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.

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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.\(^1\)

Under past forest practices rules, forest practices-caused landslides contributed to the acceleration of naturally occurring landslide processes\(^2\) and may have contributed to the threatened and endangered status of certain species\(^3\) as well as endangered human life in some instances\(^4\). 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 as a “Class IV-special” FPA 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 that 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).

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1 e.g., Reeves et al., 1995; Geertsema and Pajar, 2007; Restrepo et al., 2009.
2 e.g., Swanson et al., 1977; Robinson et al., 1999; Montgomery et al., 2000; Turner et al., 2010.
3 e.g., Sidle et al., 1985; Beechie et al., 2001.
4 e.g., Oregon Landslides and Public Safety Project Team, 2001.
Translational failures can also occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes\(^5\) 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>
<thead>
<tr>
<th>Type of Movement</th>
<th>Type of Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bedrock</td>
</tr>
<tr>
<td></td>
<td>Predominately Coarse</td>
</tr>
<tr>
<td>Falls</td>
<td>Rock Fall</td>
</tr>
<tr>
<td>Topples</td>
<td>Rock Topple</td>
</tr>
<tr>
<td>Slides</td>
<td>Rotational Rock Slide</td>
</tr>
<tr>
<td></td>
<td>Translational</td>
</tr>
<tr>
<td>Lateral Spreads</td>
<td>Rock Spread</td>
</tr>
<tr>
<td>Flows</td>
<td>Rock Flow</td>
</tr>
<tr>
<td>Complex</td>
<td>Combination of two or more principal types of movement</td>
</tr>
</tbody>
</table>

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\(^5\) Robinson et al., 1999; Turner et al., 2010.
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.
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. 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

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Pierson and Scott, 1985.
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.\(^7\)

**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.\(^8\) 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.\(^9\) 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 and hyper-concentrated floods](image)

**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).

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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. 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 (5.2 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

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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 reoccur 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.11 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.12 Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches.13 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 volcaniclastic 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

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12 Gerstel and Badger, 2002.
slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control large translational failures in the Chumstick and Roslyn Formations\textsuperscript{14}, the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone\textsuperscript{15}. 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.\textsuperscript{16}

**PART 3. MEASUREMENT OF SLOPE ANGLES**

The forest practices rules contain specific slopes gradients (degrees and percent) for potentially unstable slope or landform descriptions. Part 3 provides 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).

\textsuperscript{14} Tabor et al., 1987.
\textsuperscript{15} Wegmann, 2003.
\textsuperscript{16} Harp et al., 1997.
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 $\alpha$. 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.

PART 4. SLOPE FORM
Slope form 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 on 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. Typically, convergent areas with slope gradients equal to or greater than 35 degrees (70%) are at a higher risk of sliding.17

17 Benda et al., 1997.
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 %) (see 5.1);
- Toes of deep-seated landslides with slopes steeper than 33 degrees (>65 %) (see 5.2);
- Groundwater recharge areas for glacial deep-seated landslides (see 5.3);
- 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.

Bedrock hollows
Convergent headwall
Inner gorge

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

Bedrock hollows
Convergent headwalls
Inner gorges

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.¹⁸ 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.

¹⁸ Crozier et al., 1990; Dietrich et al., 1986.
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).

![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.
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).

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). 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).](image)

**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).](image)

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19 Montgomery et al., 2000.
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. 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).](image)

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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 Toes of Deep-Seated Landslides
Toes of deep-seated landslides with slopes greater than 33 degrees (65%) are a rule-identified forest practices regulatory landform. In this context, “toes of deep-seated landslides” means the down slope toe edges, not the entire toe area of displacement material (Figure 23 shows the toe in relation to other landslide features).

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 18 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. 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 18. 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).

5.3 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. 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 19a), whereas the alpine glacial deposits (Figure 19b) can be found in mid-to-high elevation mountain ranges.

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21 Terzhagi, 1951.
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 (the rate water moves through a geologic material) and storage capacity (the amount of water released or taken into storage per unit area of geologic material for a given change in hydraulic head). Glacial till is comprised of unsorted and non-stratified glacial materials (ranging in size from clay to boulders) that was generally overrun 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, during either the advance or the 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. Glaciomarine deposits are similar to glaciolacustrine deposits except the materials are deposited directly into marine waters. Glaciomarine and glaciolacustrine deposits typically have low permeability and low storage capacity, similar to glacial tile. See Appendix F for hydraulic properties of various soils.

Deep-seated landslides can be affected by the hydrologic budget of an area (Figure 20). The hydrologic budget is the amount of groundwater 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.
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.

5.3.1 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.23 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 21). This is a common configuration of the glacial deposits in much of the northern half of western Washington, for example landslides in Seattle24 and landslides in the Stillaguamish River valley25, 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.

23 Bauer and Mastin, 1997; Vaccaro et al., 1998.
24 Gerstel et al., 1997.
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.

![Diagram illustrating failure surface resulting from groundwater recharge to a glacial deep-seated landslide (DNR, 2014).](image)

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.26

5.3.2 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

26 Tubbs, 1974.
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.

5.4 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 (see Figure 22). 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 Areas Containing Features 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.
• 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.28

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.29 Initiation of such landslides has also been associated with changes in land use30, increases in groundwater levels31, 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.32

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 Washington33; thinly layered rocks, such as phyllite in northwest Washington34; and deeply weathered volcanic rocks present in the Willapa Hills of southwest Washington35. 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.36 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.37

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31 van Asch et al., 2005.
32 Roering et al., 2005.
33 Gerstel and Badger, 2002.
34 Kovanen and Slaymaker, 2008.
35 Turner et al., 2010.
37 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. These can be seen in Figures 18 and 23. 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.

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. 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.

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38 Cronin, 1992.
39 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.\textsuperscript{40} 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).

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 (Light Detection and Ranging) data, 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.

\textsuperscript{40} 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.
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). “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, 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 conducted by general practitioners achieve:

1. identification of potential and existing areas of slope instability within or around 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 (e.g., 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 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. The qualified expert’s objective is to develop a preliminary geotechnical assessment of landform characteristics and landslide potential prior to initiating field work, in order to verify initial interpretations in subsequent field investigations. The qualified expert’s geotechnical office review is generally more in-depth than a general practitioner’s 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
appropriate combination of assembled information based on the project objectives, requirements, and desired level of confidence in assessment products.

**Outcome.** The office review typically leads to a field review, especially where unstable areas 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. 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. 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. 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. 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; (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux; (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows; and (4) subsurface investigations. 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 derived from hillshade and slope maps when unstable areas exist around the proposal.

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41 e.g., Haugerud et al., 2003; Burns and Madin, 2009; Roering et al., 2013; Tarolli, 2014.
42 Tarolli, 2014.
43 Roering et al., 2009; Handwerger et al., 2013; Scheingross et al., 2013.
44 Mackey and Roering, 2011.
45 e.g., Ardizzone et al., 2007; Booth et al., 2009; Burns and Madin, 2009; Tarolli et al., 2012; Van Den Eeckhaut et al., 2012.
46 Travelletti and Malet, 2012.
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. 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. 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.

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 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), (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

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48 For a review of filtering techniques, see Liu, 2008.
49 Van Den Eeckhaut et al., 2007.
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.50 Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005, 2007), and Haugerud (2014).

50 McKean and Roering, 2004; Glenn et al., 2006; Booth et al., 2009; Berti et al., 2013.
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. 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. 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 identified 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 and landforms, using definitions of the landform types and guidance provided in this Board Manual section. In addition to assessing the potentially unstable areas identified in the initial office screening, the general practitioner surveys the operations area for any landforms missed in the office review. This assessment is typically accomplished 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 reports.

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51 Corsini et al., 2007; Delong et al., 2012; Daehne and Corsini, 2013.
52 Burns et al., 2010.
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 the operations area, and proposes to conduct timber harvest or construction activities on them. The landowner may retain a qualified expert to conduct geotechnical office and field reviews, and prepare a geotechnical report as required by WAC 222-10-030 or other format, depending on DNR’s particular request for information. The landowner submits the FPA and includes the geotechnical information. (See Washington State Department of Department of Natural Resources website for a list of qualified experts.)

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 visual observations and photos of geological features and other site indicators at identified locations (e.g., GPS waypoints) are summarized in a geotechnical report to substantiate landform and process interpretations. A more quantitative investigation might include such data collection techniques as topographic surveying for measuring landslide surfaces (i.e., that 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. 16-40
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.53 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 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 harvest or construction activity is proposed on or around a glacial deep-seated landslide, the area adjacent to the landslide needs to be assessed by a qualified expert to determine if a groundwater 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, driller's logs, and hydrologic data at regional scales such as Puget Sound54 and the Columbia Plateau55. However, it is also important to understand groundwater movement at smaller local scales.

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54 Vacarro et al., 1998.
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 a 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 help the qualified expert determine next steps if further investigation is needed.

6.3.1 Qualified Expert’s Office Review for Groundwater Recharge Areas

When a qualified expert performs an office review 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. 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 maintains a searchable database of well logs for Washington State, however

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56 Freeze and Cherry, 1979.
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, driller’s logs, and hydrologic data at regional scales such as Puget Sound and the Columbia Plateau, 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 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 25(a) shows the approximate groundwater recharge area for a landslide based on upslope topographical delineation. The cross section shown in Figure 25(b) illustrates the approximate stratigraphy 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 that the hillslope morphology displayed by the DEM is accurate. For the purpose of groundwater recharge delineation, collecting GPS waypoints along the topographic boundaries of the groundwater recharge area is helpful for mapping and for revisiting the site if necessary.

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57 Vacarro et al., 1998.
After the qualified expert has identified the groundwater recharge area, further inspection should identify drainage patterns and surface water influencing the landslide area. 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 a field assessment it is important to examine the characteristics of the surface materials within the groundwater recharge area and document whether 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 driller’s logs or other subsurface information such as geologic mapping and reports.

Excavation of test pits, driving soil probes, 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 any uncertainties about subsurface groundwater conditions 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)\(^{59}\) 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.). A drill rig 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 that a 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.

\(^{59}\) Williamson, 1994.
7.1 Landslide Activity

The three components of landslide activity for evaluation during the office and field review process are the state of activity, the distribution of activity, and the style of activity.\(^{60}\)

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.\(^{61}\) Although based on a Rocky Mountain-type climate, the framework described by Keaton and DeGraff (1996) 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 style of landslide activity will be one of the movement types 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.

\(^{60}\) Cruden and Varnes, 1996.

\(^{61}\) Keaton and DeGraff, 1996, Table 2.
Table 2. Guidelines for estimating landslide activity level based on vegetation and morphology in Rocky Mountain-type climates
(from Keaton and DeGraff, 1996)

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

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.
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.
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.
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.
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 sublimes 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 landforms.

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; and (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 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.

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62 Jassal et al., 2009.
63 Bosch and Hewlett, 1982.
64 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.\(^{65}\)

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\(^{66}\); snow or rain losses from these dense canopies can account for up to 30 to 50 percent of gross annual precipitation.\(^{67}\) Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10 to 30 percent. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21 to 35 percent, based on canopy characteristics and climate conditions. Hanell (2011) reported hydrologic modeling\(^{68}\) 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.\(^{69}\)

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 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.\(^{70}\) Recharge is commonly estimated by calculating the residual component of the water budget where 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

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\(^{65}\) Hanks and Ashcroft, 1980.
\(^{66}\) Link et al., 2004.
\(^{67}\) Dingman, 1994.
\(^{68}\) DHSVM; Wigmosta, Njssena and Stork, 2002.
\(^{69}\) Ramirez and Senarath, 2000.
\(^{70}\) Scanlon et al., 2002.
Model\textsuperscript{71}, Precipitation Runoff Modeling System\textsuperscript{72}, and the Variable Infiltration Capacity Model\textsuperscript{73}. 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.\textsuperscript{74} 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**

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 of forest practices activities to natural resources and public safety. This quantitative assessment 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.\textsuperscript{75}

Development of a two dimensional model for analysis requires inputting the following 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

\textsuperscript{71} Bauer and Vaccaro, 1987.
\textsuperscript{72} Leavesley et al., 1983.
\textsuperscript{73} Liang et al., 1994.
\textsuperscript{74} Harbaugh et al., 2000.
\textsuperscript{75} e.g., LISA, DLISA, STABL, SLOPE-W.
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 landsides 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 move great distances at gentle gradients, but are 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. In many cases, an evaluation of deliverability will 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 debris on the hillslope, and typically do not 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 distances over a low-gradient surface is a function of the debris flow’s 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 to determine the runout distance of the debris flow.

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 identifications, delineation, and interpretation 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 where public safety could be threatened (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 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 that 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 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 results are included in reports, they should be accompanied by a statement of model assumptions, limitations, and alignment with existing information (e.g., field data). For example, it would not be appropriate to include a modeled reconstruction of landslide failure-plane geometry based on data from one borehole or drive probe sample. The modeled results 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 is available, or where input values are extrapolated or estimated from other locations or databases.

The report conclusions should include documentation of the outcomes of the slope stability investigation based on the synthesis of all geologic and hydrologic information and interpretations used in the office review and field assessment, qualitative information and data analyses, geo- and hydro- technical modeling, and evaluation of material deliverability. Report conclusions might also include a description of the suitability of the proposed activity for the site, and likely direct and indirect effects of the activity on the geologic environment and processes. Conclusions should be substantiated by the evidence presented and the expert’s logical thought processes during analysis and synthesis.

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 will assist the landowner and report reviewer when 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 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 WACs 308-15-010 through 308-15-150, or visit the Geologist Licensing 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 with GPS coordinates if possible.

(b) Describe the geographic, geologic, and 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.76

(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

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76 e.g., Unified Soil Classification System (USCS), American Association of State Highway and Transportation Officials (AASHTO) and Rock Mass Rating (Bieniawski, 1989).
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 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.

Driller’s 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. Driller’s 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 one (1), the slope is stable; when the factor of safety is less than one (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

An area or drainage basin in which water reaches the zone of saturation following infiltration and percolation. Beneath it, downward components of hydraulic head exist and groundwater moves downward into deeper parts of the aquifer. “Groundwater recharge areas for glacial deep-seated landslides” is defined in WAC 222-16-010.

Glacial terrace

A relatively flat, horizontal, or gently inclined surface formed by glacial processes, sometimes long and narrow, bounded by a steeper ascending slope on one side and a steeper descending slope on the opposite side.

Glaciolacustrine

Pertains to, derived from, or deposited in glacial lakes. Glaciolacustrine deposits and landforms are composed of suspended material brought by meltwater streams flowing into lakes.

Glaciomarine

Pertains 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; 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 groundwater moves in the direction of lower hydraulic head (i.e., toward lower energy), and hydraulic head is a measure of water pressure, groundwater 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 and the major output is stream flow.

Lahar

A mudflow composed chiefly of volcaniclastic 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, either transported or 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 layer. 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  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.
REFERENCES


16-64


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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 website.
- Forest Practices Application Review System (FPARS) – 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 systems, 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 of 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 Division of Geology and Earth Resources website with links to online publications where available.
- Geologic maps, various scales, 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 the Division of Geology and Earth Resources 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:
- 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 on 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, three dimensional (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;


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](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/](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](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/](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/](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 GIS software to view.

- **Snohomish County Landscape Imaging: SnoScape** ([http://gis.snoco.org/maps/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/](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 and 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 at http://www.dnr.wa.gov/ResearchScience/Topics/WatershedAnalysis/Pages/fp_watershed_analysis.aspx (the URL may change without notice)

• 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.

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


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):

- 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

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 for indicating the general range of values for these properties. It should be considered representative, but is not a substitute for site-specific laboratory and field information.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Permeability (feet per minute)</th>
<th>Storage Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial (High Energy)</td>
<td>0.01-10</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td>Alluvial (Low Energy)</td>
<td>0.0001-0.1</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>Eolian (Loess)</td>
<td>0.001-0.01</td>
<td>0.05-0.1</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>0-0.001</td>
<td>0.0-1</td>
</tr>
<tr>
<td>Glacial Outwash</td>
<td>0.01-10</td>
<td>0.01-0.3</td>
</tr>
<tr>
<td>Glaciolacustrine</td>
<td>0-0.1</td>
<td>0.0-1</td>
</tr>
<tr>
<td>Lacustrine (Inorganic)</td>
<td>0.0001-0.1</td>
<td>0.05-0.3</td>
</tr>
<tr>
<td>Lacustrine (Organic)</td>
<td>0.0001-1.0</td>
<td>0.05-0.8</td>
</tr>
<tr>
<td>Marine (High Energy)</td>
<td>0.001-1.0</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td>Marine (Low Energy)</td>
<td>0.0001-0.1</td>
<td>0.05-0.3</td>
</tr>
<tr>
<td>Volcanic (Tephra)</td>
<td>0.0001-0.1</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>Volcanic (Lahar)</td>
<td>0.001-0.1</td>
<td>0.05-0.2</td>
</tr>
</tbody>
</table>

Permeability differences reflect variations in gradation between geologic materials. Very high permeability is associated with high-energy alluvial deposits or glacial outwash where coarse, openwork 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 low 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**


Hydrogeology


**Landslide Inventories and Mapping**


**Landslide Processes**


**Remote Sensing / LiDAR**
