understanding of cause-effect relationships; (5) assess relative potentials for material delivery associated with the proposed forest practices to areas of resource sensitivity and threats to public safety; (6) evaluate levels of confidence in office and field findings; and, (6) write a geotechnical report summarizing review findings, conclusions, and recommendations (see Part 8 for guidance on geotechnical report writing).

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Comment [K62]: Clarifies that a QE field review will also consider the general practitioner's field review.

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Comment [K63]: Writing a geotech report is not necessarily a part of the field review.

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Summary of Procedures The qualified expert determines the nature of the field review required to meet the objectives stated above subject to DNR's review. Depending on the analyst's level of confidence in potentially unstable landform identifications, delineations, and interpretations for any given site, the field review might range from qualitative to more quantitative in nature. An example of a qualitative review would be one in which the qualified expert collects visual observations and photos of geological features and other site indicators at identified locations (i.e., GPS waypoints) and summarizes those observations in a geotechnical report, as a means for substantiating landform and process interpretations. A more quantitative investigation might include such data collection techniques as topographic surveying for measuring landslide surfaces (i.e., needed for slope stability modeling), soil sampling to test material properties, and subsurface sampling that is especially important in analyzing the depths, materials, and hydrology of deep-seated landslides. Fieldwork needed to complete the review can take one or more days, and the qualified expert might be asked to return to the field for an interdisciplinary team meetings if required by DNR.

The field review performed by a qualified expert should include the preparation of a site-specific geologic map, because the scope of work associated with most published geologic maps is insufficient to identify small-scale unstable landforms that could have a significant effect on the proposed forest activity. The purpose of geologic mapping is to document surface conditions and provide a basis for the interpretation of subsurface conditions. Ideally the geologic map should be prepared on a scale of 1:10,000 or less using high-resolution LiDAR-generated topography. If high-resolution LiDAR is not available base maps can consist of U.S. Geological Survey 7.5-Minute topographic maps, DNR forest practices activity maps, or aerial photographs.

The geologic map should ideally include the location, elevation and attitude of all geologic contacts, although such data collection is not feasible or necessary in all situations. Particular emphasis should be placed on the contact between high permeability soils and underlying low permeability soils or bedrock and the location of groundwater seeps or springs, especially where deep-seated landslide activity is suspected or encountered. If an unstable or potentially unstable landform is present, the location of pertinent components and effects of the landform should be identified on the map, such as headwall and side scarps, tension cracks, drainage patterns, hummocky topography, and run out areas

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Comment [K64]: This language seems to be very specific to deep-seated landslides and should probably be moved back to that section.

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Geologic field data collection, analysis, and map compilation are undergoing a revolution in methods, largely precipitated by GPS and GIS-equipped mobile computers (Whitmeyer et.al, 2010; U.S. Geological Survey, 2008; Edmondo, 2002). Geologic reports prepared for FPAs should include GPS locations of landforms and other relevant features with an accuracy sufficient for others to identify the landforms in the field. Significant landforms or their components should also be photographed if their spatial scales are compatible with ground-based photography. Indicators of potential slope instability or active movement should be noted during the field review. These include topographic, hydrologic, and vegetation indicators as described in Part 6.3.

Outcomes Common results of a geotechnical field review include:

1. The qualified expert determines that potentially unstable landforms identified in the office review do not technically meet the definitions provided in this Board Manual section; the qualified expert reports to the landowner that no potentially unstable landforms are present and the slope stability assessment is complete;
2. The qualified expert determines that potentially unstable landforms within or adjacent to the operations area have minimal potential for material delivery to areas of resource sensitivity and/or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings and the slope stability assessment is complete;
3. The qualified expert determines that unstable landforms within or adjacent to the operations area have the potential for material delivery to areas of natural resource sensitivity or threats to public safety. The qualified expert completes a geotechnical report for the landowner summarizing these findings;

Comment [K65]: The modifier does not add clarity.

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Comment [K66]: This subsection seems to fit more logically in Section 7 below.

6.3 Visual Indicators of Slope Instability or Active Movement

Topographic indicators are manifested by the land surface. Relatively large and recent topographic indicators can be observed on air photos, topographic maps, and LiDAR images, but the identification of smaller and older indicators requires careful field observations. Topographic indicators for all types of potentially unstable landforms may include:

- Bare or raw, exposed, un-vegetated soil on the faces of steep slopes. This condition may mark the location of a debris flow or the headwall or side wall of a slide.
- Hummocky topography at the base of steep slopes. This may mark the accumulation zone (run out area) for a flow or slide.
- In-filled valleys.
- Benched surfaces, especially below crescent-shaped headwalls, indicative of a rotational

slide.

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- Fresh deposits of rock, soil, or other debris at the base of a slope.
- Tension cracks in the surface (across or along slopes, or in roads). Tension cracks may mark the location of an incipient headwall scarp or a minor scarp within the body of an existing slide.
- Multiple scarps in a downslope direction.
- Intact sections (blocks) and grabens, translational blocks and grabens.
- Pressure ridges typically occur in the body or toe of the slide and may be associated with hummocky topography.
- Side scarps or shear margins or lateral scarps.
- Transverse ridges.
- Radial cracks.
 - Displaced surface features like roads, railroads, foundations, and fence lines.
 - Stratigraphic indicators, including disconformities, offset contacts, and overturned sections.
 - Back tilted surfaces from rotation within the slide.

Hydrologic indicators result from local hydrogeologic conditions and the interaction of landslides with hydrologic features. Hydrologic indicators may include:

- Chaotic drainage patterns as a result of landslide activity.
- Deflected or displaced streams (streams that have moved laterally to accommodate landslide deposits).
- Seepage lines or springs and ground water piping. These conditions often mark the contact between high permeability and low permeability soils.
- Ponding of water in irregular depressions in undrained or poorly drained areas on the hill slope above the valley floor. These conditions are often associated with hummocky topography which can be signature of landslide activity.
- Sag pond (ponded water in a tension crack).

Vegetation indicators may include:

- Jack-strawed, back-rotated, or leaning trees and stumps. These are typically indicative of active or recently active landslides.
- Bowed, kinked, or pistol-butted trees. These are typically indicative of soil creep, but may indicate incipient land sliding particularly if other indicators are present.
- Split trees and stumps. These may be associated with tension cracks.
- Water-loving vegetation (horsetail, skunk cabbage, etc.) on slopes. These conditions may indicate the presence of groundwater seeps and associated hydrogeologic conditions.
- Uneven age of trees or changes in stand composition. This condition may indicate recent or historical landslide activity. For example, a grove of alder in a conifer-dominated forest may mark the location of a debris flow.

No single indicator necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

6.4 Office and Field Assessment for Groundwater Recharge Areas Conducted by the Qualified Expert

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The recharge, occurrence, and movement of groundwater through water-bearing units (aquifers) and confining units that inhibit groundwater movement can have an effect on slope stability. Hydrogeologic frameworks, which define the groundwater-recharge environment and the subsurface environment in which groundwater occurs, have been developed from mapped geologic units, drillers lithostratigraphic logs, and hydrologic data at regional scales such as Puget Sound (Vacarro, 1998, et al.) and the Columbia Plateau (Bauer and Hansen, 2000). Groundwater movement is important to understand at smaller local scales associated with the area related to landslides.

Comment [K67]: Again, the identification of the "first approximation" of the GWRA is within the capability of the general practitioner and does not require qualified expert involvement. This section should be bifurcated similar to 6.1.1/6.1.2 and 6.2.1/6.2.2 above.

The groundwater recharge area for glacial deep-seated landslides is a rule-identified landform. The technical methods used to identify groundwater recharge areas in glacial deep-seated landslides are no different than those for other (e.g., non-glacial) deep-seated landslides.

Comment [K68]: This is redundant information – listed in above sections.

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Comment [K69]: This observation is an interesting parenthetical which could be a footnote.

Comment [K70]: and

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6.4.1 Office Review Assessment for Groundwater Recharge Areas

An office review of information for evaluating the area contributing groundwater recharge to a landslide includes reviewing the surrounding topography, land cover and vegetation, soils, and the distribution of hydrogeologic units. Timescales of groundwater movement from areas of recharge to discharge may vary over several orders of magnitude, depending on the hydraulic characteristics of the hydrogeologic units, which include water bearing and non-water-bearing rocks and sediments (aquifers) and confining units, respectively.

In a simplified hydrogeologic setting in a humid environment, the groundwater table forms a subdued replica of surface topography with groundwater flow from high-altitude areas of recharge to low-altitude areas of discharge (Freeze and Cherry, 1979). The surficial contributing area may be delineated from digital elevation models derived from high-resolution LiDAR, if available, or alternately the lower resolution U.S. Geological Survey topographic quadrangles. This analysis provides a first-order approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.

The land cover of the recharge area also influences the spatial extent and magnitude of groundwater recharge. The type and distribution of vegetation affect the amount of precipitation that is intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may also influence groundwater recharge. Remotely-sensed land cover data is available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's National Land Cover Database. In addition, land cover data is available for Washington State through the Washington Department of Natural Resources (DNR) Forest Resource Inventory System.

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Comment [K71]: This is not a delineation issue. This paragraph relates to the evaluation of the possible significance of a proposal which could be considered by a QE – it doesn't seem to fit here.

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Geologic maps provide a basis for delineating the areal extent, orientation, stratigraphic relations, and thickness of rocks and sediments that influence the occurrence and movement of groundwater. The U.S. Geological Survey, DNR, and others have published geologic maps at scales of at least 1:100,000 across Washington and locally at larger scales (1:24,000). Drillers logs of wells and geotechnical borings may supplement geologic mapping by describing the vertical extent of rocks and sediments and providing information about grain size distributions, sorting, and other physical

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properties that may influence the hydraulic characteristics of hydrogeologic units. The Washington

State Department of Ecology (Department of Ecology) maintains a searchable database of well logs for Washington State. Hydrogeologic frameworks have been developed from mapped geologic units, drillers lithostratigraphic logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000) to local scales for sites across Washington State. Hydrogeologic reports are available from sources such as the U.S. Geological Survey and Department of Ecology.

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Comment [K72]: Should this be qualified? Should be a disclosure that this resource is rarely available for most forest lands.

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6.4.2 Field Review Assessment for Groundwater Recharge Areas

A groundwater recharge area of a deep-seated landslide is the area up-gradient of a landslide that can contribute water to the landslide. In simple terms the groundwater recharge area is the topographic area or hillslope area that is at a higher elevation and capable of delivering water into the landslide.

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Comment [K73]: The only recharge area identified in the rule is the recharge area associated with a glacial deep-seated landslide. Other landslides may or may not have a recharge area.

Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types so field inspection of the initial groundwater recharge area map will be necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation.

Typically once a landslide has been mapped, initial designation of the topographic groundwater recharge area is a straightforward task that can be performed by a general practitioner on a detailed topographic map of the area. Topography developed from high resolution digital elevation models (DEMs) generated from LiDAR is preferred. Figure 24 shows the groundwater recharge area for a landslide based on upslope topographical delineation. Line A corresponds to a cross section showing approximate stratigraphy (Figure 24b) through the groundwater recharge area and landslide.

Comment [K74]: More accurate statement.

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After initial designation of the groundwater recharge area, field review should be conducted in order to determine if the initial designation accurately reflects the recharge area topography up-gradient of the landslide. Depending on the available topographic data for the site in question, examination of the boundaries of the mapped groundwater recharge area will be necessary to ensure the hillslope morphology displayed by the DEM is accurate. If possible it would be optimum. In some landscapes particularly those with low topographic relief or poor quality remote-sensing data it may be helpful to have GPS waypoints collected in the field along the topographic boundaries of the groundwater recharge area.

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Comment [K75]: Additional language provides more context.

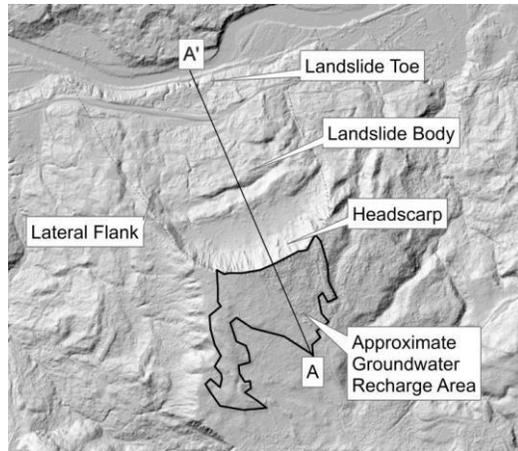


Figure 24a Glacial deep-seated landslide (approximate upslope contributing groundwater recharge area is the black lined polygon) (DNR, 2014).

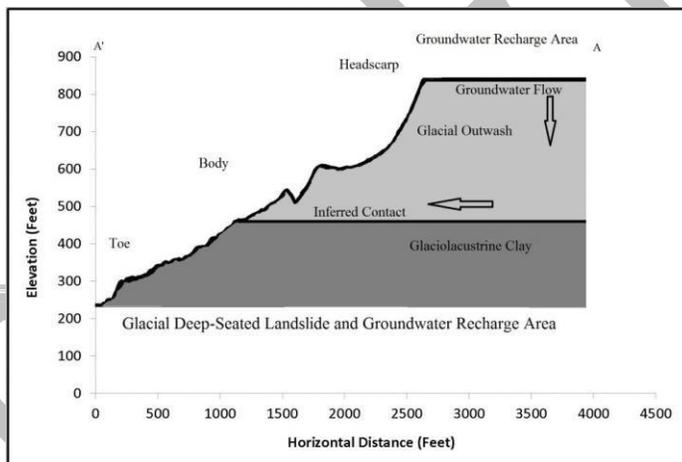


Figure 24b Hillslope cross-section derived from 2-meter DEM of a glacial deep-seated landslide showing groundwater recharge area, geologic units and generalized groundwater flow paths (DNR, 2014)

The groundwater recharge area should be inspected and any surface water drainage features should be mapped that indicate that surface water may be directed into or out of the landslide. Stream drainages on or adjacent to the deep-seated landslide should also be identified, mapped, and assessed for the potential to contribute water to the recharge area and landslide.

Comment [K76]: More accurate statement.

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During field review it is important to examine the characteristics of the surface materials within the groundwater recharge area and document that the soil types and subsurface geologic units are consistent with those mapped for the location of interest.

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Mapping the stratigraphic units that compose the hillslope (i.e., the distribution of geologic units or horizons with depth below the groundwater recharge area) should be done in order to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide

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Exposures of strata within the groundwater recharge area may be examined in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps at the top of the landslide. The distribution of geologic units with increasing depth below the surface may be also be available from well drillers logs or other subsurface information such as geologic mapping and reports.

Comment [K77]: These two paragraphs seem to be part of a process to refine the GWRA beyond the "first order approximation" because they would logically lead to a different delineation than the topographic basin above the slide. They probably belong in their own section, specific to practice by a QE.

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Excavation of test pits, driving soil probes and well-points, drilling monitoring wells or using other geophysical techniques such as seismic or electric resistivity methods should be considered in order to accurately characterize and reduce uncertainties of the subsurface conditions of the groundwater recharge area and when topographic indicators are uncertain. See Part 6.5 for further discussion on quantitative field review methods.

Often landslide failure planes are co-incident with subsurface aquitards such as silt or clay beds that form elevated groundwater tables within hillslopes. Understanding the morphology of these aquitards can help inform the spatial extent of the groundwater recharge area beyond the surface topographic expression of the hillslope up-gradient of a landslide.

Human-caused activities such as construction of road networks and installation of on-site sewage systems can direct surface and groundwater towards or away from deep-seated landslides and/or contribute relatively large volumes of water within a groundwater recharge area. The location of such infrastructure should be mapped and evaluated with respect to possible water volumes likely to be contributed to or removed from a landslide.

Comment [K78]: More accurate statement.

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Comment [K79]: More accurate statement.

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6.5 Quantitative Field Review Methods for Subsurface Investigations

If an unstable or potentially unstable landform with a potential to deliver sediment to public resources or threaten public safety is identified during the office and field review, additional field analysis may be needed to more quantitatively assess the hazard. This is generally accomplished with a subsurface investigation.

Comment [K80]: It is unclear if this subsection is intended to be specific to GWRA of glacial deep-seated landslides or any type of RIL – that should be clarified. While this level of analysis may be appropriate for glacial deep-seated landslides, it is likely not be necessary for other RILs

The subsurface investigation should be designed to gather the data necessary to evaluate the landslide in accordance with the evapotranspiration, recharge, groundwater flow and slope stability modeling when uncertainties related to subsurface conditions exist (see Part 7).

Further, this entire level of analysis is not consistent with the standard of practice for the overwhelming majority of Class IV-S forest practices. We assume that this is intended to apply to those proposals determined to "have a high or extremely high likelihood of delivery" in the agency's SEPA threshold determination, and evaluated in an EIS.

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Selection of exploration methods are based on the study objectives, size of the landslide area, geologic and hydrogeologic conditions, surface conditions and site access, and limitations of budget and time. Subsurface exploration to assess landslides is generally described by McGuffey et al. (1996), as summarized in the following paragraphs:

Test Pits. Shallow test pits can be dug by hand with a shovel. Trackhoes or excavators can be used to advance test pits to depths of nearly 20 feet in certain soils. They are useful for exposing subsurface soil and rock conditions for purposes of mapping or logging the underlying conditions, and to identify groundwater elevations and failure planes.

Hand Auger. A hand auger can be used to identify soil types to depths up to nearly twenty feet (in loose soils) but does not provide significant information regarding soil material properties.

Hand Probe. A simple hand probe can be used to estimate soil density and the depth to dense soil. The Williamson Drive Probe (Williamson, 1994) was developed as an inexpensive and portable alternative for determining soil relative densities and groundwater table elevations. Sections of hardware pipe are coupled and driven into the ground manually with a sliding hammer. The number of blows, in even distance increments, required to drive the probe is used to describe soil conditions. Blow-count data theoretically can be correlated with the Standard Penetration Test (SPT; ASTM, 2014).

Method limitations include manual labor intensity, which can limit the number of holes drilled in a given day. The WDP can also be used to estimate depth to ground water if perforated pipe is used. With these many uses and the low cost, the Williamson Drive Probe is an effective alternative to other tests which require expensive equipment and are less portable.

Drill Rigs. Borings constitute a common method for collecting geotechnical data. Accessibility is a common problem in the forested environment, but this problem can be overcome if logging roads are fortuitously located, or by using track-mounted equipment. In some cases, undisturbed or lightly disturbed soil samples can be collected for quantitative laboratory testing (i.e., direct shear, bulk density, moisture content, etc.). Drill rigs can also be used to install groundwater monitoring wells that contain pressure transducers, and as a conduit for geotechnical instrumentation (i.e., inclinometer, extensometer, etc.)

Geophysical Methods. Surface-based geophysical methods can be an economical method of collecting general subsurface information over large areas of rugged terrain. These include ground penetrating radar, electromagnetic, resistivity, and seismic methods. These techniques can provide information on the location of boundaries between coarse-grained and fine-grained strata and the depth to the water table.

A qualified expert should be present in the field during the completion of a subsurface investigation so that the field activities are properly executed and the desired results can be achieved.

Comment [K81]: Subsurface exploration is a very technical field. A QE may not be available or relevant for this type of work.

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PART 7 DELIVERY LANDSLIDE ACTIVITY ASSESSMENT

An assessment of landslide activity is an important component of evaluating landslide hazard. It is recommended that the landslide activity assessment be conducted by a qualified expert.

7.1 Landslide Activity

Three components of landslide activity should be assessed based in the office and field review process: (1) the state of activity, (2) distribution of activity, and (3) style of activity (Cruden and Varnes, 1996).

The state of activity refers to the timing of landslide movements and ranges from active (currently moving) to relict (clearly developed in the geomorphic past under different conditions than are

currently present). When an active landslide stops moving, it becomes classified as suspended and if

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it remains stationary for more than one annual cycle, it becomes inactive. If the conditions that contributed to prior movement are still present even though the landslide is inactive, the landslide is considered dormant because it may become reactivated at a later time. If the conditions promoting failure have naturally changed to promote stability, the landslide is considered abandoned, while if human intervention has protected against future movement the landslide is considered stabilized. Interpretation of vegetation cover, surface morphology, and toe modification by a stream, if present, all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes (Table 3, Keaton and DeGraff, 1996). Although based on a Rocky Mountain-type climate, the framework described by Keaton and DeGraff has successfully applied in the Pacific Northwest. New vegetation generally begins to colonize a landslide's scarp, lateral flanks, or other areas of disturbed ground once the landslide becomes dormant and progresses to mature vegetation cover according to the local climate. The scarp, flanks, and internal hummocky morphology of the landslide also tend to become increasingly subdued with time after the landslide becomes dormant, and the internal drainage network of the landslides tends to become more connected and organized. If the toe of the landslide enters a stream, that stream progressively modifies the landslide's toe as recorded by terraces and the establishment of floodplain comparable to reaches unaffected by landslide activity.

The distribution of activity refers to the geometry and spatial pattern of landslide movements and how these patterns may change with time. One key distinction is if the landslide is advancing by extending downslope in the main direction of movement, or retrogressing by extending upslope in the direction opposite movement. A landslide can also widen or narrow in the direction perpendicular to movement, and more generally can be enlarging or diminishing if its total volume is increasing or decreasing.

The main style of landslide activity is defined as the type of movement options shown in Table 1. Many landslides involve different styles of landslide activity, and movements should be described as complex if they happen in succession, or as composite if they happen simultaneously at different parts of the landslide. Many landslides are also reactivate repeatedly over time and their movements are noted as "multiple" if the same style of activity affects any previously displaced material, or "successive" if the same style of activity affects previously stable material in the immediate vicinity of the previous landslide.

Table 3. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates (from Keaton and DeGraff, 1996).

Active State	Main Scarp	Lateral Flanks	Internal Morphology	Vegetation	Toes Relationships	Estimated Age (Years)
Active reactivated, or suspended; dormant-historic	Sharp; unvegetated	Sharp; unvegetated streams at edge	Undrained depressions; hummocky topography; angular blocks separated by scarps	Absent or sparse on lateral and internal scarps; trees tilted and/or bent	Main valley Stream pushed by landslide; floodplain covered by debris; lake may be present	< 100 (historic)
Dormant-young	Sharp; partly vegetated	Sharp; partly vegetated; small tributaries to lateral streams	Undrained and drained depressions; hummocky topography; internal cracks-vegetated	Younger or different type or density than adjacent terrain; older tree trunks may be bent	Same as for active class but toe may be modified by modern stream	100 to 5,000 (Late Holocene)

<u>Dormant-mature</u>	<u>Smooth; vegetated</u>	<u>Smooth; vegetated; tributaries extend onto body of slide</u>	<u>Smooth, rolling topography; disturbed internal drainage network</u>	<u>Different type or density than adjacent terrain but same age</u>	<u>Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain</u>	<u>5,000 to 10,000 (Early Holocene)</u>
<u>Dormant-old or relict</u>	<u>Dissected; vegetated</u>	<u>Vague lateral margins; no lateral drainage</u>	<u>Smooth, undulating topography; normal stream pattern</u>	<u>Same age, type, and density as adjacent terrain</u>	<u>Terraces cut into slide debris; uniform modern floodplain</u>	<u>> 10,000 (Late Pleistocene)</u>

Decision flow chart

The following decision pathway was developed by the DNR as a guide to the assessing the risk associated with landslides. Generally, the pathway is defined by the level landslide activity and how likely the landslide is to deliver sediment to public resources. The decision pathway uses a glacial deep-seated landslide and associated ground water recharge area as an example for how a qualified expert would assess the risk associated with the landform. The same decision pathway may be used for other types of deep-seated landslides.

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Comment [K82]: How has this flow chart been vetted? What process was used to adopt this assessment? Does it comport with the SEPA policies in WAC 222-10-030?

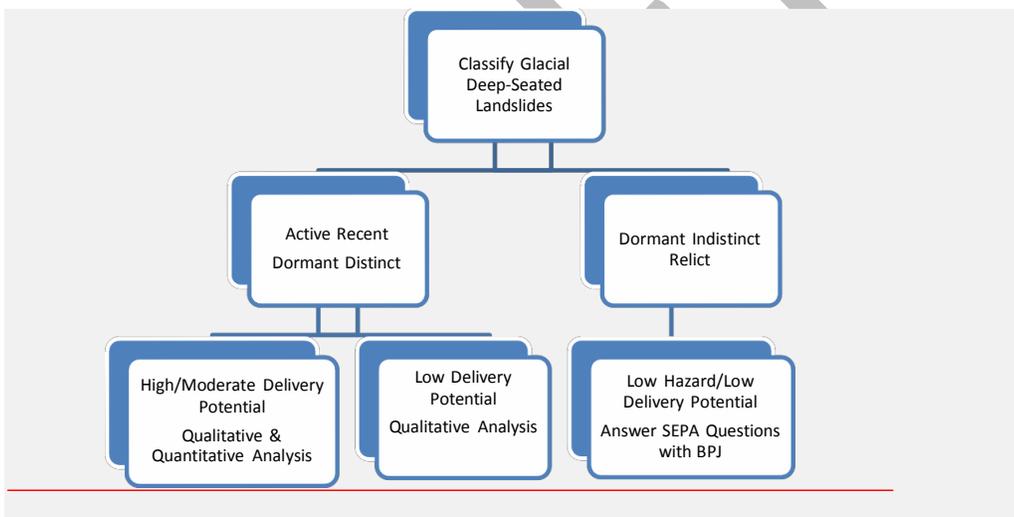


Figure 25 Decision pathway for implementing qualified expert investigations of groundwater Recharge area harvests for glacial deep-seated landslides (DNR Forest Practices Division).

1. Identify and map glacial deep-seated landslides and groundwater recharge areas
2. Classify landslides using the Landslide Hazard Zonation (LHZ) protocol (modified from Keaton and DeGraff, 1996) for deep-seated landslides as:
 - a. active
 - b. dormant/distinct c.
 - c. dormant/indistinct d.
 - d. relict

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3. Map landslides and related up-gradient groundwater recharge areas and calculate areas.

4. Evaluate delivery potential if landslide were to move for:
 - a. public safety (houses, roads etc);
 - b. public resources (water quality and fish habitat)
5. If the landslide is relict or dormant/indistinct, and has low delivery potential, no additional analysis may be necessary. Documentation of this analysis may be provided by letter, memo or other appropriate form. If required, answer the State Environmental Policy Act (SEPA) checklist questions using best professional judgment of the landslide hazard.
6. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge and evidence of landslide movement from aerial photographs, LiDAR and other screening methods. Answer SEPA checklist questions with qualitative information and best professional judgment.
7. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (6), if appropriate, perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. Answer SEPA checklist questions with quantitative information from modeling exercises.
8. Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

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Comment [K83]: Current practice is to provide a geo-letter to document relict or dormant/indistinct features not use of the SEPA check-list. The added language allows flexibility.

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Comment [K84]: Modeling may not be required to deal with the relevant questions at a site.

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Comment [K85]: This highlighted language is a confusing reference to the SEPA checklist. These highlighted areas should reference questions in WAC 222-10-030(2).

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Comment [K86]: This section is outside the scope of the Forest Practices Board motion and needs further evaluation.

7.2 Water budget and Hydrologic Contribution to Slope Stability

A water budget of a groundwater/surface-water system describes the input, movement, storage, and output of water from a hydrologic system. Water enters a hydrologic system through precipitation in the form of rainfall and snowmelt. Some of this water is intercepted by vegetation and evaporates before reaching the ground or sublimates from the snowpack. Water that reaches the ground may run off directly as surface flow or shallow, sub-surface runoff, or evaporate from the soil, or transpire through vegetation foliage. Water that percolates below the root zone and reaches the water table is considered to be groundwater recharge. Groundwater moves from areas of recharge of high hydraulic head to areas of low hydraulic head where it leaves the groundwater-flow system through wells, springs, streams, wetlands, and other points of groundwater discharge. The occurrence and movement of groundwater through the subsurface depends on the hydraulic properties of subsurface material as well as the distribution of groundwater recharge.

7.2.1 Modeling Evapotranspiration

Modeling evapotranspiration is a data intensive exercise that requires regional and/or site-specific information regarding precipitation types and rates, wind speed, relative humidity, temperature, solar energy, and plant community stand characteristics.

The goal of evapotranspiration modeling is to derive estimates of the potential increase in water available to the groundwater recharge area from changes in energy balances, wind speeds and plant community characteristics (i.e., aerodynamic roughness) after forest harvest.

Effects of evapotranspiration on the soil water budget can be partitioned as follows: (1) canopy interception of rainfall or snow and subsequent evaporation loss to the atmosphere; (2) transpiration of infiltrated water to meet the physiological demands of vegetation; (3) evaporation from the soil

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or litter surface. Different vegetation covers have different balances of these fundamental water loss processes. The effects of evaporation on soil water budgets are relatively small compared with canopy evapotranspiration and interception.

Transpiration is the dominant process by which soil moisture in densely vegetated terrain is converted to water vapor. Transpiration involves the adsorption of soil water by plant roots, the translocation of the water through the plant and release of water vapor through stomatal openings in the foliage. Transpiration rates depend on availability of solar energy and soil moisture as well as vegetation characteristics, including vegetation type (e.g., conifer and deciduous), stand density, height and age, rooting depth, leaf area index, leaf conductance, albedo of the foliage, and canopy structure. Rates of transpiration are similar for different vegetation types if water is freely available.

Transpiration is typically quantified using Soil-Vegetation-Atmosphere Transfer (SVAT) models where the movement of water from the soil through the plant to the atmosphere is represented by several resistances in series: (1) the integrated soil-root system; (2) the stem; (3) the branch; and (4) the effective stomatal resistance. Eddy correlation techniques are commonly used to estimate transpiration fluxes.

Interception by vegetation cover controls both the amount and timing of precipitation reaching the soil surface. The interception capacity of vegetation complexes is important because intercepted water has a high surface area to volume ratio that promotes efficient evaporation by convection. Intercepted rainfall is mostly stored on the surface of foliage and stems, while intercepted snowfall bridges between gaps in tree crowns facilitating an accumulation of snow over large surface areas of the canopy. Interception and subsequent evaporation of water from vegetation cover is particularly significant in coniferous forests; losses (both snow and rain) from these dense canopies can account for up to 30% to 50% of gross annual precipitation (Dingman, 1994). Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10% to 30%. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21% to 35%, based on canopy characteristics and climate conditions. Hannel (2011) reported hydrologic modeling (DHSVM; Wigmosta, Njssena and Stork, 2002) that predicts a 27% decrease in evapotranspiration resulting from forest conversion to shrub for a site on the western Olympic Peninsula, Washington.

The proportion of rainfall intercepted by forest canopies is inversely related to both antecedent wetness and rainfall intensity. Gentle, short-duration rainfall may be almost totally intercepted, while interception may account for as little as 5% of precipitation during intense winter storms.

Approaches for estimating changes in evapotranspiration typically involve some combination of the Penman-Monteith model for calculating the canopy resistance, the Bowen ratio energy balance technique to estimate evaporation from plant surfaces, and the Priestly-Taylor formula to estimate evaporation from the soil surface. Reviews and demonstrations of these techniques can be found in Avery and Fritschen, 1971; Fritschen, 1975; Ziemer, 1979, Hanks and Ashcroft, 1980; Campbell, 1986; Simpson, 1999; Martin et al., 1996; and Sias, 2003.

7.2.2 Groundwater Recharge and Groundwater Flow Modeling

Groundwater recharge is difficult to measure directly, but several empirical and numerical methods exist for estimating recharge within the surface-water, unsaturated zone, and saturated zone, including physical, tracer, and numerical-modeling techniques (Scanlon and others, 2002). Recharge is commonly estimated by calculating the residual component of the water budget whereby recharge equals the difference between precipitation and the sum of losses through evapotranspiration, surface runoff, and shallow groundwater flow. The accuracy of recharge estimated through this method is limited by the large uncertainties inherent in the estimating

components of the water budget such as evapotranspiration, which is typically large in magnitude relative to groundwater recharge. Examples of numerical models capable of estimating recharge based on a water budget include the Deep Percolation Model (Vaccaro and Bauer, 1987), Precipitation Runoff Modeling System (Leavesley and others, 1983), and the Variable Infiltration Capacity Model (Liang and others, 1994). Once the spatial distribution of groundwater recharge is estimated, the movement of groundwater within the subsurface may be modeled using groundwater-flow models. The movement of groundwater from areas of recharge may be modeled using groundwater flow models such as MODFLOW (Harbaugh and others, 2000). Groundwater-flow models are based on a hydrogeologic framework that incorporates the hydraulic properties of geologic materials and their stratigraphic relations. Groundwater models are calibrated using hydrologic data including groundwater levels within major water-bearing hydrogeologic units and can be used to characterize the movement of groundwater from areas of recharge to areas of discharge.

7.3 Computational Slope Stability Assessment Methods

Qualitative methods for assessing slope stability are summarized in Parts 6.2 and 6.3. Quantitative assessments of slope stability, performed by the qualified expert, may be necessary to characterize slope failure potential at a given site, as well as to evaluate potential impacts to natural resources and public safety associated with proposed forest practice activities. This quantitative assessment most often entails a two-dimensional, limit-equilibrium analysis method, but other methods may be necessary under certain conditions. Limit-equilibrium analysis calculates a factor of safety for sliding along a critical failure surface, which is expressed as a ratio of the shear strength of the earthen material resisting slope failure to the shear stresses driving instability. Relative stability is defined by a factor of safety exceeding a value of one. Computation of the most critical failure surface is an iterative process generally supported by commercially available or public-domain (e.g., LISA, DLISA, STABL, SLOPE-W) software.

Development of a 2D model for analysis requires the following input information to define an initial state of stability:

- An engineering geologic section through the slope of concern (generally cut through the steepest portion of the slope) showing the thickness and position of each engineering geologic unit; the topographic surface profile can be field-surveyed or derived remotely from digital elevation model (DEM) topographic data whereas the subsurface failure plane geometry might need to be interpolated between known or hypothesized points (i.e., the locations at which the failure plane intersects the ground surface) in the absence of field data acquired from boreholes or with other geotechnical methods;
- Location/elevation of groundwater regimes along this critical section; and
- Saturated and unsaturated unit weights and shear strength of each engineering geologic unit.

The potential effects of the proposed forest practice activities on slope stability can then be evaluated by modifying the initial model with the expected condition based on the proposed activities, such as placement of fill for road construction or elevating groundwater levels (pressures) due to forest canopy removal. Limit-equilibrium models also allow the analyst to reconstruct pre-failure slope conditions of existing landslides by varying the input parameters (e.g., surface topography, engineering geologic unit properties, failure plane geometries, groundwater table elevations) such that the reconstructed original slope fails. These exercises are useful for evaluating

reasonable strength parameters of the units involved likely failure plane geometries or groundwater table elevations in the absence of real data or field indications. Two-dimensional models also can be used to evaluate upslope, as well as downslope, threats to natural resources and public safety in situations where retrogressive failure mechanisms are suspected. Turner and Schuster (1996), as well as many other references, provide more details on the process and methodologies for performing limit-equilibrium stability analyses, including method assumptions and limitations. All of the above steps require considerable engineering geologic/geotechnical data (e.g., subsurface instrumentation, laboratory) and expertise to achieve an accurate and meaningful representation of the actual conditions at the site.

7.4 DELIVERY-Delivery Assessment

Landslides occur naturally in forested basins and are an important process in the delivery of wood and gravel to streams. Wood and gravel play important roles in creating stream diversity that is essential for fish use as habitat and spawning grounds. In the past, landslides as a result of forest practices activities have created a catastrophic regime that has contributed to the threatened and endangered status of certain species, as well as endangering human life in some instances.

The forest practices rules apply where there is *potential* for sediment and debris to be delivered to a public resource or threatens public safety. When the potential for instability is recognized, the likelihood that sediment and debris would travel far enough to threaten a public resource or public safety should be considered/evaluated. Many factors are part of that consideration/evaluation, including:

- Proximity to a public resource or safety concern;
- Nature of the geologic material involved;
- the initial failure volume of a landslide;
- Landslide type of failure mechanism;
- Slope of channel conditions; and
- Observed deformation characteristics of nearby landslides with comparable geologic/geomorphic attributes, the runout distance of a landslide, and landscape geometry.

It is difficult to prescribe guidelines for delivery distances because each situation has a special combination of process and topography. Deep-seated landslides can move anywhere from a few inches to a few miles depending on the friction of the slip plane, the forces pulling the landslides down, and the shear strength resisting those forces. Larger landslides are more likely to be able to move great distances at gentle gradients, but they are also less likely to be significantly affected by forest practices activities.

Because many factors can influence landslide mobility and debris runout, it is not practical to provide generalized prescriptive guidelines to predict delivery for a broad range of conditions. An evaluation of deliverability should, in many cases, require a field review; an inquiry of historic landslide activity and behavior; and the application of experienced judgment in landslide processes and mobility.

Timber harvest and road building can cause shallow landslides on steep slopes. Travel distances for such landslides depend on the amount of water contained in or entrained by them. Considering that rain, snowmelt, or some other extreme-water inputs trigger the vast-majority of landslides in the Pacific Northwest, it should be noted that almost all landslides contain some amount of water that

tends to mobilize the soil or rock. Debris slides that do not reach streams (i.e., do not absorb large volumes of additional water) usually deposit their debris on the hillslope; and are typically unable to move far across large areas of flat ground. However, since most landslides occur during storm conditions, a large proportion of debris slides do reach flowing channels and create the opportunity to entrain enough water to become debris flows. These flows are quite mobile, and can travel great distances in steep or moderate gradient channels.

When channel gradients drop below 12° ~~degrees~~ (20%), debris flows no longer scour and generally begin to slow down. On slopes gentler than about 3-4° (5-7%) debris flows commonly start losing their momentum and the solids entrained in them (rock, soil, organic material) tend to settle out. Travel distance of a debris flow once it reaches a low-gradient surface is a function of its volume and viscosity. The solid volume of a debris slide or flow deposit is a function of soil depth, distance traveled down the hillslope, and the gradient of the traveled path. The proportion of water is the main control on viscosity. Field or empirical evidence should be used for determining the runout distance.

Even if the main mass of a landslide or debris flow comes to rest without reaching a public resource, there is the possibility that secondary effects may occur. Bare ground exposed by mass movement and disturbed piles of landslide debris can be chronic sources of fine sediment to streams until stabilized by revegetation. If flowing water (seepage, overland flow, or small streams) can entrain significant volumes of fine sediment from such surfaces, the possibility of secondary delivery must be evaluated, along with the likelihood of impact by the initial movement event itself.

To assess the potential for delivery and estimate runout distance, analysts can evaluate the history of landslide runout in the region, use field observations, and/or use geometric relationships appropriate from the scientific literature. In any situation where the potential for delivery is questionable, it is best to have a geotechnical expert examine the situation and evaluate the likelihood of delivery. If forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource, a geotechnical report written by a qualified expert is required

7.5 Synthesis, Results and Conclusions

~~All office and field review information gathered for an assessment of unstable slopes and landforms should be synthesized by the qualified expert in a geotechnical report (see Part 10 guidelines), with the following key questions in mind:~~

- ~~1. What are the project objectives (e.g., timber harvest unit evaluation, road construction or abandonment, landslide mitigation)?~~
- ~~2. Which types of unstable slopes and landforms have been identified (see Part 5)?~~
- ~~3. What are their spatial and temporal distributions (see Part 5)?~~
- ~~4. Which office and field methods were used to identify and delineate unstable slopes and landforms (see Part 6)? Have all information sources and methods been cited appropriately in the geotechnical report?~~
- ~~5. Based on an analysis of available information (see Parts 7.1, 7.2, 7.3), what is the geotechnical interpretation of physical processes governing unstable slope/landform movement, mechanics, and chronologies of each identified feature?~~

Comment [K87]: Section 7.5 is very prescriptive and reads like a rule. A QE's professional experience and judgment should control the report's content. Answering the three questions in WAC 222-10-030(2) is the only rule requirement.

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Comment [K88]: This list exceeds the requirements in WAC 222-10-030 as well as previous guidance from the DNR science team. It implies a Watershed Analysis level of analysis for every harvest unit. The language should be substantially modified or preferably deleted.

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6. What are the project limitations (e.g., quantity or quality of technical information, site access, project timeframe) that might influence the accuracy and precision of identifying, delineating, and interpreting unstable slopes and landforms?

7. What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identifying, delineating, and interpreting of unstable slopes and landforms?
8. What is the potential for material delivery from each identified unstable slope and landform to areas of natural resources sensitivity or public safety (see Parts 7.4)?
9. What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
10. What level of confidence is placed in the identification, delineation, and interpretation of unstable slopes and landforms? How does the confidence level impact any recommendations provided by the qualified expert for unstable slope management and/or mitigation?

Documentation of the project analysis and synthesis process might take the form annotated images (e.g., LiDAR-derived hillshades, aerial photos), of geologic or topographic profiles, maps, sketches, results of subsurface investigations, summaries of computational or simulation modeling, summaries of available (i.e., previously published) information and remotely sensed or field-derived data and text to explain the concrete evidence and logical train-of-thought for the conclusions and recommendations that will be presented in the geotechnical report. The only conclusions that should be included in the geotechnical report are those that can be substantiated by the presented evidence, and the logical thought process established in the analysis and synthesis process. For instance, interpreted geologic profiles used to evaluate potential groundwater recharge areas should be commensurate with the subsurface information provided in the report and should relate to the proposed project.

Field observation and sampling locations used in project analysis and synthesis should be displayed on a map in the geotechnical report. Descriptive, photo, or data-sampling observation points should be geo-referenced (i.e., with GPS waypoints). Mapped GPS track locations for field traverses also are recommended, so that it is clear which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced.

Models, such as those for slope stability and sensitivity (see Parts 7.2 and 7.3) may be used to support analyses of unstable slope and landform characteristics and mechanics. Model results, however should not be incorporated in report findings without an adequate assessment and clear statement of their assumptions, limitations, and alignment with existing information (e.g., field data). For example, a modeled reconstruction of landslide failure-plane geometry based on one borehole or drive probe sample likely is misleading and could result in spurious conclusions.

The analytical methods used to identify, delineate, and interpret unstable slopes and land forms should be described in the geotechnical report, along with information sources, data processing techniques, and the meaning and limitations of analysis results. Geotechnical reports should describe all assumptions regarding input parameters or variables, such as groundwater surface elevation estimates employed in stability sensitivity analyses, as well as the reasoning for their use. Geotechnical reports also should include an assessment of the sensitivity of the analytical method or model results to parameter variability, especially where only a range of parameter values is available or where input values are extrapolated or estimated from other locations or databases.

The analytical process being used should be described, along with the types of information needed, how data are processed, and the meaning and limitations of potential results. Assumptions such as groundwater levels should be described, including the reasoning for their use. Variability of

parameters should be described along with strength values or other data developed during the synthesis. The results of the analyses for each assumption or variation should be described.

The report conclusions document the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the assessment, including the office and field reviews, qualitative information and data analyses, geo- and hydro-technical modeling, and evaluation of material deliverability. Conclusions should describe the suitability of the site for the proposed activity. Report conclusions also should clearly state the likely direct and indirect effects of the proposed activity or use on the geologic environment as well as the likely direct and indirect effects of geologic processes on the proposed activity.

The qualified expert should provide a concise statement of confidence in and limitations of the slope stability analysis and its conclusions. Confidence levels are influenced by many factors, including project complexity and objectives, site characteristics (e.g., acreage and accessibility), project timeframes, quantity and quality of available information (e.g., reports, databases) and remotely sensed data, accuracy and precision of field observations and collected data, and the rigor of available analytical methods and models. A discussion of the primary limiting factors assists the landowner and report reviewer in evaluating the potential natural resource, public safety, and liability risks associated with implementing a project.

The geotechnical report might include recommendations regarding additional work needed to supplement the qualified expert report, including but not limited to monitoring of geologic conditions (e.g., ground water, slope movement), review of plans and specifications, and construction and/or timber harvest monitoring. The qualified expert also might be asked by the landowner to provide or evaluate possible mitigation measures for destabilized slopes or landforms.

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Comment [K89]: Clarify that these are not required elements.

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Comment [K90]: Clarify when necessary.

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PART 8. GEOTECHNICAL REPORTS

When harvesting or building roads on potentially unstable slopes a geotechnical report is required to explain how the proposed forest practice is likely to affect slope stability, delivery sediment and debris to public resources, and threaten public safety. The applicant must also submit to DNR a State Environment Policy Act (SEPA) checklist and additional information as described in WAC 222-10-030. These Geotechnical reports must be prepared by qualified experts and must meet the requirements as described in WAC 222-10-030(5)-

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Comment [K91]: The paragraph structure is confusing – the QE doesn't fill out the SEPA checklist.

Effective July 1, 2002, qualified experts must be licensed with Washington's Geologist Licensing Board. For more information on the geologist licensing process, refer to WAC 308-15-010 through 308-15-150, or visit the Geology Board's web site at (www.dol.wa.gov/business/geologist). The education and field experience on forestlands will still be required, in addition to the appropriate geologist license.

8.1 Guidelines for Geotechnical Reports

The following elements (a-f) should be included in geotechnical reports submitted by qualified experts:

Comment [K92]: The new language potentially much creates greater expectations in the report as noted specifically below. Contents of the report should be tailored to address the problem at hand (see the last paragraph in this subsection).

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Comment [K93]: More accurate statement.

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(a) Prepare an introductory section. This section should describe the qualified expert's qualifications of the expert to ensure he/she meets the aforementioned requirements. It should also reference the forest practices application number (if previously submitted), the landowner(s) and operator(s) names, and a brief description of field trip(s) to the area,

including dates, relevant weather

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conditions, and the locations visited. Geographic coordinates (latitude and longitude, GPS waypoints of observation locations should be included so reviewers can find observation locations with certainty.

Comment [K94]: More appropriate statement.

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(b) Describe the geographic, geologic, and the soil conditions of the area in and around the application site. ~~This section is to provide reviewers with general background information related to the application site.~~ Include a legal description of the proposal area, the county in which it is located, and as where appropriate, distance and direction from the nearest municipality, local landmarks, and named water bodies. Provide elevations and aspect. Describe the underlying parent materials, including their origin (i.e., glacial versus bedrock); the name(s) of any rock formations and their associated characteristics; and geologic structure relevant to slope stability. Describe ~~the soils and rocks~~ on site based on existing mapping, field observations, and any available local information. Describe soil and rock texture, depth, and drainage characteristics typically using standard soil and rock classification systems (e.g. Unified, AASHTO) and (Rock Mass Rating, Bieniawski, 1989).

Comment [K95]: More appropriate and accurate statement.

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(c) Describe the potentially unstable landforms of the site. Include a general description of the topographic conditions of the site. It may be appropriate to provide GPS coordinates for locations of observations and other important features such as borings, trenches and outcrops. Specifically identify the potentially unstable landforms located in the area (i.e., those defined in WAC 222-16-050 (1)(d)(i)), in addition to any other relevant landforms on or around the site. Describe in detail the gradient, form (shape), and approximate size of each potentially unstable landform. Include a description of the dominant mass wasting processes associated with each identified landform, as well as detailed observations of past slope movement and indicators of instability. Assign a unique alphabetic and/or numeric identifier label to each landform on a detailed site map of a scale sufficient to illustrate site landforms and features. Where the proposal involves operations on or in the groundwater recharge area of a glacial deep-seated landslide(s) specifically discuss the probable direct and indirect impacts to groundwater levels and those impacts to the stability of the deep-seated landslide(s).

Comment [K96]: More appropriate and accurate statement.

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(d) Analyze the possibility that the proposed forest practice will cause or contribute to movement on the potentially unstable slopes. Explain the proposed forest management activities on and adjacent to the potentially unstable landforms. Clearly illustrate the locations of these activities on the site map, and describe the nature of the activities in the text. Discuss in detail the likelihood that the proposed activities will result in slope movement (separate activities may warrant separate evaluations of movement potential). The scope of analysis should be commensurate with the level of resource and/or public risk. Include a discussion of both direct and indirect effects expected over both the short- and long-term. For proposals involving operations on or in the groundwater recharge area of a glacial deep-seated landslide, conduct an assessment of the effects of past forest practices on slide/slope movement. Explicitly state the basis for conclusions regarding slope movement. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or slope stability model output. Input parameters, model assumptions, and methods should be fully substantiated within the report.

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Comment [K97]: This is a matter of professional practice under licensing regulations; is it necessary to be paraphrased here?

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(e) Assess the likelihood of delivery of sediment and/or debris to any public resources, or to a location and in a way that would threaten public safety, should slope movement occur. Include an evaluation of the potential for sediment and/or debris delivery to public resources or areas where public safety could be threatened. Discuss the likely magnitude of an event, if it occurred.

Comment [K98]: Why was this proposed for deletion?

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Separate landforms may warrant separate evaluations of delivery and magnitude. Explicitly state the basis for conclusions regarding delivery. Conclusions may be based on professional experience, field observations, unpublished local reports, watershed analyses, published research findings, and/or landslide runout model results, which should have site specific data.

Input parameters, model assumptions, and methods should be fully substantiated within the report

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Comment [K99]: See comment above.

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- (f) *Suggest possible mitigation measures to address the identified hazards and risks.* Describe any modifications necessary to mitigate the possibility of slope movement and delivery due to the proposed activities. If no such modifications are necessary, describe the factors inherent to the site or proposed operation that might reduce or eliminate the potential for slope movement or delivery. For example, an intact riparian buffer down slope from a potentially unstable landform may serve to intercept or filter landslide sediment and debris before reaching the stream. Discuss the risks associated with the proposed activities relative to other alternatives, if applicable.

The report should be as detailed as necessary to answer these and any other relevant questions. In particular, examination of aerial photographs (preferably taken over many years) would be appropriate to evaluate the stability characteristics of the area and the effects of roads or previous logging on the subject or similar sites. Field observations will usually be necessary to define the local geology, landforms, etc. Quantitative estimates of site stability produced using SHALSTAB, XSTABL, or other slope-stability models may be useful.

GLOSSARY

- Aquiclude** A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.
- Aquifer** Saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.
- Aquitard** A less permeable bed in a stratigraphic sequence.
- Confined aquifer** An aquifer that is confined between two aquitards. Confined aquifers occur at depth.
- Disconformity** Unconformity between parallel strata,; for example, strata below not dipping at an angle to those above.
- Discontinuity** Sudden or rapid change with depth in one or more of the physical properties of the materials constituting the earth.
- Drift** Any rock material, such as boulders, till, gravel, sand, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice. Generally used of the glacial deposits of the Pleistocene Epoch.
- Drillers log** A record filled out on tabular form by the chief of a drilling crew of an oil, gas, water, or resource protection well drilling rig. The log shows rock character being drilled, drilling progress, drilling tools used, bit size and type, mud additives used, as well as a description of operations and personnel on duty each tour, along with any other pertinent or unusual event occurring during the drilling operations. Drillers logs may also include information on groundwater elevation.
- Earthflow** A slow flow of earth lubricated by water, occurring as either a low-angle terrace flow or a somewhat steeper but slow hillside flow.
- Engineering geology** Performance of geological service or work including but not limited to consultation, investigation, evaluation, planning, geological mapping, and inspection of geological work, and the responsible supervision thereof, the performance of which is related to public welfare or the safeguarding of life, health, property, and the environment, and includes the commonly recognized practices of construction geology, environmental geology, and urban geology.
- Evapotranspiration** A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Commonly designated by the symbols (E_t) in equations.

Factor of safety — The ratio of the resistant force acting on the sliding surface to the driving force acting on the potential slide mass. When the factor of safety is greater than 1, the slope is stable, when the factor of safety is less than 1, the slope is unstable.

Glacial outwash — Drift deposited by meltwater streams beyond active glacier ice.

Graben — A block, generally long compared to its width, that has been downthrown along faults relative to the rocks on either side.

Groundwater — Subsurface water that occurs in soils and geologic formations. Encompasses subsurface formations that are fully saturated and near-surface, unsaturated, soil-moisture regimes that have an important influence on many geologic processes.

Groundwater

Recharge area — That portion of a drainage basin in which the net saturated flow of groundwater Recharge is the process by which water is absorbed and is added to the zone of saturation, either directly into a formation, or indirectly by way of another formation. Also, the quantity of water that is added to the zone of saturation.

Glacial terrace — Relatively flat, horizontal, or gently inclined surfaces, sometimes long and narrow, which are bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side formed by glacial processes.

Glaciolacustrine — Sediments deposits consisting of sorted, predominantly stratified, formations of varying composition, from coarse sands to clays deposited into lakes from glacial meltwater.

Glaciomarine — Sediments which originated in glaciated areas and have been transported to an oceans environment by glacial meltwater.

Glacial till — Non-sorted, non-stratified sediment carried or deposited by a glacier.

Hydrogeology — The science that involves the study of the occurrence, circulation, distribution, chemistry, remediation, or quality of water or its role as a natural agent that causes changes in the earth, and the investigation and collection of data concerning waters in the atmosphere or on the surface or in the interior of the earth, including data regarding the interaction of water with other gases, solids or fluids.

Hydro budget — An accounting of the inflow to, outflow from, and storage in, a hydrologic unit, such as a drainage basin, aquifer, soil zone or water body. For watersheds the major input is precipitation, major output is streamflow.

Piezometer — The basic device for the measurement of hydraulic head. Tube or pipe in which the elevation of a subsurface water level can be determined.

Qualified expert For the purpose of the section, a person who is licensed with Washington's Geologist Licensing Board as either an engineering geologist or as a hydrogeologist, with three years field experience in the evaluation of relevant land features in forested lands.

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Comment [K100]: This definition is referenced in the WAC; does it need to be included here?

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Resistivity method Observation of electric potential and current distribution at the earth's surface intended to detect subsurface variation in resistivity which may be related to geology, groundwater quality, porosity, etc.

Seismic method A method of geophysical prospecting using the generation, reflection, refraction, detection and analysis of elastic waves in the earth.

Soil That earth material which has been so modified and acted upon by physical, chemical and biological agents that it will support rooted plants.

Strata Plural of stratum.

Stratum A section of a formation that consists throughout of approximately the same material; a stratum may consist of an indefinite number of beds, and a bed may consist of numberless layers; the distinction of bed and layer is not always obvious.

Stratification A structure produced by the deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and other essentially tabular units.

Unconfined aquifer Aquifer in which the water table forms the upper boundary. Unconfined aquifers occur near the ground surface.

Vadose zone Also referred to as the unsaturated zone, it is the layer of the earth surface below the land surface and above of the zone of saturation, or water table.

Water table The surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric. The location of this surface is revealed by the level at which water stands in a shallow well open along its length and penetrating the surficial deposits just deeply enough to encounter standing water at the bottom.

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Appendix A Maps and Surveys

Map and survey data resources available to the qualified expert include:

Multi-disciplinary map and survey data resources:

- Washington State Geologic Information Portal – create, save, and print custom digital maps of Washington State or download map data for GIS applications; includes a variety of base layer selections with interactive Geologic Map, Seismic Scenarios Catalog, Natural Hazards, Geothermal Resources, Subsurface Geology Information, and Earth Resource Permit Locations; available on WDNr website;
- Forest Practices Application Review System (FPARS) – interactive online mapping tool with a variety of digital map base layer selections including topography, surface water (streams, water bodies, wetlands), soils, transportation network, forest site class, and potential slope instability (designed for shallow landslide susceptibility mapping only); available on WDNr website;
- County interactive GIS map viewers – create, save, and print custom digital maps with some combination of the following data: topography (LiDAR and/or USGS DEM), surface water, soils, wetlands, sensitive areas, 100-year floodplain designations, transportation net and traffic counts, property ownership and structure location; available online at select county websites (e.g., King County iMAP);
- Washington State Coastal Atlas Map – interactive map utility for shoreline areas with multiple data layers including shoreline geomorphology (coastal slope stability and landforms), biology (plant communities), land and canopy cover, beaches and shoreline modifications, wetlands and estuaries, historic shoreline planforms, assessed waters, and Shoreline Management Act (SMA) designations; see Department of Ecology website.
- Washington Department of Natural Resources, Surface Mining Permits and associated geotechnical reports.

Topographic maps:

- USGS topographic 7.5 minute quadrangle maps (10-m resolution DEM preferred); available from a number of government and non-government online vendors and free downloadable websites;
- LiDAR-based topographic maps (LiDAR-derived DEM (LDEM), typically 1- to 3- m resolution); see Appendix C for LiDAR map and data sources.

Geologic maps:

- Geologic maps, various scales, in-print and compiled by DNR, Division of Geology and Earth Resources as Map Series, Open File Reports, Bulletins, and Information Circulars; see most recent “Publications of the Washington Division of Geology and Earth Resources”; this publication and a status map of 7.5 minute quadrangle geologic mapping efforts (USGS STATEMAP program) are available on the DNR website with links to online publications where available;
- Geologic maps, various scales, in- and out-of-print or historic; all sources including dissertations and theses; see Catalog of the Washington Geology Library, available through the DNR website with links to online publications where available;
- Geology digital data: small-scale geology coverage in ArcGIS shapefile format, available on DNR website;

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- Geologic maps, various scales, available via The National Geologic Map Database (NGMDB; compiled by USGS and Association of American State Geologists; see NGMDB website catalog) and USGS Online Store (paper and digital copies).

Geologic hazards and landslide inventory maps:

- See Washington State Geologic Information Portal referenced previously;
- Landslide Hazard Zonation (LHZ) Project – mapped existing and potential deep-seated landslides and landforms in select watersheds; hazard classifications provided with supporting documentation for completed projects; available through the DNR website;
- Landslide inventory and Mass Wasting Map Unit (MWMU) maps contained in Watershed Analysis Reports prepared under Chapter 222-22 WAC, Washington Forest Practices Board – mapped landslides (including deep-seated and earthflows) for select Watershed Administrative Units (WAU); Adobe pdf versions of DNR-approved Watershed Analysis Reports are available via the DNR website;
- modeled slope stability morphology (SLPSTAB, SHALSTAB, SINMAP) output maps
- landslide-hazard maps from the Regional (Unstable) Landform Identification Project (RLIP)
- US Forest Service watershed analyses – available from US Forest Service offices for select watersheds; some documents and maps are available online
- Washington State tribal watershed analyses – available from tribal agency offices; some documents and maps are available online;
- Washington State Coastal Atlas Map – slope stability maps developed prior to 1980, based on aerial photography, geologic mapping, USGS topographic quadrangle map, and field observations. Maps have not been updated with landslide data since 1980 but are used currently in land-use planning and in the Department of Ecology interactive Coastal Map tool; read data limitations on Department of Ecology's website.
- Qualified Expert reports on deep-seated landslides in glaciated and non-glaciated terrain, for select timber harvest units or other forest management projects regulated by the Washington Forest Practices Act. Often contain mapped landslides; available from DNR region offices.

Soil surveys:

- Natural Resources Conservation Service (NRCS) soil survey maps and data – Online Web Soil Survey map and database service; historical soil survey publications (CD or paper copies); NRCS website administered through the US Department of Agriculture;
- Geochemical and mineralogical soil survey map and data – USGS Mineral Resources Program, open-file report available online (Smith et al., 2013) in Adobe pdf;
- National Cooperative Soil Survey Program (NCSS), Washington State – online soil survey data and link for ordering in-print surveys not available electronically; see NRCS website.

Appendix B Earth Imagery and Photogrammetry

The most common sources of imagery for deep-seated landslide identification, mapping, and photogrammetric analysis include:

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- Aerial photography, preferably stereo-pair photos – Historic aerial photos were produced in color or black-and-white depending on the year flown and were taken at various altitudes (typical scales in the 1:12,000 to 1:60,000 range); aerial photos acquired by the US Soil Conservation Service are available in some areas as early as the 1930’s. Multiple flight years are required for chronologically reconstructing deep-seated landslide activity and developing time-constrained landslide inventories. Forest landowners typically purchased photos from regional vendors on a 2-10 year cycle until recently, when other freely acquired imagery became available (e.g., Google Earth, ESRI World Imagery). Stereo-pair photos are highly valued for landslide detection and reconstruction because they allow stereoscopic projection in three dimensions and can display high-quality feature contrast and sharpness;
- Google Earth – map and geographic information program with Earth surface images created by superimposing satellite imagery (DEM data collected by NASA’s Shuttle Radar Topography Mission (SRTM)), aerial photos, and GIS 3D globe. Ortho-rectified, generally 1-m resolution, 3D images are available for multiple years (Historical Imagery tool), allowing chronologic deep-seated landslide mapping; Google Earth supports desktop and mobile applications, including managing 3D geospatial data. See Google website for download information;
- Bing Maps Aerial View – part of Microsoft web mapping service; overlays topographic base maps with satellite imagery taken every few years. See Microsoft site for download information;
- ESRI World Imagery – ArcGIS online image service utilizing LandSat imagery based on the USGS Global Land Survey (GLS) datasets and other satellite imagery, with onboard visualization, processing, and analysis tools that allow imagery integration directly into all ArcGIS projects. Requires ArcGIS capability; see ESRI website.
- NAIP (National Agriculture Imagery Program) aerial imagery – ortho-rectified, generally 1-m resolution Earth surface images taken annually during peak growing season (“leaf-on”), acquired by digital sensors as a four color-band product that can be viewed as a natural color or color infrared image. The latter are particularly useful for vegetation analysis. Data available to the public via the USDA Geospatial Data Gateway and free APFO viewing software, as well as through ESRI for ArcGIS applications; see USDA Farm Service Agency (FSA) website;
- Washington State Coastal Atlas Map and Photos – oblique shoreline photos spanning years 1976-2007; part of an interactive map tool; see Department of Ecology’s website.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) Archive of downloadable aerial photos.

Appendix C Sources for LiDAR Data

Sources for viewing and downloading airborne LiDAR of Washington State include the following (URLs may change without notice):

- King County iMAP: Interactive mapping tool
(<http://www.kingcounty.gov/operations/GIS/Maps/iMAP.aspx>) – Displays shaded relief maps derived from LiDAR data at locations where it is available. LiDAR data have been filtered to remove vegetation and manmade structures and can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- National Oceanic and Atmospheric Administration Digital Coast
(<http://csc.noaa.gov/digitalcoast/>) – Archive of downloadable LiDAR data focused on coasts, rivers, and lowlands. Options for downloading point cloud, gridded, or contour data that require geographic information system software such as ArcGIS to view and analyze.
- National Science Foundation OpenTopography facility
(<http://www.opentopography.org/index.php>) – Archive of downloadable LiDAR data collected the National Center for Airborne Laser Mapping (NCALM) for research projects funded by the National Science Foundation. Options for downloading point cloud or gridded data for use with geographical information system software, or LiDAR derived hillshade and slope maps that can viewed in Google Earth.
- Oregon Lidar Consortium (<http://www.oregongeology.org/sub/projects/olc/>) – Small amount of Washington State data available along the Columbia River. Lidar Data Viewer displays hillshade maps that have been filtered to remove vegetation and manmade structures.
- Puget Sound Lidar Consortium (<http://pugetsoundlidar.ess.washington.edu/>) – Archive of LiDAR data from Western Washington, downloadable as quarter quad tiles. Data format is ArcInfo interchange files and requires geographic information system software to view.
- Snohomish County Landscape Imaging: SnoScape (<http://gis.snoco.org/maps/snoscape/>) – Displays hillshade maps of bare or built topography derived from LiDAR data where it is available. Can be overlain with a wide range of additional maps relating to county infrastructure, property, hydrographic features, and planning.
- United States Geological Survey EarthExplorer (<http://earthexplorer.usgs.gov/>) – Archive of downloadable LiDAR data acquired by the USGS through contracts, partnerships, and purchases from other agencies or private vendors. File format is LAS and requires GIS software for viewing.

Appendix D Technical Reports and Resources

In addition to library and online sources, the following technical reports, published and unpublished papers and searchable databases are available online and at DNR region offices:

- Catalog of the Washington Geology Library. Searchable database of the Washington Department of Geology Library containing a comprehensive set of dissertations and theses, watershed analyses, environmental impact statements, and refereed/un-refereed publications on state geology; see DNR website with links to online publications where available.
- Landslide Hazard Zonation Project (LHZ).
- US Geological Survey Open File Reports. Searchable online database containing reports covering deep-seated landslide investigations and related topics (Haugerud, 2014); see USGS Online Publications Directory, USGS website.
- Watershed Analysis, Mass Wasting Assessment reports per chapter 222-22 WAC, Washington Forest Practices Board. Adobe pdf versions of DNR-approved reports are available via the DNR website.
- US Forest Service watershed analysis reports. Available from US Forest Service offices for select watersheds; some electronic documents are available online via the USFS website for national forest of interest.
- Interagency watershed analysis reports. Collaborative projects between federal agencies (US Geological Survey, US Forest Service, US Fish and Wildlife Service), tribal agencies, and industry (e.g., Cook and McCalla basins, Salmon River basin, Quinault watershed) . Documents available online via US Geological Survey, Washington Water Science Center.
- Washington Soil Atlas. Available as downloadable Adobe pdf file from the Natural Resources Conservation Service website.

Appendix E Physical Databases

- Landslide Hazard Zonation (LHZ) Project;
- Regional Landslide Inventory Project (RLIP)

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- National Resources Inventory for Washington State – statistical survey of land use, natural resource conditions and trends in soil, water, and related resources on non-federal lands; see NRCS website;

Meteorological databases –

- National Weather Service (NWS) cooperative weather stations – coordinated by National Oceanic and Atmospheric Administration (NOAA) – database managed by Western Regional Climate Center
- NWS Weather Surveillance Radar – Doppler and NEXRAD -
- Remote Automatic Weather Stations (RAWS) – operated by USFS and BLM – database managed by Western Regional Climate Center

Stream-flow gauge databases – USGS National Water Information System website

Seismic data – Pacific Northwest Seismic Network (PNSN) – database managed by USGS, University of Washington, and IRIS Consortium in Seattle; contains records from seismometers located throughout Washington and Oregon; see PNSN website.

Climate Data for Washington

The availability of climate data is highly variable for the State of Washington. The following sites provide access to most of the available data useful for evapotranspiration modeling (The URLs may change without notice):

- United States Geological Survey Washington Water Data - <http://wa.water.usgs.gov/data/>
- National Surface Meteorological Networks – <https://www.col.ucar.edu/projects/hydrometer/northwest/northwest.html>
- National Weather Service - <http://www.wrh.noaa.gov/sew/observations.php>
- National Climate Data Center - <http://www.ncdc.noaa.gov/>
- University of Washington Atmospheric Sciences - <http://www.atmos.washington.edu/data/>
- Washington State University - <http://weather.wsu.edu/awn.php>
- Community Collaborative Rain, Hail, and Snow Database - <http://www.cocorahs.org/>
- Western Regional Climate Summary for Washington - <http://www.wrcc.dri.edu/summary/climsmwa.html>
- Natural Resource Conservation Service - <http://www.nrcs.usda.gov/wps/portal/nrcs/main/wa/snow/>
- Washington Dept. of Ecology Water Resources - <http://www.ecy.wa.gov/programs/wr/wrhome.html>
- Washington Dept. of Transportation - http://www.wsdot.com/traffic/weather/weatherstation_list.aspx

Appendix F Additional Resources

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Forest Hydrology

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**Addendum to
Board Manual Section 16 (WFPB, 11/2004)
Guidelines for Evaluating Potentially Unstable Slopes and Landforms**

Assessing Groundwater Recharge Areas of Glacial Deep-Seated Landslides

The purpose of this document is to provide guidance for assessing groundwater recharge areas (GWRA) of glacial deep-seated landslides (GDSDL). The following decision pathway was developed by the DNR as a guide to assessing the risk associated with groundwater recharge areas of glacial deep-seated landslides. See Addendum Step 1 through Step 7 for guidance in completing each step.

1. Identify and map glacial deep-seated landslides.
2. Delineate and map groundwater recharge areas.
3. Classify glacial deep-seated landslide activity.
4. Assess run-out and material delivery potential:
Evaluate delivery potential if the glacial deep-seated landslide were to move for:
 - a. public safety (houses, roads etc);
 - b. public resources (water quality and fish habitat).
5. Synthesis:
 - a. If the landslide is relict or dormant/indistinct, and has low delivery potential, no additional analysis may be necessary. Answer the State Environmental Policy Act (SEPA) checklist questions using best professional judgment of the landslide hazard.
 - b. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge area and evidence of landslide movement from aerial photographs, LiDAR and other screening methods. Answer SEPA checklist questions with qualitative information and best professional judgment.
 - c. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (b), retain a qualified expert to perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. Answer SEPA checklist questions with quantitative information from modeling exercises.
6. Review by Qualified Expert, if Step 5c is applicable or in other certain situations.
7. Mitigation: Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

The Forest Practices Board Manual “*Addendum for Assessing Groundwater Recharge Areas of Glacial Deep-Seated Landslides*” is not a rule. The objective of the manual addendum is to provide guidance pathways which, if followed, meet the requirements for the implementation of forest practices rules. – *This is a placeholder for summary of guidance intent and target audience.*

The described processes for analysis in combination with professional judgment will allow the field practitioner and the qualified expert to determine the need for additional geologic analysis and

mitigation, or if a detailed geotechnical analysis is required as part of an environmental assessment under the State Environmental Policy Act (SEPA) with a forest practices application (FPA).

STEP 1. Identify and map glacial deep-seated landslides

In order to identify and delineate groundwater recharge areas in glacial terrain it is necessary to first identify and delineate glacial deep-seated landslides. Glacial deep-seated landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however their failure mechanics are similar to deep-seated landslides developed in other materials (Terzhagi, 1951).

Document would benefit from a description of the triggers that would lead the field practitioner (i.e., landowner, landowner representative, engineer, forester) to suspect potential groundwater recharge areas of glacial deep-seated landslides in the harvest unit or project area. For example, the discussion framework could involve key questions that would include:

- A. Is the project area located in glacial terrain?*
- B. Are there mapped glacial landforms and deposits in the project area or other available information (e.g., watershed analysis reports, geotechnical reports for adjacent areas) indicating glacial materials are present?*
- C. Is there evidence of past, present, or potential deep-seated landslides in glacial deposits?*
- D. What physical conditions (e.g., glacial materials, stratigraphy, hydrology, slope movement characteristics) indicate potential glacial deep-seated landslide activity?*
- E. What are the potential contributing factors to slope destabilization?*
- F. Is there a groundwater recharge area associated with an identified glacial deep-seated landslide?*

See following text for guidance on answering questions A through F.

A. Is the project area located in glacial terrain?

Glacial deep-seated landslides occur in glacial terrain and are defined as such where most of the slide plane or zone lies within glacial deposits below the maximum rooting depth of trees, to depths of tens to hundreds of feet beneath the ground surface. Glacial deep-seated landslide deposits occur in continental or alpine glacial deposits, or a combination of both. Continental glacial deposits in Washington are located in the northern areas of the state (Figures 18a and b), whereas alpine glacial deposits can be found in mid-to-high elevation mountain ranges (Booth et al., 2003; Booth et al., 1994; Thorsen, R.M., 1980; Barnosky, 1984; Heusser, 1973; Crandall, 1965).

Geographic distribution of terrain susceptible to glacial deep-seated landslides:

- *Puget Lowlands – North Cascades Foothills:* The Puget Lowlands-North Cascade Foothills is a region that has been extensively modified by continental, and to a lesser extent, alpine glaciations. Unconsolidated sediments associated with glaciation include thick interlayered packages of fine-grained glacial lake sediments (fine sand, silt, and clay), coarse-grained outwash (sand, gravel, cobbles, and boulders), and till. Much of these sediments are very compact, having been overridden by thousands of feet of ice. Groundwater systems are complex and often vertically and laterally discontinuous within these deposits. Perched and confined aquifers are commonly present above and between fine-grained aquitards. Glacial meltwater and subsequent river and marine erosion have left over-steepened slopes on the margins of river valleys and marine shoreline, which are often highly susceptible to a great

variety of landslide types. Falls and topples are common on near-vertical exposures of these sediments. Translational landslides controlled by bedding surfaces and rotational failures that cross-cut bedding are widespread and can be very large. They initiate rapidly or reactivate episodically. Debris flows can recur within steep drainages incised in these deposits.

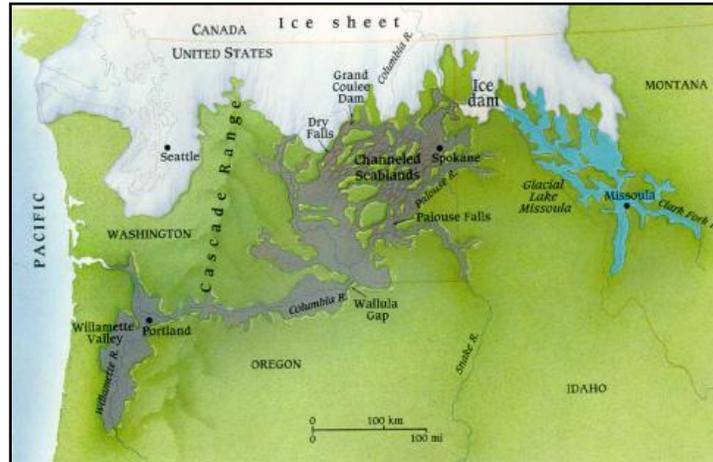


Figure 18a Extent of continental glaciation in the Pacific Northwest (Origin unknown).

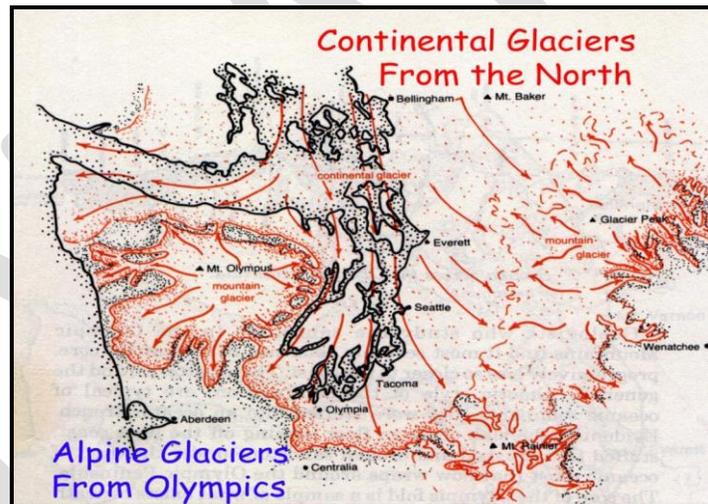


Figure 18b Continental and alpine glaciation in western Washington (Alt, D. D., & Hyndman, D. W., 1984).

- *Olympic Peninsula:* Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower reaches of the Quinault, Queets, Hoh, and Bogachiel valleys.

- *Okanogan Highlands*: Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides.

B. Are there mapped glacial landforms and deposits in the project area or other available information (e.g., watershed analysis reports, geotechnical reports for adjacent areas) indicating glacial materials are present?

- *Brief pointers would be helpful – including list of glacial landforms to look for (e.g., moraines, terraces, outwash plains).*
- *This section could reference appendices in 9/22/14 draft that list maps & other resources.*

C. Is there evidence of past, present, or potential deep-seated landslides in glacial deposits?

- *Brief pointers would be helpful on what to look for.*
- *This section could also reference existing BM Section 16 discussions regarding deep-seated landslides, as well as information resources in appendices in 9/22/14 draft.*

D. What physical conditions (e.g., glacial materials, stratigraphy, hydrology, slope movement characteristics) indicate potential glacial deep-seated landslide activity?

Glacial deep-seated landslides can occur in any type of glacial deposit including till, outwash, glaciolacustrine and glaciomarine silt and clay, and they often involve multiple glacial strata. Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area (Bauer and Mastin, 1997; Vaccaro et al., 1998).

Glacial till generally has low permeability, comprises an unsorted and non-stratified glacial material that can range in size from clay to boulders, and is typically deposited and over run during periods when glacial ice is advancing. Glacial outwash contains typically sorted and stratified sediments deposited by water flowing from glacial ice either during the advance of the glacier or during glacial recession. Glaciolacustrine deposits are typically fine-grained silts and clays deposited in ice-marginal lakes. Glaciomarine deposits are similar to glaciolacustrine deposits except that these materials are deposited directly into marine waters.

Glacial deep-seated landslides can be affected by the hydrologic budget of an area. The hydrologic budget includes precipitation (rain and snow), interception by vegetation, evapotranspiration, surface storage, surface runoff, and groundwater recharge. Groundwater recharge is the component of a hydrologic budget that infiltrates into the subsurface below the root zone. The groundwater component is composed of water within the unsaturated, or vadose, and the saturated zones.

Groundwater perching and the characteristics of the overlying groundwater recharge area can be important factors in a glacial deep-seated failure, especially where glacial sand and other unconsolidated sequences overlie fine-grained glacial-lake clay deposits or till (Figure 20). A classic example of a geologic setting where glacial deep-seated landslides are common is in Puget Sound where the Esperance Sand overlies the Lawton Clay. In this setting, groundwater recharge from precipitation infiltrates downward within the hillslope until it encounters the relatively impermeable Lawton Clay. Because the water cannot infiltrate into the Lawton Clay at the same rate at which it is supplied from above, the water table rises vertically above the clay surface. The elevated water table increases the pressure within the Esperance sand and forms a hydraulic gradient which causes water to flow horizontally along the sand-clay contact, resulting in springs where this contact is exposed at the surface (Tubbs, 1974).

One or more indicators of slope instability or active movement also might be present. Relatively large and recent topographic indicators can be observed on air photos, topographic maps and LiDAR images, but the identification of smaller and older indicators requires careful field observations. In addition to the diagnostic features listed in BM Section 16, part 5.2, other topographic, hydrologic and vegetation indicators of slope instability in glacial terrain may include:

- stratigraphic indicators, including offset contacts, overturned sections, and unconformities or unconformities between glacial sedimentary units showing different permeabilities and groundwater seepage characteristics
- back tilted surfaces from rotation within the slide
- sag ponds (ponded water in a tension crack)
- jack-strawed, back-rotated, or leaning trees and stumps
- split trees and old growth stumps
- other patterns of disturbed vegetation or changes in stand composition (early seral stage or lack of mature trees within a hillslope.
- In-filled valleys.
- Multiple scarps in a downslope direction.
- Intact sections (blocks) and grabens, translational blocks and grabens.
- Pressure ridges typically occur in the body or toe of the slide and may be associated with hummocky topography.
- Side scarps or shear margins or lateral scarps.
- Transverse ridges.
- Radial cracks.
- Displaced surface features like roads, railroads, foundations, and fence lines.

No single indicator necessarily proves that slope movement is happening or imminent, but a combination of several indicators could indicate a potentially unstable site.

E. What are the potential contributing factors to slope destabilization?

Factors contributing to glacial deep-seated landslides can include:

- The presence of an impermeable stratigraphic layer beneath a permeable stratigraphic layer.
- Saturation, by rain on snow events or heavy and/or prolonged rains that can saturate soils and create instability in soil and weakened or weathered bedrock.
- Erosion by rivers, glaciers, or ocean waves that over-steepen slopes or result in removing support from the base of the slopes.
- Ground shaking caused by earthquakes that increase the driving force and weaken the supporting soils structure.
- Excess weight from accumulation of rain or snow, stockpiling of rock or earth from waste piles, or manmade structures that exert excessive stress on slopes.
- Human activities, such as construction, logging, or road building that disturbs soils and weakens or removes the support for slopes, increases runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.

F. Is there a potential groundwater recharge area associated with an identified glacial deep-seated landslide?

Groundwater flows from areas of recharge in upland areas to points of discharge including springs, streams, and other surface water features at lower elevations. The areal extent of recharge that

contributes groundwater to a glacial deep-seated landslide constitutes that landslide's groundwater recharge area and includes the landslide itself.

Groundwater recharge to a glacial deep-seated landslide may originate as recharge to an adjacent non-glacial geologic unit that flows into glacial sediments, or it may run off from upland non-glacial geologic units and recharge within glacial sediments. A component of groundwater recharge can be surface flow.

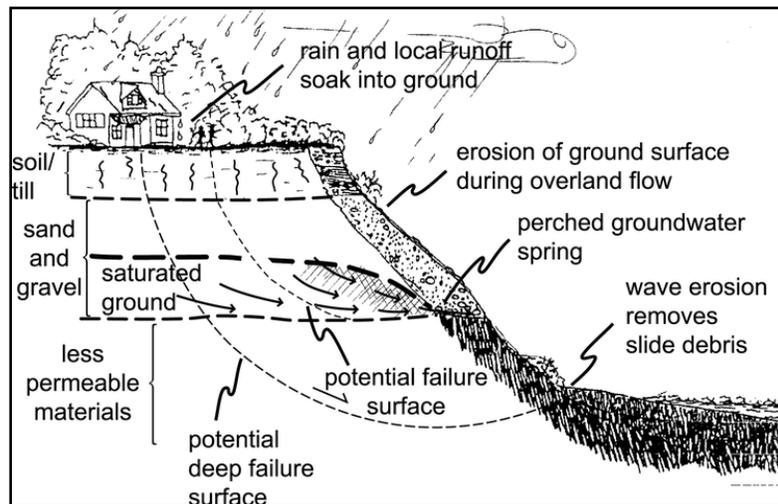


Figure 20. Diagram illustrating failure surface resulting from groundwater recharge to a glacial deep-seated landslide (modified from Gerstel et al., 1997).

STEP 2. Delineate and map groundwater recharge areas

Summary: The first order approximation of the recharge area is the surface drainage basin (topographically defined) directly upslope of and including the active landslide. Typically once a landslide has been mapped, initial designation of the topographic groundwater recharge area is a straightforward task that can be performed on a detailed topographic map of the area. Topography developed from high resolution digital elevation models (DEMs) generated from LiDAR is preferred. The spatial extent of a groundwater recharge area can be also be interpreted from field observations of soil profiles, geologic structure, stratigraphy, well logs or boreholes, or geologic maps, if such information is available. The landowner or designated representative determines if groundwater recharge areas of glacial deep-seated landslides might be present that require field assessment, and whether a qualified expert is desired or needed for more extensive site analyses. If an unstable or potentially unstable landform with a potential to deliver sediment to public resources or threaten public safety is identified during an office and field review, or during project lay-out, additional field analysis may be needed to more quantitatively assess the hazard. The qualified expert typically determines the type and level of field investigation needed to verify preliminary landslide and groundwater-recharge-area interpretations, develop cause-effect relationships, and assess potential for material delivery and potential adverse impacts to natural resources and threats to public safety.

Office Review: An office review of information for evaluating the area contributing groundwater recharge to a landslide includes reviewing the surrounding topography, land cover and vegetation,

soils, and the distribution of hydrogeologic units. Timescales of groundwater movement from areas of recharge to discharge may vary over several orders of magnitude, depending on the hydraulic characteristics of the hydrogeologic units, which include water bearing and non-water-bearing rocks and sediments (aquifers) and confining units, respectively.

- a) *Surface topography*: In a simplified hydrogeologic setting in a humid environment, the groundwater table forms a subdued replica of surface topography with groundwater flow from high-altitude areas of recharge to low-altitude areas of discharge (Freeze and Cherry, 1979). The surficial contributing area may be delineated from digital elevation models derived from high-resolution LiDAR, if available, or alternately the lower resolution U.S. Geological Survey topographic quadrangles. This analysis provides a first-order approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with more complex topography and depositional and deformational environments.
- b) *Land cover*: The land cover of the recharge area also influences the spatial extent and magnitude of groundwater recharge. The type and distribution of vegetation affect the amount of precipitation that is intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may also influence groundwater recharge. Remotely-sensed land cover data is available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's National Land Cover Database. In addition, land cover data is available for Washington State through the Washington Department of Natural Resources (DNR) Forest Resource Inventory System.
- c) *Geology/soils*: Geologic maps provide a basis for delineating the areal extent, orientation, stratigraphic relations, and thickness of rocks and sediments that influence the occurrence and movement of groundwater. The U.S. Geological Survey, DNR, and others have published geologic maps at scales of at least 1:100,000 across Washington and locally at larger scales (1:24,000).
- d) *Subsurface data*: Previously collected data might help the general practitioner or qualified expert further refine groundwater recharge areas estimated using land surface data. Drillers logs of wells and geotechnical borings may supplement geologic mapping by describing the vertical extent of rocks and sediments and providing information about grain size distributions, sorting, and other physical properties that may influence the hydraulic characteristics of hydrogeologic units. The Washington State Department of Ecology (Department of Ecology) maintains a searchable database of well logs for Washington State. Hydrogeologic frameworks have been developed from mapped geologic units, drillers lithostratigraphic logs, and hydrologic data at regional scales such as Puget Sound (Vacarro et al., 1998) and the Columbia Plateau (Bauer and Hansen, 2000) to local scales for sites across Washington State. Hydrogeologic reports are available from sources such as the U.S. Geological Survey and Department of Ecology.

Field verification: Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types so field inspection of the initial groundwater recharge area map will be necessary to confirm that surface topography is a reasonable approximation of the groundwater recharge area delineation. Field verification might include any or all of these steps, depending on the nature of the project, landslide activity in the project site (see Step 3), and potential for material delivery to natural resources or threats to public safety (see Step 4).

- a) *Surface topography*: After initial designation of the groundwater recharge area, field verification should be conducted in order to determine if the initial designation accurately reflects the recharge area topography up-gradient of the landslide. Depending on the available topographic data for the site in question, examination of the boundaries of the mapped groundwater recharge area will be necessary to ensure the hillslope morphology displayed by the DEM is accurate. If possible it would be optimum to have GPS waypoints collected along the topographic boundaries of the groundwater recharge area.
- b) *Surface water drainage*: The groundwater recharge area should be inspected and any surface water drainage features should be identified that indicate that surface water may be directed into the landslide. Stream drainages on or adjacent to the deep-seated landslide should also be assessed for the potential to contribute water to the recharge area and landslide.
- c) *Geology/soils*: Examine the characteristics of the surface materials within the groundwater recharge area and verify that the soil types and subsurface geologic units are consistent with those mapped for the location of interest. Exposures of strata within the groundwater recharge area may be examined in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps at the top of the landslide.
- d) *Ground alterations in groundwater recharge area*: Human-caused activities such as construction of road networks and installation of on-site sewage systems can direct surface and groundwater towards deep-seated landslides and/or contribute relatively large volumes of water within a groundwater recharge area. The location of such *infrastructure* should be mapped and evaluated with respect to possible water volumes likely to be contributed to a landslide.

STEP 3. Classify glacial deep-seated landslide activity

An assessment of landslide activity is an important component of evaluating glacial deep-seated landslide activity. Although not required, it is recommended that the landslide activity assessment be conducted by a qualified expert.

Three components of glacial deep-seated landslide activity should be assessed based in the office and field review process: (1) the state of activity, (2) distribution of activity, and (3) style of activity (Cruden and Varnes, 1996). Guidelines for estimating landslide activity levels are shown in Table 3, (Keaton and DeGraff, 1996). Although based on a Rocky Mountain- type climate, this framework has successfully applied in the Pacific Northwest.

Table 3. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates (from Keaton and DeGraff, 1996).

Active State	Main Scarp	Lateral Flanks	Internal Morphology	Vegetation	Toes Relationships	Estimated Age (Years)
Active reactivated, or suspended; dormant-historic	Sharp; unvegetated	Sharp; unvegetated streams at edge	Undrained depressions; hummocky topography; angular blocks separated by scarps	Absent or sparse on lateral and internal scarps; trees tilted and/or bent	Main valley pushed by landslide; floodplain covered by debris; lake may be present	< 100 (historic)

**Appendix B: WFPA Suggested Approach for an Unstable Slopes Board Manual 16 Addendum
Developed From DNR's Board Manual 16 Rewrite dated 9-22-2014
Rough Draft: 10-8-2014**

Dormant-young	Sharp; partly vegetated	Sharp; partly vegetated; small tributaries to lateral streams	Undrained and drained depressions; hummocky topography; internal cracks vegetated	Younger or different type or density than adjacent terrain; older tree trunks may be bent	Same as for active class but toe may be modified by modern stream	100 to 5,000 (Late Holocene)
Dormant-mature	Smooth; vegetated	Smooth; vegetated; tributaries extend onto body of slide	Smooth, rolling topography; disturbed internal drainage network	Different type or density than adjacent terrain but same age	Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain	5,000 to 10,000 (Early Holocene)
Dormant-old or relict	Dissected; vegetated	Vague lateral margins; no lateral drainage	Smooth, undulating topography; normal stream pattern	Same age, type, and density as adjacent terrain	Terraces cut into slide debris; uniform modern floodplain	> 10,000 (Late Pleistocene)

The state of activity refers to the timing of landslide movements and ranges from active (currently moving) to relict (clearly developed in the geomorphic past under different conditions than are currently present). When an active landslide stops moving, it becomes classified as suspended and if it remains stationary for more than one annual cycle, it becomes inactive. If the conditions that contributed to prior movement are still present even though the landslide is inactive, the landslide is considered dormant because it may become reactivated at a later time. If the conditions promoting failure have naturally changed to promote stability, the landslide is considered abandoned, while if human intervention has protected against future movement the landslide is considered stabilized.

Interpretation of vegetation cover, surface morphology, and toe modification by a stream, if present, all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes. New vegetation generally begins to colonize a landslide's scarp, lateral flanks, or other areas of disturbed ground once the landslide becomes dormant and progresses to mature vegetation cover according to the local climate. The scarp, flanks, and internal hummocky morphology of the landslide also tend to become increasingly subdued with time after the landslide becomes dormant, and the internal drainage network of the landslides tends to become more connected and organized. If the toe of the landslide enters a stream, that stream progressively modifies the landslide's toe as recorded by terraces and the establishment of floodplain comparable to reaches unaffected by landslide activity.

The distribution of activity refers to the geometry and spatial pattern of landslide movements and how these patterns may change with time. One key distinction is if the landslide is advancing by extending downslope in the main direction of movement, or retrogressing by extending upslope in the direction opposite movement. A landslide can also widen or narrow in the direction perpendicular to movement, and more generally can be enlarging or diminishing if its total volume is increasing or decreasing.

Many landslides involve different styles of landslide activity, and movements should be described as complex if they happen in succession, or as composite if they happen simultaneously at different parts of the landslide. Many landslides are also reactivate repeatedly over time and their movements are noted as “multiple” if the same style of activity affects any previously displaced material, or “successive” if the same style of activity affects previously stable material in the immediate vicinity of the previous landslide.

STEP 4. Assess run-out and material delivery potential

Note that this step was not addressed by the Phase 1 Board Manual Rewrite Team. The expectation was/is that a Phase 2 Board Manual Rewrite Team will complete this section.

In any situation where the potential for delivery is questionable, it is best to have a geotechnical expert examine the situation and evaluate the likelihood of delivery. If forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource, a geotechnical report written by a qualified expert is required. (BM Section 16, 2004, p.M16-23; see STEP 5, Option C, and STEP 6).

STEP 5. Synthesis

Based on the outcome of Steps 4 and 5, there are three options for completing the assessment of groundwater recharge areas associated with glacial deep-seated landslides. According to the DNR decision pathway, they are:

- a. If the landslide is relict or dormant/indistinct (Step 4), and has low delivery potential (Step 5), no additional analysis may be necessary. Answer the State Environmental Policy Act (SEPA) checklist questions using best professional judgment of the landslide hazard.
- b. If the landslide is active/recent or dormant/distinct (Step 4) with a low delivery potential (Step 5), perform a qualitative assessment of historic patterns of timber harvesting within groundwater recharge area and evidence of landslide movement from aerial photographs, LiDAR and other screening methods. Answer SEPA checklist questions with qualitative information and best professional judgment.
- c. If the landslide is active/recent or dormant/distinct (Step 4) and has moderate or high delivery potential (Step 5), in addition to a qualitative assessment of historic pattern of timber harvesting and landslide movement described in (b), retain a qualified expert to perform a quantitative assessment of potential increase in groundwater recharge from timber harvest and effect on stability of the landslide. Answer SEPA checklist questions with quantitative information from modeling exercises.

STEP 6. Review by Qualified Expert

A qualified expert is engaged if:

- Step 5, Option C is applicable;
- the potential for delivery is questionable (BM Section 16, 2004, p. M16-23);

- forest practices are to be conducted on an unstable landform with questionable or obvious potential to impact a public resource (BM Section 16, 2004, p. M16-23) or threaten public safety; or,
- the landowner wishes to have the assessment of groundwater recharge areas completed by a qualified expert.

The qualified expert typically conducts a geotechnical office and field review with a final report. The objectives of the geotechnical field review are to: (1) verify and document the presence of glacial deep-seated landslide features and associated groundwater recharge areas identified in a geotechnical office review, as well as features that were missed due to insufficient remote-sensing data coverage or resolution; (2) refine preliminary maps constructed during the office review; (3) confirm or refute initial hypotheses regarding landslide behavior, failure mechanisms, and level of activity; (4) solidify understanding of cause-effect relationships; (5) apply more quantitative methods for assessing landslide movement, slope hydrology and changes in groundwater recharge, and landslide runout and material delivery to areas with public resources and/or public safety; (6) evaluate levels of confidence in office and field findings; and, (6) write a geotechnical report summarizing review findings, conclusions, and recommendations. The qualified expert determines the nature of the field review required to meet the project objectives subject to DNR's review. See Addendum xxx for further discussion on quantitative field review methods. For example, quantitative methods that might be applied include:

- mapping the stratigraphic units that compose the hillslope to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide.
- subsurface investigations including excavation of test pits, driving soil probes and well-points, drilling monitoring wells or using other geophysical techniques such as seismic or electric resistivity methods to reduce uncertainties of the subsurface conditions of the groundwater recharge area.
- surface and groundwater flow modeling. Groundwater recharge is difficult to measure directly, but several empirical and numerical methods exist for estimating recharge within the surface-water, unsaturated zone, and saturated zone (Scanlon and others, 2002).
- quantitative slope stability assessment methods, to characterize slope failure potential at a given site, as well as to evaluate potential impacts to natural resources and public safety associated with proposed forest practice activities. A quantitative assessment most often entails a two-dimensional, limit-equilibrium analysis method (e.g., factor of safety model).

STEP 7. Mitigation

Note that this step was not addressed by the Phase 1 Board Manual Rewrite Team. The expectation was/is that a Phase 2 Board Manual Rewrite Team will complete this section.