Section 16
Guidelines for Evaluating
Potentially Unstable Slopes and Landforms

PART 1. INTRODUCTION

Board Manual Section 16 contains guidelines to evaluate potentially unstable slopes and landforms on forest lands. Like all Board Manual sections, it serves as an advisory technical supplement to the forest practices rules. The section:

- Provides general practitioners with tools to better understand potential landslide hazards and risks in the areas of proposed forest practices activities;
- Identifies when a qualified expert is needed;
- Assists qualified experts with tools and methods to conduct geotechnical investigations; and
- Provides guidance to prepare geotechnical reports.

The intended audience is:

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

The current rules related to potentially unstable slopes and landforms were developed to avoid an increase over natural background rates from forest practices on high-risk sites at a landscape scale. The rules apply when it is determined that proposed forest practices activities may contribute to the *potential* for sediment and debris delivery to a public resource or cause a threat to public safety. When the potential for slope instability is recognized, the likelihood of landslide movement and damage must be considered. The factors in determining this likelihood could include initial failure volume, the nature of the landslide, slope or channel conditions, and potential runout distance.

Certain landforms are particularly susceptible to slope instability or indicate past slope instability. Forest practices applications (FPAs) proposing activities on or near these landforms may be classified Class IV-special and receive additional environmental review under the State Environmental Policy Act (SEPA). These landforms, commonly referred to as “rule identified landforms”, are listed in WAC 222-16-050(1)(d) and described in Part 4.

Board Manual Section 16 is composed of seven parts:

- Parts 2, 3, and 4 contain general background information for all readers on how to recognize the various landslide types in Washington State (Part 2), how slope form affects slope stability (Part 3), and how to recognize potentially unstable slopes and landforms (Part 4).
- Parts 5, 6, and 7 contain procedures and resources for conducting reviews and assessments of potentially unstable areas in relation to proposed forest practices. General practitioners will find 5.1.1 and 5.2.1 most useful for their office reviews and field assessments. The information in 6.5 will be useful to both general practitioners and qualified experts for landslide runout assessments. The remainder of Parts 5 and 6, and all of Part 7 provides guidance to qualified experts for conducting expert-level office reviews and field assessments and for preparing geotechnical reports.

The manual includes a glossary of terms that may not be familiar to many readers, references cited throughout the document, and appendices containing lists of informational resources.

PART 2. LANDSLIDE TYPES IN WASHINGTON

Landslides occur naturally in forested basins and are an important geomorphic 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]

Landslide is a general term for any downslope movement of rock, unconsolidated sediment, soil, and/or organic matter under the influence of gravity. The term also refer to landslide deposits and slide materials in mountainous terrain that typically are separated from more stable underlying material by a zone of weakness, commonly referred to as the failure zone, plane, or surface.

[1] e.g., Reeves et al. 1995; Geertsema and Pojar 2007; Restrepo et al. 2009.

Landslides can be classified in several ways. The classification shown in 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 translational and rotational geometries (see Figure 1). Translational failures can also occur on non-planar surfaces (i.e., concave or convex) in shallow soils overlying bedrock on steep slopes[2] 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 while they are at rest. A landslide can also permanently cease moving and undergo erosion and revegetation over long periods of geologic time; this is a relict landslide.

Landslides occur when gravitational forces overcome the strength of the soil and rock on a slope. Factors contributing to slope instability may include:

- The presence of an impermeable stratigraphic layer underlying a permeable layer.
- Soil saturation by snowmelt, rain-on-snow events, or heavy and/or prolonged rains that can create instability in soil and weakened bedrock.
- Erosion by rivers, glaciers, or wave action that causes the over-steepening of slopes and removal of support from the base of the slopes.
- Ground shaking caused by earthquakes that increases the driving force and weakens the supporting soil structure.
- Adding excess weight to slopes from activities such as stockpiling of rock or earth, depositing road sidecast, and constructing landings.
- Timber harvest and road construction activities that weaken or remove the support for slopes, or increase runoff and groundwater recharge over a seasonal timescale or during prolonged heavy precipitation events.
- Diverting streams from one basin to another or concentrating water in unstable locations during road construction.

2.1 Landslide Types and Effects

Geologists and other professionals use several classification schemes to identify and describe landslides. The classification scheme of Varnes (1978), as modified by the U.S. Geological Survey (2004) and Hungr et al. (2001), is used for the purposes of this Board Manual section (see Table 1). This scheme is based on the type of movement and type of materials involved in the slope failure, with further classification possible based on the rate of movement. Hungr et al. (2001) proposed modifications to definitions of flow-type landslides, many of which are commonly associated with forest practices in Washington. For example, a debris flow is defined as a rapid flow of non-plastic debris within a steep stream channel, distinguished from a debris avalanche, which occurs on an open slope.

[2] Robison et al. 1999; Turner et al. 2010.

Table 1. Landslide Classification

Based on Varnes (1978) as modified by U.S. Geological Survey (2004) and Hungr (2001).

Type of Movement		Type of Material		
			Soils	
		Bedrock	Predominately Coarse	Predominately Fine[3]
Falls		Rock Fall	Debris Fall	Earth Fall
Topples		Rock Topple	Debris Topple	Earth Topple
Slides	Rotational	Rock Slide	Debris Slide	Earth Slide
	Translational			
Lateral Spreads		Rock Spread	Debris Spread	Earth Spread
Flows-Confined		Rock Flow	Debris Flow	Earth Flow
Flows-Unconfined		Rock Avalanche	Debris Avalanche	Debris Flood
Complex		Combination of two or more principal types of movement		

Landslides are described by terms referring to the type of material and method of movement (rock fall, debris flow, and so forth). Materials in a landslide mass are either rock or soil (or both) and may 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 movement describe the internal mechanics of how the landslide mass is displaced: fall, topple, slide, spread, or flow. The types of landslides commonly found in forested areas in Washington are slides and flows.

Landslides may also occur as a complex failure encompassing more than one type of movement. A common example is a debris slide that evolves into a debris flow. Less common, but potentially of great import, are deep-seated landslides that periodically fail as a debris flow or debris avalanche. 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. Figure 1 shows simplified illustrations of the major types of landslides.

[3] The terms used in the "Predominately Fine" column are seldom used in the forest environment where coarse materials including wood are common.

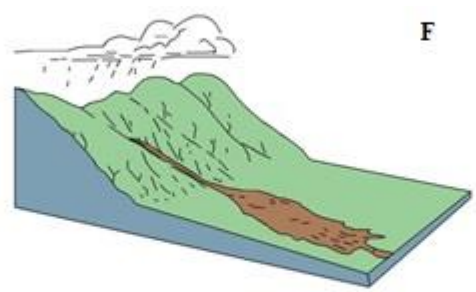
Falls: Falls occur when a mass of rock or soil detaches from a steep slope or cliff, and are often caused by the undercutting of the slope. The failure is typically rapid to very rapid. The fallen mass may continue down the slope until the terrain flattens.

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.

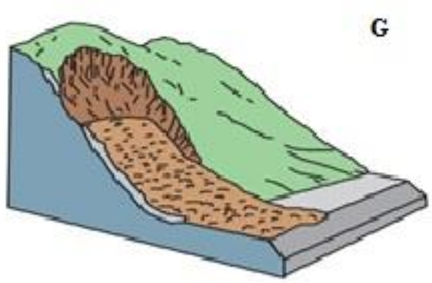
Rotational slides: Landslides where the surface of rupture is concave-up and the slide movement is rotational about an axis that is parallel to the contour of the slope

Translational slides: Landslides where the surface of the rupture is roughly planar with a surface roughly parallel to the ground surface. These are called rock slides, block glides, slab slides, or debris slides.

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.



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



Debris avalanches: Rapid to extremely rapid shallow flows of partially or fully saturated debris on steep unconfined slopes.

Earth flows: Landslides consisting of fine-grained soil or clay-bearing weathered bedrock. They can occur on gentle to moderate slopes. Overall, there is little or no rotation of the slide mass.

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

2.2 Shallow Landslide Types

Shallow landslides are unstable features that 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. Reduced root strength in slide prone areas resulting from timber harvest, fire and other natural processes can contribute to slope failure. Additionally, the amount of water and the materials contained within shallow landslides can affect the manner and 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 by sliding or rolling forward. The results are irregular hummocky deposits that are typically poorly sorted and non-stratified. If debris slides entrain enough water, they can become debris flows.

Debris flows are channelized slurries composed of sediment, water, vegetation, and other debris. Solids typically constitute more than 60% of the volume.[4] Debris flows usually occur in steep channels when debris becomes charged with water (from soil water or upon entering a stream channel) and liquefies as it breaks up. Channelized debris flows often entrain material and can significantly bulk up in volume during transport. These landslides can travel thousands of feet or miles from the point of initiation, scouring the channel to bedrock in steeper channels. Debris flows commonly slow where the channel makes a sharp bend and stop where the channel slope gradient becomes gentler than about 3 degrees (6%), or the valley bottom becomes wider and allows the flow to spread out. Hyper-concentrated floods may travel greater distances and on lower gradient slopes than debris flows based on their water content.[5]

Figure 2. Debris flow (DNR 2000).

Debris avalanches. Hungr et al. (2001) defined a debris avalanche as a very rapid to extremely rapid shallow flow of partially or fully saturated debris on steep slopes without confinement in an established channel. Sharpe (1938) described a debris avalanche as morphologically similar to a snow avalanche. Debris avalanches may enter steep drainage channels and become debris flows.

[4] Pierson and Scott 1985.
[5] Iverson and Reid 1992.

Therefore, the term debris avalanche is reserved for events that remain poorly channeled without a defined recurrent path or laterally bounded deposition landform.

Dam break floods are a subset of flow-type landslides defined as very rapid surging flows of water heavily charged with debris in a steep channel.[6] They contain a mixture of water and sediment (dominantly sand-sized) and organic debris with solids that range between 20% and 60% by volume.[7] In forested mountains, they are commonly caused by the collapse of dams, such as those formed by landslide dams (Figure 3) 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.[8] Such 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, or the active floodplain.

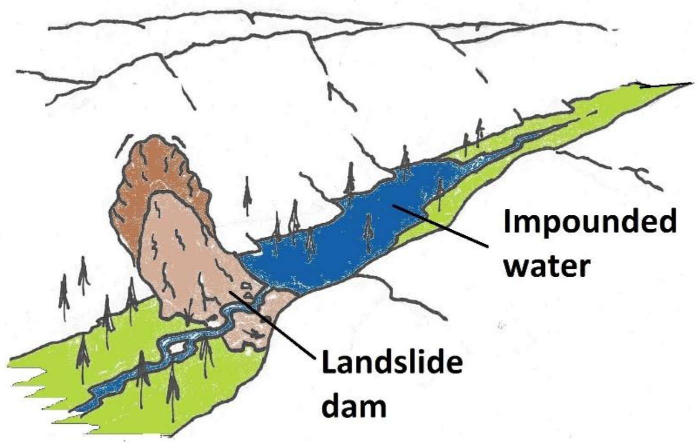


Figure 3. Impounded water caused by landslide dam.

Debris flows and dam break floods can occur in any potentially unstable terrain with susceptible valley geometry. In natural systems, debris flows and dam break floods are responsible for moving sediment and woody debris from hillslopes and small channels down into larger streams. They can also scour channel reaches, disturb riparian areas, deposit debris onto salmonid spawning areas, elevate turbidity, adversely affect water quality downstream, and threaten public safety.

[6] Hungr et al. 2001.
[7] Pierson and Scott 1985.
[8] Johnson 1991.

Figure 4. Left: Road-initiated debris flows in unstable landforms, Sygitowicz Creek, Whatcom County (Photo: DNR 1983). Right: Same hillslope 28 years later (2011 aerial photo).

The photo on the left in Figure 4 shows debris flows that coalesced and, after exiting the confined channel at the base of the slope, spread into 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 slope and the river, the debris flow affected a county road, residential sites, and more than 60 acres of cultivated farm fields. The photo on the right shows the same hillslope after harvest with trees left in the bedrock hollows and inner gorges.

2.3 Deep-Seated Landslides

Deep-seated landslides are those in which the slide plane or zone of movement is typically below the maximum rooting depth of forest trees (generally greater than 10 feet). They may extend to hundreds of feet in depth and may involve underlying bedrock. They can be a wide range of sizes up to several miles across. Deep-seated slides may respond to rainfall events over periods of days to weeks, or weather patterns over months to years or even decades.[9]

Deep-seated landslides can occur almost anywhere on a hillslope. Many occur in the lower portions of hillslopes and extend directly into stream channels, whereas those confined to upper slopes may lack connectivity to deposit material directly into channels. They occur in weak materials such as thinly layered rocks, unconsolidated sediments, deeply weathered bedrock, or rocks with closely spaced fractures. They can also occur where a weak layer is present in otherwise strong rocks. Deep-seated landslides in glacial deposits are usually associated with hydrologic responses in the permeable glacial materials overlying less permeable materials.

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 (Figure 5). A deep-seated landslide may have one or more of these component parts because small deep-seated landslides can be found within larger slides. The head and side scarps together form an arcuate or

[9] Washington State Department of Emergency Management 2013.

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 irregular patterns 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 sideslopes) and toe edges.

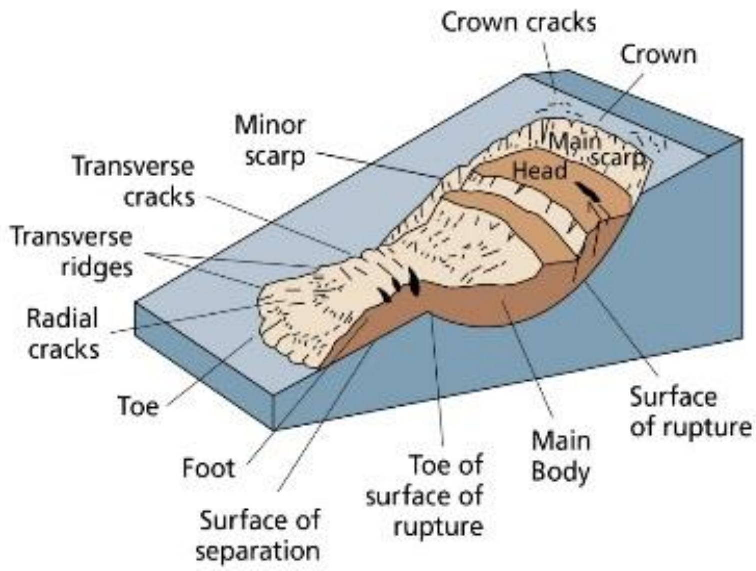


Figure 5. Rotational deep-seated landslide. Rotational displacement of blocks of soil commonly occur at the head of the landslide (adapted from USGS 2004).

Movement of deep-seated landslides can be complex, ranging from slow to rapid, and may include numerous small to large horizontal and vertical displacements triggered by one or more failure mechanisms.[10] Deep-seated landslides are often part of large landslide complexes, parts of which can be intermittently active for hundreds of years or more.[11] The bodies and toes of deep-seated landslides and earth flows consist of incoherent collapsed materials weakened from previous movement. Because the original mass experienced movement, the disrupted portions of a landslide may be subject to secondary deep landsliding or debris flow initiation. As a result, sediment delivery can occur from shallow landslides on steep stream-adjacent toes of deep-seated landslides, and from steep side slopes along marginal stream channels within the bodies of deep-seated landslides.

Purely rotational slumps (Figure 5) in cohesive soils are rare in nature because the shape of the rupture surface usually departs from constant curvature.[12] Instead, as the host slump moves, internal deformation during transport may cause segmentation of the failure surfaces, resulting in the evolution of secondary landslides in hummocky terrain, which are more prone to saturation and movement.[13] Landslides may fail sequentially, exhibiting multiple instabilities containing smaller secondary landslides within a host landslide during a single event, from secondary movements over time, or a combination of both. The term compound is used by Cronin (1992) to describe large host landslides that encompass smaller secondary slides.

[10] Roering et al. 2005.
[11] Bovis 1985; Keefer and Johnson 1983.
[12] Hungr 2014.
[13] Cronin 1992.

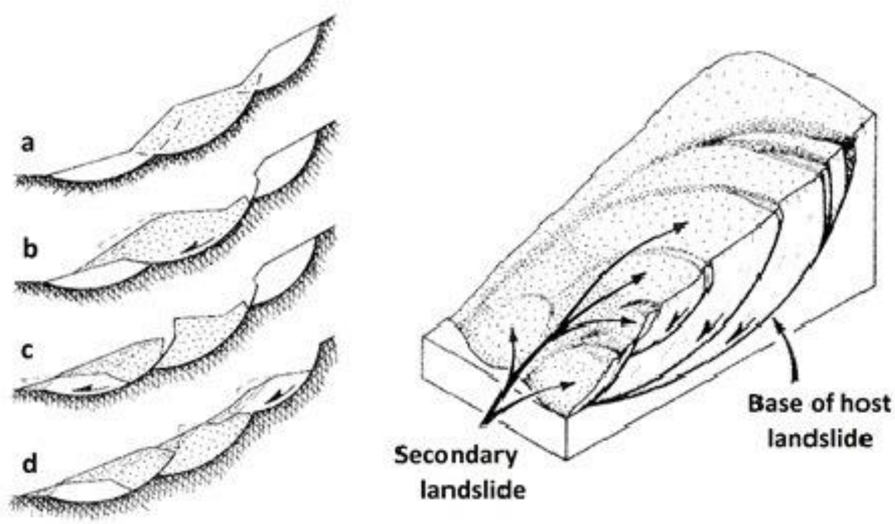


Figure 6. Left: Schematic of sequential instability within a rotational slide. The original slope configuration a) initially at rest until sliding movement begins, at which time the b) middle (stippled) slump mass loads the lower slide, removing support from the upper scarp. As the lower landslide mass becomes active, c) it may rotate outward, causing the d) unsupported upper slide mass to fail. Right: Block diagram of a compound landslide, showing a variety of secondary landslides within the host landslide (adapted from Cronin, 1992).

Some compound deep-seated landslides found in glaciated and non-glaciated terrain have the potential to become highly mobile failures. The SR 530 landslide in the Stillaguamish River valley is an active rotational glacial deep-seated failure that hosted both a debris flow/avalanche and a rotational slide[14] and raised awareness regarding the potential range of activity within large failures particularly in areas underlain by glacial sediments. Unlike shallow (translational) landslides and debris flows that may occur repeatedly and are better understood, secondary failures within compound landslides are less common and present an unrecognized hazard potential.

Triggering mechanisms of deep-seated landslides can result from over-steepening of the toe by natural means such as glacial erosion or fluvial undercutting (channel incision), earthquakes, or human activities such as excavating for land development.[15] Movement in landslides is usually triggered by accumulations of water at the slide zone; therefore, land-use changes that alter the amount or timing of water delivered to a landslide can initiate or accelerate movement.[16] Initiation or re-initiation of such landslides has also been associated with increases in groundwater levels[17] from individual storms or in response to seasonal accumulation from rainfall or snowmelt, depending on soil and bedrock properties, and the degradation of material strength through natural processes. When subsurface water is presumed to influence the movement of a deep-seated landslide, the process used to identify how groundwater affects the slide zone should be appropriate for the geologic materials within the landslide.

[14] Keaton et al. 2014.
[15] Schuster and Wieczoreck 2002.
[16] Cronin 1992.
[17] van Asch et al. 2005.

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. However, deep-seated landslide movement can be diverse and influenced by geomorphic and hydrologic factors, and is not always associated with up gradient groundwater sources.[18] Generally, avoiding the following practices will minimize human-caused re-initiation or acceleration of deep-seated landslide movement: removing material during road construction or quarrying at the toe; overloading slopes by placing spoils on the upper or mid-scarp areas; changing subsurface hydrology by excessive soil compaction; and directing additional water into the slide from road drainage or captured streams.

Recent advances in high-resolution LiDAR (Light Detection and Ranging) have demonstrated it to be a highly effective tool for identifying the footprint of dormant and active deep-seated landslides. Larger landslides can usually be identified from LiDAR imagery, topographic maps, and aerial photos, whereas smaller landslides are more difficult to identify and often require a field inspection. For information on how LiDAR is used for identifying potentially unstable landforms see Parts 5.1.4 and 6.5.6.

PART 3. 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 identifying potentially unstable landforms. There are three major slope forms observed when looking across the slope (contour direction): divergent (ridgetop); planar (straight); and convergent (spoon-shaped) (Figure 7a). 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, ridges are convex areas (bulging outward) and tend to be more stable than planar (straight) mid-slopes and concave areas (sloping inward) (Figure 7b).

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.

[18] van Asch et al. 2009.

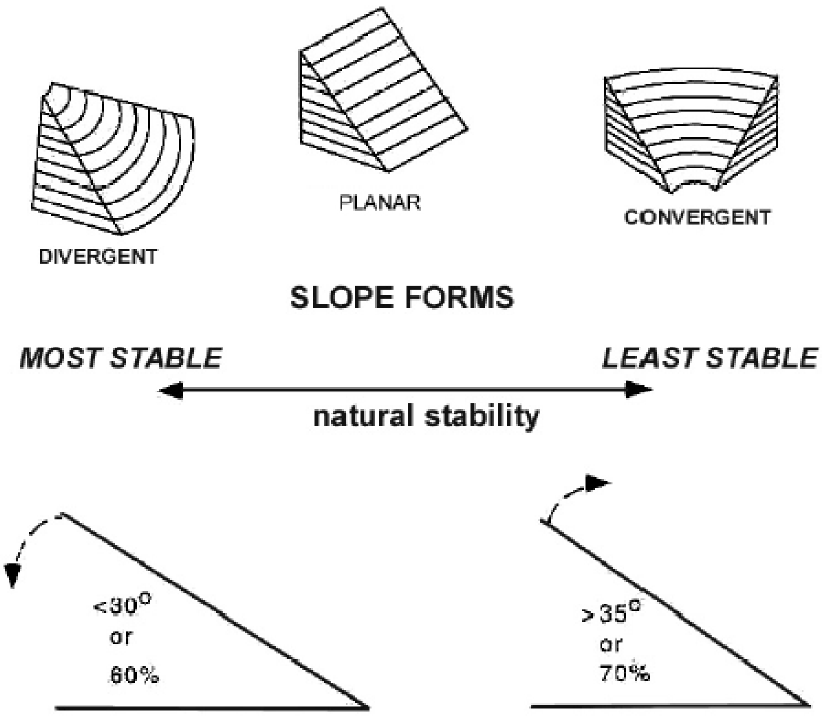


Figure 7a. Slope configurations as observed in map view.

Figure 7a shows three major slope forms (divergent, planar, and convergent) and their relative stability. These terms refer to the contour directions across a slope. Typically, convergent areas with slope gradients equal to or greater than 35 degrees (70%) are at a higher risk of sliding.[19]

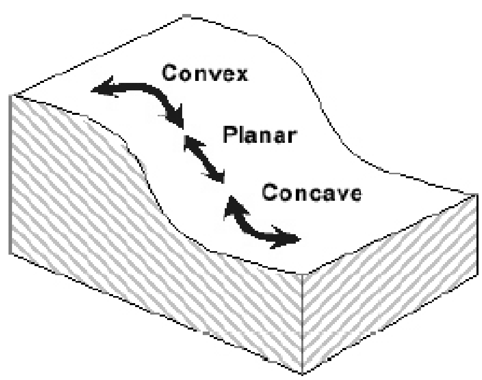


Figure 7b. Slope configurations as observed in profile: convex, planar, and concave. These terms refer to up and down directions along a slope (drawing by Jack Powell, DNR 2004).

[19] Benda et al. 1997.

PART 4. CHARACTERISTICS OF UNSTABLE AND POTENTIALLY UNSTABLE SLOPES AND LANDFORMS

This part describes the characteristics of the potentially unstable slopes and landforms listed in WAC 222-16-050(1)(d)(i), commonly referred to as "rule-identified landforms." They are listed in the rule from (A) to (E) as follows:

A. Inner gorges, convergent headwalls, or bedrock hollows with slopes steeper than 35 degrees (>70%) (see 4.1);
B. Toes of deep-seated landslides with slopes steeper than 33 degrees (>65%) (see 4.2);
C. Groundwater recharge areas for glacial deep-seated landslides (see 4.3);
D. Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream (see 4.4); or
E. Any areas containing features indicating the presence of potential slope instability, which cumulatively indicate the presence of unstable slopes (see 4.5).

The rule-identified landforms represent the most common landforms with the potential to fail in response to natural and management factors. They can 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 needed to verify their presence and precisely delineate landform boundaries, measure gradients, and note other characteristics. In addition to the information provided in Part 4, guidance for identifying potentially unstable landforms is offered in Part 5.

In most instances, the 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 (degrees and percent) are specifically provided. Appendix A provides information on measurements of slope gradients.

<u>4.1 Bedrock Hollows, Convergent Headwalls, Inner Gorges</u>

These three landforms are commonly found together as shown in Figures 8 and 9.

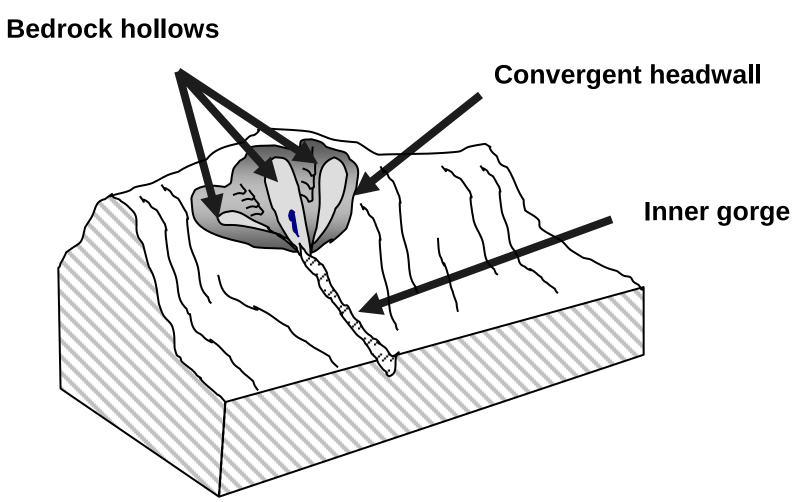


Figure 8. Typical hillslope relationships between bedrock hollows, convergent headwalls, and inner gorges (drawing by Jack Powell, DNR 2003).

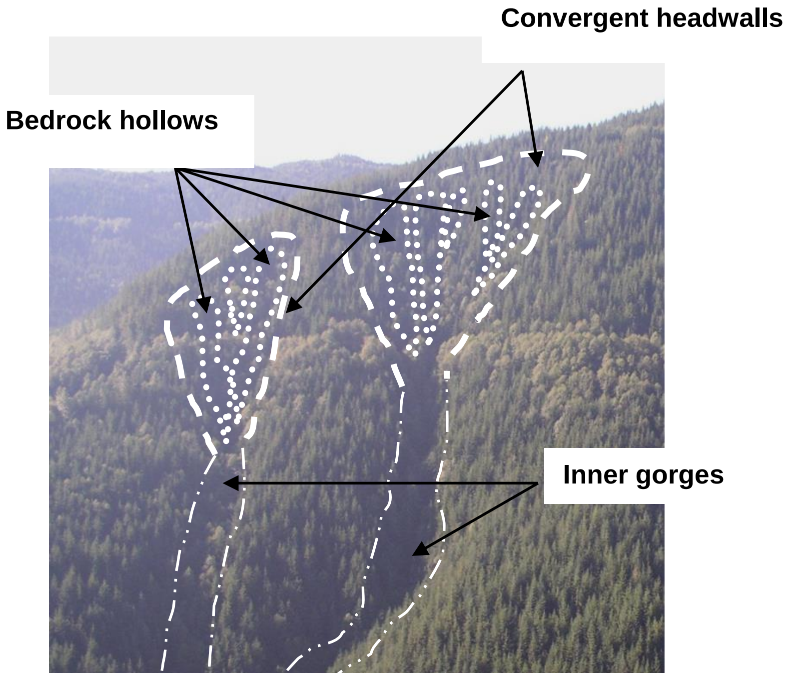


Figure 9. Common hillslope relationship: bedrock hollows in convergent headwalls draining to inner gorges (photo and drawing by Jack Powell, DNR 2003).

Bedrock hollows are also called colluvium-filled bedrock hollows, zero-order basins, swales, bedrock depressions, or simply hollows.[20] Not all hollows contain bedrock so the term "bedrock" hollow can be a misnomer. In the forest practices rule context, the bedrock hollows listed in category A are hollows formed in bedrock. Hollows formed in other materials, such as glacial outwash without a bedrock substrate may also show signs of instability. These would need evaluation similar to hollows containing bedrock and would fit into category E of the rule.

Bedrock 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 ridgeline. Most bedrock 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. Bedrock 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.

Bedrock 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 10).

[20] Crozier et al. 1990; Dietrich et al. 1986.

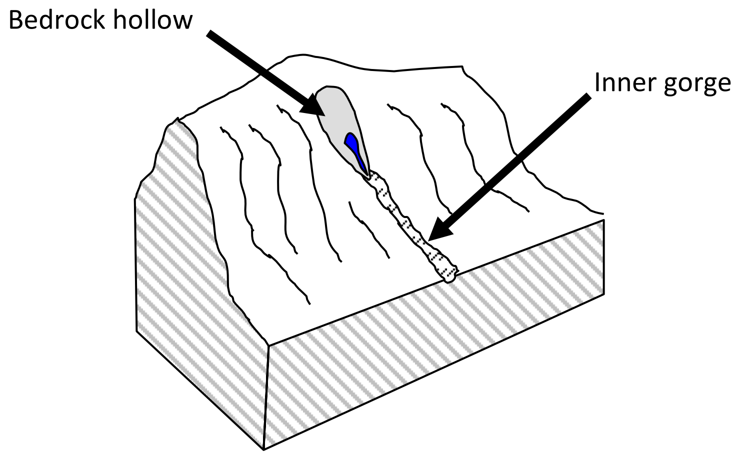


Figure 10. Bedrock hollow and relationship to inner gorges (drawing by Jack Powell, DNR 2003).

Bedrock 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, bedrock hollows are partially or completely filled with colluvial soils that are typically deeper than those on adjacent planar slopes. Recently evacuated bedrock hollows may have water flowing along their axis, whereas partially evacuated bedrock hollows will have springs until they fill with sufficient colluvium to allow water to flow subsurface.

Figure 11 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 6 feet, the likelihood of landslides increases. Recurrent landslide activity within the bedrock hollow slowly erodes bedrock and maintains the form of the bedrock hollow (drawing “b”). After a landslide occurs in a bedrock hollow, seeps or springs may be exposed and the risk of additional sliding diminishes. Drawing “c” shows soil from the surrounding hillsides (colluvium) slowly re-filling the bedrock hollow. As vegetation and trees establish the site after past failures, the roots help stabilize the soil.

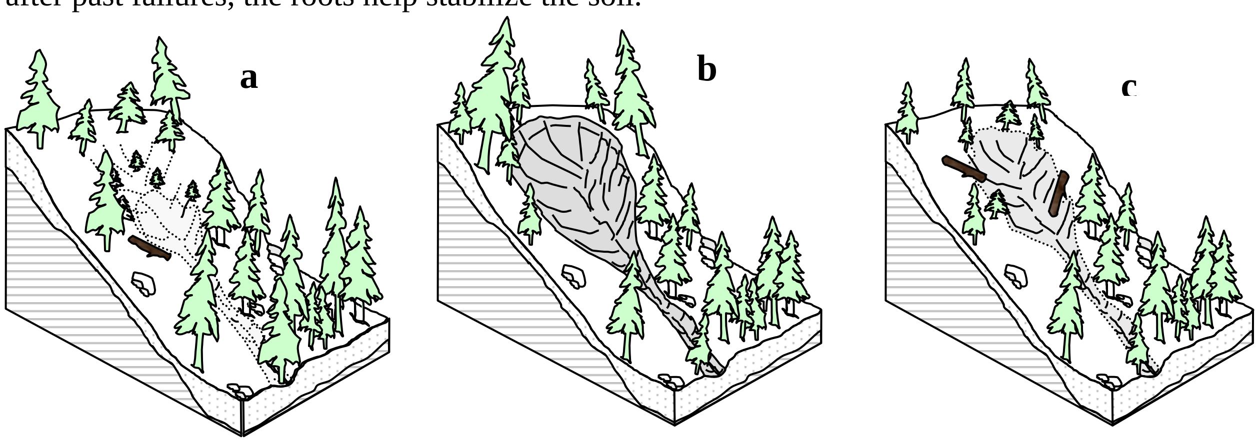


Figure 11. Evolution of a bedrock hollow following a landslide (adapted from Dietrich et al. 1988; drawing by Jack Powell, DNR 2004).

The common angle of repose for dry, cohesion-less materials is about 36 degrees (72%), and saturated soils can become unstable at lower gradients. Thus, slopes steeper than about 35 degrees (70%) are considered susceptible to shallow debris slides. Bedrock hollows form on slopes of varying steepness. Bedrock hollows with slopes steeper than 35 degrees (70%) are potentially unstable in well-consolidated materials, whereas bedrock hollows in poorly consolidated materials may be unstable at lower angles. For the purpose of this document and when considering slope instability, bedrock hollow slopes are measured on the steepest part of the slope, and generally not along the axis unless the bedrock hollow is full (Figure 12).

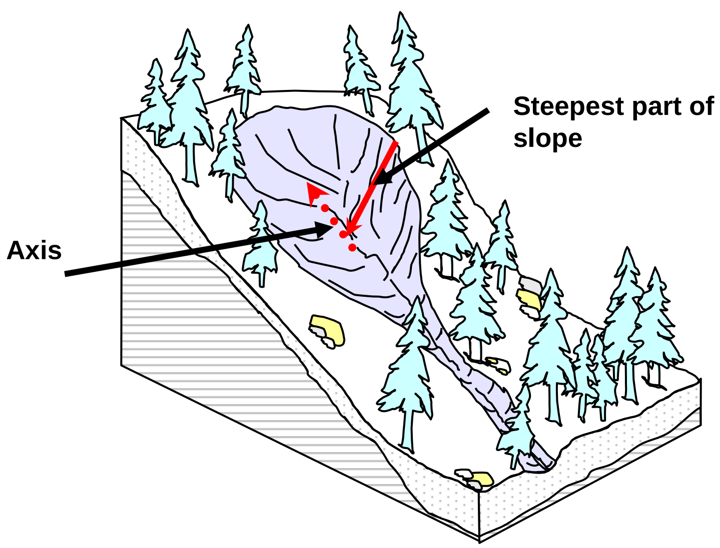


Figure 12. Bedrock hollow slopes are measured at the steepest part of the slope, rather than along the axis (drawing by Jack Powell, DNR 2004).

Vegetation can provide cohesion on marginally stable slopes and removes water from the soil through evapotranspiration. Leave trees in steep, landslide-prone bedrock hollows help maintain rooting strength and should reduce the likelihood of landslide activity[21] (Figures 4 and 13). However, windthrow of the residual trees following harvest can be associated with debris slide or debris flow events. In high wind environments, harvest practices that will limit the susceptibility of the residual trees to windthrow and reduce the potential for landslides include leaving wider strips, pruning or topping trees in the strips, or feathering the edges of leave tree strips.

[21] Montgomery et al. 2000.

Figure 13. Example of leave tree strips protecting unstable slopes (photo by Venice Goetz, DNR 2004).

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

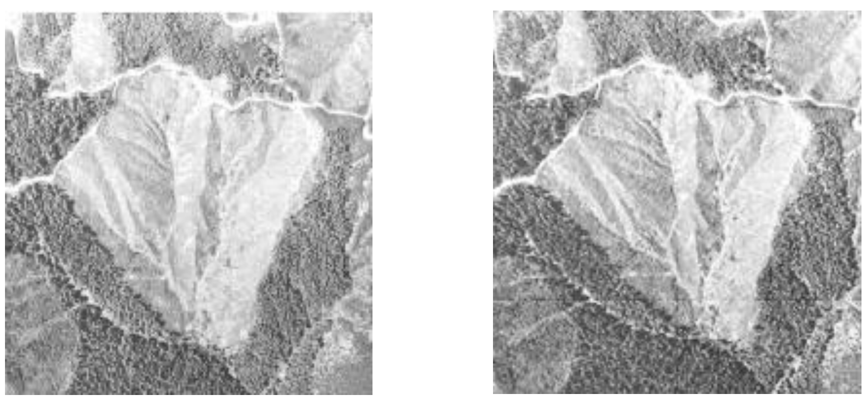


Figure 14a. Stereo pair of a clearcut convergent headwall in Pistol Creek basin, North Fork Calawah River, Washington.

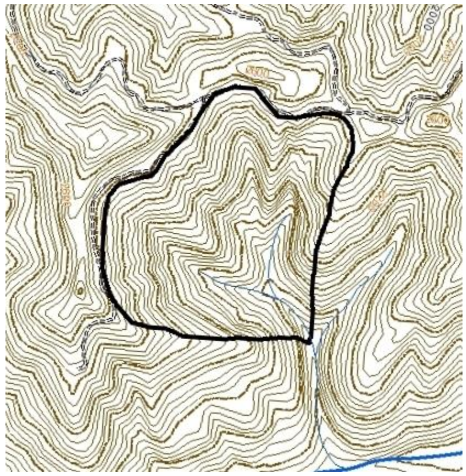


Figure 14b. Rotated topographic map and outline of convergent headwall displayed in the stereo pair of Figure 14a (Hunger Mountain and Snider Peak USGS 7.5' quadrangles).

Convergent headwalls generally range from about 30 to 300 acres. Slope gradients are typically steeper than 35 degrees (70%) and may exceed 45 degrees (94%). Soils are thin because landslides are frequent in these landforms. History of erosion and landslide activity 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 convergent shape of the slope, coupled with thin soils, may allow for a more rapid onset of soil saturation. The mass wasting response of these landforms due 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. The convergent headwall in Figure 15 contains approximately 25 bedrock hollows (not visible through the canopy), and eons of high erosion caused the entire ridgeline to set back several hundred feet from that of the extended hillslope. Landslide scars from convergent headwalls may be prone to surface erosion.

Figure 15. Convergent headwall in North Fork Calawah River, Washington.

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 form below headwalls are formed by repeated debris flow erosion. Debris fans are commonly found at the base of their slopes.

Inner gorges are canyons created by a combination of stream down-cutting and mass movement on slope walls.[22] Inner gorges are steep, straight or concave, side slope walls, which commonly have a distinctive break in slope (Figure 16). Debris flows 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 raw non-vegetated slopes, young even-aged disturbance vegetation, or areas that are convergent in contour and concave in profile. Because of steep slopes and proximity to water, landslide activity in inner gorges is highly likely to deliver sediment to streams or structures downhill. Exceptions can occur where benches of sufficient size to stop moving material exist along the gorge walls.

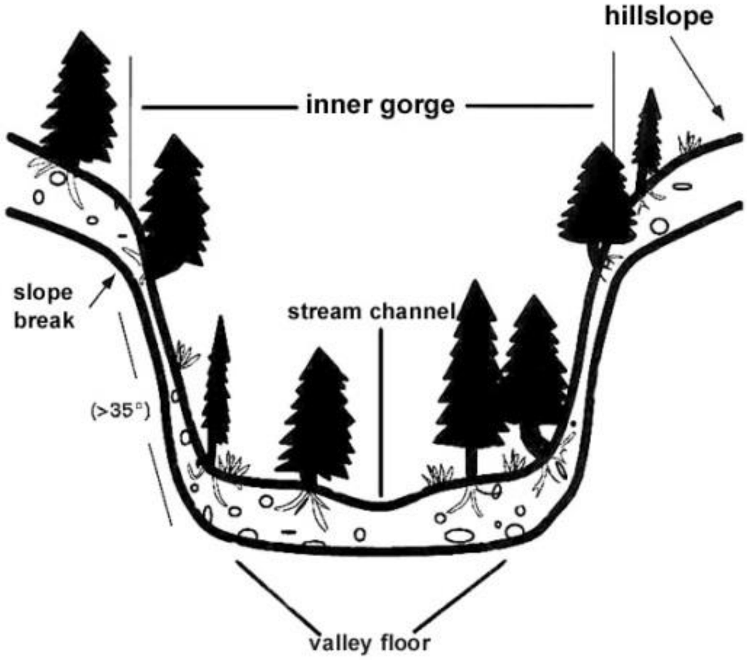


Figure 16. Cross-section of an inner gorge. This view emphasizes the abrupt steepening below the break-in-slope (drawing from Benda et al. 1998).

[22] Kelsey 1988.

Figure 17. Photograph showing how debris flows help shape features related to inner gorges: over-steepened canyon wall; U-shaped profile; buried wood; and distinctive break-in-slope along margins of inner gorge (photo by Laura Vaugeois, DNR 2004).

The geometry of inner gorges varies from simple to complex. Steep inner gorge walls can be continuous for great lengths, such 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 side. Stream-eroded valley sides along main stem rivers can be V-shaped with distinct slope breaks at the top. These commonly show evidence of small-scale landsliding but do not display severe impact, such as hillslope inner gorges which tend to be U-shaped. In practice, a minimum vertical height of 10 feet is usually applied to distinguish between inner gorges and slightly incised streams.

The upper boundary of an inner gorge is assumed to be a line along the first break in slope of at least 10 degrees, or the line above which gradients are mostly less 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. This can increase the likelihood of landslide activity. Similar to bedrock hollows, inner gorge slopes are measured along the steepest portion of the slope (see Figure 12).

The steepness of inner gorges depends 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 28 degrees (53%) can be unstable in inner gorges cut into incompetent bedrock, weathered materials, or unconsolidated deposits.

Stream erosion creates instability by undercutting the toe of the slopes in an inner gorge. Erosion along the inner gorge walls may be exacerbated by the interception of shallow groundwater, which forms seeps along the sides of the inner gorge. Root strength along walls and margins of inner gorges provides soil stability and lessens 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.

4.2 Toes of Deep-Seated Landslides

The toe of a landslide is the lower, displaced material most distant from the place of origin or main scarp. Toes of deep-seated landslides with slopes greater than 33 degrees (65%) are a rule-identified landform. In this context, toes of deep-seated landslides means the downslope toe edges, not the entire toe area of displacement material. Figures 5 and 18 show the toe in relation to other landslide features.

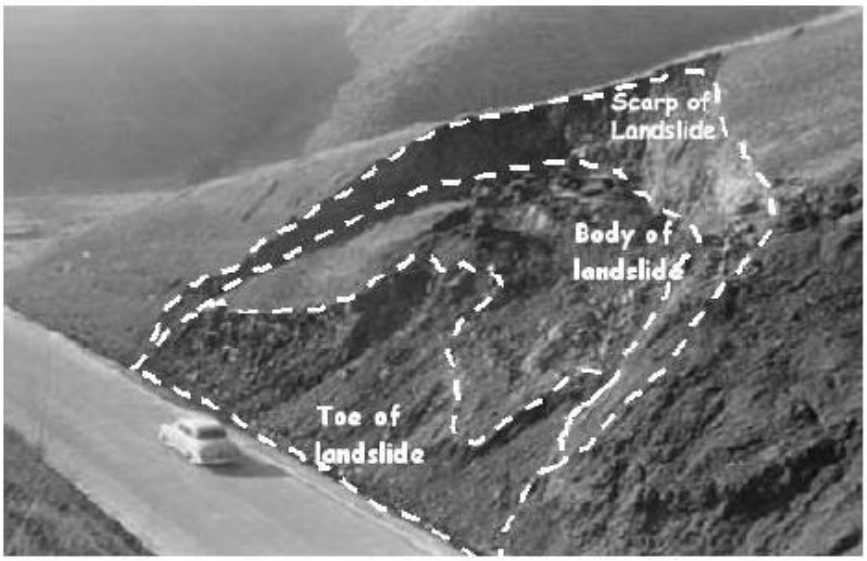


Figure 18. Deep-seated landslide showing the head scarp, side-scarps, body, and toe. Some of the toe was removed in building and maintaining the highway (adapted from a USGS photo).

Landslides with 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 removed a portion of the toe, causing reactivation of the landslide. Resulting instability can take the form of shallow landslides, small-scale slumping, or reactivation of parts or the whole of a landslide. Because deep-seated landslides occur in weak materials (further weakened by previous movement), an angle of 33 degrees (65%) is the regulatory threshold 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.

4.3 Groundwater Recharge Areas for Glacial Deep-Seated Landslides

Groundwater recharge areas for glacial deep-seated landslides are rule-identified landforms. Part 5.3 provides methods for delineating these areas. In order to identify and delineate a groundwater recharge area in glacial terrain, it is necessary to first identify the associated landslide.

Glacial deep-seated landslides are landslide features 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 landslides are distinguished from other forms of deep-seated landslides by the materials in which they occur; however, their failure mechanics can be similar to deep-seated landslides developed in other materials.[23]

Glacial deep-seated landslides 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), and the alpine glacial deposits (Figure 19b) are found in mid-to-high elevation mountain ranges.[24]

Figure 19a. Extent of continental ice sheet in the Pacific Northwest (DNR 2014).

[23] Terzhagi 1951.
[24] Booth et al. 2003; Booth et al. 1994; Thorsen, R.M. 1980; Barnosky 1984; Heusser 1973; Crandall 1965.

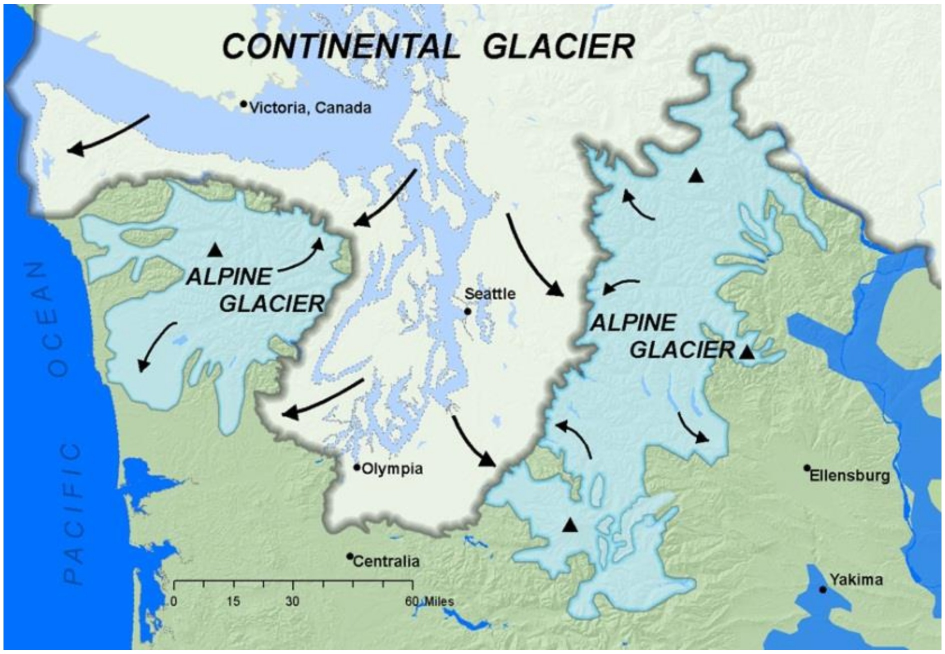


Figure 19b. Continental and alpine glaciation in western Washington (DNR 2014).

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

Glacial and interglacial deposits display a wide range of hydrogeologic 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) deposited or overrun by glacial ice during periods when the ice was advancing. Till typically has low permeability and low water storage capacity. Glacial outwash typically contains sorted and stratified sediments deposited by water flowing from glacial ice during the advance or the retreat of the glacier, and have higher permeability and 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 till. See Appendix H for the hydrologic properties of various soils.

Glacial 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 vegetative rooting zone. The groundwater component is composed of water within the unsaturated and saturated zones.

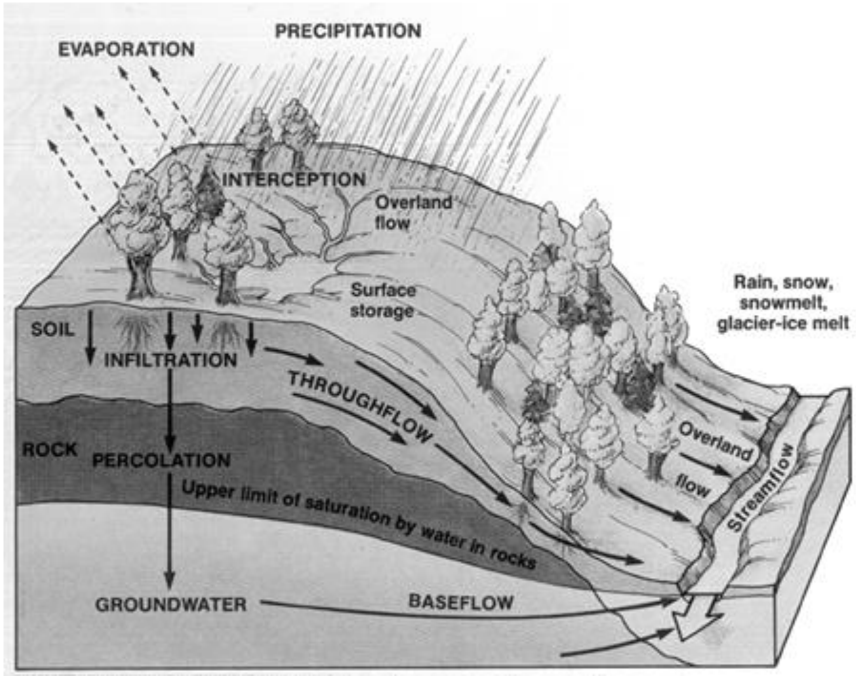


Figure 20. Hydrologic budget of a hillslope (University of Colorado).

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

The area that contributes groundwater to a glacial deep-seated landslide, including the landslide itself, constitutes that landslide's groundwater recharge area. However, parts of the landslide may not be hydrologically connected to glacial material, sediments, or deposits. Groundwater flows originating in upland areas can discharge as springs, streams, and other surface water features at lower elevations.

Differences in permeability within glacial sediments control the infiltration and movement of groundwater within the recharge area.[25] Groundwater perching and routing, and the characteristics of the overlying groundwater recharge area can be important factors in a deep-seated failure. This is especially true for landslides in glacial sand and other unconsolidated deposits that overlie less permeable strata such as fine-grained glacial lake deposits, till, or bedrock (Figure 21). This is a common configuration of the glacial deposits in much of the Puget Lowlands (e.g., landslides in Seattle)[26] and in the North Cascades foothill river valleys (e.g., the Stillaguamish River valley)[27], but also occurs in alpine glacial deposits elsewhere in Washington apart from the maximum extent of continental glaciation.

A common example of failure is where groundwater is flowing through permeable sand layers perched above the less permeable clay or till layers. Glacial deep-seated landslides can respond to precipitation events, where the permeable layer (e.g., sand and gravel from recessional outwashes)

[25] Bauer and Mastin 1997; Vaccaro et al. 1998.
[26] Gerstel et al. 1997.
[27] Benda et al. 1988.

becomes saturated above a less permeable layer (e.g., glaciolacustrine clay), forming a perched groundwater table that weakens the contact between the clay and sand. Saturated conditions can increase soil pore water pressure and reduce the soil strength causing landslide failure planes to occur along these sand/clay contacts. A common predictor of perched groundwater is the presence of springs (groundwater discharge) or hydrophytic (moisture loving) vegetation. Groundwater discharging as springs along the sand-clay contact can aid draining of the aquifer.

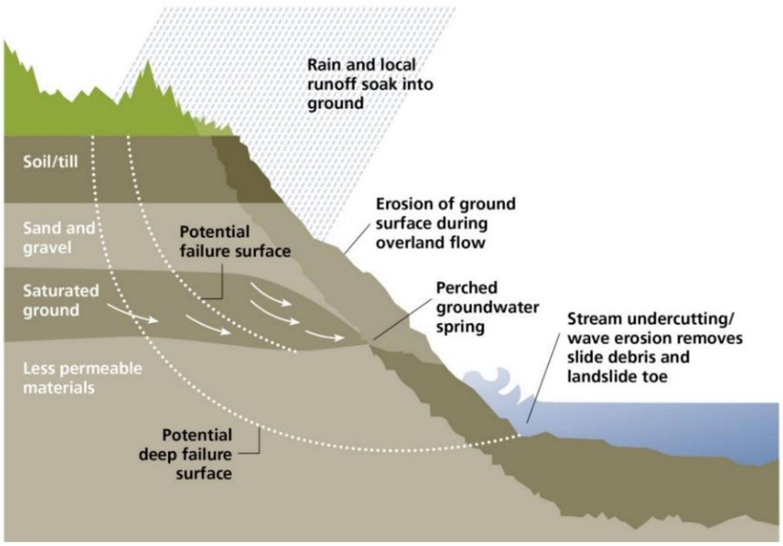


Figure 21. Diagram illustrating failure surface resulting from groundwater recharge to a glacial deep-seated landslide (DNR 2014).

A classic example of a geologic setting where glacial deep-seated landslides are common is in the Puget Sound lowlands where Esperance Sand or Vashon advance outwash overlies 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 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 that causes water to flow horizontally along the sand-clay contact, resulting in springs where this contact is exposed at the surface.[28]

Saturation of the pore spaces within sediments reduces grain-to-grain contact, which reduces the effective strength of materials. Because soil saturation reduces the effective strength of the soil, which in turn reduces the stability of a slope, certain forest practices activities proposed within recharge areas for glacial deep-seated landslides may be classified Class IV-special per WAC 222-16-050(1)(d)(i)(C). Such proposals 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 is delivered to a glacial deep-seated landslide.

[28] Tubbs 1974.

The first order approximation of the recharge area is the surface basin (topographically defined) directly above and including the landslide. The spatial extent of a groundwater recharge area can be interpreted from LiDAR data, field observation of soil profiles, geologic structure, stratigraphy, well logs or boreholes, and geologic maps, to the extent these resources are applicable. See 5.3 for guidance on delineating groundwater recharge areas for deep-seated landslides.

<u>4.4 Outer Edges of Meander Bends</u>

Streams can create unstable slopes by undercutting the outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream.[29] The outer edges of meander bends are susceptible to deep-seated and shallow landslide activity, including debris avalanching and small-scale slumping. They are less susceptible where mature trees exist on lower terraced slopes in riparian or channel migration zones. The roots and woody structure of riparian trees act to deflect erosive flows and lessen undercutting along meander bend walls.

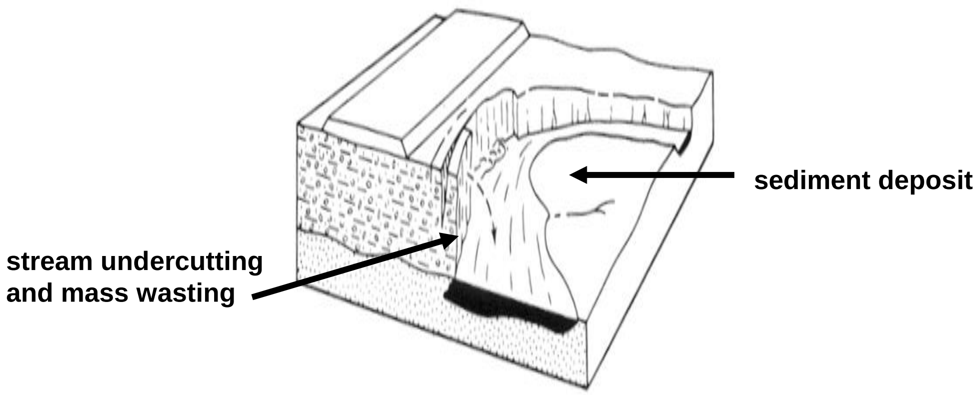


Figure 22. Outer edge of a meander bend showing mass wasting on the outside of the bend and deposition on the inside of the bend (adapted from Varnes 1978).

<u>4.5 Areas Containing Features Indicating the Presence of Potential Slope Instability</u>

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 that cumulatively indicates the presence of unstable slopes, the area can be considered a rule-identified landform. Proposed forest practices activities in this situation may be classed as a Class IV-special per WAC 222-16-050(1)(d)(i)(E) if there is potential to deliver sediment and debris to a public resource or threaten public safety. General practitioners and qualified experts commonly refer to these features as "category E" landforms.

Active bedrock deep-seated landslides are an example of a category E landform because they display multiple indicators of slope instability. Toes greater than 33 degrees (65%) are a rule-identified landform, but other areas, such as portions of the head scarp within a bedrock deep-seated landslide, may have shallow landslide and delivery potential and require protection.

Another common example of a category E landform is concave features greater than 35 degrees (70%) in glacial sediments or unconsolidated sediments such as Quaternary terrace deposits. These features are not true bedrock hollows because bedrock is not present, but landslide inventories from

[29] Schuster and Wieczorek 2002.

watershed analyses and landslide hazard projects have demonstrated that these features are unstable and routinely recognized and protected as category E landforms.

Relatively large and recent topographic indicators of such features can be observed from air photos, topographic maps, and LiDAR images, but identifying smaller and older indicators requires careful field observation. Indicators of slope instability or active movement may include the following:

Topographic indicators
- Bare or raw, exposed, non-vegetated soil on steep slopes. This condition may mark the location of a debris flow, or the headwall or sidewall of a slide or evidence of active movement.
- Benched or back tilted surfaces, especially below crescent-shaped headwalls, indicative of rotational movement within the slide.
- Hummocky topography at the base of steep slopes. This may mark the accumulation zone (runout area) for a flow or slide.
- Boulder piles or 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.
- Side scarps, shear margins, or lateral scarps; multiple scarps in a downward direction.
- Displaced surface features like roads, railroads, foundations, and fence lines.
- Presence of debris fans at the mouths of canyons indicating past runout events.

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

Vegetative indicators
- Jack-strawed, back-rotated, or leaning trees and stumps. These are typically indicative of active or recently active landslides.
- Trees with curved-based lower stems 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 landsliding, particularly if other indicators are present.
- Split trees and split old growth stumps. These may be associated with tension cracks.

- Hydrophytic (water-loving) vegetation (skunk cabbage, devil's club, salmon berry, etc.) on slopes. These conditions may indicate the presence of groundwater seeps and associated hydrogeologic conditions.
- Patterns of disturbed vegetation such as changes in stand composition (early seral stage or lack of mature trees within a hillslope) or small groupings 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 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[30]; Hillslope Stability and Land Use[31]; Landslides, Processes, Prediction and Land Use[32]; and Slope Stability Reference Guide for National Forests in the United States[33].

PART 5. IDENTIFYING POTENTIALLY UNSTABLE SLOPES AND LANDFORMS

The identification, delineation, and characterization of unstable and potentially unstable landforms should be completed to address the relevant questions for each site. Each step of the review process might uncover new information that could modify assessment methods and findings. General practitioners (landowners, foresters, engineers) typically conduct an initial screening and field review of project sites. In some cases, a qualified expert may be engaged to review and verify the general practitioner's slope assessment or perform additional geologic investigation.

The steps in the investigation process typically include an office review (5.1) and field assessments (5.2 and 5.3). If desired by the landowner or required by rule, further geotechnical assessments may include those described in Parts 6 and 7 as follows:

- deep-seated landslide activity assessment (6.1);
- glacial deep-seated landslide assessment (6.1.1);
- quantitative field assessment methods for qualified experts' subsurface investigations (6.2);
- water budget and slope stability modeling assessments for glacial deep seated landslides (6.3);
- slope stability sensitivity assessment (6.4);
- runout and delivery assessment (6.5);
- synthesis and evaluation (7.1); and
- geotechnical reports (7.2).

The appropriate investigation process cannot be defined by the rigid application of a set of procedural rules.[34] The following is a general overview of the typical sequence and elements of a slope-stability assessment:

[30] Chatwin et al. 1994.
[31] Sidle et al. 1985.
[32] Sidle and 2006.
[33] Hall et al. 1994.
[34] Turner and McGuffy 1996.

1. Preliminary fact-finding to answer: What actions do the proposed forest practices activities include (e.g., partial cut, clearcut, road building, stream crossing)? In which landslide province (Appendix B) are the proposed forest practices activities located and what are the geologic 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 data, and other information identified during the preliminary fact-finding phase.
3. Field review to confirm office review findings, and identify unstable and potentially unstable landforms not recognized during the office review. The field review may also involve a more detailed geologic investigation for collecting additional geologic data and 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.

5.1 Office Review

An office review is 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 involves compiling and evaluating all pertinent site-specific and regional data to help identify, delineate, and interpret potentially unstable slopes and landforms (e.g., aerial imagery, LiDAR, GIS-based model predictions of surface attributes derived from digital high-resolution topographic data). It may also include 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 public resource and public safety considerations, and make a determination regarding next steps in the site assessment. See Parts 5.1.3 and 5.1.4 for information regarding remote sensing tools and topographic data, and appendices C through E for data sources.

5.1.1 General Practitioner’s Office Review

The objectives of the general practitioner’s office review are to identify and locate potential and existing areas of slope instability within or around proposed forest practices activities using descriptions provided in Part 4; locate areas of public resource sensitivity or public safety exposure in the area of the planned operations that could be adversely affected by mass wasting processes; and to develop a strategy for assessing the landforms in the field. The general practitioner can use this information when completing a Forest Practices Application (FPA).

Summary of Procedures.

The following are typical resources for a general practitioner’s office review:

- Maps and imagery to screen areas for visual indicators of potentially unstable slopes and landforms. 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 D.

- 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 F for a list of online sources).
- Sources that may be available to the user online via the Forest Practices Application Review System (FPARS) and Washington State Geologic Information Portal. The Geographic Information System (GIS) with map display and analysis capabilities (e.g., ESRI ArcGIS) can provide an efficient and spatially accurate means for overlaying digital maps and images for geospatial analysis. However, if these tools are not available, an initial screening can be performed manually by inspecting each map or image separately. Various county websites also offer online interactive GIS information for maps and imagery products. Sources of imagery, data, maps, reports, and other documents are listed in appendices C through G.

In addition, the general practitioner's past knowledge about site-specific conditions will supplement the information gathered during the office review process.

The office review 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, identifying the full extent of a groundwater recharge area from topographic maps, or detecting landslides under a mature forest canopy using aerial photography exclusively may be unreliable. Therefore, one or more follow-up field assessments can verify results of the initial screening. The final step of an office review may be 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 review will help the general practitioner determine any portions of the proposed harvest and construction area that may need further assessment in the field. The general practitioner might also elect to have a more thorough office review conducted by a qualified expert.

5.1.2 Qualified Expert's Office Review

A qualified expert is needed when an investigation 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 geologic assessment of landform characteristics and landslide potential prior to initiating field work. The qualified expert's 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 pertinent data in order to identify physical indicators of past, existing, and potential landslide instability, 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 assess any potential for delivery of sediment or debris to a public resource or threat to public safety.

Summary of Procedures.
Most qualified experts have GIS capabilities, are experienced in using remotely sensed data techniques 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 include assessing the accuracy, limitations, and uncertainties of remotely sensed information and previously prepared materials, as well as adjusting any preliminary interpretations of landform features 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 precedes a field review by either a general practitioner or a qualified expert, especially where potentially unstable slopes and landforms are identified and require verification. Interpretations based solely on remote sensing data should not be used as substitutes for site-specific field assessments. If the expert determines from the office review that potentially unstable slopes or landforms are likely present, the landowner may exclude these areas from the proposed forest operations. Reports or information provided to DNR should include relevant results of the qualified expert's office review findings.

5.1.3 Remote Sensing Tools Available for Office Reviews
Common sources of remotely sensed information used in identifying, delineating, and interpreting landforms are grouped broadly in two 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, physical databases, technical reports, and other published and unpublished literature. 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 (see Figure 23).[35] However, LiDAR is not a panacea; rather it complements traditional aerial photo interpretation and the analysis of both information sources are useful. Aside from the information provided in 5.1.4, see Appendix E for more information about LiDAR processing, applications, and data sources.

5.1.4 LiDAR Use in Identifying Potentially Unstable Landforms
Hillshade, contour, and slope class maps derived from bare earth LiDAR digital elevation models (DEMs) are common LiDAR products used to identify landforms and landslides. A hillshade map is created by simulating sunlight shining on the topographic surface at a specified angle. A slope map shows 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

[35] e.g., Haugerud et al. 2003; Burns and Madin 2009; Roering et al. 2013; Tarolli 2014.

sun angle and more contrast on slopes facing away from the incident sun angle, either of which can obscure topographic features. Analyzing several hillshade maps generated with different sun angles or employing methods such as those described in Burns and Madin (2009) may minimize 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.

LiDAR-derived maps can reveal key topographic features indicating potential instability (e.g., visual indicators listed in 4.5) that are not always identifiable using other remote sensing data. Hummocky topography, benched surfaces, tension cracks, scarps, horst and graben features, pressure or transverse ridges, and irregular drainage patterns (Figures 25 and 26) 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 Figure 23. In Figure 23f, a hillshade map derived from 3-foot LiDAR data allows the user to approximately delineate the landslide’s main scarp, body, and toe, whereas such features may not be recognized using lower resolution quality (i.e., 30-meter resolution).

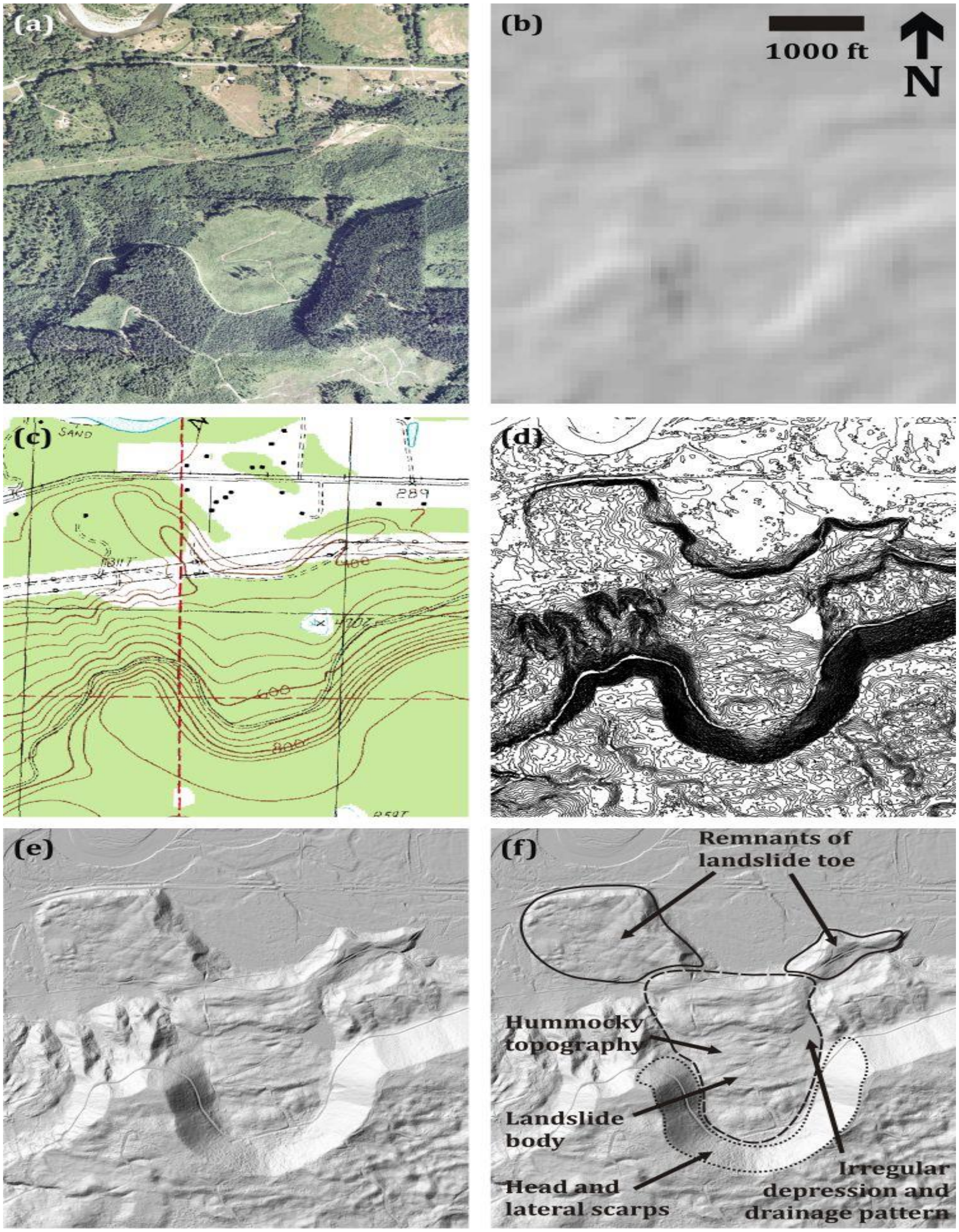


Figure 23. Example of a dormant glacial deep-seated landslide as seen in different types of remotely sensed data and with varying resolution quality:
(a) Digital Orthophoto Quadrangle, (b) hillshade map derived from 30-meter resolution ASTER Global Digital Elevation Model, (c) topographic map, (d) 6-foot contour map derived from 3-foot resolution airborne LiDAR, (e) hillshade map derived from 3-foot resolution airborne LiDAR, and (f) an annotated version of (e) (Adam Booth, Portland State University 2014).

LiDAR hillshades can be used to delineate and interpret deep-seated and, with less 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.[36] Recent regional examples of deep-seated landslide mapping that used LiDAR-based protocols include Burns and Madin (2009), Schulz (2005 and 2007), and Haugerud (2014).

LiDAR-based comparisons of landslide features are useful to ascertain relative age because younger scarp features generally produce a sharper image on high-resolution topography (i.e., 2-meter pixels) than older, more eroded features that are less clear (Figure 24). It is important to consider DEM raster resolution to avoid misrepresenting landslide age from lower-resolution images. Visual inspection of LiDAR imagery is also useful for change detection to ascertain evidence of movement prior to and after an event[37].

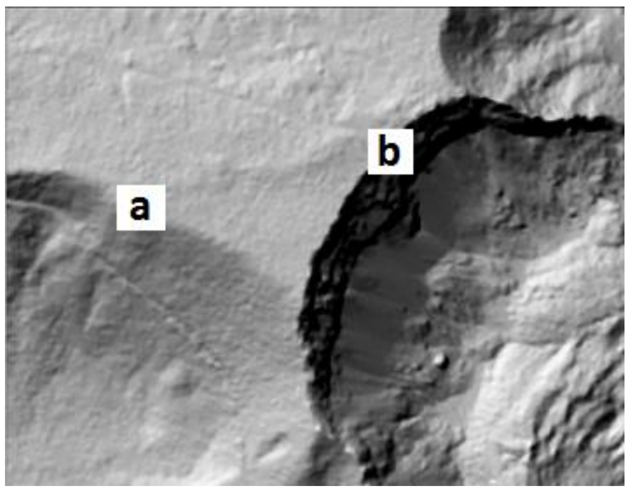


Figure 24. LiDAR image comparison between two deep-seated landslide scarps with the same resolution showing (a) subdued topography and (b) crisp topography. The less defined topography (a) suggests a greater relative age (DNR 2016).

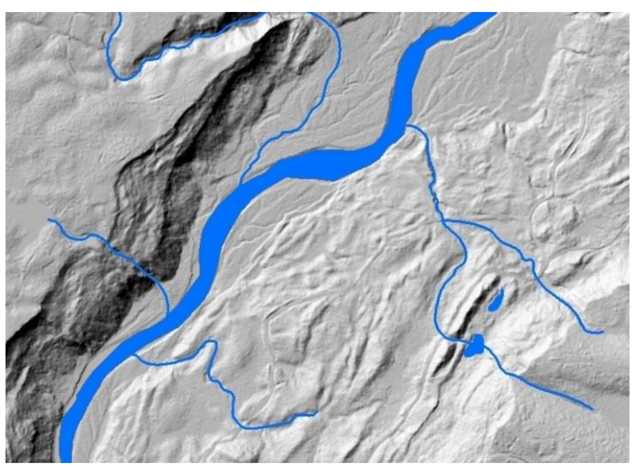


Figure 25. Large slump feature showing displaced (deflected) streams within the landslide mass and sag ponds impounded by ridges (DNR 2016).

[36] McKean and Roering 2004; Glenn et al. 2006; Booth et al. 2009; Berti et al. 2013.
[37] Iverson et al. 2015.

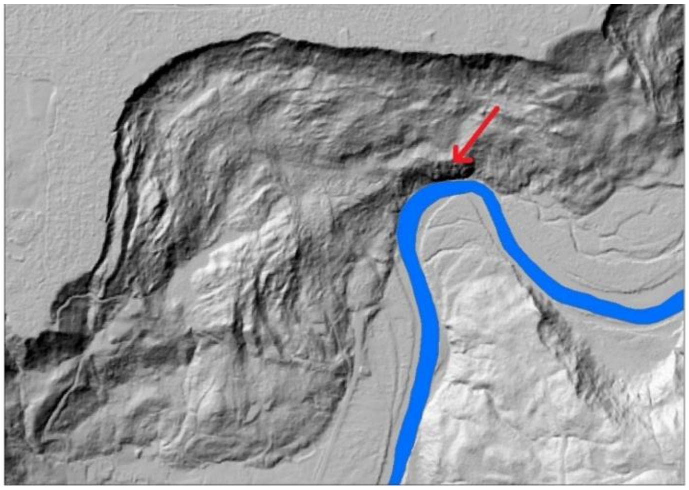


Figure 26. LiDAR image showing channel incision within a large deep-seated slump feature in the Tolt River valley, King County (DNR 2016).

<u>5.2 Field Assessment</u>

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

<u>5.2.1 General Practitioner's Field Assessment</u>

The objective of the general practitioner's field assessment is to determine the presence or absence of the rule-identified landforms described in Part 4 and survey the area for any landforms missed in the office review. This assessment can typically be conducted during the reconnaissance and lay out of proposed forest practices activities (e.g., marking unit boundaries, establishing riparian management zones, laying out road systems). When the field assessment indicates that complex geological features are present or the scenario is beyond the general practitioner's expertise, the landowner may ask a qualified expert to complete a further assessment. The practitioner should refer to 4.5 for indicators of slope instability and 5.3.2 for field review of groundwater recharge systems.

Outcomes.

Common results of the general practitioner's field assessment are one of the following:

- The general practitioner does not identify any potentially unstable slopes or landforms within or around the planned area for the forest practices activities.
    - The landowner documents the finding in the slope stability sections of the FPA.
- The general practitioner identifies potentially unstable slopes or landforms in or around the planned operations area, and the landowner avoids timber harvest or construction on them.
    - The landowner documents the finding in the slope stability sections of the FPA, along with any additional required information that DNR may have requested.
- The general practitioner identifies potentially unstable slopes or landforms in or around the planned operations area, and the landowner proposes timber harvest or construction activities on them.

- The landowner retains a qualified expert to conduct geologic office and field reviews, and prepare a geotechnical report (see 7.2 for information required in a geotechnical report).[38] The landowner documents the finding in the slope stability sections of the FPA, along with the geotechnical report prepared by the qualified expert.

5.2.2 Qualified Expert's Field Assessment

When an investigation by a qualified expert is necessary, the objectives of the field assessment are to verify the presence or absence of potentially unstable slopes and landforms identified during office reviews and identify landforms previously undetected due to insufficient remote sensing data coverage or resolution. To meet the objectives, the qualified expert should collect sufficient information to describe the landforms in or around the site and may:

1. Refine any preliminary maps constructed during office reviews, including features not detected in the office review;
2. Assess failure mechanisms and the likelihood that the proposed forest practices will cause movement on, or contribute to further movement of potentially unstable slopes or landforms;
3. Analyze cause-effect relationships relative to the proposed activity;
4. Assess the likelihood of delivery of sediment or debris to public resources or threats to public safety;
5. Determine any possible mitigation for the identified hazards and risks;
6. Evaluate levels of confidence in office and field findings; and
7. Produce geologic information when requested or write a geotechnical report when required summarizing review findings, conclusions, and recommendations (see 7.2 for guidance on preparing in a geotechnical report).

Summary of Procedures.

The qualified expert determines the nature of the field review required to meet the objectives stated above. The field work can take one or more days and may involve an interdisciplinary team meeting if required by DNR. 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 quantitative in nature.

An example of a qualitative assessment would include visual observations and photos of geological features and other site indicators at identified locations (e.g., GPS waypoints), which are summarized in a geotechnical report to substantiate landform and process interpretations. A more quantitative investigation could 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 could be important in analyzing the depths, materials, and hydrology of deep-seated landslides.

Preparation of a site-specific geomorphic map is helpful because most published geologic maps, although useful for understanding and locating bedrock and Quaternary sediment deposits, are insufficient to identify small-scale landforms that could have a significant effect on the proposed activity. In addition, some geologic information may not have been field verified or developed with high-resolution LiDAR. The purpose of mapping is to capture surface conditions, provide a basis

[38] The Department of Natural Resources' Forest Practices Division maintains a qualified experts list that can be viewed online at http://www.dnr.wa.gov/Publications/fp_geo_experts.pdf.

for the interpretation of subsurface conditions, and prepare more site-specific descriptions of relevant features.

A geomorphic map ideally includes the location, elevation, and attitude of known geologic contacts and relevant landforms, although such data collection is not feasible or necessary in all situations. In glacial materials, 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. The location of pertinent geologic components and potentially unstable indicators should be identified on the map or in the geotechnical report. Ideally, mapped products should be prepared on a scale of 1:12,000 or less using high-resolution LiDAR-generated topography, aerial photos, and field data. 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.

Geologic field data collection, analysis, and map compilation are undergoing a revolution in methods largely precipitated by GPS and GIS-equipped mobile computers.[39] To facilitate a review of the proposal, geologic reports containing GPS locations of landforms and other relevant features will assist locating such sites in the field. It is also helpful to include photographs of significant landforms or their components if the spatial scales are compatible 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 vegetative indicators described in 4.5.

Outcomes.
Each site contains a unique set of slopes and landforms and will require a distinct set of possible management strategies. In some cases, the qualified expert may recommend avoidance of a rule-identified landform, setbacks to a feature, or specific mitigation measures to lessen impacts to a landform. Results of a qualified expert's field assessment may include one of the following:

- The finding that areas of concern identified in the preliminary office review and field assessment do not meet the definitions of the rule-identified landforms (Part 4).
    - The qualified expert reports these findings to the landowner; the landowner documents the findings in the slope stability sections of the FPA.
- The finding that potentially unstable slopes or landforms in or around the operations area have minimal potential to deliver sediment or debris to a public resource or threaten public safety.
    - The qualified expert reports these findings to the landowner; the landowner documents the findings in the slope stability sections of the FPA.
- The finding that potentially unstable slopes or landforms within or, when appropriate, around the operations area have the potential to deliver sediment or debris to a public resource or threaten public safety.
    - The qualified expert prepares information listed in WAC 222-10-030(1) in a geotechnical report. 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. The landowner documents the findings in the slope stability sections of the FPA and includes the report with the FPA.

[39] Whitmeyer et.al 2010; U.S. Geological Survey 2008; Edmondo 2002.

5.3 Delineating Groundwater Recharge Areas for Glacial Deep-Seated Landslides

As explained in Part 4, the groundwater recharge area for a glacial deep-seated landslide is a rule-identified landform. This landform is the area up-gradient of a landslide that can contribute water to the landslide. When timber harvest or construction activities are proposed on or around a verified glacial deep-seated landslide or its associated groundwater recharge area, a landslide activity assessment needs to be performed (see 6.1), including whether a groundwater recharge area exists, and if so, determining its spatial extent. DNR requires that a qualified expert make the final determination about the existence and boundaries of a groundwater recharge area for a glacial deep-seated landslide. However, a general practitioner may have a role in office reviews and field work under the direction of the qualified expert.

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. The most accurate tool available for mapping surface topography is high resolution DEM generated from LiDAR. Figure 27a shows the approximate groundwater recharge area for a landslide based on upslope topographical delineation. The cross section shown in Figure 27b illustrates the approximate stratigraphy through the groundwater recharge area and landslide body. 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.

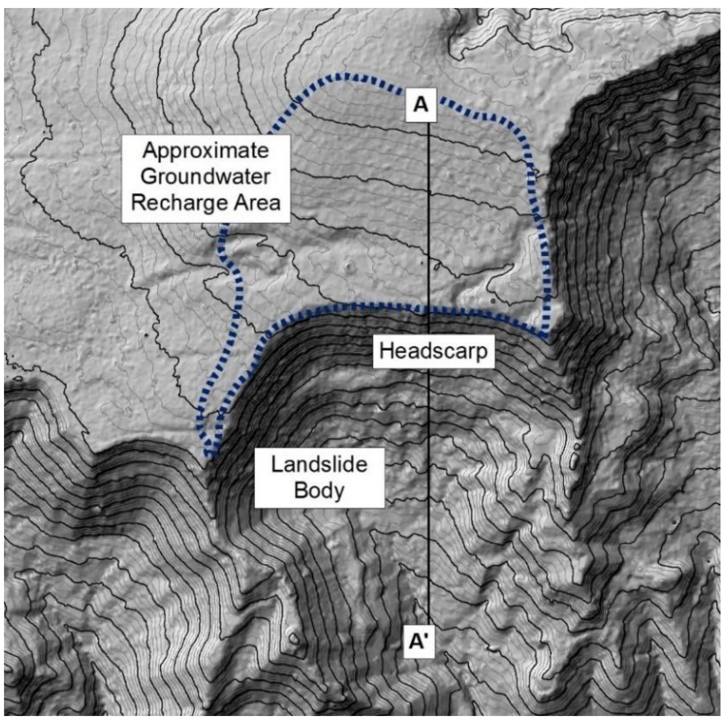


Figure 27a. Glacial deep-seated landslide. The dash-lined polygon is an approximate delineation of a groundwater recharge area based on LiDAR data (DNR 2014).

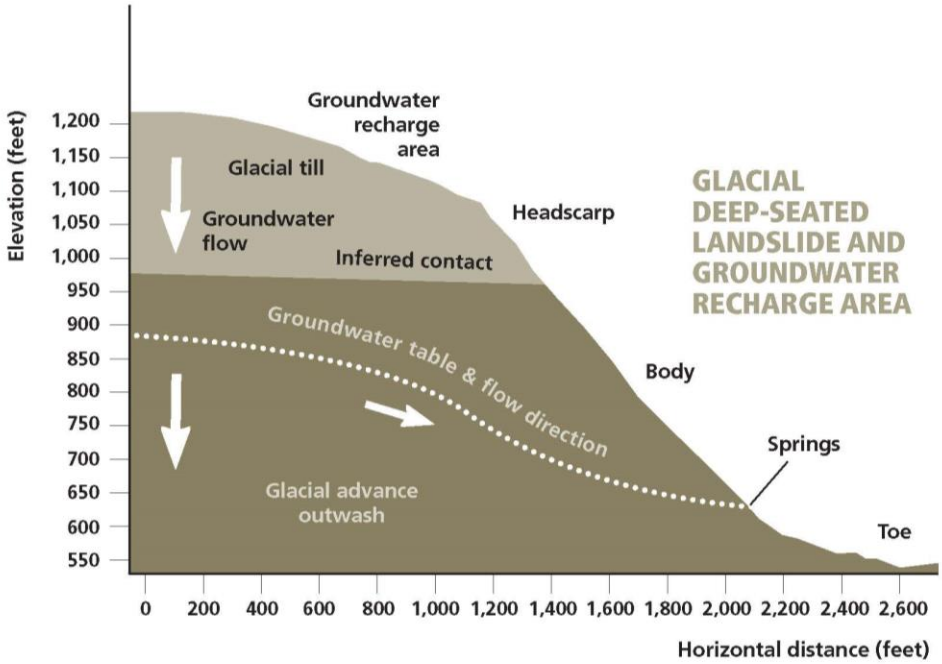


Figure 27b. Hillslope cross-section (A-A' in figure 27a) derived from 2-meter DEM of a glacial deep-seated landslide showing the groundwater recharge area, geologic units, and generalized groundwater flow paths (DNR 2016).

The recommended first step in delineating the groundwater recharge area is to evaluate its stratigraphic and/or topographic relationship to the landslide. Further investigations and analyses may be necessary when uncertainties remain as to the accuracy of the recharge area boundary. DNR uses the results of these analyses provided by qualified experts in geotechnical reports to determine FPA classifications and other decisions based on applicants' proposed activities.

5.3.1 Office Review for Groundwater Recharge Areas

The office review should include an assessment of the surrounding topography, land cover and vegetation, soils, and the distribution of hydrogeologic units. 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 higher altitude areas of recharge to lower altitude areas of discharge.[40] The surficial contributing area may be delineated from digital elevation models (DEMs) derived from LiDAR, or U.S. Geological Survey topographic quadrangles. Topography developed from high-resolution LiDAR is the most accurate tool available for mapping surface topography. This analysis provides an approximation of the potential area of recharge, but may not be valid in heterogeneous rocks and sediments with complex topography, depositional history, or deformational environments.

[40] Freeze and Cherry 1979.

The land cover of the recharge area can influence the magnitude of groundwater recharge. Vegetation type and distribution effect the amount of precipitation intercepted by foliage and leaf litter and the resultant through-flow that is available for recharge. In addition, land development and agricultural uses may influence groundwater recharge.

The reviewer may also find the following resources useful in the office review:

- Land cover data available nationally at a spatial resolution of 30 meters from the U.S. Geological Survey's (USGS) National Land Cover Database;
- Geologic maps for providing a basis for delineating the areal extent, orientation, and stratigraphic relationships of rocks and sediments that influence the occurrence and movement of groundwater. The USGS, 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 revealing 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. Department of Ecology maintains a searchable database of well logs for Washington State; however, subsurface data will generally be confined to developed areas.
- 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 Sound[41] and the Columbia Plateau[42]. However, it is also important to understand groundwater movement at smaller local scales. Hydrogeologic reports are available from sources such as the USGS and the Department of Ecology.

5.3.2 Field Assessment for Groundwater Recharge Areas

Groundwater recharge areas may occupy a range of hillslope gradients, shapes, and soil and rock types. Therefore, it is necessary to conduct a field inspection to determine if the initial designation accurately reflects the recharge area topography, including the topography up-gradient of the landslide. It is helpful to collect GPS waypoints along the topographic boundaries of the groundwater recharge area for mapping and revisiting the site if necessary. The field inspection should include:

- Examining the characteristics of the surface materials within the initially delineated groundwater recharge area, and documenting whether the soil types and subsurface geologic units are consistent with maps examined during the office review. In some cases, published soil and geologic data in forested areas may be inaccurate at the scale of an FPA activity map.
- Mapping the stratigraphic units that compose the hillslope (i.e., the distribution of geologic units or horizons below the groundwater recharge area) in order to describe the likely flow paths that could potentially connect the groundwater recharge area with the failure plane of the landslide. Landslide failure planes are often 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. Subsurface investigations may be needed to adequately determine geologic units where mapping cannot be accurately accomplished by surface data alone.

[41] Vacarro et al. 1998.

[42] Bauer and Hansen 2000.

- Examining observable strata in exposures along marginal streams on the edges of the groundwater recharge area, or in head scarps 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 maps and reports.
- Mapping and evaluating infrastructure such as road construction and landings with respect to relative water volumes flowing to or from a landslide or groundwater recharge area.
- Identifying surface water and stream drainages on or adjacent to deep-seated landslides and assessing the potential of water flowing to or away from a landslide and recharge area.

Although rarely applied in the forested environment, excavating test pits, driving soil probes, drilling monitoring wells, or using geophysical techniques such as seismic or electric resistivity methods can better characterize and reduce uncertainties about subsurface groundwater conditions where topographic indicators are inconclusive.

PART 6. ADDITIONAL ANALYSES FOR UNSTABLE SLOPES

Part 5 provides guidance for office and field reviews appropriate for both general practitioners and qualified experts. The preliminary assessment of landslide risk, and the potential for forest practices to affect risk, has occurred during the office and field reviews. A proposed forest practice in or around a glacial deep-seated landslide and its associated groundwater recharge area may require the additional analyses discussed in Part 6. These analyses may also be useful for other situations, such as assessing the landslide activity level of a bedrock deep-seated landslide or calculating the slope stability and failure potential of an individual unstable hillslope where a forest practice is proposed. The qualified expert identifies which analyses are needed on a site-by-site basis.
Part 6 provides guidance on:

- Deep-Seated Landslide Activity Assessment (6.1);
- Glacial Deep-Seated Landslide Assessment (6.1.1);
- Quantitative Field Assessment Methods for the Qualified Expert's Subsurface Investigations (6.2);
- Water Budget and Hydrologic Contribution to Glacial Deep-Seated Landslides (6.3);
- Computational Slope Stability Assessment Methods (6.4); and
- Runout and Delivery Assessment (6.5).

6.1 Deep-Seated Landslide Activity Assessment

A landslide activity assessment is an important component of evaluating potential landslide hazard and risk. Assessing past geomorphologic features and current landslide conditions can contribute to a qualified expert's geologic evaluation. 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.[43]

The *state of activity* refers to the timing of landslide movements and ranges from active (current or recent movement) to dormant (has not moved in recent decades or centuries) to relict (clearly developed in the geomorphic past under different conditions than currently present). If the conditions that contributed to prior movement are still present even though the landslide is dormant, it may become reactivated at a later time. The landslide may be considered stabilized if the

[43] Cruden and Varnes 1996.

conditions promoting failure have naturally changed to promote stability or if human intervention has protected against future movement.

Interpretation of vegetation cover, surface morphology, and toe modification by a stream all aid in determining the state of activity based on local knowledge of typical rates of biologic and geomorphic processes.[44] The characteristics described by Keaton and DeGraff (1996) have been successfully applied in the Pacific Northwest. A modified version is presented in Table 2. 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. 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 patterns 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 head cutting by extending in the upslope direction. A landslide can also widen or narrow in the direction perpendicular to movement, and can enlarge or diminish if its total volume is increasing or decreasing.

The *style of landslide activity* refers to the type of movement as shown in Table 1, Landslide Classification. Landslides may also occur as complex failures encompassing more than one type of movement. Deep-seated landslides may reactivate or develop successive or secondary landslides over time as compound failures.

Table 2. Guidelines for estimating deep-seated landslide activity level based on vegetation and morphology
(modified from Keaton and DeGraff 1996)

Active State	Main Scarp	Lateral Flanks	Internal Morphology	Vegetation+	Toes Relationships
Active/recent*	Sharp; unvegetated	Sharp; unvegetated streams at edge	Undrained depressions; hummocky topography; angular blocks separated by scarps	Absent or sparse on lateral and internal scarps; trees tilted and/or bent	Main valley Stream pushed by landslide; floodplain covered by debris; lake may be present
Dormant-distinct	Sharp; partly vegetated	Sharp; partly vegetated; small tributaries to lateral streams	Undrained and drained depressions; hummocky topography; internal cracks vegetated	Younger or different type or density than adjacent terrain; older tree trunks may be bent	Same as for active class but toe may be modified by modern stream

[44] Keaton and DeGraff 1996, Table 2.

Dormant-indistinct	Smooth; vegetated	Smooth; vegetated; tributaries extend onto body of slide	Smooth, rolling topography; disturbed internal drainage network	Different type or density than adjacent terrain by same age	Terraces covered by slides debris; modern stream not constricted but wider upstream floodplain
Relict	Dissected; vegetated	Vague lateral margins; no lateral drainage	Smooth, undulating topography; normal stream pattern	Same age, type, and density as adjacent terrain	Terraces cut into slide debris; uniform modern floodplain
*Recent is defined as being within the photo history or within the period of forest management.					
+Vegetative indicators are forest vegetation and not grasses, forbs, or shrubs. It is important to note that in most areas of western Washington, landslide scars re-vegetate within 15 years and may be difficult to detect from aerial photographs 10 to 15 years after the slide occurred.					

<u>6.1.1 Glacial Deep-Seated Landslide Assessment</u>

Following on the information in Part 6.1, below is a list of basic steps appropriate for a landslide activity assessment of a glacial deep-seated landslide and its associated groundwater recharge area. The steps provide a guide for assessing the risk associated with a particular landslide based on the level of landslide activity and how likely the landslide is to deliver sediment to public resources. Working through steps 1 through 3 will help the qualified expert determine if the next step should be 4, 5, or 6. Where it is appropriate to follow step 4, 5, or 6, step 7 may need to be accomplished as well.

1. Identify and map the glacial deep-seated landslide and associated groundwater recharge area.
2. Classify landslide activity using the protocol (modified from Keaton and DeGraff 1996) for deep-seated landslides as:
   - active;
   - dormant/distinct;
   - dormant/indistinct; or
   - relict.
3. Evaluate delivery potential if the landslide were to move for:
   - public safety (e.g., houses and public roads); and
   - public resources (water, fish, wildlife, and capital improvements).
4. If the landslide is relict or dormant/indistinct, and the potential for reactivation of any portion of the landslide by harvest within the groundwater recharge area is highly unlikely, then additional analysis may not be necessary. Documentation of this analysis may be provided by a letter, memo, or other appropriate form.
5. If the landslide is active/recent or dormant/distinct with a low delivery potential, perform a qualitative assessment of factors contributing to landslide movement including natural disturbance, channel influences, and historic patterns of timber harvesting within the groundwater recharge area.
6. If the landslide is active/recent or dormant/distinct and has moderate or high delivery potential, in addition to a qualitative assessment, the qualified expert may consider additional analyses such

as assessing whether a potential increase in groundwater recharge from timber harvest will affect the stability of the landslide.

7. Design appropriate landslide mitigation measures commensurate with delivery potential and hazard.

<u>6.2 Quantitative Field Assessment Methods for the Qualified Expert's Subsurface Investigations</u>

Subsurface investigations can be necessary for assessing proposed forest practices activities where more detailed information on landslide geometries, soil properties, or groundwater conditions is needed. They can be designed to gather data necessary to evaluate the landslide in accordance with the evapotranspiration, recharge, groundwater flow, and slope stability modeling.

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, limitations of budget and time, and risk potential.[45] A qualified expert should supervise the subsurface investigation so that the field activities are properly executed and the desired results can be achieved. Subsurface exploration to assess landslides is generally described by McGuffey et al. (1996) and summarized in the following paragraphs.

Test Pits. Shallow test pits can be dug by hand with a shovel. Backhoes or track excavators can advance test pits to depths of up to 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 identifying 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)[46] was developed as an inexpensive and portable alternative to other more expensive and less portable methods 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 has been empirically correlated with the Standard Penetration Test (American Society for Testing and Materials 2014).[47] 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..

Drill Rigs. Borings constitute a 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.). For long-term monitoring, 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.).

[45] McGuffy et al. 1996.
[46] Williamson 1994.
[47] Adams et al. 2007.

Geophysical Methods. Surface-based geophysical methods are used to collect 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.

6.3 Water Budget and Hydrologic Contribution to Glacial Deep-Seated Landslides

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 hydrogeologic system through precipitation in the form of rainfall, snowmelt, and other confined or unconfined groundwater sources. Not all precipitation, however, becomes groundwater; some is intercepted by vegetation or surface duff and debris and evaporates before reaching the ground or sublimates from the snowpack (see 6.3.1). Water that reaches the ground may run off directly as surface flow or shallow near-surface runoff, infiltrate 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 groundwater flow 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.

Further assessments for evaluating the influence of water to a glacial deep-seated landslide may be necessary when preliminary assessments suggest that the proposed forest practices activity increases the potential for contributing to movement of unstable landforms. The extent of the analysis depends on site-specific geological and hydrogeological conditions. The following discussions of evapotranspiration and groundwater flow may be useful to the qualified expert.

6.3.1 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.[48] 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. The various vegetation covers provide for varying balances of these fundamental water loss processes. The effects of evaporation on soil water budgets are relatively small compared to canopy evapotranspiration and interception.[49]

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

[48] Jassal et al. 2009.
[49] Bosch and Hewlett 1982.

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.[50]

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.[51]

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 snowfall collects in the 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[52]; snow or rain losses from these dense canopies can account for up to 50% of gross annual precipitation[53]. Moore and Wondzell (2005) estimated that interception loss in Pacific Northwest conifer forests ranged from 10% to 30%. Dingman (2002) reported similar values for Pacific Northwest plant communities, ranging from 21% to 35%, based on canopy characteristics and climate conditions. Hanell (2011) reported hydrologic modeling[54] that predicts a 27% decrease in evapotranspiration resulting from forest conversion to shrub for a site on the western Olympic Peninsula.

The proportion of rainfall intercepted by forest canopies is inversely related to both antecedent wetness and rainfall intensity. Gentle short-duration rainfall may be almost totally intercepted, while interception may account for as little as 5% of precipitation during intense winter storms.[55]

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 are 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.

<u>6.3.2 Groundwater Recharge and Groundwater Flow Modeling</u>

Groundwater recharge is difficult to measure directly, but several empirical and numerical methods exist for estimating recharge within unsaturated and saturated zones, including physical, tracer, and numerical-modeling techniques.[56] Recharge is commonly estimated by calculating the residual

[50] Campbell 1986.
[51] Hanks and Ashcroft 1980.
[52] Link et al. 2004.
[53] Dingman 1994.
[54] DHSVM; Wigmosta, Njssena and Stork 2002.
[55] Ramirez and Senarath 2000.
[56] Scanlon et al. 2002.

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 Model[57], the Precipitation Runoff Modeling System[58], and the Variable Infiltration Capacity Model[59]. 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.[60] 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.

6.4 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, and evaluate potential impacts of forest practices activities to public resources and public safety. This quantitative assessment may entail one or more methods. Limit equilibrium and numerical stability analyses may be used to evaluate the potential effects of increased groundwater recharge on glacial deep-seated landslides, 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. A two-dimensional limit-equilibrium analysis method may be applied to deep-seated landslides but can also be useful for smaller local site situations. Computation of the most critical failure surface is an iterative process generally supported by commercially available or public domain software.[61] Field-developed cross sections, back calculation of soil strength parameters, and estimation of groundwater elevations can be done where field accessibility is limited using the methods of Williamson (1994).

Development of a two dimensional model for analysis requires 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

[57] Bauer and Vaccaro 1987.
[58] Leavesley et al. 1983.
[59] Liang et al. 1994.
[60] Harbaugh et al. 2000.
[61] e.g., LISA, DLISA, STABL, SLOPE-W.

surface) in the absence of field data acquired from boreholes or with other geotechnical methods;
- Location and 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 from 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 unit properties, failure plane geometries, groundwater table elevations) such that the reconstructed original slope fails. These exercises are useful for evaluating reasonable strength parameters of subsurface materials, likely failure plane geometries, and groundwater table elevations in the absence of real data or field indications. Two-dimensional models can also be used to evaluate downslope material impacts to public resources and threats to public safety, as well as upslope impacts in situations where retrogressive failure mechanisms are suspected. Turner and Schuster (1996) and 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.

6.5 Runout and 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 forest practices are proposed on a rule-identified landform, the likelihood that sediment and debris would travel, or runout, far enough to threaten a public resource or public safety should be evaluated.

The following information is provided in 6.5:
- 6.5.1 provides an overview of the common landslide types associated with rule-identified landforms.
- 6.5.2 and 6.5.3 cover the factors to consider in a debris flow runout assessment. Shallow-rapid landslides are discussed because they are the single most common type of landslide and because extensive research about the factors influencing runout has been accomplished over the past three decades.
- 6.5.4 contains summaries of scientifically-derived methods for predicting shallow-rapid landslide deposition and runout distances. Predictive methods for calculating deep-seated landslide runout are not discussed because they are still under development by the scientific community.
- 6.5.5 provides a brief overview of the use of barrier trees for mitigating potential landslide delivery.
- 6.5.6. provides an overview on how LiDAR can be used to evaluate potential runout based on past deep-seated landslide deposits.

Runout and delivery distance, the total distance landslide debris is transported and deposited, depends on a combination of processes and topography. For example, debris flows are highly mobile and can move miles in steep confined channels. Deep-seated landslides can move anywhere from a few feet 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.

Factors to consider in a runout and delivery assessment may include the following depending on the landform and landslide type:

- Initial failure volume of a landslide;
- Type of failure mechanism;
- Nature of the geologic material involved;
- Topographic features of potential runout paths;
- Historic landslide activity and runout characteristics in the area;
- Proximity to a public resource or safety concern; and
- For deep-seated landslides, observed deformation characteristics of nearby landsides with comparable geologic/geomorphic attributes.

Because each site has a unique set of geomorphic characteristics, it is not practical to provide prescriptive guidelines to predict delivery. An evaluation of deliverability will require a field assessment and professional judgment in landslide processes and mobility. However, professionals often rely on observed patterns and simple evaluations to determine whether an extensive delivery assessment and runout calculation is needed. For example, deposition generally will not continue where the channel becomes unconfined and transitions to a gradient of 6% or less. Also, historical deposits may reveal patterns. If a debris fan exists at the base of a confined channel, the extent of future deposition may predictably occur close to the existing debris fan. Or if many shallow-rapid landslides have occurred in the area, the deposition in that area will likely mimic that history.

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 use appropriate geometric relationships from the scientific literature. Historical patterns can be evaluated by gathering aerial photos and landslide inventories. LiDAR data is valuable for mapping evidence of previous deep-seated and larger shallow-rapid landslide deposits, and identifying likely initiation points during initial investigations. Site visits can verify potential initiation points and depositional areas, and are useful for measuring previous landslide events.

In a situation where the potential for delivery is questionable, it is best to have a qualified expert examine the site and evaluate the likelihood of delivery. If forest practices are planned on a potentially unstable landform with questionable or obvious potential to affect a public resource or public safety, a geotechnical report written by a qualified expert is required.

<u>6.5.1 Landslide Types Associated with Rule-Identified Landforms</u>

High hazard landforms and associated geomorphic criteria provide the basis for the rule-identified landforms (refer to Part 4 for more information on rule-identified landforms). Inherent in the assessment of rule-identified landform presence is the detection of these criteria as well as estimating landslide travel distance relative to the location of at-risk public resources or areas that could result in a risk to public safety. Once a potential rule-identified landform has been identified, considerations are made as to the type of landslide that might occur, the rate of movement, potential volume, flow properties, and the topography of runout paths (e.g., gradient, confinement) before delivery potential can be determined.

The type of landslide and travel distance that can occur is typically constrained by factors such as landform scale, soil depth, and topographic features within and below an unstable landform. For example, the width and depth of shallow landslides from bedrock hollows rarely exceed tens of meters, and failures typically occur at the soil-bedrock interface where soil depths are typically one meter or less.[62] Failures are commonly translational, move very rapidly, and accumulate additional materials significantly with travel distance unless they enter confined channels and continue to propagate as debris flows. Landslides that initiate within inner gorge landforms are predominantly shallow with rapid sediment delivery. Inner gorge landslide volumes tend to be relatively small compared to convergent headwall landslides, and they may not propagate down the receiving channel as debris flows. Conversely, active deep-seated earthflows may move less than a few feet per year. They can deliver sediment to streams, but rarely are considered a high public safety hazard due to the typically episodic and slow rate of movement. However, secondary failures along lateral stream channels and on deep-seated landslide toes may be subject to rapid debris flow initiations. Table 3 identifies common associations between rule-identified landforms, mass movement modes and rates, and composition and relative depth of the failed mass.

Table 3. Landslide types associated with rule-identified landforms.

Rule-identified Landform	**Typical mass movement mode(s)**	**Common landslide types**	**Material / Depth of failure**
Bedrock hollow	Translational and rapid	Debris slides and debris flows	Colluvial soil mantle / Shallow
Convergent headwall	Translational and rapid	Debris slides and debris flows	Colluvial soil mantle / Shallow
Inner gorge	Translational or rotational, rapid or slow	Debris slides, debris flows, debris avalanches, shallow or deep slumps	Colluvial soil mantle, residual soil mantle, bedrock outcrops; glacial, fluvial, and lacustrine deposits / Shallow
Deep-seated landslide toe	Rotational or translational, rapid or slow	Debris slides, debris flows, debris avalanches, deep-seated slumps, earth flows	Colluvium / Variable depths
Outer edges of meander bends	Translational and rapid	Debris slides, debris flows, debris avalanches, shallow or deep slumps	Colluvial soil mantle; glacial, fluvial, and lacustrine deposits / Shallow
Groundwater recharge areas associated with glacial deep-seated landslides	Rotational or translational, rapid or slow	Deep-seated slumps, debris flows, debris avalanches, earth flows	Glacial, fluvial, and lacustrine deposits / Variable depths

6.5.2 Factors Influencing Debris Flow Runout

Debris flow runout distances within valleys or inner gorges and across debris fans, have been studied by empirical observation in the Pacific Northwest.[63] It has been generally demonstrated that basin topography controls the flow types that reach a fan at the base of the hillslope, causing fan

[62] Dietrich et al. 2007

[63] e.g., Benda and Cundy 1990; Robison et al. 1999; May 2002; Guthrie et al. 2010.

gradient and the presence of various deposits to be somewhat predictable.[64] Predictive models based on simple height and gradient parameters have been developed, and several are described in 6.5.4.

There is considerable variability in the empirical observations. A debris flow may stop as a discrete deposit, debris fan, or sediment wedge above wood accumulations; or it may deposit gradually along a significant length of channel. In general, gradients are steep at initiation sites, remain steep where scour-to-bedrock occurs, and moderate in transport and deposition areas. Figure 28 is a generalized illustration of debris flow processes.

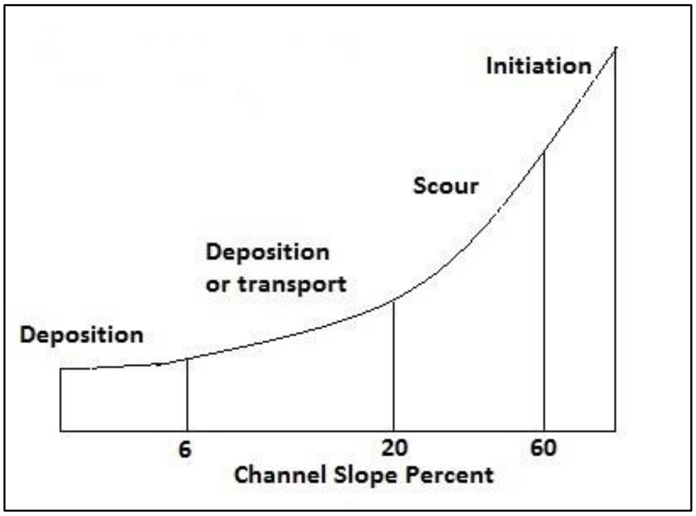


Figure 28. Debris flow characteristics relative to channel slope (adapted from Benda et al. 1998).

Initiation and Gradient
Initiation typically occurs on hillsides steeper than 70% but sometimes occurs on slopes as low as 60%.[65] When channel gradients drop below 20%, debris flows no longer cause significant scour and start to lose their momentum. On slopes gentler than about 5% to 7%, debris flows further slow and the solids entrained in them (rock, soil, and organic material) tend to settle out and deposit. Travel distance 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.

Many data sets show significant overlap in the gradient ranges of erosional and depositional behavior where erosion can occur at lower slope angles (approximately 3% to 10%) and deposition can occur at higher gradients (55% to 80%).[66] Figure 29 displays detailed field data that demonstrates both the real differences and the large overlap.[67] Two of the larger data sets show that net deposition generally occurs from 14% to 21% [68] and from 21% to 27%[69]. Guthrie et al. (2010) specifically conclude that, "[d]eposition and scour occur on steeper and flatter slopes, respectively,

[64] e.g., Melton 1965; Scheidl and Rickenmann 2010.
[65] Robison et al. 1999.
[66] e.g., May 2002; Guthrie et al. 2010.
[67] May 2002.
[68] Hungr et al. 1984.
[69] Guthrie et al. 2010.

than previously reported…”, in part because of the detailed field work they conducted. Benda and Cundy (1990) found that debris flows from their Oregon Coast Range study sites almost always stop within the confined channel network where the channel gradient drops below about 6% and where the tributary junction angle is greater than 70 degrees. They do note that the deposit typically continues 150 to 500 feet further downstream. A conservative approach would be to predict deposition only after 1000 feet of a channel with a gradient of less than 6%.

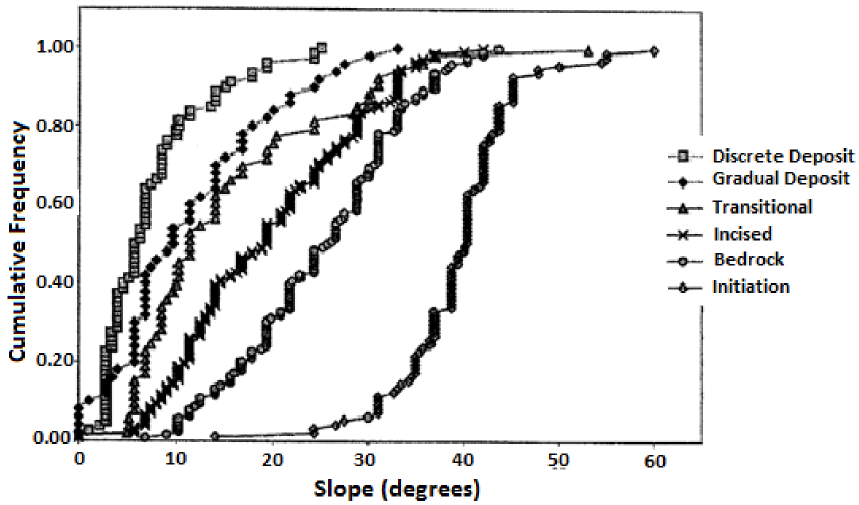


Figure 29. Slope distributions for depositional zones (discrete and gradual), transitional zones, erosional zones (incised and bedrock), and initiation sites for debris flows (from May 2002).

The overlap between erosional and depositional behavior within generally confined valley settings means that factors other than just channel gradient are influencing debris flow runouts. Several studies[70], but not all[71], find that runout length has been strongly correlated with event volume such that larger events travel further than smaller events.

Confinement

Channel confinement, the ratio of valley width to channel width, plays a role in debris flow runout. For example, Lancaster et al. (2003) and Benda and Cundy (1990) found that deposition may begin at higher channel gradients where confinement is low, while erosion may continue at lower channel gradients where confinement is high. Confinement alone appears to account for much of the overlap in gradient between erosional and depositional behavior, and in turn exerts influence on runout lengths. Additionally, Fannin and Rollerson (1993) demonstrated that a ratio of channel width to channel gradient delineated the zones of scour and deposition.

Saturation

Initial water content of the landslide mass and the amount of water in the receiving channel both influence landslide saturation. Saturation of the landslide and the resulting debris flow influences mobility, which is a function of landslide speed and travel distance. Considering that rain, snowmelt, or other water inputs trigger the majority of landslides in the Pacific Northwest, 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 on

[70] e.g., May 2002; Sheidl and Rickmann 2010.
[71] Prochaska et al. 2008.

the hillslope and typically do not travel across large areas of flat ground. However, since most landslides occur during storm events, a large proportion of debris slides do reach flowing channels and create the opportunity to entrain enough water to become debris flows that can travel considerable distances in steep or moderate channels.

Lithology

Lithology and its influence on soil development may affect runout distances. Qualified experts in Washington State have noted that debris fans are steep and short where local material includes large boulders, and that fine-grained silt loams may liquefy and flow across nearly level surfaces. Krogstad and O'Conner (1997) noted that relatively cohesion-less soils in the South Fork Skokomish produced long runout distances but had limited scour ability. However, the relationship between lithology and/or soil type and runout distance has not been systematically studied. Qualified experts are encouraged to conduct empirical studies (e.g., a landslide inventory with emphasis on runout and delivery) to better predict the probability of delivery and impact in a local area for an individual lithology.

Vegetation

Runout distances are also influenced by standing forest vegetation along the runout path. Using empirical data, May (2002) reported shorter runout lengths in older stands. She found that large trees or large woody debris scoured or entrained by debris flows may reduce runout distances.[72] Lancaster et al. (2003) created simulations designed to mirror natural debris flows and concluded that without wood, basin sediment yield increases, runout length increases, and deposits are concentrated in low-gradient reaches. See 6.5.5 for further information on influence of trees along the runout path.

Potential for debris flows to evolve into debris floods or hyper-concentrated flows

The prediction of both channelized and unconfined runout distances is complicated by the potential for debris flows to evolve into debris floods and/or hyper-concentrated flows. A debris flood as classified by Hungr et al. (2001) is a torrent with substantial transport of coarse sediment – a debris flow with a higher water content. Hyper-concentrated flow is a slurry of finer particles, usually with a predominance of sand and coarse sand with some gravel.[73] Pierson and Scott (1985) describe the transformation of debris flows to hyper-concentrated flows from the 1980 eruption of Mt. St. Helens as they traveled down the Toutle River. Their basic hypothesis is that the debris flow entrained additional channel water as it flowed down valley, which caused coarser materials to settle out and become bedload, while the sand-rich hyper-concentrated flow increased its velocity and pulled ahead of the coarser materials. (In this relatively channelized environment, a tail of debris flow materials actually deposited on top of the hyper-concentrated flow deposits.) They describe the hyper-concentrated flow deposits as poorly sorted (i.e., less than typical alluvial materials but more so than debris flow deposits) sands, with faint horizontal stratification but an overall massive appearance, and thin lenses of gravel.

<u>6.5.3 Debris Fan Formation</u>

Identifying debris fans and understanding their formation is part of a runout assessment. The presence and size of a debris fan indicates past accumulations of sediment deposits and debris flows. Fans may be constructed from stream deposits (alluvial fans), debris flow deposits (debris

[72] May 2002; Lancaster et al. 2003; Robison et al. 1999.

[73] Beverage and Culbertson 1964; Pierson and Scott 1985.

fans), or multiple depositional processes (composite fans). They are typically located at the mouths of canyons. They can also form anywhere a channel loses sufficient confinement to promote deposition as well as at the base of steep slopes.

Landslide runout distances and the amount of direct delivery are influenced by the presence or absence and size of fans. These factors are in turn influenced by the contributing basin and valley width where the fan forms. May and Gresswell (2004) found that smaller drainages had lower recurrence rates of debris flows which led to smaller fans, and where valley width was narrow no fans were present (or were truncated) because rivers and streams eroded the fans faster than they were created. Debris flow delivery potential, particularly from small and confined drainages across narrow valley bottoms, is likely to be high. Conversely, larger drainages had higher recurrence rates which led to larger fans, particularly where valley widths were greater. In addition, the higher recurrence rates down higher order channels sometimes precludes debris flows from continuing to bulk up in the lower channels because they are already devoid of material. Delivery, from larger drainages across wider valley bottoms, may be limited by deposition on a large fan where the main stem is less likely to, or less capable of, eroding.

The processes that create a fan surface (e.g., alluvial or debris flow) can be predicted by the fan gradient and the "Melton number" of the watershed above the fan. The empirical studies that have contributed to this work are summarized in Scheidl and Rickenmann (2010). The Melton number stems from Melton (1965), although it was not identified as such in the original reference. It is calculated by dividing the height of the watershed taken as the maximum elevation, minus the elevation of the fan apex by the square root of the area of the watershed. An ESRI user forum provides clarification of the Melton number, also called the Melton Roughness Number.

Figure 30 from Scheidl and Rickenmann (2010) displays average fan slope on the vertical axis and the Melton number on the horizontal axis. Three diagonal lines labelled "A" are derived from previous empirical studies, and represent observed transitions between purely alluvial processes and mixed processes. The two diagonal lines labelled "B" are also derived from previous empirical studies, and represent observed transitions between mixed processes and debris flow processes.

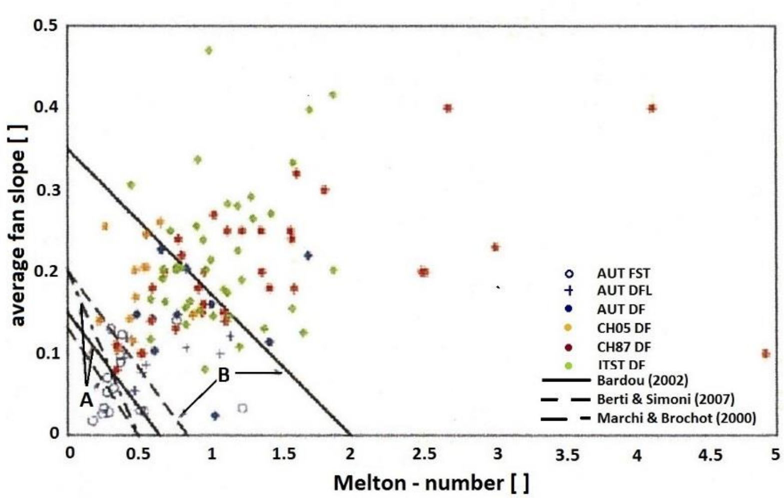


Figure 30. Relation between average fan slope (S_f) and Melton number (M_E) for European landslide datasets.

Threshold lines (A and B) distinguish zones with dominant process types, and symbols represent three process types: DF = debris flow, DFL = debris flood, FST = fluvial sediment transport (Scheidl and Rickenmann 2010).

6.5.4 Methods and Models for Predicting Shallow-Rapid Landslide Runout and Delivery

This part contains brief summaries of selected methods, listed roughly in chronological order of publication, which landslide scientists have developed for estimating shallow-rapid runout distances for various landslide types. Although it is not an exhaustive list, these are included because of their applicability on forest lands in the Pacific Northwest. *If reviewed in their entirety*, they may contain helpful information to supplement professional judgment and experience.

Empirically-based methods for assessing debris flow hazards rely on quantitative data, whereas numerical simulation models use mathematical equations and procedures to arrive at estimates for erosion and depositional processes. Those summarized below are based on data from shallow-rapid landslide events occurring in the Pacific Northwest and British Columbia, and in most cases derived from hundreds of observations. The simplest models can be applied at the field scale using clinometers and range finders in conjunction with digital elevation data. The methods should be applied to conditions similar to those on the site being assessed.

Other methods not listed here may be viable and the appropriate method for a site is left to the analyst. While many of them are at the technical level of a qualified expert, several may be useful for a general practitioner such as the 2003 guidance in the methods in the Tolt Watershed Analysis[74] and the Oregon Department of Forestry's Technical Notes 2 and 6[75].

Benda and Cundy 1990

Benda and Cundy's 1990 article, *Predicting deposition of debris flows in mountain channels*, describes an empirically-derived method for predicting potential impacts from debris flows. It is typically referred to as the Benda-Cundy model. The technique uses easily measured topographic criteria (channel slope, channel confinement, and tributary junction angle) to calculate debris flow runout distance from the point of initiation and the final deposition volume of debris flows in steep mountain channels.

The method was developed and tested using data from debris flows in the Oregon Coast Range and the Washington Cascades. An Oregon Department of Forestry study of 361 debris flows[76] validated the model, and numerous resource professionals in the Pacific Northwest have reported good success in applying it to mountain debris flows regionally.

Tolt Watershed Analysis 1993

The Tolt Watershed Analysis[77] contains mass wasting prescriptions for determining landslide delivery potential based on physical processes from empirical results in northwestern Washington and western Oregon. The *Mass Wasting Delivery Flow Chart Road and Harvest* procedure in the analysis is summarized in the following paragraph. Although intended for use in the Tolt River basin, the method can be applied in other similar physiographic provinces.

[74] Weyerhaeuser Timber Company 1993.
[75] ODF Technical Note 2, 2003 and ODF Technical Note 6, 2003.
[76] Robison et al. 1999.
[77] Weyerhaeuser Timber Company 1993.

In this method, delivery potential for a hypothetical mass failure is determined by considering topographic conditions at the failure initiation site, along the runout path, and at the deposition zone. The assessment is based on slope gradient changes as material travels downslope. If a failure becomes channelized, it becomes a debris flow deposit. As debris flow deposition continues downslope, the potential for a dam-break flood is evaluated based on channel confinement. Estimated runout distances are provided as outputs from the above hillslope and up-channel geomorphology. A description and flow chart illustrating the method is included in the mass wasting prescription chapter. The Tolt Watershed Analysis is available on the Washington State Department of Natural Resources web site at https://fortress.wa.gov/dnr/protectionsa/ApprovedWatershedAnalyses.

Coho and Burges 1994

Coho and Burges identified and characterized a relatively infrequent but distinctive and destructive type of flood wave known as a dam-break flood that can occur and travel long distances in forested watersheds. The study relied on data from observed dam-break floods in the Olympic Mountains and Washington Cascades. Their report contains a simple strategy for evaluating the dam-break flood potential and runout distance with easily measured field and topographically derived criteria (valley width, channel gradient, presence of sufficient small organic debris, and riparian condition) to identify susceptible stream channels and the affected downstream extent.

Dynamic Analysis (DAN) 1995

To understand the internal strength, erosion ability, and rheology of a landslide, Hungr (1995) developed a numerical model called Dynamic Analysis (DAN). The model was originally developed as a tool for modelling post-failure motion of rapid landslides and can be used for predicting runout. It allows for the selection of a variety of material rheologies, which can vary along the slide path or within the slide mass. The model is calibrated by back analysis and has been widely used in many inverse or back analysis calculations[78] and has been improved over several years.[79] Currently, there are two models used worldwide: DAN-W (release 10) and DAN3D. Both models work best for rock and debris avalanches and but have utility with debris flows.[80] The model was validated on mine tailing failures in southern British Columbia.

Corominas 1996, Hunter and Fell 2003

Corominas (1996) provided an equation for estimating a travel distance angle based on the type of landslide, slide volume, and degree of confinement. Hunter and Fell (2003) reanalyzed the data and found that for landslides smaller than one million cubic yards, a size typical in Pacific Northwest forests, the following equation is more applicable. For unconfined shallow landslides, the volume and expected height of the landslide from topographic data is applied as follows:

$$\frac{H}{L} = 0.77(\tan\alpha_2) + 0.087$$

[78] Pirulli et al. 2003, Revellino et al. 2004.
[79] Shu et al. 2014.
[80] Oldrich Hungr, personal communication, June 2015.

H and L are the landslide height and travel distance respectively; α_2 is the downslope angle (Figure 31).

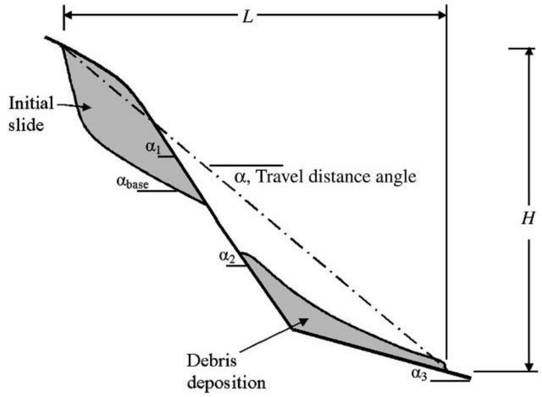


Figure 31. Cross section showing travel distance, travel distance angle, and slope geometry (Hunter and Fell 2003).

The equation above could be applied to unconfined shallow-rapid landslides.

Acme Watershed Analysis 1999

A sediment delivery model for open slopes was developed for the Acme Watershed in Washington.[81] It is based on empirical observations that debris flows can develop a coulomb-viscous rheology controlled by the shear stress of the moving debris and the resistance to that stress, which determines the critical thickness (the landslide thickness at deposition). Use of the model requires assumptions regarding landslide initiating volume, moisture content of the debris, gradient of the slope over which the debris is transported, yield strength of the debris, and slope roughness as influenced by trees, stumps, and surface morphology. The model should not be applied to thin soils on hillslopes greater than 70%. Other model limitations are described in the Acme Watershed Analysis mass wasting document. Model predictions are presented in tabular form to aid the field practitioner in using a range of hillslope gradients and landslide volume classes. The Acme Watershed Analysis is available on the Washington State Department of Natural Resources web site at https://fortress.wa.gov/dnr/protectionsa/ApprovedWatershedAnalyses.

UBCDFLOW (University of British Columbia) 2001

The UBCDFLOW model is based on field observations of landslides from clearcuts.[82] Four sites in coastal British Columbia with 449 events were used to develop the model for predicting debris flow travel distance in confined and unconfined (open) slopes. All of the sites were glaciated and included areas in western Vancouver Island with similar geology and climate as Washington State. The study found that the total entrainment volume along runout paths does not equal the total volume deposited. Inspection of the survey data showed that "…reach morphology exerts a strong influence on flow behavior."[83] The model, complete with a user guide and tutorial, is available at http://dflow.civil.ubc.ca/.

Oregon Department Forestry Technical Guidance 2003

[81] Crown Pacific Limited Partnership 1999.
[82] Fannin and Wise 2001.
[83] Ibid.

The Oregon Department of Forestry developed technical guidelines to maintain regulatory compliance with the landslides and public safety rules for shallow, rapidly moving landslides. The guidance is detailed in two technical documents[84] to guide forest practices activities where shallow landslide hazards exist, and is based on published empirical data from the Pacific Northwest and British Columbia.

- Technical Note Number 2, *High Landslide Hazard Locations, Shallow, Rapidly Moving Landslides and Public Safety: Screening and Practices*, is intended for engineers and foresters in conducting the initial public safety screening; i.e., to determine if an operation is subject to shallow rapid landslides and Oregon's public safety rules. Part B provides guidance on how to determine the downslope extent of regulatory Further Review Areas for proposed operations. It provides gradient, confinement, and runout metrics for channelized and open slope topography.
- Technical Note Number 6, *Determination of Rapidly Moving Landslide Impact Rating*, assists geotechnical specialists in completing detailed, field-based investigations of associated upslope hazards and downslope public safety risks. The guidance draws upon Benda and Cundy (1990), Robison (1999), and Benda (1999). Although it is intended for use within the context of Oregon's regulations, it can be applied throughout the Pacific Northwest for predicting shallow-rapid landslide runout and delivery potential.

Hungr et al. 2005; Corominas et al. 2014

Evaluating where previous landslides have deposited is applicable to forecasting the extent of possible future debris flow hazards.[85] Using historic landslide inventory data is appropriate because it is based on field observations of past landslide runout behavior.[86] These measurements are used to forecast future runout distances. However, the shortcomings of this technique include the fact that old deposits may be modified by more recent events that erode or cover them up, and the technique is best to use in areas where large events occur infrequently.[87] Additionally, this technique may not be transferable to other areas because the size, type, and driving forces may be different for future events in other locations.[88] Because landslide deposits have similar textural properties to glacial deposits (e.g., unsorted and unstratified), Hungr et al. (2005) suggest that careful evaluation of the deposits is necessary to differentiate between the two in glaciated areas.

Prochaska et al. 2008

Prochaska et al. (2008) provide a simple topographic model that utilizes parameters that can be measured without estimating initiation point, initiation volume, or the down-valley bulk-up process. The model only applies to debris flows that reach a fan apex. Prochaska et al. (2008) do not present a final formula and do not show any of their calculations, nor do they provide sufficient data to check any of their calculations. For that reason, a user-friendly formula is provided below.

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[84] ODF Technical Notes 2 and 6, 2003.
[85] Hungr et al. 2005.
[86] Corominas et al. 2014.
[87] Corominas et al. 2014.
[88] Ibid.

The model predicates on determining the elevation of the highest point in the drainage and the elevation of the apex of the fan. The half-height, which is the elevation half way between the first elevations, is located on the stream in the example below. β is the angle in degrees between the half-height and the MAX and fan apex; it is calculated by measuring the horizontal distance to the fan apex. α equals 0.88 times β where α is the angle in degrees from 0.5 times height to the end of the runout. Using α to project the runout down the fan surface requires knowing the fan gradient. A licensed professional engineer created a formula where β can be calculated in percent and the fan gradient measured in percent; the calculation then requires arctan to convert β to degrees before multiplying by 0.88, and then tan to convert the α value back to percent. α does not actually appear in the formula; it is present as [(arctan (β%))*(0.88)].

Runout = 0.5 h [(β%-f%)/((tan[(arctan (β%))*(0.88)] – f%) -1]

Where:
h = elevation of highest point of the drainage – elevation of fan apex
β% = 0.5 h / horizontal length between the midpoint of elevation and the fan apex (this value is a decimal %, not a degree)
f% = average gradient of the fan in decimal %

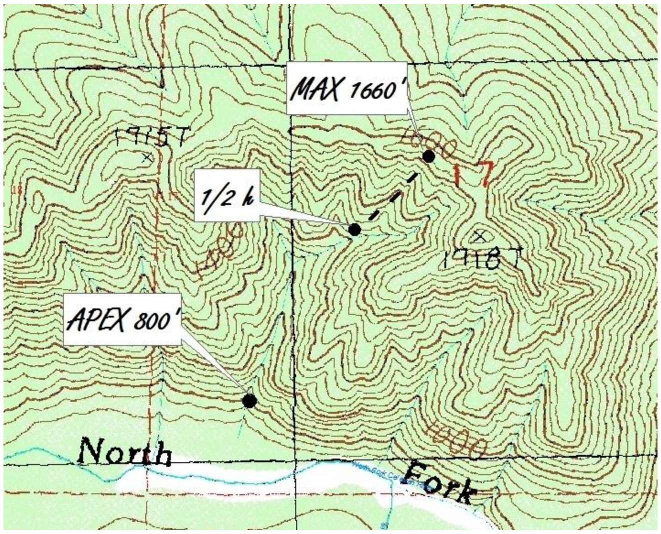

Figure 32. From USGS 7.5' Deadmans Hill Topographic Quadrangle.
Maximum elevation of the small watershed is 1660 feet. Fan apex is 800 feet. The variable 1/2h (labeled) equals 1230 feet. B% is 0.243 (calculated from topo sheet); f% is 0.10 (field measured). Runout is 163 feet as estimated by the formula presented above.

Guthrie et al. 2010

Using over 1700 field observations supplemented by aerial photography interpretation in British Columbia on Queen Charlotte and Vancouver Islands, Guthrie et al. (2010) examined landslide deposits from open sloped and channelized debris flows. They used these data to develop a sediment balance approach (erosion versus deposition) to estimate runout in similar terrain. Their study found that deposition occurred on open slopes between 32% and 45%.

These are steeper angles than those found in other local studies.[89] Channelized debris flows deposited between 21% and 27%. The study also determined that one of the reasons for the steeper deposition slope angles was boundary trees. After traveling through logged slopes, most of the debris flows stopped entirely within 150 feet of the boundary in 72% of the examined flows.

6.5.5 Runout Mitigation Strategy: Barrier Trees

If landslide initiation site avoidance, application of rule-required RMZs, or other mitigation measures appear inadequate, debris flow runout may be further mitigated by leaving barrier trees in the low gradient depositional reaches of debris flow-prone streams. Barrier trees can be retained to encourage the deflection, deceleration, and/or deposition of debris flows[90] and dam-break floods.[91]

Riparian forests adjacent to larger channelized streams add woody debris and act as natural barriers to debris flows, independent of management practices. Furthermore, standing trees in mature forests may promote more rapid deposition, which can minimize landslide size.[92] Therefore, leaving mature trees where forest practices rules do not require RMZs (i.e., portions of Type N waters) may reduce landslide impacts. Large trees near the areas of debris flow deposition (such as on fans at the mouths of steep tributaries) may be the most effective in inhibiting movement and protecting structures and highways.[93] Trees can also be retained or restored on the sides of a potential debris flow runout path to constrain its lateral movement and protect structures on a debris fan.[94]

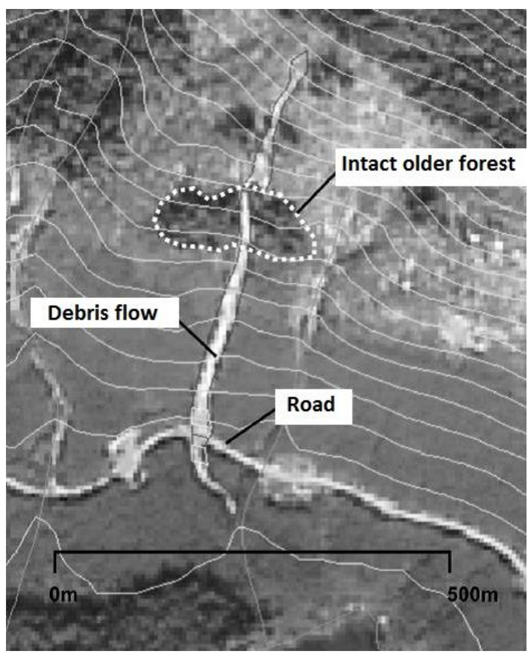

Figure 33. Debris flow path (from bottom to top of the photo) showing width changes from traveling through an older forest stand (Guthrie 2010).

[89] Hungr et al. 1984: Fannin and Wise 2001; Horel 2007.
[90] VanDine 1996, Benda et al. 1998, Guthrie et al. 2010.
[91] Coho et al. 1994.
[92] Guthrie et al. 2010.
[93] Benda et al. 1998.
[94] Eisbacher and Clague 1984.

Figure 33 shows the path of an open slope debris flow initiated from a clearcut that traveled through a small stand of older forest to where it narrowed considerably following the contact with the forest edge. The debris flow increased in width as it entrained additional material below the intact forest, and a slight reduction in width is evident below the road before it stopped at the lower gradient valley floor.

6.5.6 Deep-Seated Landslide Runout Evaluation

The same tools used to identify deep-seated landslides (Parts 2.3, 5.1.4) can be used by the qualified expert during an evaluation of runout distances. For example, landslide deposits are mapped with variable accuracy on geologic maps and landslide inventories. They are more accurately mapped during field reconnaissance and with high-resolution topographic data such as LiDAR bare earth DEM. The extent of past landslide deposits at a given site, or in similar geologic materials in the vicinity, may indicate the extent of future landslide deposits[95]. For instance, Figure 34 shows the approximate runout distance of neighboring glacial deep-seated landslides in the North Fork Stillaguamish River valley. When assessing the potential runout distance of a deep-seated landslide, it is important to examine not only the immediate vicinity but also the larger landscape (at least at 1:24,000 scale) for evidence of past landslide deposits. In cases where recent fluvial erosion or deposition has eroded or buried older landslide deposits, the true extent of older deposits may be underestimated by current morphology. A runout evaluation may be used to supplement other site-specific assessments such as landslide chronology, stratigraphy, mechanics and river channel migration.

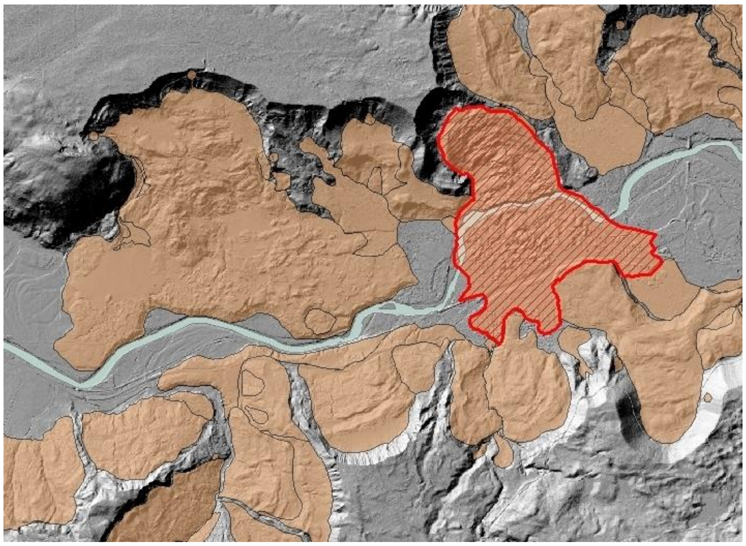

Figure 34. LiDAR derived image revealing past glacial deep-seated landslide deposits in the Stillaguamish River valley. The crosshatch polygon marks the approximate extent of the 2014 SR 530 landslide. (DNR 2016).

[95] Schulz 2007.

PART 7. SYNTHESIS OF RESULTS, EVALUATION, AND GEOTECHNICAL REPORTS

This part is intended for qualified experts when preparing geologic evaluations. The following questions and guidance are provided to assist the qualified expert when synthesizing the information assembled in the office review and field assessment, and can be useful when preparing a geologic evaluation or report.

7.1 Synthesis and Evaluation

Consideration of the following questions may help to synthesize findings:

- Based on an analysis of available information, what is the geotechnical interpretation of physical processes governing unstable slope/landform movement, mechanics, and chronologies of each identified feature?
- 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?
- What are the scientific limitations (e.g., collective understanding in the scientific community of landform physical processes) that might influence the identification, delineation, and interpretation of unstable slopes and landforms?
- What is the potential for material delivery from each relevant unstable slope and landform to areas of public resource sensitivity or where public safety could be threatened?
- What are the relative roles of natural processes and land management activities in triggering or accelerating instability?
- 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?

Models for slope stability and sensitivity (see 6.4) may be used to support analyses of potentially unstable slope and landform characteristics and mechanics. If modeled results are included in reports, they should be accompanied by a statement of model assumptions, analysis 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.

To provide the necessary information for DNR to evaluate a proposal, the analytical methods and processes used by the qualified expert to identify, delineate, and interpret unstable slopes and landforms should be described in their reports along with information sources, data processing techniques, and the limitations of analysis results. 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. Reports may also 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.

Confidence levels in the slope stability analysis and model results 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 public resource, public safety, and liability risks associated with implementing a project.

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 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.

7.2. Geotechnical Reports

When harvesting timber or building roads on potentially unstable slopes, a written report is required to be part of the FPA to explain whether the proposed forest practices are likely to affect slope stability, deliver sediment and debris to public resources, or threaten public safety. For the purposes of this Board Manual section, such a report is called a "geotechnical report." The geotechnical report is prepared by a qualified expert and must meet the requirements described in WAC 222-10-030(1). If the FPA is classed as a Class IV-special, the applicant must also include a SEPA checklist and additional information listed in WAC 222-10-030.

Qualified experts must be licensed with Washington's Geologist Licensing Board. Specific rules addressing a geologist's professional conduct are listed in WAC 308-15-140(1) and (2). For more information about the geologist licensing process, refer to WACs 308-15-010 through 308-15-150, or see the Geologist Licensing Board's web site at www.dol.wa.gov/business/geologist. The education and field experience on forest lands is required, in addition to the appropriate geologist license.

The qualified expert is encouraged to consult with DNR Region geologists when preparing a geotechnical report to ensure important elements are covered. Region contact information is available on DNR's web site at http://www.dnr.wa.gov/contact-us.

The report should be as detailed as necessary to address these and any other relevant elements:

(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 and relevant weather conditions.

(b) *Describe the geographic, geologic, and soil conditions of the area in and around the application site*. Include a vicinity map and geographical location of the proposal area and, where appropriate, the distance and direction from the nearest municipality, local landmarks, and 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.[96]

(c) *Describe the potentially unstable landforms within and around the site*. Include a general description of the topographic conditions of the site. 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 mass wasting processes associated with each identified landform, as well as detailed observations of past slope movement and indicators of potential future landslide activity.

Relevant field observations, important features, and sampling locations used in project analysis can be displayed on a map in the geotechnical report. Relevant photos and data-sampling observation points should be geo-referenced (i.e., with GPS waypoints) and mapped. GPS track locations of field traverses can indicate which portions of the project site were evaluated. In addition, field-derived cross sections and geologic profile locations should be geo-referenced. Assign a unique alphabetic or numeric identifier label to each landform or observation point relevant to the assessment and note these on a detailed site map of a scale sufficient to illustrate site landforms and features. Where the proposal involves operations within 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 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 slopes and 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 landslide/slope movement. Explicitly state the basis for conclusions regarding slope movement. Conclusions are 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 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 are 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,

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

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 downslope 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. Some geotechnical reports 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.

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. 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.

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.
Complex deep-seated landslide	A combination of at least two types of movement (slide, fall, topple, flow or spread) within the same landslide.
Compound deep-seated landslide	A large host landslide that encompass smaller secondary slides during a single event or over time.
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	A plane or surface that marks a change in physical or chemical characteristics in a soil or rock mass (bedding, joint, fracture, or fault plane).
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 (Et) 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.

Fluvial	Pertains to the deposits and landforms produced by the action of a river or a stream.
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. Glacialacustrine 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	Matrix-supported, non-sorted, non-stratified sediment carried or deposited by a glacier. If over-ridden by a glacier, it can become compacted. Compacted till can be nearly impermeable and can sometimes perch water.
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.
LiDAR	Light Detection and Ranging. A detection system that works on the principle of radar, but uses light from a laser.
Lithology	The study of general physical characteristics of rocks.
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.
Rheology	The branch of physics that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids.
Seismic method	A geophysical method using the generation, reflection, refraction, detection and analysis of seismic waves in the earth to characterize the subsurface.
Soil	The unconsolidated mineral or organic material on the immediate earth's surface that serves as a natural medium for the growth of plants.
Strata	Plural of stratum.
Stratum	A section of a formation that consists throughout of approximately the same material. A stratum may consist of an indefinite number of beds, and a bed may consist of numberless 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.
Water table	The surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric. The location of this surface is revealed by the level at which water stands in a shallow well open along its length and penetrating the surficial deposits just deeply enough to encounter standing water at the bottom.

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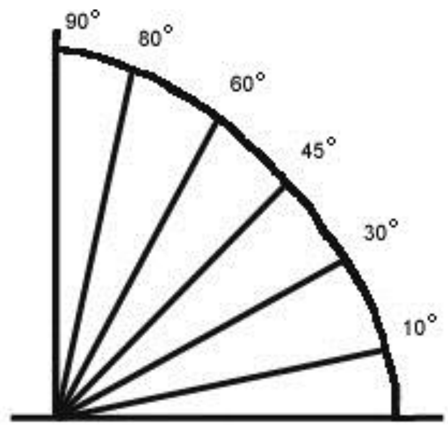
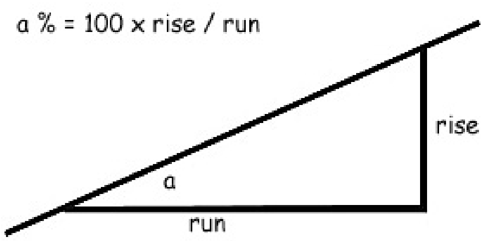
APPENDIX A – MEASUREMENTS OF SLOPE GRADIENTS

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



Angles in degrees.

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.

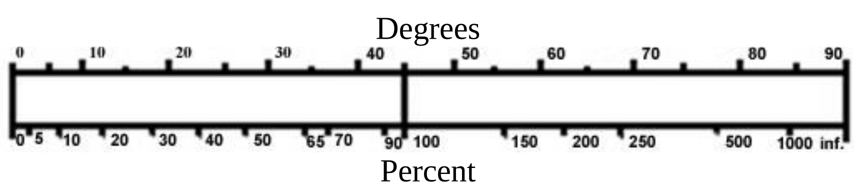


Angles in percent.

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

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. However, for steeper slopes, the constant angular difference and smaller numbers (e.g., 85 degrees = 1143% slope) make degrees more useful.

The figure below 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), conversely this relationship changes dramatically at gentler and steeper angles.



Slope gradients in degrees and percent.

APPENDIX B – LANDSLIDE PROVINCES IN WASHINGTON

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

Puget Lowlands-North Cascade Foothills

This region 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.

Olympic Peninsula

Somewhat similar geologic materials are present on the Olympic Peninsula. The lowlands and major river valleys are underlain by sediments derived by both continental and alpine glaciations, which are in turn underlain by very weak sedimentary and volcanic rocks. Large landslide complexes, predominantly in glacial sediments, are widespread along Hood Canal and lower reaches of the Quinault, Queets, Hoh, and Bogachiel valleys. 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.[97] Debris flows and avalanches are often generated in steeper drainages and slopes.

Southwest Washington

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.[98] Thick, deeply weathered loess deposits are sources for shallow landslides, debris flows, and avalanches.[99] These deposits are prevalent along the lower Columbia

[97] Tabor and Cady 1978; Badger 1993.
[98] Gerstel and Badger 2002.
[99] Thorsen 1989.

River valley, as well as other areas where colluvial deposits have accumulated on slopes and in drainages underlain by strong and relatively unweathered rock.

Cascade Range

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. Rock falls and complex rock slides are dominant in the steep bedrock slopes in the North Cascades. In the South Cascades and Columbia Gorge, weak interbeds control large translational failures in the Chumstick and Roslyn Formations[100], the Columbia River Basalts and other volcanic flow rocks, and Cowlitz Formation and Sandy River Mudstone[101]. Shallow landslides generating debris avalanches and flows are common on steep slopes and drainages.

Okanogan Highlands

Pleistocene glacial sediments that mantle the mostly crystalline core of the Okanogan Highlands are prone to both shallow and deep-seated landslides. The debris flows in this region can be a hazard during intense thunderstorms, usually moving through the area during late spring to late summer. Deep-seated landslides are most common in the areas surrounding Lake Roosevelt and landslide movement usually occurs in areas where relict to dormant deep-seated landslides exist. Rock falls and rock slides are common from the many steep bedrock exposures in the region.

Columbia Basin

This province is largely composed of thick sequences of lava flows known as the Columbia River Basalts. Catastrophic flood events scoured the soils and a portion of the bedrock in much of this region before re-depositing it in watersheds along the edges of the main floodway. Landslides include slope failures in bedrock along the soil interbeds and in the overlying flood sediments and loess deposits. Bedrock slope failures are most common in the form of very large deep-seated translational landslides, deep-seated slumps or earth flows. The Blue Mountains in southeastern Washington also have experienced recurring and widespread shallow landsliding and debris flows related to storm events.[102]

[100] Tabor et al. 1987.
[101] Wegmann 2003.
[102] Harp et al. 1997.

APPENDIX C – 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 – 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 the DNR website.
- Forest Practices Application Mapping Tool – online mapping tool with a variety of digital map base layer selections including topography, surface water (streams, water bodies, wetlands), soils, transportation network, soil site class, and potential slope instability (designed for shallow landslide susceptibility mapping only). Available on the DNR website.
- County interactive GIS map viewers – 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 designations. Available on Department of Ecology's 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), typically 1- to 3-meter resolution; see Appendix E 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 on 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. Available on the 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 – various 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 U.S. 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; data limitations available on Department of Ecology's website.
- Qualified expert reports on deep-seated landslides, 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.

APPENDIX D – 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 Natural Resource Conservation Service (NRCS) 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 three dimensional (3D) globe. Ortho-rectified, generally 1-meter resolution, 3D images are available for multiple years (Historical Imagery tool), allowing chronologic deep-seated landslide mapping. Google Earth supports desktop and mobile applications, including managing 3D geospatial data;
- Bing Maps Aerial View – part of Microsoft web mapping service; overlays topographic base maps with satellite imagery taken every few years.
- 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;
- 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;
- Washington State Coastal Atlas Map and Photos – oblique shoreline photos spanning 1976-2007; part of an interactive map tool at Department of Ecology's website;
- United States Geological Survey EarthExplorer (http://earthexplorer.usgs.gov/) archive of downloadable aerial photos.

APPENDIX E – LiDAR: PROCESSING, APPLICATIONS, AND DATA SOURCES

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.[103] 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.[104] 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.[105]

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.[106] 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.[107] Care should be taken to precisely align the repeat LiDAR DEMs.

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.[108] Examples include using LiDAR-derived Digital Elevation Models (DEM) and Digital Terrain Models (DTM) with: (1) radar data (for example infrared or InSar) and historical aerial photographs to quantify deep-seated landslide

[103] Carter et al. 2001.
[104] For a review of filtering techniques, see Liu 2008.
[105] Van Den Eeckhaut et al. 2007.
[106] Corsini et al. 2007; Delong et al. 2012; Daehne and Corsini 2013.
[107] Burns et al. 2010.
[108] Tarolli 2014.

displacement and sediment transport[109]; (2) ortho-rectified historical aerial photographs to map earthflow movement and calculate sediment flux[110]; (3) GIS-based algorithms for LiDAR derivatives (e.g., hillslope gradient, curvature, surface roughness) to delineate and inventory deep-seated landslides and earthflows[111]; and (4) subsurface investigations[112].

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

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

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[109] Roering et al., 2009; Handwerger et al. 2013; Scheingross et al. 2013.
[110] Mackey and Roering 2011.
[111] e.g., Ardizzone et al. 2007; Booth et al. 2009; Burns and Madin 2009; Tarolli et al. 2012; Van Den Eeckhaut et al. 2012.
[112] Travelletti and Malet 2012.

APPENDIX F – 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 https://fortress.wa.gov/dnr/protectionsa/ApprovedWatershedAnalyses (the URL may change without notice)
- U.S. Forest Service watershed analysis reports. Available from U.S. Forest Service offices for select watersheds; some electronic documents are available online through the U.S. Forest Service website for national forest of interest.
- Interagency watershed analysis reports. Collaborative projects between federal agencies (U.S. Geological Survey, U.S. Forest Service, U.S. Fish and Wildlife Service), tribal agencies, and industry (e.g., Cook and McCalla basins, Salmon River basin, Quinault watershed). Documents available online through the USGS, Washington Water Science Center.
- Washington Soil Atlas. Available as downloadable Adobe pdf file on the Natural Resources Conservation Service website.

APPENDIX G – 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 U.S. Forest Service and Bureau of Land Management – database managed by Western Regional Climate Center

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

Seismic data: Pacific Northwest Seismic Network – database managed by USGS, University of Washington, and Incorporated Research Institute for Seismology Consortium in Seattle. Contains records from seismometers located throughout Washington and Oregon.

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

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

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

APPENDIX H – 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.

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

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

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