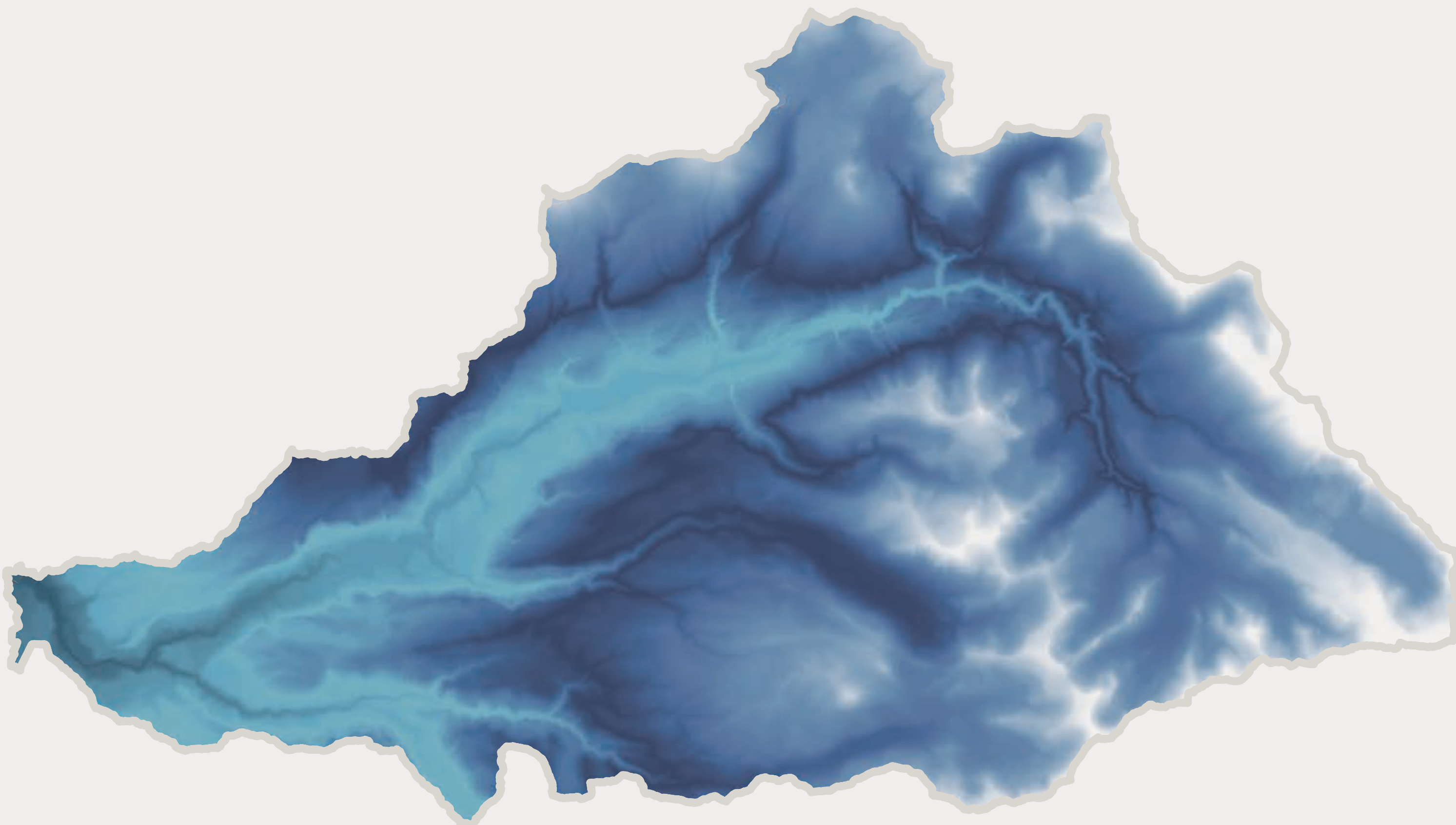
BULL RUN WATERSHED

Surficial and Bedrock Engineering Geology, Landslide Inventory and Susceptibility, and Surface Hydrography of the Bull Run Watershed, Clackamas and Multnomah Counties, Oregon

By William J. Burns, Katherine A. Mickelson, Cullen B. Jones, Mathew A. Tilman, and Daniel E. Coe



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SURFICIAL AND BEDROCK ENGINEERING GEOLOGY, LANDSLIDE INVENTORY AND SUSCEPTIBILITY, AND SURFACE HYDROGRAPHY OF THE BULL RUN WATERSHED, CLACKAMAS AND MULTNOMAH COUNTIES, OREGON

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2015

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Cover image: *Lidar-derived bare-earth image showing surface relief in the Bull Run Watershed. (Image credit: W. J. Burns)*

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feature classes: *Deposits (polygons)*
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Scarp_Flanks (polygons)
Scarps (polylines)

Bull_Run_Shallow_Deep_Landslide_Susceptibility.gdb
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Bedrock_geology (polygons)
Deep_Landslide_Susceptibility (polygons)
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1.0 SUMMARY

In May 2013 the Oregon Department of Geology and Mineral Industries (DOGAMI) entered into an intergovernmental agreement with The City of Portland Water Bureau (PWB) (IGA Number 12122012). The purpose of this project was to assist the PWB in better understanding the landslide hazard within the Bull Run Watershed, thus helping the PWB to become more resilient to landslide hazards. The primary reason for performing the study in 2013-2014 was the availability of light detection and ranging (lidar) data at that time for the entire Bull Run Watershed. Deliverables of the study include:

- this report text and four appendices
- five map plates
- detailed Geographic Information System (GIS) datasets including:
    - landslide inventory—map of locations of landslides that have occurred at some time in the past
    - shallow landslide susceptibility—map of areas more or less prone (low, moderate, high) to future shallow landslides
    - deep landslide susceptibility—map of areas more or less prone (low, moderate, high) to future deep landslides
    - surficial hydrography—map of locations of surficial water features such as waterbodies, streams, and marshes

Because the Bull Run Watershed is a surface water collection system and most of the related infrastructure is on or near the ground surface, the risk of landslide impact directly to the water and/or the infrastructure is relatively greater than for example, an underground well system located on a flat valley plain. We found 21 previous studies related to the geology, soils, and landslides had been performed in the study area and this new study built on that previous work.

The new landslide susceptibility datasets modeled as part of this project rely on a best available map of the geology. Therefore, new, generalized bedrock and surficial engineering geology datasets and maps were created as part of this study.

Several past studies focused on landslide inventory, or mapping of existing landslides, in the watershed. Beaulieu (1974) mapped 23 landslide areas within the watershed, and Schulz (1980) mapped 86 landslides. The new landslide inventory created as part of this project has 1,068 landslide deposit areas within the Bull Run Watershed, which cover approximately 15 percent of the watershed. We found approximately 21 percent of the watershed is highly susceptible to future shallow landslides and 19 percent has high susceptibility to future deep landslides. The new surface hydrography data consists of: 1) stream lines, 2) waterbody polygons, and 3) watershed and basin polygons.

From results of this new study and other studies by DOGAMI in Oregon, we make the following conclusions and recommendations. Lidar data are critical for mapping landslides and hydrography. The Bull Run Watershed has approximately 18 percent of the watershed mapped as high landslide hazard (15 percent landslide inventory; 21 percent high susceptibility to shallow landslides; 19 percent high susceptibility to deep landslides); therefore 82 percent of the watershed has a moderate to low susceptibility to landslides. The primary reason for the landslide hazard appears to be the geology combined with past surficial processes that shaped the watershed into its current morphology along with several triggers including high precipitation and earthquake shaking. Our statistics show that, in addition to existing landslides, geologic units most prone to landslides are the Rhododendron and Troutdale Formations and the basalt of the Bull Run Watershed.

Although there is a relationship between shallow landslide susceptibility and debris flow fans, most of the existing fans are not at the mouths of the primary streams (e.g., North Fork, Falls Creek, Cougar Creek, South Fork). Therefore, we conclude that it is not likely that shallow landslides or erosion-induced, relatively small (typical western Oregon) debris flows will move directly as debris flows all the way down these primary streams into the Bull Run River. Erosion and sediment transport down these streams is likely dominated by regular stream processes rather than by typical western Oregon debris flows. This is true unless the volume of material involved in the debris flow approaches that of a large deep landslide; for example, when a relatively larger landslide transforms into a channelized debris flow. This scenario would likely transport significant amount of debris down to the Bull Run River as a debris flow. This scenario probably occurred during the Boody Reservoir/Lake outburst flood in 1972. The spillway for Boody Reservoir/Lake was apparently blocked by ice, which eventually broke and released a pulse of water. The flood outburst caused the reactivation of an existing large deep prehistoric landslide downstream within the North

Fork Bull Run River. The reactivation of the large deep landslide combined with the flood outburst sent a large volume of debris into Bull Run Reservoir Number Two. This combination of events is now referred to as the 1972 North Fork slide. This is likely the origin of the mapped fan at the mouth of the North Fork Bull Run River (Plate 1).

The relatively large deep landslides appear to be the primary threat in the watershed for several reasons. First, they can contribute large volumes of sediment leading to significant turbidity in the system and possible extended turbidity for long periods of time (weeks to years). The large volume can also transform into large debris flows which can then reach the main Bull Run River and reservoirs directly, and, in extreme cases, temporarily block the river. The large deep landslides can and have caused significant damage to the infrastructure (conduits and roads for example) and can be relatively expensive to mitigate.

All of these data indicate that a landslide risk exists in the Bull Run Watershed and thus that there is a strong need for continued landslide risk management. Landslide risk management can be performed in various ways. We provide recommendations and conclusions based on our findings. Recommendations include future improvements, continual maintenance, regional risk analysis, emergency response, landslide monitoring, and further detailed studies of specific landslides.

2.0 INTRODUCTION

Landslides are one of the most widespread and damaging natural hazards in Oregon. In order to begin reducing damage and losses from landslides, areas of landslide hazard must first be accurately located. The first step in landslide hazard assessment is to create an inventory of past historic (<150 years) and prehistoric (>150 years) landslides (Plate 1). Next, the inventory and computer models can be used to create landslide susceptibility maps that display areas with various relative potential (low, moderate, high) for future landslides (Plates 2 and Plate 3). Landslide mapping in the Bull Run Watershed has been performed in the past by the Portland Water Bureau (PWB) staff, student researchers, external consultants, and the Oregon Department of Geology and Mineral Industries (DOGAMI). However, none of these past studies used airborne light detection and ranging (lidar) derived high resolution topographic data and a Geographic Information System (GIS). Burns (2007) concluded that lidar data should be used for all future landslide studies, especially in densely vegetated western Oregon where key landslide features are frequently obscured. The lidar-derived topographic data provides a high resolution view of the ground surface, which was not available in the past. The use of lidar-derived bare-earth digital elevation model (DEMs) was fundamental to the landslide mapping performed in this study.

The general term “landslide” refers to a range of mass movements including rock falls, debris flows, earth slides, and other mass movements (Varnes, 1978). Different types of landslides have different frequencies of movements, triggering conditions, and very different resulting hazards (Plate 1). All landslides can be classified into six types of movement (Plate 1): 1) falls, 2) topples, 3) slides, 4) spreads, 5) flows, and 6) complex. Most slope failures are complex combinations of these distinct types, but the generalized groupings provide a useful means for framing discussion of the type of hazard associated with the landslide, the landslide characteristics, identification methods, and potential mitigation alternatives (Burns and Madin, 2009; Appendix A).

There are many different extents and definitions of the Bull Run Watershed. In this report, we define the study extent as the natural watershed boundary encompassing the area which drains from the Bull Run River into the Sandy River (Plate 5).

2.1 The Study Area

The Bull Run Watershed is the primary drinking water supply for the City of Portland and several suburbs and thus approximately 1 million people rely on it. It is cooperatively managed by the PWB and the U.S. Forest Services and covers an area of approximately 140 mi^2 (362 km^2) (Figure 1). The watershed has been managed for drinking water supply since the late 1800s and the majority of the land is owned by the Mount Hood National Forest. There is restricted access to the watershed to protect and sustain clean drinking water to a quarter of Oregon's population (Portland Water Bureau, 2014).

The watershed is located 25 miles (40 km) east of downtown Portland on the western slopes of the Cascade Range. The main river, the Bull Run River, joins the Sandy River, which flows into the Columbia River and then out to the Pacific Ocean. Inside the watershed is a network of streams, rivers, natural lakes, and man-made reservoirs. Bull Run Lake is the largest lake in the upper portion of the watershed and is dammed by a massive landslide (Figure 1). Bull Run Reservoir Number One is located in the middle portion of the Bull Run River and held back by a concrete gravity arch dam which was finished in 1929 (Figure 1). Bull Run Reservoir Number Two is in the lower reaches of the Bull Run River and is held back by an earthen dam with a concrete spillway (Figure 1). Although many Portland residents believe the Bull Run Watershed gets water from Mount Hood, there is no surface hydrologic connection between Mount Hood and the Bull Run Watershed. The watershed gets water from rain and snowmelt input directly into the watershed. The Bull Run Watershed has a West Coast marine climate, which consists of cool, wet winters and warm, dry summers (Snyder and Brownell, 1996). The precipitation is driven by a strong orographic effect associated with warmer moist air coming inland from the Pacific Ocean. As this moist air is driven up the Cascade Range, prolonged periods of precipitation result. The average annual precipitation ranges between 80 and 130 in/yr and varies across the watershed. Snowpack depths can be 6 to 9 ft (1.8 to 2.7 m) in the upper, higher elevation portions of the watershed (Snyder and Brownell, 1996).

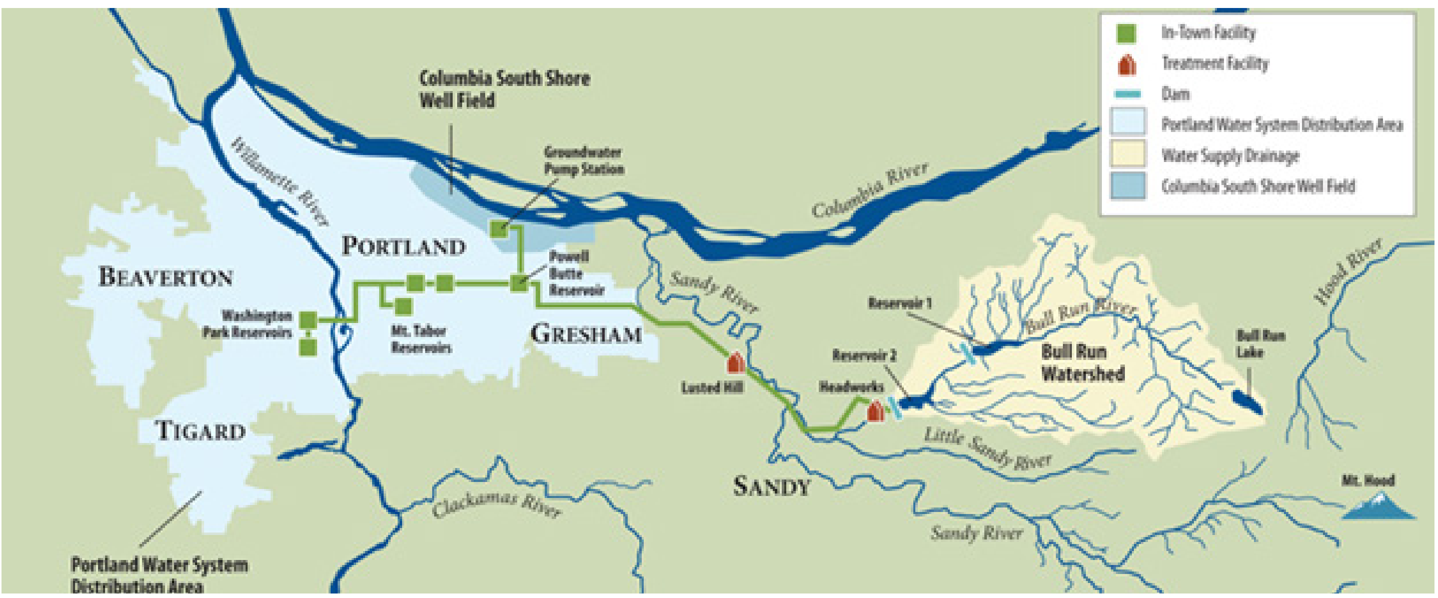


Figure 1. Map of the location of the Bull Run Watershed (Portland Water Bureau, 2014).

The topography of the watershed ranges from an elevation of approximately 240 ft (73 m) at the Sandy River along the western boundary to 4,664 ft (1,422 m) at the top of Hiyu Mountain above Bull Run Lake along the eastern boundary (Figure 2A). In general, the slopes are steeper in the western and northern portions of the watershed. The Bull Run River flows from its headwaters out of Bull Run Lake to the Sandy River. Several creeks and rivers flow into the Bull Run River from the north including Bear Creek, Cougar Creek, Deer Creek, North Fork Bull Run River, Falls Creek, West Branch Falls Creek, and Log Creek. From the south, the creeks and rivers are longer with lower channel gradients and include Little Sandy River, South Fork Bull Run River, Camp Creek, Fir Creek, and several smaller creeks in the uppermost portions of the watershed. Above approximately 2,000 ft (610 m) elevation, most of the main drainages are "U" shaped, a result of the last episode of glaciation, likely from the glacial period ending 10,000 to 12,000 years ago (Figure 2B; Beaulieu, 1974). Below an elevation of approximately 2,000 ft (610 m) down to an elevation of 350 ft (107 m) (just below the confluence of the Bull Run River and the Little Sandy River), the Bull Run River drainage is geomorphologically similar in appearance to the Missoula Floods Scablands in western Washington, first identified by J Harlen Bretz in the early 1920s (Figure 2B; Bretz, 1925; Allen and others, 2009). This area, interestingly, also lacks any significant residual soil on the Columbia River Basalt and several of the geologic units are truncated and exposed to the surface along the edges of this unique feature. The exposure of these units is correlated to many of the landslides in the Bull Run Watershed. This area is discussed more in the geology section of this report.

There is a landslide hazard in the watershed as indicated both by historic slides and by many prehistoric slides that could reactivate due to erosion, heavy rainfall events, or earthquakes. The current Statewide Landslide Information Database for Oregon (SLIDO) release 3 has 249 mapped landslide polygons within or touching the Bull Run Watershed (Burns and Watzig, 2014). Most of these landslides are likely prehistoric—more than 150 years old and, in some cases, thousands to tens of thousands of years old. Many slides are indicated by overlapping polygons, the result of different authors mapping the same area. Previous reports (see section 2.3) and discussion with the Portland Water Bureau also indicate the watershed has landslide hazards. For example, the Ditch Camp landslide, which damaged conduit number 2 in 1965, the North Fork landslide in 1972 which caused significant sediment input and turbidity in Bull Run Reservoir Number One, and the prehistoric (>150 years) and likely much older massive Bull Run Lake landslide (Preachers Peak landslide), which holds back Bull Run Lake. Several recent landslides have occurred within the Bull Run Watershed, including several that occurred during the 1996-97 storms and the 2012 landslide along the South Fork Bull Run River.

Throughout this report we use the engineering geology terms *hazard*, *susceptibility*, and *risk*. The term hazard is defined here as a possible source of danger and in this report we are specifically referring to landslides as a hazard. The term susceptibility is defined here as capable of a specified action or process and in this report the process is landsliding. The term risk is defined here as the possibility of loss or injury. In this report risk is the overlap of the hazard with assets (such as infrastructure) and their vulnerability to the hazard.

2.2 Purpose

Because the Bull Run Watershed is a surface water collection system and most assets are on or near the ground surface, landslides can impact these assets. Landslides can also move sediment and other debris into the water supply. The better we understand the location, spatial extent, likelihood, and magnitude of the landslide hazard, the better we can evaluate the landslide impact and reduce risk. The primary reason for performing the study in 2013-2014 was the availability of light detection and ranging (lidar) data for the entire Bull Run Watershed. The purpose of this study was to assist the PWB in understanding the landslide hazard better and thus increase their ability to reduce future risk. We accomplished this by using high-resolution lidar-derived digital elevation model (DEM) data to perform the following GIS tasks:

1. creating a detailed landslide inventory
2. creating shallow and deep landslide susceptibility maps
3. updating the surface hydrography dataset

We performed our services in accordance with the intergovernmental agreement with the City of Portland (IGA number 12122012). DOGAMI is not responsible for independent conclusions, opinions, or recommendations made by others based on information provided in this report.

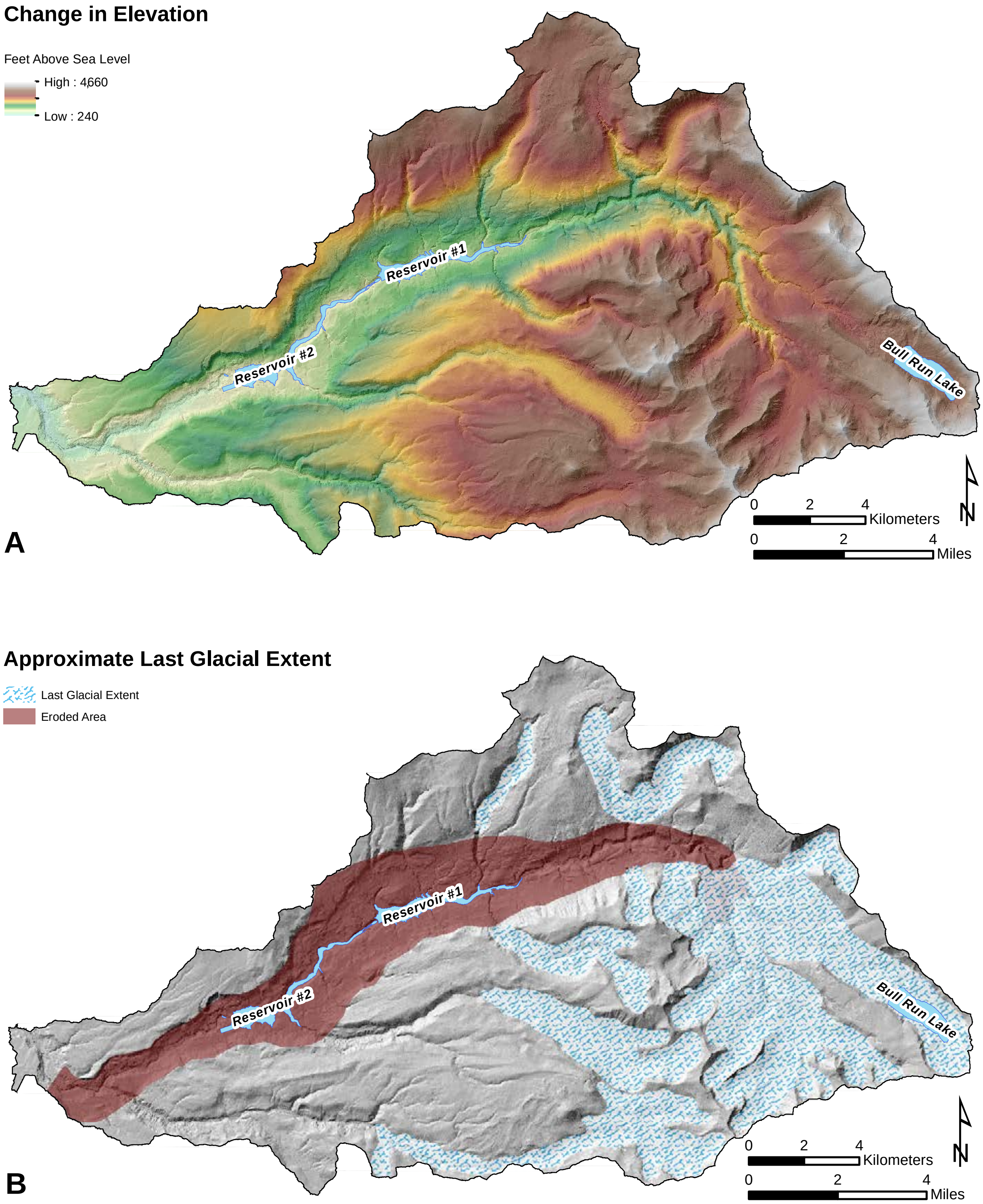


Figure 2. (A) Map of the elevation change in the Bull Run Watershed. (B) Map of approximate last glacial extent (down to ~2,000 ft [610 m]) and the area that appears to have had significant erosion.

2.3 Previous Work

Many geologic, geologic hazard, and site-specific reports have dealt with the Bull Run Watershed. Reports referenced in this study are:

- Geologic map of the Hood River quadrangle (Korosec, 1987)
- Preliminary map of the Mount Hood 30- by 60-minute quadrangle (Sherrod and Scott, 1995)
- Reconnaissance geologic map of the Columbia River Basalt Group (Swanson and others, 1981)
- Geologic map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range (Sherrod and Smith, 2000)
- Geologic hazards of the Bull Run Watershed, Multnomah and Clackamas Counties (Beaulieu, 1974)
- Columbia River Basalt Group stratigraphy and structure in the Bull Run Watershed (Vogt, 1981)
- Oregon geologic data compilation [OGDC], release 5 (statewide) (Ma and others, 2009)
- Soil survey of Multnomah County (National Cooperative Soil Survey, 1976)
- Soil survey of Clackamas County (National Cooperative Soil Survey, 1982)
- Statewide landslide information database for Oregon, release 3 (SLIDO-3; Burns and Watzig, 2014)
- Landslide inventory maps for the Sandy quadrangle, Clackamas and Multnomah Counties (Burns and others, 2012a)
- Multi-hazard and risk study for the Mount Hood region, Multnomah, Clackamas, and Hood River Counties (Burns and others, 2012b)
- The quantification of soil mass movements and their relationships to bedrock geology in the Bull Run Watershed, Multnomah and Clackamas Counties (Schulz, 1980)
- Geotechnical evaluation of the Ditch Camp Slide, Bull Run, Oregon, Report to the City of Portland Bureau of Water Works (Cornforth Consultants, 2001)
- Portland Water Bureau trestle replacement, Trestle #20, Conduit #2, Larson Site, Bull Run Watershed, Clackamas County (GeoDesign Inc., 2005)
- Report of preliminary geotechnical investigation Headworks Microwave Tower, Bull Run Reservoir Number Two, Clackamas County (Carson Geotechnical, 2011)
- 2010/2011 Annual report: geotechnical issues and monitoring data (Hogan and Collins, 2012)
- Landslide affecting water supply pipelines, Bull Run Dam Number 2 (Landslide Technology, 1995)
- Landslide and pipeline bridge repair, report to the City of Portland Bureau of Water Works (Landslide Technology, 1996)
- Draft geotechnical analytical report, Bull Run supply treatment improvements (Shannon and Wilson, 2010)
- Hydrogeologic setting and preliminary estimates of hydrologic components for Bull Run Lake and the Bull Run Lake drainage basin, Multnomah and Clackamas Counties (Snyder and Brownell, 1996)
- GIS overview map of potential rapidly moving landslide hazards in western Oregon (Hofmeister and others, 2002)

Neither lidar topographic data nor GIS data were available when many of these studies were undertaken. While creating the new landslide inventory as part of this study, we incorporated as much from these previous studies as possible into the GIS database. The advantage of a GIS database includes easy transfer of information, quicks updates, and spatial analysis with other data.

The best available digital geology for the area is Oregon geologic data compilation, release 5 (OGDC-5; Ma and others, 2009). By its nature, OGDC-5 comprises a number of maps at various levels of detail (Figure 3). Consequently, many geologic contacts in the Bull Run Watershed fail to match across map boundaries. In order to model the watershed for deep and shallow landslide susceptibility, we needed accurate bedrock and surficial geologic maps. Because the landslide models rely heavily on the geologic input, we created composite bedrock and surficial maps (described in section 3 of this report). We did not undertake any new mapping as part of this investigation other than refinements of geologic formation boundaries important for their engineering properties and apparent from inspection of lidar data.

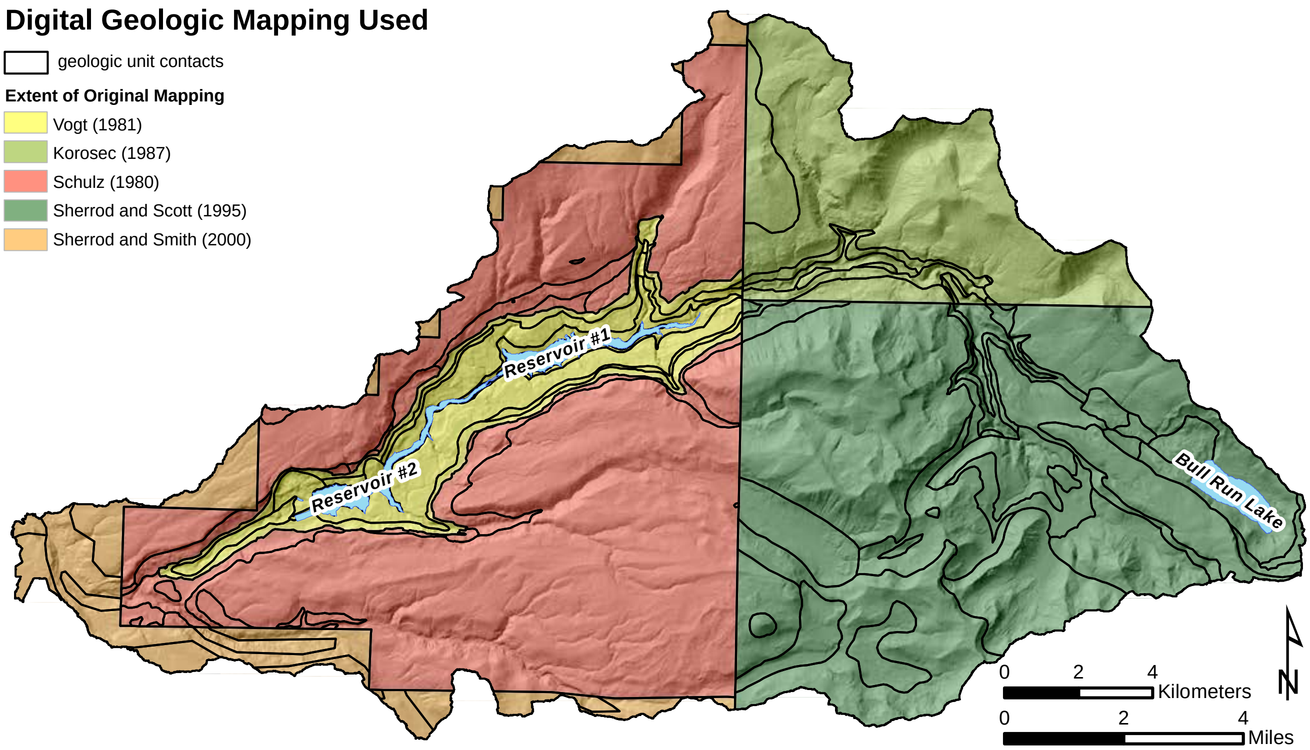


Figure 3. Extents of the five maps covering the Bull Run Watershed used for the digital geology layer in this study (Ma and others, 2009). Thicker black polygons show original units; colors show the source maps.

3.0 GEOLOGY

We created bedrock and surficial engineering geologic maps of the watershed to help assess deep and shallow landslide susceptibilities described later in this report. The engineering geologic maps are more generalized than conventional geologic maps and do not contain structural features such as faults and folds. For example, in the upper reaches of the Bull Run River in the watershed, the Columbia River Basalt units are discontinuous due to faults and folds, but we do not show this. For additional information on faults and folds, see Sherrod and Scott (1995), Vogt (1981), and Korosec (1987).

3.1 Generalized Bedrock Engineering Geologic Map

3.1.1 Map construction

The generalized bedrock engineering geologic map is derived from geologic mapping by Korosec (1987), Sherrod and Scott (1995), Swanson and others (1981), Sherrod and Smith (2000), Beaulieu (1974), and Vogt (1981), as compiled by Ma and others (2009). To create the bedrock engineering geologic map, we simplified stratigraphic geologic units into 11 engineering geologic units on the basis of similar geologic and geotechnical properties (Figure 4). For example, we show the Columbia River Basalt Group, which consists of many geologic units, as two generalized engineering geologic units. See section 3.1.2 for descriptions of all bedrock engineering geologic units.

To create the geologic engineering unit polygons, we used the lidar-based bare-earth DEM and derived datasets (hillshade, slope, and contours) to re-delineate the contacts to better match the topography. We removed all surficial deposits (landslides, alluvium, etc.) from the map presentation, and we approximated contacts that were previously mapped as concealed below surficial units. We performed this process mainly in the upper part of the watershed where slopes are covered by glacial deposits and postglacial colluvium. We modified the Rhododendron Formation contact in the upper part of the watershed by using adjacent mapping (Sherrod and Scott, 1995) just outside the Bull Run Watershed. We projected the elevation range of the Rhododendron Formation where mapped outside the study area into the watershed to approximate the formation's extent. In other areas, we projected this formation's extent into areas where landslides suggest the presence of the Rhododendron, which is landslide-prone.

The bedrock engineering geologic map shows the following generalized geologic history. (Figure 4). The Columbia River Basalt Group (CRB) was deposited first and is considered the watershed's bedrock foundation. The volcaniclastic Rhododendron Formation was deposited on top of the CRB. Above the Rhododendron, in the western portion of the watershed only, sedimentary rocks of the Troutdale Formation were deposited. On top of the Rhododendron and/or the Troutdale Formation, a series of volcanic rocks including the Boring Lava and the basalt of the Bull Run Watershed were deposited. Finally, during the last several million years, glaciers carved out canyons that now expose some older deposits (CRB and Rhododendron in particular) and deposited alluvium. Also during the Quaternary and to the present day, alluvium has been deposited along the rivers as terraces and landslides have moved material primarily down slope.

3.1.2 Unit descriptions

The bedrock engineering geologic units in the Bull Run watershed range in age from middle Miocene (~17 Ma) to Quaternary (<2 Ma). We simplified the geology into 11 units on the basis of similar geologic and geotechnical properties (Figure 4):

Quaternary (<2 Ma) volcanic rocks:
- Aschoff Buttes cinder cone
- basaltic andesite of Aschoff Buttes

Quaternary to Pliocene (~2–5 Ma) volcanic rocks:
- Boring Lava
- andesite of Hiyu Mountain
- Pliocene lava flows, undivided
- basalt of the Bull Run Watershed

Pliocene to Middle Miocene (~5–10 Ma) volcanic and sedimentary rocks:
- Troutdale Formation
- andesites of ZigZag Mountain and Lolo Pass
- Rhododendron Formation

Middle Miocene (~5–17 Ma) volcanic rocks:
- CRB - Wanapum Basalt
    - *Vantage Horizon*
- CRB - Grande Ronde Basalt

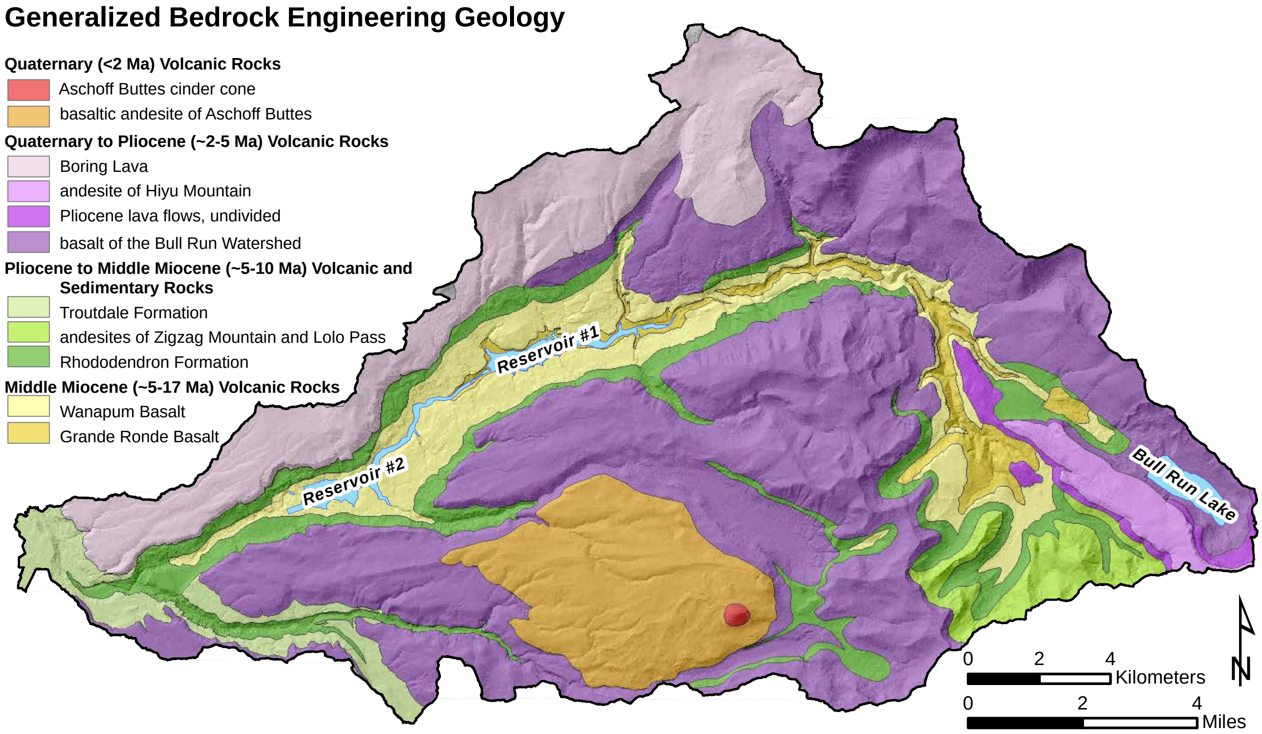


Figure 4. Map of generalized bedrock engineering geology in the Bull Run Watershed.

Aschoff Buttes cinder cone

Mapped separately is the cinder cone of Aschoff Buttes, source vent for the basaltic andesite lava flows of Aschoff Buttes. The Aschoff Buttes vent has one large, deep landslide on its northeastern flank.

Basaltic andesite of Aschoff Buttes

The basaltic andesite of Aschoff Buttes is underlain by the basalt of Bull Run Watershed and is Pleistocene, with a radiometric age of 0.2 Ma (Conrey and others, 1996). These lava flows erupted from a cinder cone (southwest of Aschoff Buttes) in the south-central part of the watershed (Sherrod and Scott, 1995; Sherrod and Smith, 2000). The basaltic andesite of Aschoff Buttes has a low susceptibility to landsliding.

Boring Lava

The Boring Lava is exposed in the northern part of the watershed, where it overlies the Troutdale Formation in the northwest, the Rhododendron Formation in the north central, and the basalt of the Bull Run Watershed in the northeast. The lavas are mostly Pleistocene in age, emplaced from 2.6 million years ago to 50,000 years ago (Evarts and others, 2009). The lava flows are associated with numerous small volcanoes across the Portland area and adjacent western slope of the Cascade Range (Evarts and others, 2009). The Boring Lava is susceptible to deep landsliding, especially where it is underlain by the Troutdale and Rhododendron Formations. Landslide deposits have an average failure depth of 112 ft (34 m) but can be over 200 ft (61 m) deep.

Andesite of Hiyu Mountain

The andesite of Hiyu Mountain rests on top of the Pliocene lava flows and basalt of the Bull Run Watershed. The unit is early Pleistocene, with a radiometric age of about 1.37 Ma (Sherrod and Scott, 1995). The unit is of limited extent, covering less than 2 percent of the watershed, and is exposed only in the southeastern part of the watershed. The andesite of Hiyu Mountain is moderately susceptible to deep landslides. Deep landslides predominantly occur at the contact with Pliocene lavas. Landslide deposits have an average failure depth of 45 ft (13.7 m) but can be over 90 ft (27 m) deep.

Pliocene lava flows, undivided

The unit of lava flows, undivided, consists of basalt and basaltic andesite flows of Pliocene age (units QTb and QTba of Sherrod and Scott, 1995). These lavas cover a small extent in the southeastern part of the watershed and cover around 1 percent of the watershed. They are underlain by the Wanapum Basalt and overlain by the andesite of Hiyu Mountain. This unit is moderately susceptible to deep landslides. Deep landslides occur predominantly at the contact with the andesite of Hiyu Mountain. Landslide deposits have an average failure depth of 59 ft (18 m) but can be over 100 ft (30 m) deep.

Basalt of the Bull Run Watershed

The basalt of the Bull Run Watershed overlies the Troutdale Formation in the southwestern part of the watershed and the Rhododendron Formation elsewhere in the watershed. It is overlain locally by the basaltic andesite of Aschoff Buttes. The basalt of the Bull Run Watershed consists of lava flows that are predominantly basaltic in composition. The unit is Pliocene in age, with isotopic ages chiefly between 3 and 2 Ma (Sherrod and Scott, 1995). This unit is the most extensive formation exposed in the watershed, covering 45 percent of the area.

The basalt of the Bull Run Watershed is susceptible to deep landsliding, especially where in contact with the weakly cemented Troutdale or Rhododendron Formations. Approximately 50 percent of all deep landslides in the watershed occur at the contact of the Troutdale or Rhododendron or within the basalt of the Bull Run Watershed. Landslide deposits have an average failure depth of 60 ft (18 m) but can be over 500 ft (152 m) deep. This unit is also prone to debris flows on steep slopes.

Troutdale Formation

The Troutdale Formation is middle Miocene to early Pliocene in age and overlies the Rhododendron Formation in the southwestern part of the watershed. This unit consists of conglomerate, sandstone, and siltstone deposited by the ancestral Columbia River (Beaulieu, 1974). The sandstone and siltstone sections of the Troutdale Formation (sometimes referred to as the Sandy River Mudstone) form moderately steep slopes. The Troutdale is prone to failure due to weak cementation (Beaulieu, 1974). Landslide deposits have an average failure depth of 48 ft (14.6 m) but can be over 100 ft (30 m) deep.

Andesites of Zigzag Mountain and Lolo Pass

This unit lies predominantly in the southeastern part of the watershed and, for geotechnical purposes, combines two previously mapped units: andesite of Zigzag Mountain and andesite of Lolo Pass. The unit overlies the Rhododendron Formation and underlies the basalt of the Bull Run Watershed. The andesite of Zigzag Mountain is Miocene in age (K-Ar ages range from 10.7 to 9.04 Ma; Sherrod and Scott, 1995); the andesite of Lolo Pass is late Miocene and early Pliocene(?) in age (ages range from 6.25 to 5.8 Ma; Sherrod and Scott, 1995). This unit is susceptible to large, deep landslides in the watershed. These landslide deposits have an average failure depth of 47 ft (14.3 m) but can be over 100 ft (30 m) deep.

Rhododendron Formation

The Rhododendron Formation overlies the Wanapum Basalt Formation. The Rhododendron Formation is middle to late Miocene in age. The unit consists of pyroclastic flows and lahars, mudflow breccia, volcaniclastic sandstone, mudstone, and tuff (Figure 5; Beaulieu, 1974; Sherrod and Scott, 1995). Due to weak cementation and/or physical and chemical weathering this unit is prone to large, deep landslides in the watershed. These massive landslide deposits have an average failure depth of 60 ft (18 m) but can be over 200 ft (61 m) deep. This unit is also prone to slope failure that gives rise to debris flows on steep slopes.

Columbia River Basalt Group—Wanapum Basalt

Above the Vantage Horizon lies the Wanapum Basalt. The lava flows of the Wanapum Basalt erupted during middle Miocene time, between 15.57 and 14.5 Ma (Watkins and Baksi, 1974; Barry and others, 2010). The Wanapum Basalt in the watershed consists of seven flows. Six of the seven flows belong to the Frenchman Springs Member and the seventh belongs to the Priest Rapids Member. In total, these seven basalt flows are over 470 ft (143 m) thick (Vogt, 1981). The Wanapum Basalt is relatively stable and resistant to weathering, forming steep cliffs in the watershed. These cliffs are prone to rockfall, which can be triggered by freeze-thaw conditions, heavy rainfall, and earthquakes. In the watershed, rockfall is more common in the Grande Ronde Basalt than in the Wanapum Basalt because incision by the Bull Run River has left near-vertical exposures and oversteepened slopes. Large, deep

Figure 5. Lahar deposit within the Rhododendron Formation, characterized here by inch to multiple-foot size fragments in an sandy matrix. (Photo credit: K. A. Mickelson)

landslides are more abundant in the Wanapum Basalt than in the Grande Ronde in the watershed likely because of the presence of the Vantage Horizon at the base of the Wanapum and the directly overlying Rhododendron Formation. These landslide deposits have an average failure depth of 75 ft (23 m) but can be over 500 ft (152 m) deep.

Columbia River Basalt Group—Grande Ronde Basalt

The Columbia River Basalt Group (CRB) formed during the Miocene and consists of over 300 basalt and basaltic andesite lava flows that cover more than 63,000 square miles in Oregon, Washington, and Idaho (Beeson and Tolan, 1987; McClaughry and others, 2012; Tolan and others, 1989, 2002). These flows erupted from north-northwest-oriented fissures near the eastern Washington-Oregon border and parts of western Idaho. The CRB erupted over a period from 17 to 6 Ma; however, the majority of volcanic activity, over 96 percent of the total volume, spanned the time from 17 to 14.5 Ma (Tolan and others, 2002). For our purposes, members of the CRB exposed in the Bull Run Watershed include the generalized Grande Ronde Basalt (all CRB units below the Vantage Horizon) and the generalized Wanapum Basalt (all CRB units above the Vantage Horizon). Lava flows of the Grande Ronde Basalt erupted in the middle Miocene, between about 16.0 and 15.6 Ma (Barry and others, 2010). Regionally, the Grande Ronde exhibits the thickest section of the CRB and is the most voluminous, covering 57,000 square miles (Tolan and others, 1989). In the study area the Grande Ronde Basalt floors the watershed, with thickness exceeding 300 ft (91 m). The base of the formation is not exposed in the study area (Vogt, 1981; Beaulieu, 1974). The rock forms well-developed columnar jointing locally within the watershed (Figure 6).

The Grande Ronde unit is relatively stable and resistant to weathering, forming steep cliffs in the watershed. These cliffs are prone to rockfalls, which can be triggered by freeze-thaw conditions, heavy rainfall, and earthquakes. Rockfall is common in the northeastern part of the watershed where the Bull Run River has cut down through the Grande Ronde, creating near-vertical cliffs. This unit is also prone to large, deep landslides in the watershed. The landslide deposits we found in this unit have an average failure depth of 63 ft (19 m) but can be over 500 ft (152 m) deep.

Figure 6. Well-developed columnar jointing of the Grande Ronde Basalt within the Bull Run Watershed. (Photo credit: K. A. Mickelson)

Above the Grande Ronde Basalt is the Vantage Member of the Ellensburg Formation (Swanson and others, 1979), a sedimentary interbed that formed during a hiatus in volcanism between the Grande Ronde and Wanapum Basalts. In the Cascade Range, where sedimentation was sporadic in distribution, a soil developed on the weathered Grande Ronde surface, forming what is known informally as the Vantage Horizon. The Vantage Horizon or corresponding interbed lies between the Grande Ronde and Wanapum basalts and can be up to 5 ft (1.5 m) thick.

Although the deeply weathered Vantage Horizon can act as a slip surface for large, deep landslides, especially where it has been exposed to the surface, in the Bull Run Watershed there are limited exposures of the Vantage Horizon, and the soil (or interbed) is thin, making it only a sporadic source of failure (Vogt, 1981).

3.2 Generalized Surficial Engineering Geologic Map

3.2.1 Map construction

We created a generalized surficial engineering geologic map by combining individual geologic units with similar material properties into seven surficial engineering units (Figure 7). The composite map is derived from previously mapped surficial deposits, including alluvium and terrace deposits (Sherrod and Scott, 1995; Sherrod and Smith, 2000; Beaulieu, 1974) as compiled by Ma and others (2009). We performed limited field work to map surficial geology, but the field work did result in additional alluvial deposits along the current stream channels and terrace deposits along the Bull Run and Little Sandy Rivers. We then redelineated the deposits by using the lidar-based bare-earth DEM and lidar-derived datasets. We used topographic breaks in slope visible in the lidar-derived datasets to position some contacts.

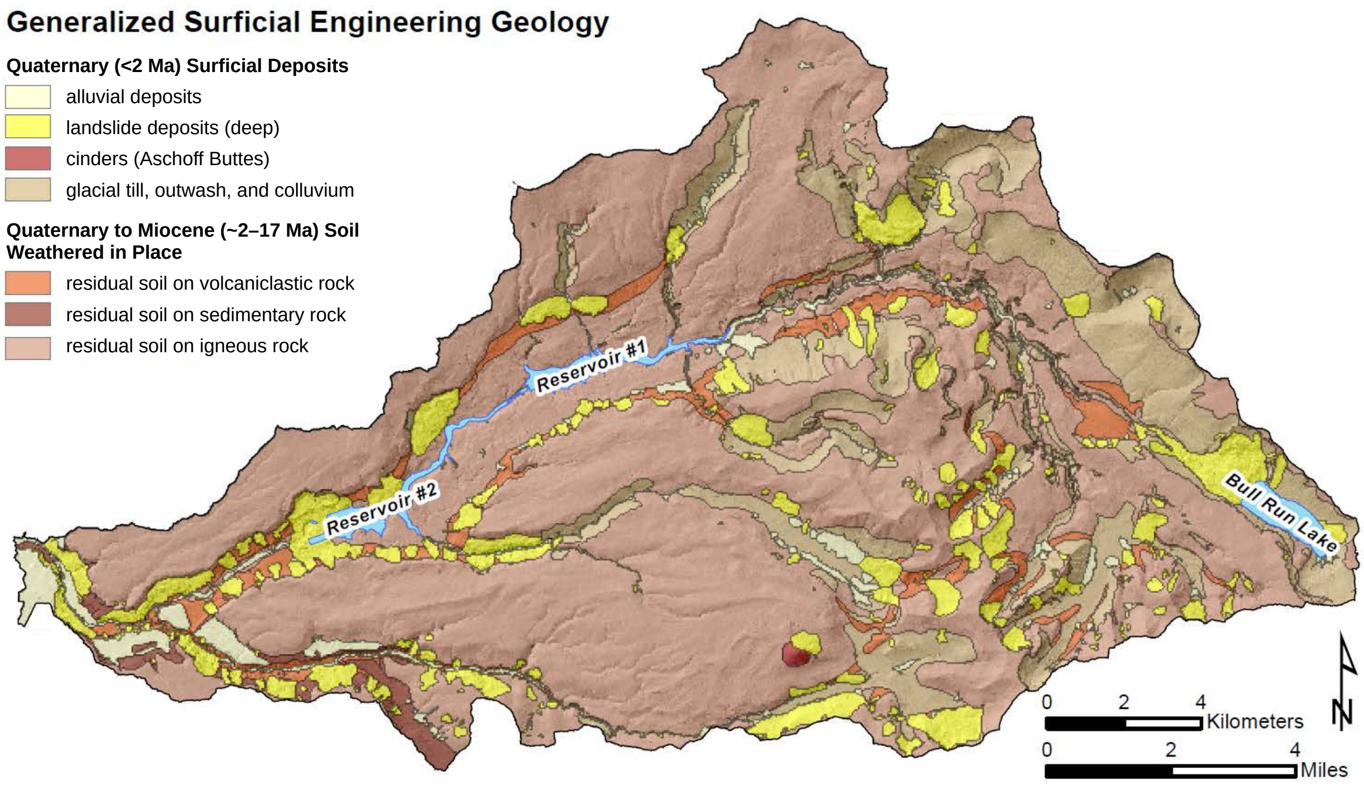


Figure 7. Map of generalized surficial engineering geology in the Bull Run Watershed.

We outlined glacial till and outwash deposits by starting with areas mapped in previous studies (see section 2.3). We edited contacts by using lidar-derived datasets. We mapped colluvium by using soil surveys for Clackamas and Multnomah Counties (National Cooperative Soil Survey [NCSS], 1976, 1982). The surveys map soils developed in colluvium and glacial till. For example, in Multnomah County the soil series includes the map unit "Kinzel-Lastance-Rubble land association (very steep)" in the Bull Run Watershed. We reviewed the soil survey to find other soil series with descriptions matching or close to this soil, and we re-delineated surficial engineering geologic unit polygons by using the lidar-derived bare-earth DEM and lidar-derived datasets. We also appended to the colluvium unit areas of rockfall mapped in the landslide inventory.

We added the deep landslides from the landslide inventory as an additional surficial geologic map unit. In areas not covered by the surficial units described above, we created surficial soil polygons and classified them as residual soil or in-place weathered bedrock that has become mostly a soil derived from the underlying bedrock. Finally, we used the lidar slope map to locate areas that are most likely bedrock without any residual soil or bare rock. For example, we considered areas with slopes steeper than 55 degrees (upper slope limits of the rockfall talus areas) to be bedrock with no residual soil.

3.2.2 Unit descriptions

We simplified the surficial geology into seven engineering geologic units on the basis of similar geotechnical properties (Figure 7):

Quaternary (<2 Ma) surficial deposits:
- alluvial deposits
- cinders (Aschoff Buttes)
- landslide deposits (deep)
- glacial till, outwash, and colluvium

Quaternary to Miocene (~2–17 Ma) soil weathered in place:
- residual soil on volcaniclastic rock
- residual soil on sedimentary rock
- residual soil on igneous rock

Alluvial deposits

This unit includes valley-flooring sand and gravel deposited by active rivers and streams in the watershed, terrace deposits left by somewhat older streams, and debris-flow fan deposits. The unit is composed predominantly of silt, sand, and gravel. Shallow landslides in this unit have an average failure depth of 12 ft (3.7 m) and have an average pre-failure slope angle of 37 degrees. Shallow landslides can occur when the slope is greater than 11 degrees.

Cinders (Aschoff Buttes)

This spatially limited unit includes the upper zone of weathered soil resting on the southwest flank of the Aschoff Buttes cinder cone. The unit is composed predominantly of silt, sand, and gravel. No shallow landslides were noted in this unit.

Landslide deposits (deep)

This unit includes all deep landslides mapped within the watershed, 450 in our estimation. These landslides have failure depths greater than 15 ft (4.5 m). Shallow landslides commonly occur within the unconsolidated material in deep landslides. Approximately 30 percent of all shallow landslides occur within the boundaries of deep landslides in the watershed. Shallow landslides activated in this unit have an average failure depth of 8 ft (2.4 m) and average pre-failure slope angle of 35 degrees. Shallow landslides can occur when the slope is greater than 9.5 degrees.

Glacial till, outwash, and colluvium

This unit consists of glacial till, glacial outwash, colluvium, and talus deposits. The glacial till and outwash were deposited in late Pleistocene time and consist of pebbles, cobbles, boulders, and silty sand. These glacial deposits are found at elevations above 2,000 ft (610 m). The colluvium in the watershed forms sheets and fans on the lower part of valley walls as it is transported by water and gravity (Figure 8). It consists of sand, silt, clay, gravel, and boulders. Rockfall forms aprons below steep cliffs and consists of blocky boulders and gravels (talus unit of Sherrod and Scott, 1995). Shallow landslides in this unit have an average failure depth of 12 ft (3.7 m) and average pre-failure slope angle of 38 degrees. Shallow landslides can occur when the slope is greater than 16 degrees.

Figure 8. Colluvium forming sheets and fans at the base of a valley wall in the eastern portion of the watershed above the Bull Run Lake landslide. (Photo credit: K. A. Mickelson)

Residual soil on sedimentary rock

This unit includes the upper zone of weathered soil resting upon the Troutdale Formation. The unit is composed predominantly of silt, sand, and gravel. Most of the soil has formed in place or nearly so (residual soil). Shallow landslides are uncommon in this unit, with zero failures mapped. Shallow landslides, however, can occur where the slope is greater than 11.5 degrees.

Figure 9. Weathered soil from the Rhododendron Formation containing silty clay with gravel and small boulders. (Photo credit: K. A. Mickelson)

Residual soil on volcaniclastic rock

This unit includes the weathered soil resting upon the Rhododendron Formation. The soil is composed predominantly of silty clay with gravel and boulders (Figure 9). Most of the soil has formed in place or nearly in-place (residual soil). There are few shallow landslides in this unit. Shallow landslides in this unit have an average failure depth of 11 ft (3.4 m) and average pre-failure slope angle of 41 degrees.

Residual soil on igneous rock

This unit includes the upper zone of weathered soil developed on all lava flow sequences in the map area. Most of the soil has formed in place or nearly so (residual soil). The unit is composed predominantly of silty clay with gravel and boulders (Figure 10). Approximately 54 percent of all shallow landslides occur in the unit. Shallow landslides in this unit have an average failure depth of 8 ft (2.4 m) and have an average pre-failure slope angle of 34 degrees.

Figure 10. Igneous residual soil (silty clay with boulders) developed on weathered basalt. Spheroidal weathering of the lava flow is responsible for the boulder-like appearance. (Photo credit: K. A. Mickelson)

4.0 LANDSLIDE HAZARD EVALUATION METHODS

To study and evaluate the landslide hazard and update the surface hydrography, we performed three primary tasks. First we created a detailed landslide inventory. Then we used models to create shallow and deep landslide susceptibility. Finally, we updated the surface hydrography. The methods we used to perform and create these datasets are described in detail in the following sections of this report and in Appendices A–D and are the same methods we use on landslide hazard projects throughout Oregon.

4.1 Landslide Inventory

Prior to beginning lidar-based mapping of landslides in the Bull Run Watershed for the landslide inventory, we reviewed three existing landslide data sources:

- Statewide Landslide Information Database for Oregon (SLIDO), release 2 (Burns, and others, 2011)
- data from the Portland Water Bureau on historic landslides
- published geologic and hazard maps and a thesis

After review of regional landslide hazard studies, we followed the methodology of Burns and Madin (2009) (Appendix A) to create the landslide inventory at a scale of 1:8,000. A fundamental part of the methodology is manipulating lidar-derived data to enhance landslide morphology (Figure 11).

To visualize the data, we mapped the entire watershed using a lidar-derived bare-earth DEM and derivatives including shaded relief, slope maps, and topographic contours. The lidar DEM has a grid size of 3 ft by 3 ft (~1 m by ~1 m) and was collected by Watershed Sciences, Inc. between March and May 2007. In addition to lidar-derived imagery, we used an orthophotos of similar age (2005 and 2009 National Agriculture Imagery Program [NAIP] imagery; http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai) as the lidar data to help differentiate between some man-made and natural landforms.

We mapped the Bull Run Lake Landslide (also referred to as the Preachers Peak Landslide) in greater detail than the Burns and Madin (2009) protocol requires, and we show this map at a scale of 1:5,000 scale on Plate 4. Detailed landslide features on this map include shear and thrust features, closed depressions with depth, and captured streams (surface stream which goes underground) and springs (underground water which comes to the surface). We include this detailed landslide map to give readers an idea of the complexity that individual landslides can have.

Finally, we performed limited ground reconnaissance to verify and/or to collect additional information about some mapped landslides and revised the lidar-based landslide inventory map as needed.

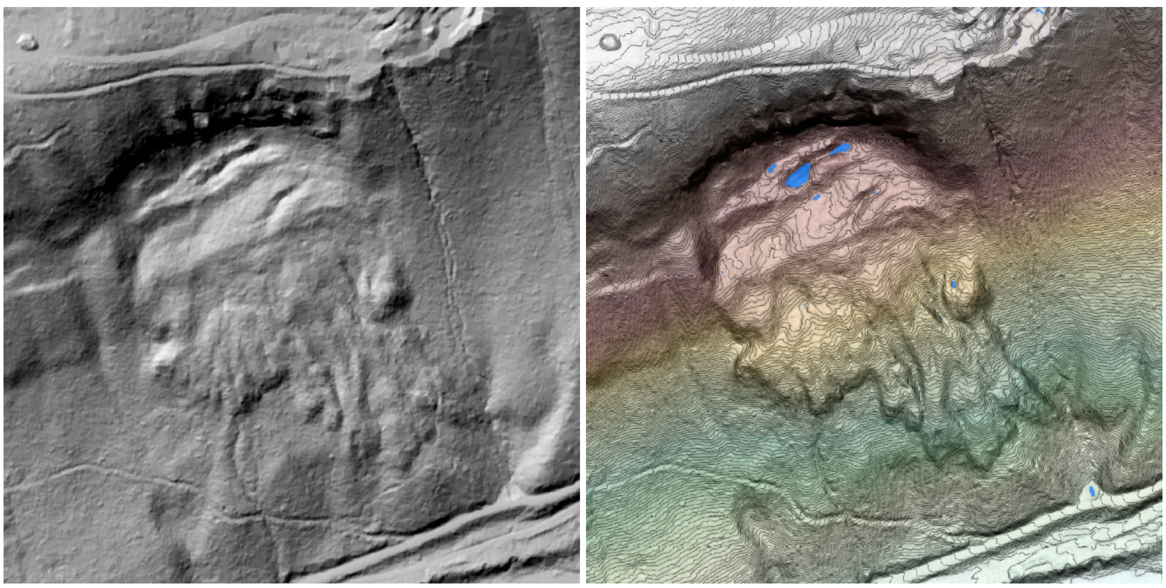


Figure 11. (A) Standard lidar-derived hillshade imagery and (B) enhanced visualization imagery created by following method of Burns and Madin (2009). The image on the right includes a slope shade, elevation color ramp (lower elevations in green to higher elevations in red and white), 3-ft contours, and areas of closed depressions (blue). Imagery is of the area in the western portion of the Bull Run Watershed, directly below Bull Run Dam Number 2 and above Waterworks Road.

4.2 Shallow Landslide Susceptibility

We created the shallow landslide susceptibility map by following the methodology of Burns and others (2012c) (included as Appendix B: Protocol for shallow-landslide susceptibility mapping, Special Paper 45). The main components of the method include:

1. using a landslide inventory
2. calculating regional slope stability factor of safety (FOS)
3. removing isolated small elevation changes (overprediction)
4. creating buffers to add in susceptible areas missed in a grid type analysis (underprediction)
5. combining the four components into final susceptibility hazard zones

The first component is taken directly from the landslide inventory created as part of this project. The calculation of the FOS requires several input datasets. One is a map of the surficial geology with geotechnical material properties. As discussed in section 3.2, we created a new surficial geology map during this project. Instead of using existing generalized statewide values (Table 2 in Appendix B [Burns and others, 2012c]), we created a new table of material properties (Table 1) for each of the primary surficial geologic units in this specific study area.

To calculate the FOS (component 2), we estimated new material properties from geotechnical reports and borings (Appendix B). In many reports, cohesion and phi (angle of internal friction) values were not tested and therefore were not directly available. Therefore, we estimated these values through empirical correlations from other tests such as standard penetration test blow counts following the method described by Das (1994).

After we acquired the values either directly from reports or through correlations for each surficial geologic unit, we averaged each set of values by geologic unit. DOGAMI and PWB geotechnical engineers then reviewed these ranges of values and averaged values in order to decide the final material properties to be used for this study. The final material properties are displayed in Table 1. These material properties were then used to calculate the two slope thresholds that separate the three FOS ranges. The three FOS ranges are 1) values greater than 1.5 (generally considered stable), 2) values between 1.25 and 1.5 (generally considered potentially unstable), and 3) values below 1.25 (generally considered potentially unstable and unstable below 1.0).

To remove isolated small elevation changes (overprediction; component 3) and to add in susceptible areas missed in a grid type analysis (underprediction; component 4) we created buffers as described in detail in Appendix B. When the FOS class map is prepared using a slope map with such high resolution, many areas with shallow landslide susceptibility are falsely classified as having moderate or high susceptibility (overprediction). This occurs because many fine-scale topographic features are represented in the lidar DEM that do not have sufficient vertical or lateral extent to pose a significant shallow landslide hazard, for example features like road ditches. One disadvantage of a slope stability analysis using a raster or grid-based infinite slope equation is that the analysis looks at each raster cell independently. The FOS is calculated in the same way re-

Table 1. Summary of geotechnical material properties for primary surficial geologic engineering units in the Bull Run Watershed.

	Angle of Internal Friction (degrees)	Cohesion, lb/ft^2	Unit Weight (Saturated), lb/ft^3	Slope Threshold (FOS > 1.5)	Slope Threshold (FOS > 1.25)
Alluvial deposits	32	0	122	11	13.5
Landslide deposits (deep)	28	0	122	9.5	11.5
Cinders (Aschoff Buttes)	28	500	122	20	24
Glacial till-outwash and colluvium	34	209	122	16	19.5
Residual soil on volcaniclastic rock	28	500	122	20	24
Residual soil on sedimentary rock	33	0	122	11.5	14
Residual soil on igneous rock	40	750	122	30	36

gardless of where the cell falls on a slope or where it sits in relation to important topographic features or changes. Because the location of a cell can have an important impact on the landslide susceptibility, we have developed two buffers to help reduce underprediction.

4.3 Deep Landslide Susceptibility

We created the deep landslide susceptibility map by generally following the methodology of Burns and others (2013) (Appendix C). The main components of the method include:

1. using a landslide inventory
2. creating buffers (hazard zone expansion areas)
3. combining the following four factors to determine the moderate susceptibility zone:
    - susceptible geologic units
    - susceptible geologic contacts
    - susceptible slope angles for each engineering geology unit polygon
    - susceptible direction of movement for each engineering geology unit polygon
4. combining the three components into final susceptibility hazard zones

For each component and factor we made separate temporary GIS data layers. The first component is taken directly from the landslide inventory created as part of this project. Because many deep landslides move repeatedly over hundreds or thousands of years, and many times the continued movement is through retrogressive failure or upslope failure of the head scarp, we applied a buffer (expanded the hazard zone) to all mapped deep landslide deposits.

Next, we used four factors to determine the moderate zone. The first factor, geologic units, has a relatively widespread correlation with surficial processes. For example, it is very common that certain rock formations or soil units are more or less prone to landslides. This is generally because of the properties of the unit, such as the material strength or bedding planes within the unit.

The second factor, geologic contacts, is something we have noted in Oregon, especially since we began mapping landslide inventories using lidar. We have noted that many landslides occur along a contact, especially when a sedimentary or pyroclastic unit is overlain by hard volcanic rocks. For example, large, deep landslides are located next to each other along the contact between the overlying basalt of the Bull Run Watershed or Boring Lava and the underlying Rhododendron Formation. Most of these landslides' failure surfaces are almost completely within the Rhododendron Formation, so they are not failing or sliding along the "geologic contact" in the sense that the failure plane follows the contact below ground. It is more of a spatial relationship between the landslides and the contact surface trace in map view; this relationship is most likely caused by erosion or downcutting at the surface, which leads to exposure of the underlying weaker unit.

The third factor, slope angles, is very commonly correlated with landslide susceptibility. Most landslide susceptibility maps use slope as the primary factor or as at least one of the factors to predict future landslide locations. With regard to shallow landslides, it is very common to see more shallow landslides associated with steeper slopes. Deep landslides appear to have a less direct correlation with slope steepness, which is one reason we include the other three factors (geologic units, geologic contacts, and direction of movement).

Finally, the fourth factor, direction of movement, is probably the least commonly used. However, we record it at every landslide in our landslide inventory and therefore have data. A standard factor to examine during site-specific evaluations is the local bedding dip and dip direction, because deep landslides tend to fail along those bedding planes and in the direction of the dip, especially where slope and dip are in the same direction. Unfortunately, we do not have extensive dip and dip direction measurements, so we decided to use the recorded direction of movement from the landslide inventory database as a proxy for dip direction or preferred direction of movement.

We then added together the four GIS data layers made from the factors to delineate the line between the moderate and low hazard zones. Then we combined the four component GIS layers to create the deep landslide susceptibility map with low, moderate, and high hazard zones.

4.4 Surface Hydrography

We performed several tasks to improve the surface hydrography datasets for the Bull Run Watershed with the goal of submitting the data to the National Hydrography Dataset (NHD; U.S. Geological Survey [2012a]) and Watershed Boundary Dataset (WBD; U.S. Geological Survey [2012b]). We have summarized the tasks below and include details in Appendix D. We began with a lakes polygon and modeled stream line datasets provided by the PWB. We performed some simple edits to each dataset, mostly to fix errors created by the hydro-models (Figure 12). The hydro-models used to delineate stream locations are fairly accurate except and especially where water goes underground (e.g., through culverts or into waterbodies such as lakes). The main input into the model is the bare-earth DEM. The model does not know that a culvert or some other underground structure is present and misroutes the stream line in some other down slope direction.

Next we digitized approximately 90 lakes and other waterbodies and added them to the dataset. Finally, we modeled and edited new watershed boundaries for HU10 and HU12 (hydrologic unit) watersheds (Figure 13).

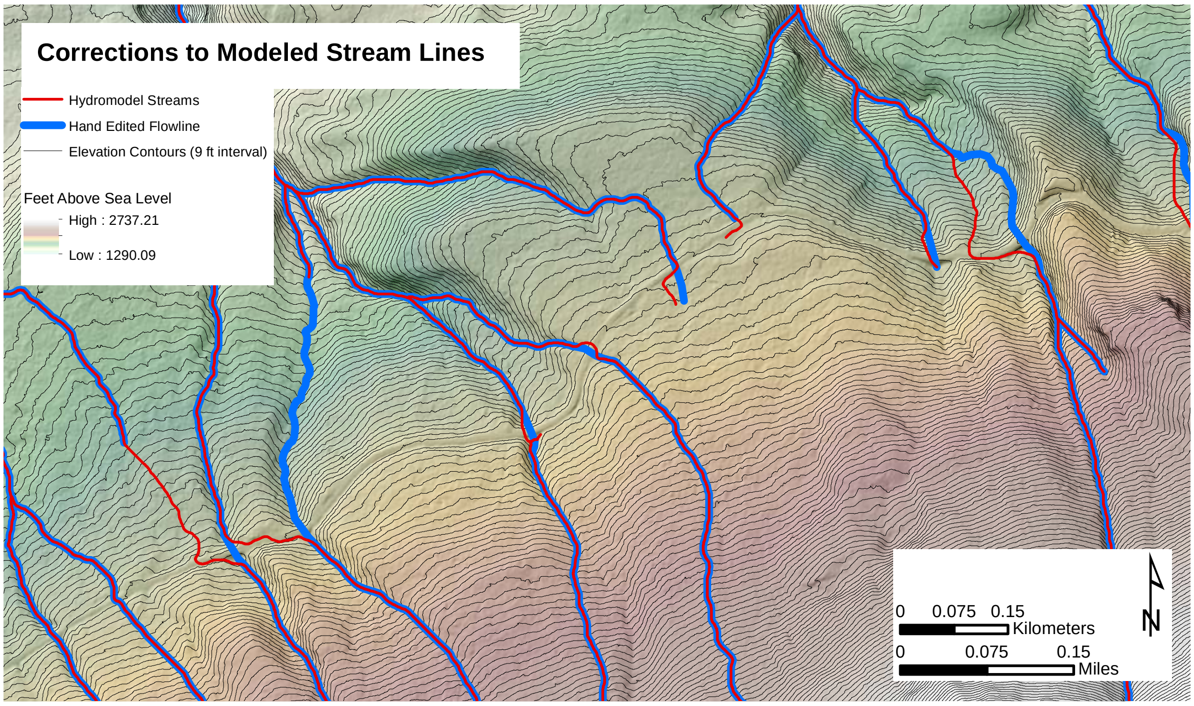


Figure 12. Map showing corrected stream lines in the central portion of the Bull Run Watershed directly above the uppermost portion of Bull Run Reservoir Number One. Hydromodeled streams (red) were edited to follow the flow line paths (blue) defined by using lidar-derived imagery

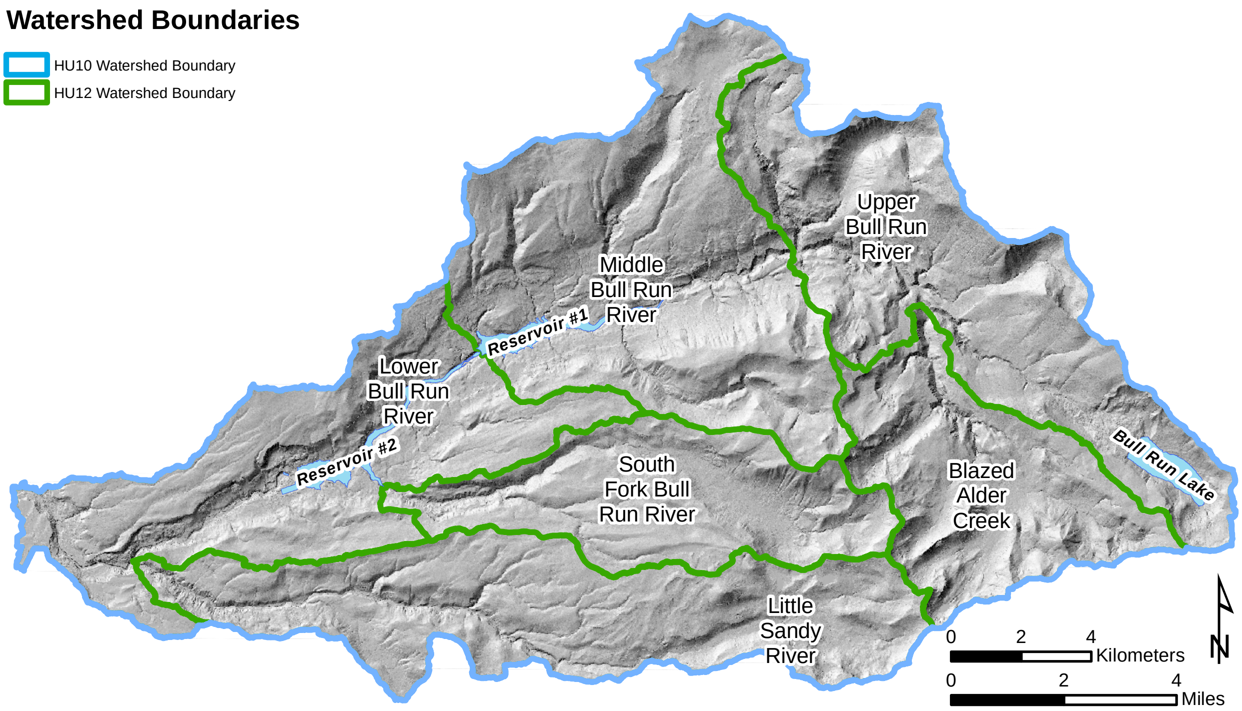


Figure 13. Map of redefined HU10 and HU12 watershed boundaries in the Bull Run Watershed. HU is hydrologic unit.

5.0 RESULTS AND DISCUSSION

The results of this study include three landslide hazard maps: landslide inventory (Plate 1), shallow landslide susceptibility (Plate 2), deep landslide susceptibility (Plate 3); a detailed map of the Bull Run Lake Landslide (Preachers Peak Landslide) (Plate 4); and an updated surface hydrography dataset (Plate 5). The results are described and discussed below.

5.1 Landslide Inventory

5.1.1 General findings

Previous workers have studied landslides in the Bull Run Watershed. Beaulieu (1974) identified 23 landslide areas within the watershed, covering 162,176,754 ft^2 (15,066,713 m^2) (5.8 mi^2 or 15 km^2), or approximately 4.5 percent of the watershed. Schulz (1980) mapped landslides in the watershed as part of his M.S. thesis. He identified 86 landslides.

In contrast, for the inventory created as part of this project, we found 1,068 landslides in the Bull Run Watershed, covering approximately 564,227,000 ft^2 (52,418,613 m^2) (20 mi^2 [52 km^2]), or approximately 15 percent of the watershed (Plate 5). These landslides range in size from a couple hundred square feet (approximately 18.5 m^2) to more than one square mile (3.1 km^2) (Bull Run Lake Landslide; Plate 4); of the 1,068 landslides, 100 (0.1%) are shallow and 450 (11%) are deep, that is, have an estimated failure surface deeper than 15 ft (4.5 m) below the surface. The other landslides are mostly debris flow fans and rock fall talus.

Out of the 1,068 landslides, 226 (20 percent) are known or estimated to have moved in the last 150 years. A very simplified historical constant rate of landslides would then be approximately 1-2 landslides per year (226 landslides/150 years). However, as discovered in other studies in Oregon, it is much more likely that tens of landslides occur during large storm events followed by periods of no or very few landslides (Burns and others, 2013; Wang and others, 2002). Most of these historical landslides are classed as earth flow and rock flow. The volumes of these landslides range from 623 ft^3 (17.5 m^3) (roughly one large dump truck load) to 48,394,496 ft^3 (1,370,379.6 m^3) with a mean of 9,370,187 ft^3 (265,334.2 m^3).

5.1.2 Historical landslides

Table 2 is a summary of some of recent landslides. Several of these landslides caused damage. It is well documented that landslides have damaged the primary water pipes or conduits and roads within the watershed (Table 2; Landslide Technology, 1995, 1996; Cornforth Consultants, 2003; Hogan and Collins, 2012; see Appendix A).

Table 2. Recent landslides in Bull Run Watershed.

Name	Date(s) of Movement	Damage/Comments	Reference
North Fork slide	January 20, 1972	turbid water	Beaulieu (1974)
Ditch Camp slide	1890s?; December 1964–January 1965	damaged conduits no. 1 and no. 4	Beaulieu (1974); Cornforth Consultants (2001)
Soapstone Hill slide	1965; 2011-2012	small shallow debris slides (2011-2012)	Beaulieu (1974)
Little Sandy River slide			Beaulieu (1974)
Boathouse slide	1973		Beaulieu (1974)
Larson’s Bridge slide		damaged conduit no. 4	Beaulieu (1974)
Penstock slide			Landslide Technology (2003)
South Fork slide	1970s; February 2012	turbid water	Beaulieu (1974)
Headworks Bridge slide	November 1995	damaged bridge and pipeline	Landslide Technology (1996, 1995)
Bowman Bridge slide	1997	triggered by leaking conduit #3	Landslide Technology (2003)
North Bull Run River slide	1996-1997	damaged road	Landslide Technology (2003)
Camp Namanu slide			Landslide Technology (2003)

5.1.3 Relationship of landslides and geology

We found that most large deep landslides in the Bull Run Watershed are associated with three engineering geologic units: Rhododendron Formation (approximately 30 percent of the landslides), the basalt of the Bull Run Watershed (approximately 30 percent of the landslides), and Troutdale Formation (approximately 25 percent of the landslides). When examined by landslide area per geologic unit area, we found 35 percent of the exposed Rhododendron was covered by landslides, 10 percent of the basalt of the Bull Run Watershed, and 25 percent of the Troutdale. These numbers indicate a strong correlation between geology and landslides, especially the Rhododendron Formation (Figure 14).

Part of the correlation between the geology and landslides is likely due to the exposure of the Rhododendron at or near the surface. This can be clearly seen along the Bull Run River, especially in the area identified in Figure 2 as eroded area (also see Figure 15). It appears the area has gone through some sort of erosion event or events, perhaps from glaciers (during an older glacial period than the latest one [represented in Figure 2]), where the glaciers extended to a lower elevation or a glacial impounded lake outburst from the upper reaches of the watershed or a landslide lake outburst or simple river erosion down to the Columbia River Basalt base level. Scott (1977) inferred maximum glacial extents at Mount Jefferson to have occurred ~20–25 ka. Orr and Orr (2000, p. 148) stated, "Glacial ice stretched from the peak of Mount Hood, down the Sandy River almost to the Columbia." Both indicate a larger older glacial period likely occurred within the Bull Run Watershed. Regardless of the event(s), the formations along the Bull Run River appear to have been removed down to the Columbia River Basalt.

The Columbia River Basalt appears to have almost no residual soil on top of it and has similar geomorphology to the Scablands in eastern Washington, leading us to believe that much of the erosion on the Bull Run River may be due to catastrophic flooding (Figure 16).

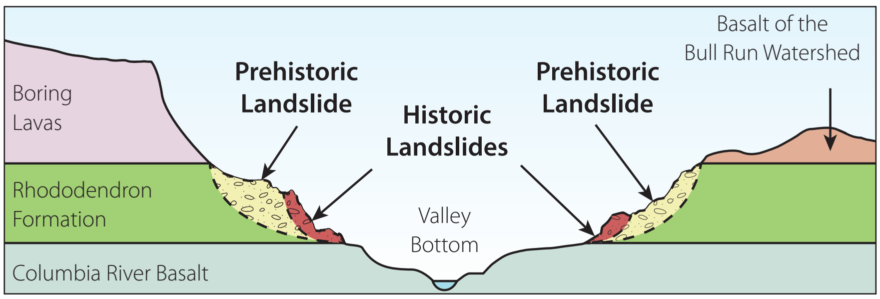


Figure 14. Schematic cross section across the Bull Run River. The central portion of the cross section is an example of an area where formations along the Bull Run River have been removed down to the Columbia River Basalt. Erosion resulted in exposure of the Rhododendron Formation and landsliding. Also see Figure 2B.

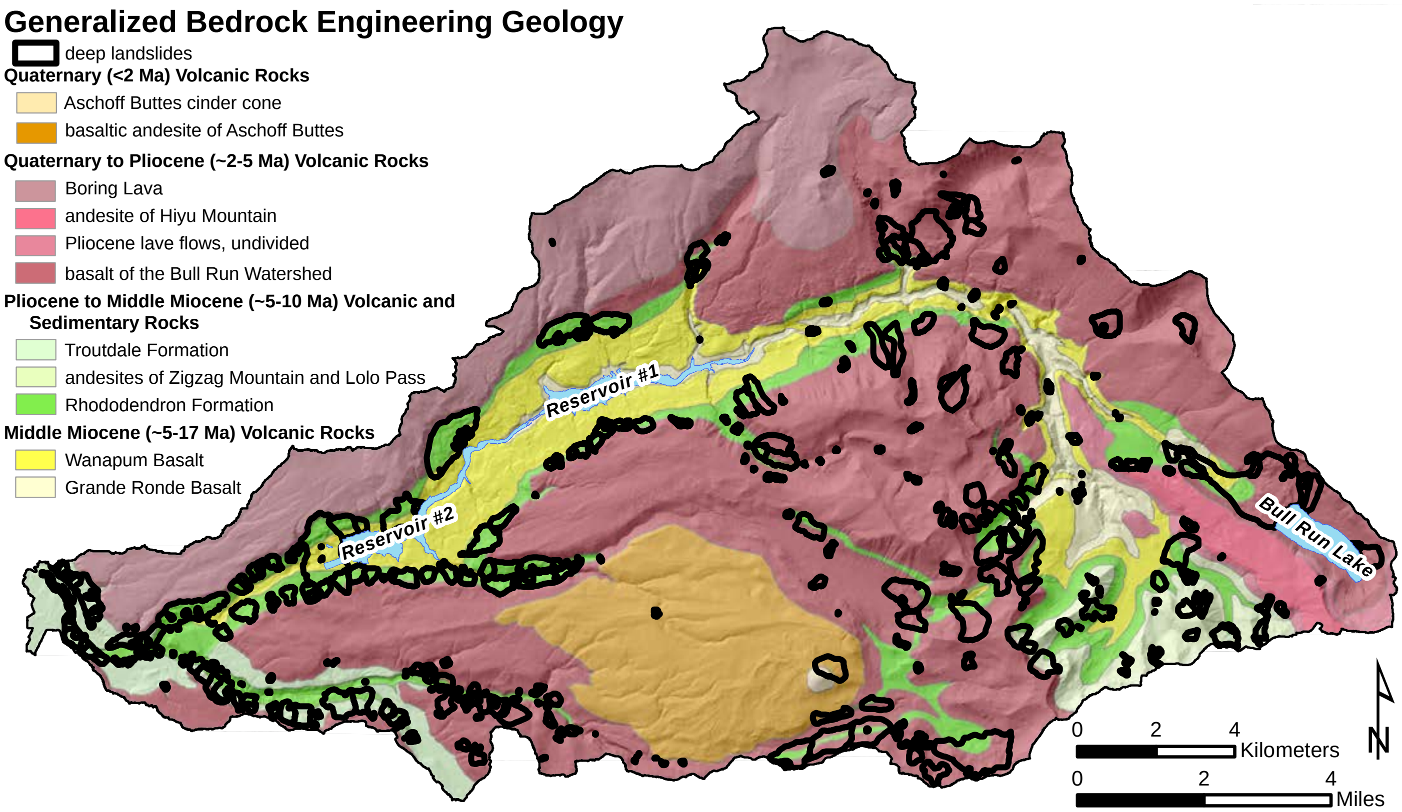


Figure 15. Map of deep landslide extents (black outlines) shown on bedrock geology for the Bull Run Watershed. Also see Plate 1.

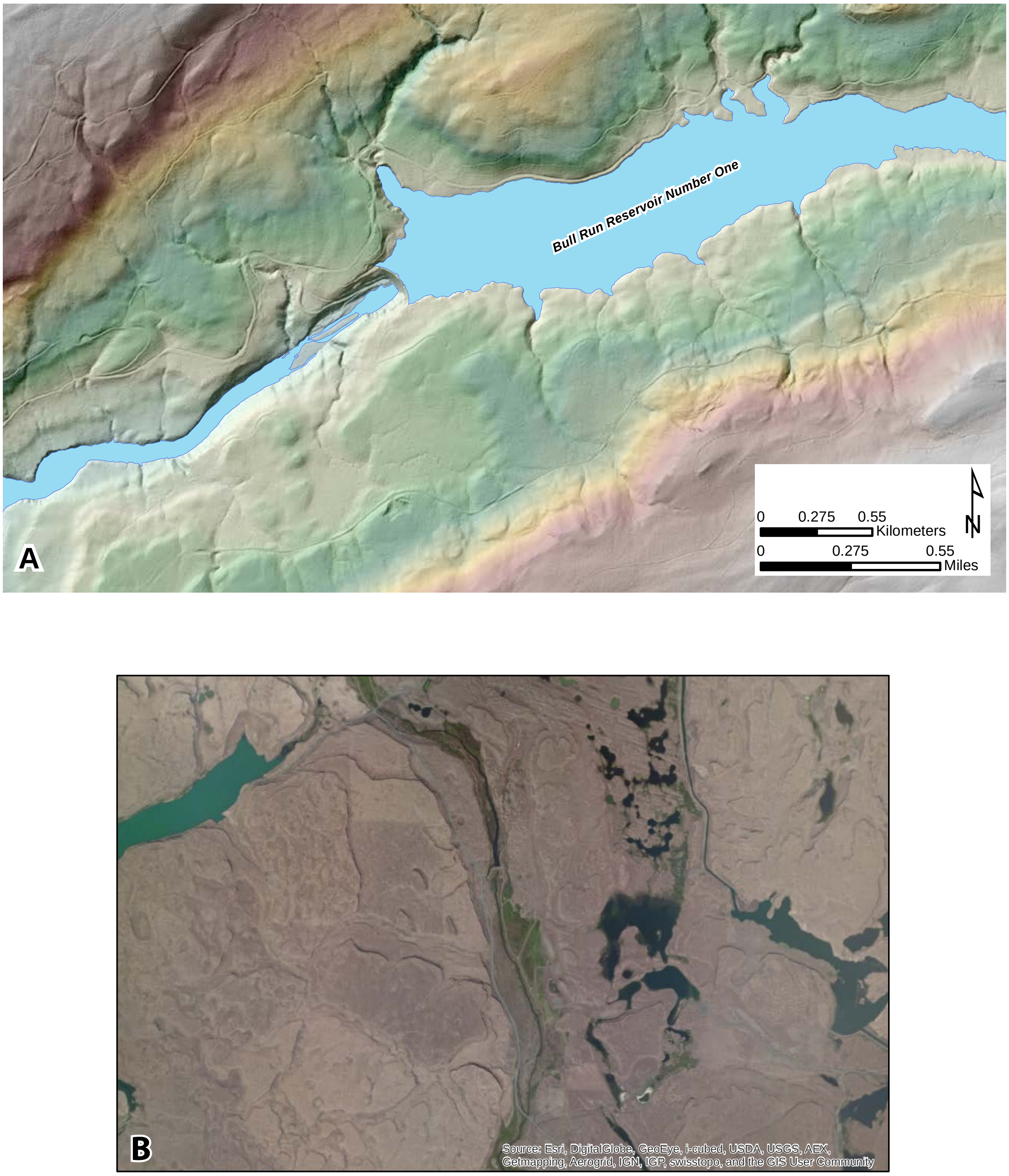


Figure 16. (A) Area along the Bull Run River with scabland like morphology. (B) Aerial photo of scabland morphology near Othello, Washington. (Image created using ArcGIS® software by Esri®. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.)

We noted, as did Schulz (1980), that younger landslides commonly occur within older (prehistoric) larger landslide complexes (Figure 17). This is because the rocks in these older slides have usually been extensively sheared, greatly reducing relative strength compared to the original geologic unit. The other change caused by an existing large older landslide complex is that the relative slope steepness is usually increased along the head scarp and toe. We commonly see smaller, younger landslides along the head scarp and toe of larger, older landslides. The Boody Reservoir/Lake outburst flood in 1972 may serve as an example. The spillway for Boody Reservoir/Lake was apparently blocked by ice, which eventually broke and released a pulse of water. The flood outburst caused the reactivation of an existing large deep prehistoric landslide downstream within the North Fork Bull Run River. The reactivation of the large deep landslide combined with the flood outburst sent a large volume of debris into Bull Run Reservoir Number Two. This combination of events is now referred to as the 1972 North Fork slide (Plate 1).

5.1.4 Debris flows

One of the better ways to identify if a particular drainage has had debris flows in the past is to locate a fan at the mouth of the drainage. The fan is usually formed by a sequence of debris flows depositing material where the channel gradient is reduced and the channel confinement is lost. Several primary rivers in the Bull Run Watershed (e.g., North Fork Bull Run River and South Fork Bull Run River) exit directly into a waterbody, so we cannot see if there is a fan from events prior to dam and reservoir construction or a delta if the material was deposited into the waterbody after to construction. However, even with this scenario, we noted small fans at the mouths of Cougar Creek and the North Fork Bull of the Run River (Plate 1). As previously noted, these fans are likely the results of large deep landslides becoming large-volume debris flows that travel longer distances. In locations where steep side channels exit onto valley bottoms, like the upper reaches of Cedar Creek, fans are extensive.

Past studies (Hungr and others, 1984; Benda and Cundy, 1990; Fannin and Rollerson, 1993; Fannin and others, 1997; Washington Department of Natural Resources,

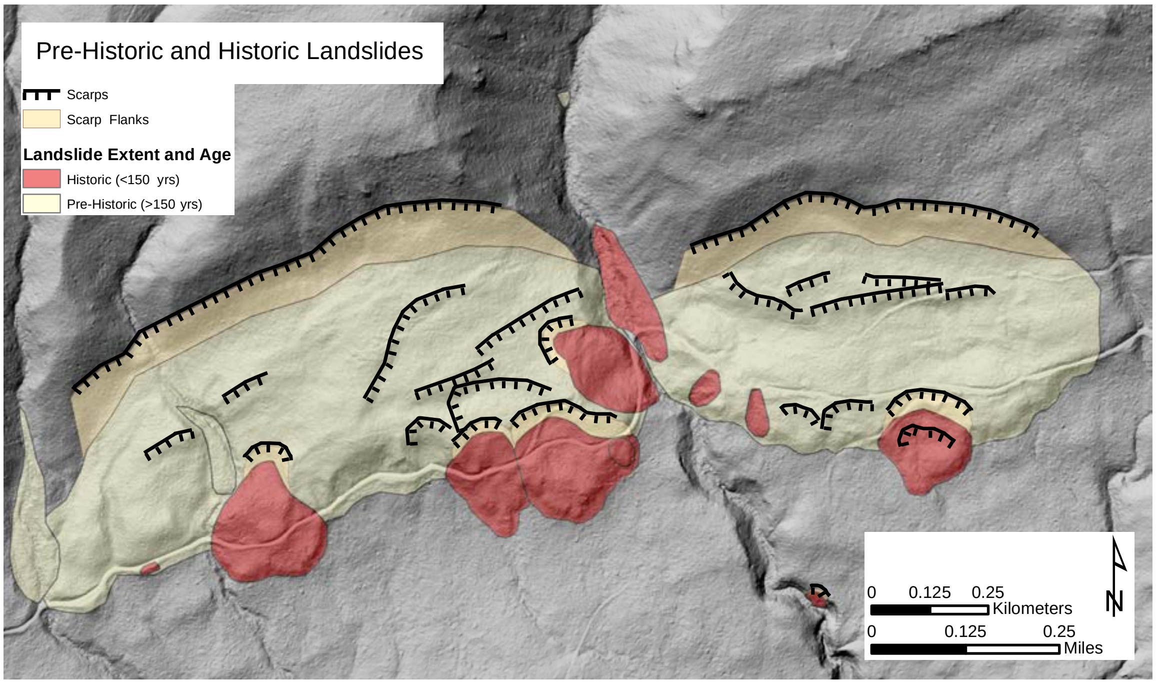


Figure 17. Example of the relationship of some historic landslides and pre-historic landslides. Map location along Cougar Creek.

2004) have shown that steeper channels transport debris flows more readily. Most of the studies have been focused on identification of the channel gradient at which debris flows stop transport and start to deposit. Some reported threshold values for deposition include 3 degrees, 3.5 degrees, 5 to 13 degrees, 8 to 12 degrees, 9 to 15 degrees, and 10 to 5 degrees.

Mapping of debris flow fan deposits following the protocol by Burns and Madin (2009) at several recent and current DOGAMI projects resulted in databases of fans. We mapped 379 fans in the North Fork Siuslaw watershed located in the Oregon Coast Range and found the mean slope angle was 16 degrees (Burns and others, 2012d). We mapped 1,310 fans in the Portland area and found a mean slope angle of 11 degrees (Burns and others, 2012e). At each of the fans we estimated the channel gradient in the fan from the lidar-derived bare-earth DEMs. Both of these mostly lidar based studies correlate with the 3 to 15 degree range from the mostly field based studies (Hungr and others, 1984; Benda and Cundy, 1990; Fannin and Rollerson, 1993; Fannin and others, 1997; Washington Department of Natural Resources, 2004). Therefore, we agree with authors of other studies that if the channel gradient is in the 3 to 15 degree range, debris flow transport does not ocur.

5.1.5 Proximity of landslides to roadways

We mapped approximately 40 small shallow landslides along the roads. We mapped many of these small landslides in the field as they were very difficult to see on the lidar-derived base map. Most of these slides appeared to be failures of the fill embankment (Figure 18). They appeared to be more prevalent where the slope was steeper than about 20 degrees (Figure 19). In fact, the mean slope angle of fill failures (landslides) is 32 degrees with a range of 16 to 50 degrees. We also noted a correlation between these slides and undersized or blocked culverts at some of these locations and the need for culverts at other locations.

We also noted historic/active landslides located just above some roads (Figure 20). In some cases the road cut slope is the same as the toe of the landslide (Figure 21). In these cases, removal of material from the cut slope/toe may cause the landslide to continue to move or even to accelerate. It appears that removal of material, likely performed as maintenance, has been occurring especially in ditch areas and adjacent slopes to keep ditches clear. As this material is removed, it very likely contributes to the slide moving again, because of removal of resisting material along the slide toe. The landslide then moves more,

Figure 18. Road fill embankment failure along NF road 10 in southeastern Bull Run Watershed. (Photo credit: K. A. Mickelson)

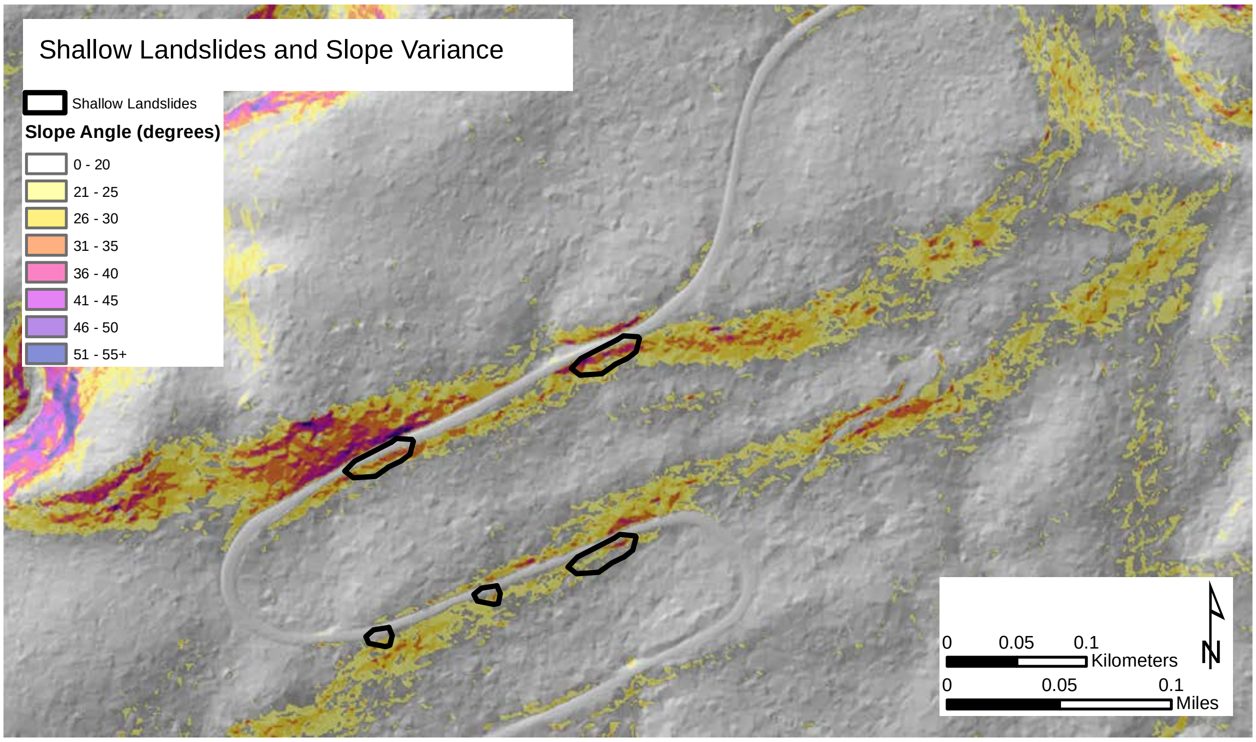
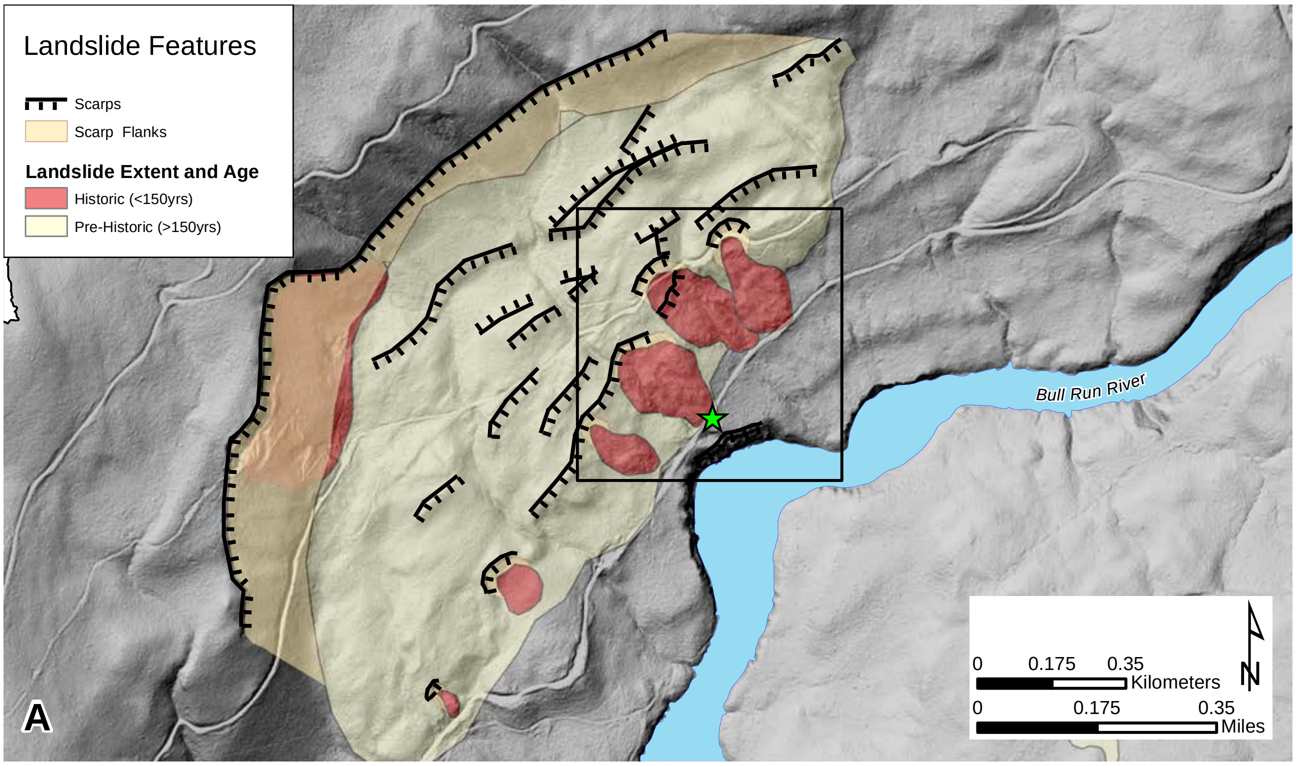


Figure 19. Map of landslides in the fill embankment and variance in slope angle along NF road 10 in the central portion of the Bull Run Watershed.



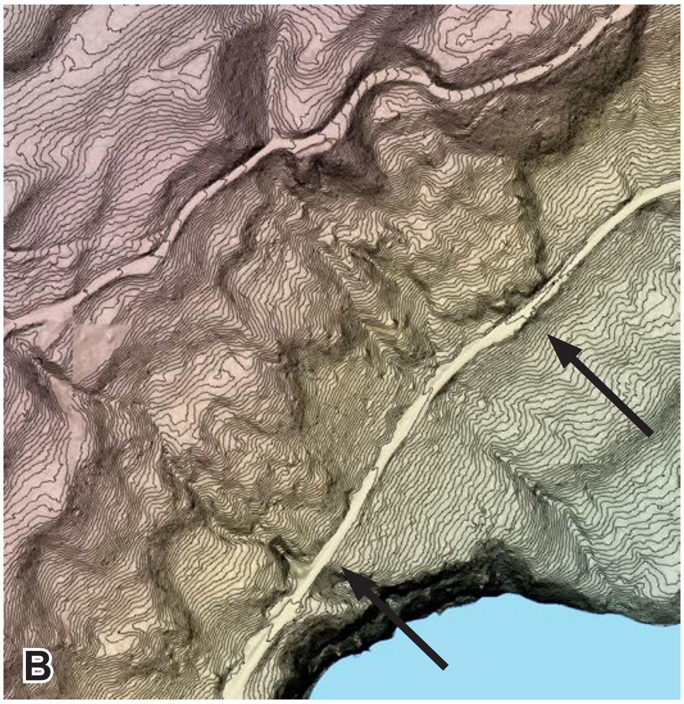


Figure 20. (A) Map of historic landslides above and intersecting NF road 10 in the central portion of the Bull Run Watershed. Green star indicates the location of the photo in Figure 21. (B) Close-up with 3-ft contours of boxed area in (A). Arrows point to two locations where landslide toes have been cut by road grading.

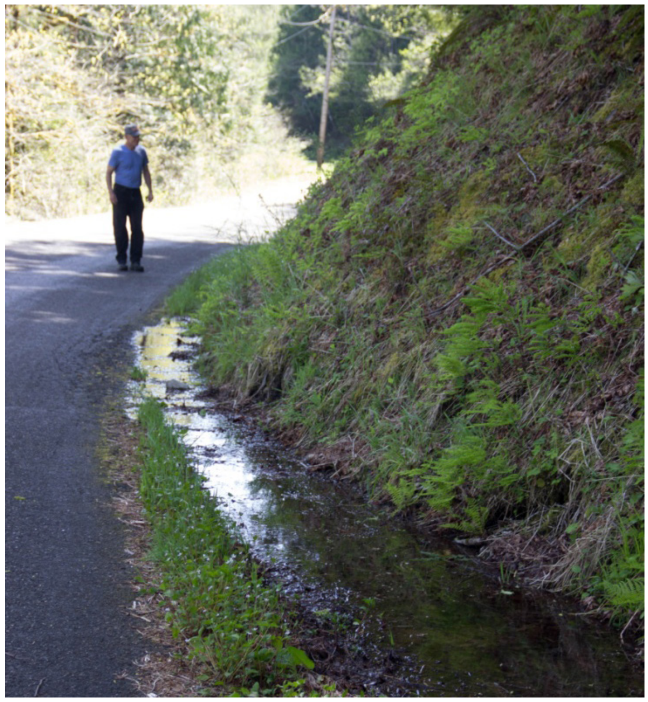


Figure 21. Photo of the toe of an historic/active landslide along NF road 10. Photo location is at the green star in Figure 20. The toe appears to be over steepened through grading. At the time, the photo was taken water was pouring out of the slope and filling the ditch. (Photo credit: K. A. Mickelson)

causing material to be deposited in the ditch from mass movement and surficial erosion; removal then triggers new movement. If enough material is removed over time by this incremental process, a catastrophic failure may occur. These landslides are located very close to the upper reaches of Bull Run Reservoir Number Two. Figure 21 shows a roadside ditch that appears to be undergoing this process.

5.1.6 Proximity of landslides to dams

There are three large lakes/reservoirs in the Bull Run Watershed:

- Bull Run Reservoir Number One (middle of the watershed)
- Bull Run Reservoir Number Two (western portion of the watershed)
- Bull Run Lake (eastern portion of the watershed; Plate 1)

Bull Run Reservoir Number One is impounded by a concrete arch dam. We did not map large deep landslides in the vicinity of this dam.

The dam impounding Bull Run Lake is a natural dam consisting of the largest deep landslide in the watershed (Plate 4). The dam impounding Bull Run Reservoir Number Two is a man-made earthen dam, which was constructed on and/or within a large deep landslide. Past reports note landslide deposits of up to 100 ft (30 m) on the island between the earthen dam and the spillway (Shannon and Wilson, 2010). These two landslides appear to have the longest landslide runout of all the deep landslides in the watershed. The Bull Run Lake Landslide (Preachers Peak Landslide) extends across the valley and up the south valley wall. It is likely that at a later date, the landslide failed again, perhaps multiple times, and moved down the Bull Run River valley channel. The Bull Run Reservoir Number Two landslide extends across the Bull Run River valley; the toe is at the base of the south valley wall. It does not appear that this landslide turned and extended down valley in a manner similar to the Bull Run Lake landslide. Because both Bull Run Lake and Bull Run Reservoir Number Two are partially or completely impounded by existing landslides, there is an elevated risk of future movement.

5.2 Shallow Landslide Susceptibility

We classified the entire watershed into areas of low, moderate, and high susceptibility to shallow landslides. Approximately 53 percent of the watershed is classified as low, 26 percent as moderate, and 21 percent as high (Figure 22; Plate 2). It is important to remember that the susceptibility map can be thought of as a worst case scenario. This is because we set the groundwater table level to the ground surface throughout the watershed. This is unlikely, but without better spatial and temporal information about groundwater this is the best and most conservative approach.

Although we did not model susceptibility to channelized debris flow transport (in channels) and deposition (in fans), we did map existing debris flow fans as part of the landslide inventory. Areas identified as highly susceptible to shallow landsliding are the most likely areas for initiation of debris flows (Figure 23).

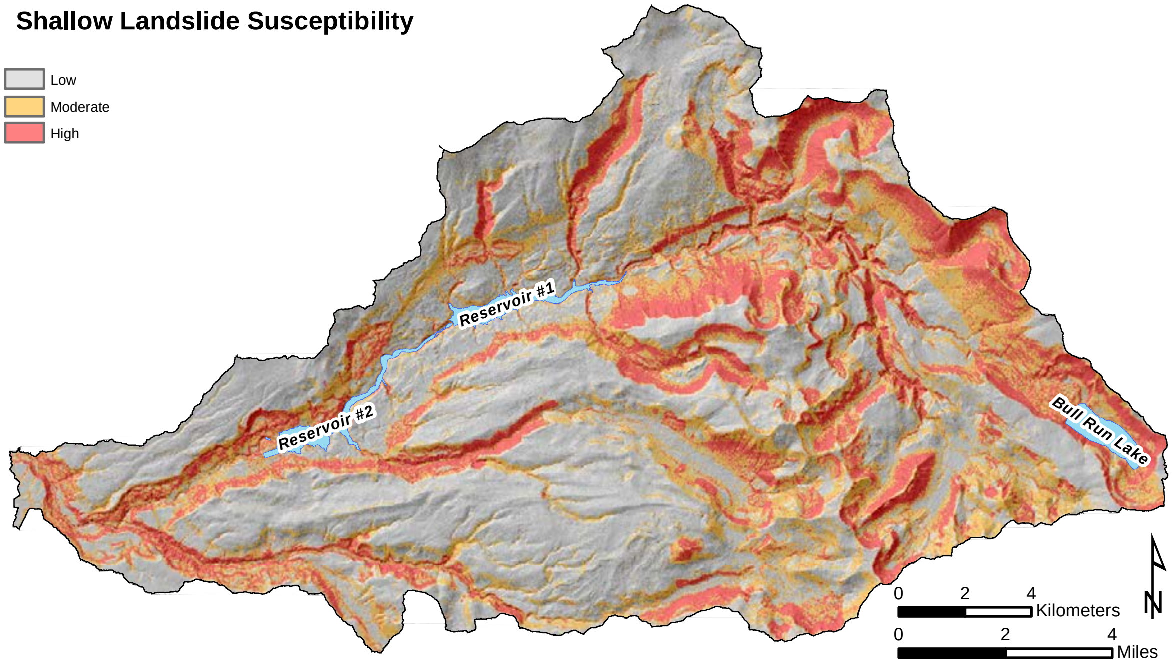


Figure 22. Map of shallow landslide susceptibility for the Bull Run Watershed. Also see Plate 2.

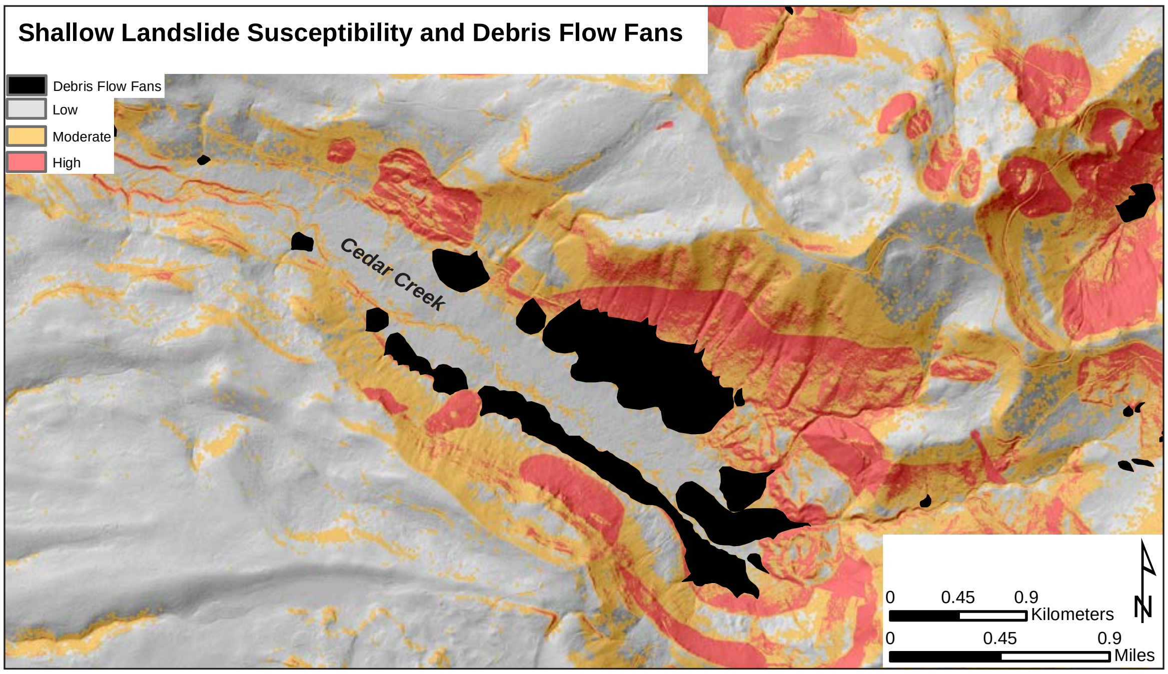


Figure 23. Map of the spatial relationship between mapped existing debris flow fans and shallow landslide susceptibility on the upper reach of Cedar Creek in the central portion of the Bull Run Watershed.

To further examine shallow landslide susceptibility, we divided the watershed into three main sections: lower Bull Run River (below Bull Run Reservoir Number Two), middle Bull Run River (everywhere that drains into Bull Run Reservoir Number Two), and upper Bull Run River (everywhere that drains into Bull Run Reservoir Number One). We then subdivided these three sections into subwatersheds of the primary named creeks and rivers within the watershed (Figure 24). This resulted in 27 subwatershed boundaries in which we were able to calculate areas of shallow and deep landslide susceptibility (Table 3). This simple spatial analysis allows us to examine and compare areas within the Bull Run Watershed. In general, the subwatersheds with the greatest areas of high susceptibility to future shallow landslides include Hickman Creek, Blazed Alder Creek, Upper Bull Run River, Falls Creek, West Branch Falls Creek, North Fork Bull Run River, Log Creek, Nanny Creek, Fir Creek, Cedar Creek, Middle Bull Run River, South Fork Bull Run River, Lower Bull Run River, and Little Sandy River. All of these subwatersheds had greater than 0.5 square miles (1.3 km) of area classified as having high susceptibility to shallow landslides. Many of these areas have had shallow historic landslides, which also indicate relatively higher susceptibility.

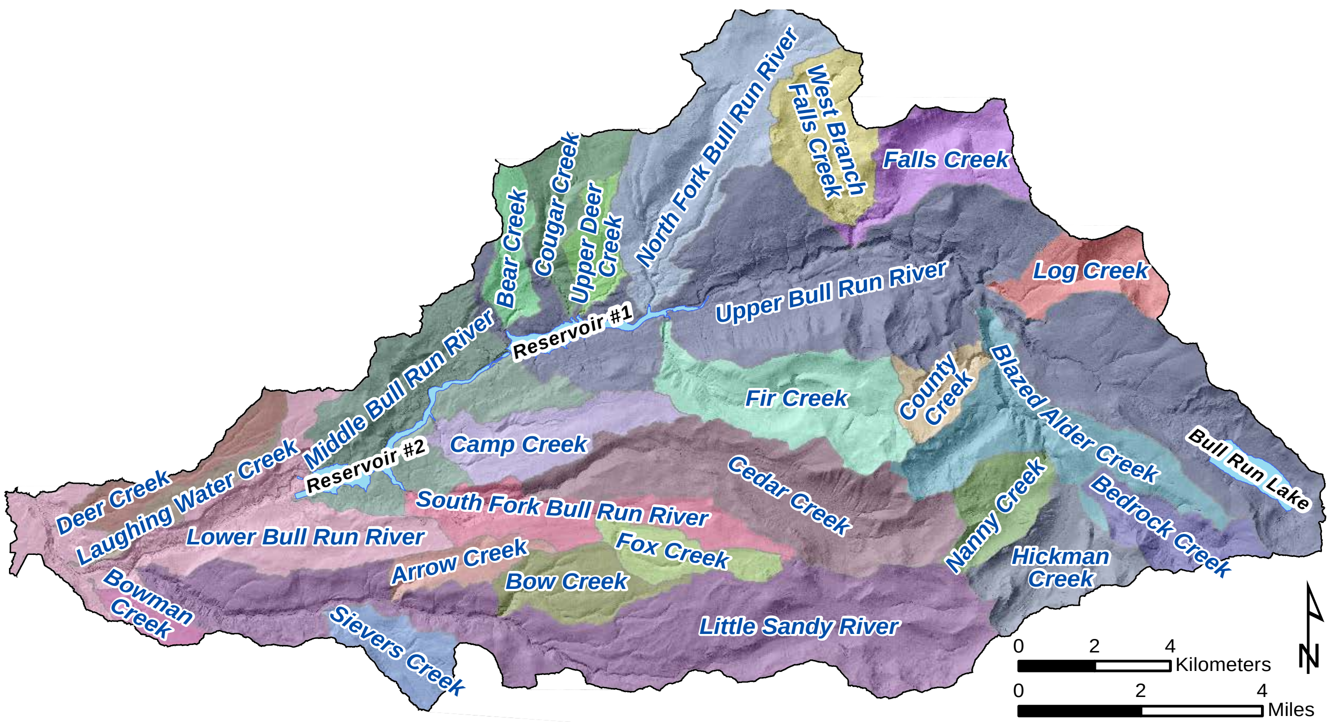


Figure 24. Map of the 27 subwatersheds of the Bull Run Watershed. Also see Plate 5.

Table 3. Summary of shallow and deep landslide susceptibility in the 27 subwatersheds of the Bull Run Watershed.

		Shallow Landslides				Deep Landslides			
		Moderate Susceptibility		High Susceptibility		Moderate Susceptibility		High Susceptibility	
Sections and Subwatersheds	**Area, miles²**	**miles²**	**percent**	**miles²**	**percent**	**miles²**	**percent**	**miles²**	**percent**
Upper Bull Run River (Reservoir No. 1)									
Hickman Creek	3.7	1.5	40%	1.21	32%	1.3	35%	0.45	12%
Nanny Creek	2.3	0.8	33%	0.69	30%	0.7	30%	0.49	21%
Bedrock Creek	2.5	1.2	48%	0.45	18%	0.9	36%	0.58	23%
Blazed Alder Creek	6.2	1.9	30%	1.61	26%	1.1	18%	1.02	17%
Upper Bull Run River	28.9	9.0	31%	8.09	28%	6.2	21%	3.86	13%
West Branch Falls Creek	3.9	1.1	27%	0.99	26%	0.4	10%	0.64	17%
Falls Creek	3.7	0.9	25%	1.86	51%	0.5	14%	0.57	15%
North Fork Bull Run River	8.0	1.3	17%	1.14	14%	0.4	5%	0.27	3%
Deer Creek	1.4	0.4	28%	0.06	4%	0.3	19%	0.10	7%
Cougar Creek	2.6	0.4	15%	0.39	15%	0.1	3%	0.19	7%
Log Creek	2.6	0.7	28%	1.41	54%	0.3	10%	0.33	12%
Bear Creek	1.6	0.5	30%	0.11	7%	0.2	15%	0.20	13%
County Creek	1.6	0.4	28%	0.30	19%	0.5	29%	0.22	14%
Fir Creek	5.8	1.6	27%	1.58	27%	1.1	19%	0.59	10%
Middle Bull Run River (Reservoir No. 2)									
Cedar Creek	9.6	3.2	33%	1.85	19%	3.2	34%	1.23	13%
Fox Creek	1.9	0.2	12%	0.02	1%	0.0	0%	0.01	1%
South Fork Bull Run River	4.1	0.7	18%	0.66	16%	0.4	10%	1.05	26%
Middle Bull Run River	8.4	1.9	23%	1.11	13%	1.4	16%	1.92	23%
Camp Creek	3.5	0.4	10%	0.12	3%	0.2	7%	0.12	4%
Lower Bull Run River									
Arrow Creek	1.5	0.1	8%	0.05	3%	0.1	4%	0.05	4%
Lower Bull Run River	8.9	2.1	24%	1.89	21%	1.8	20%	2.91	33%
Bow Creek	2.6	0.3	11%	0.03	1%	0.1	3%	0.03	1%
Bowman Creek	0.9	0.1	13%	0.07	8%	0.1	13%	0.02	2%
Little Sandy River	18.7	5.3	28%	3.36	18%	4.0	21%	3.68	20%
Sievers Creek	2.2	0.7	30%	0.28	13%	0.6	26%	0.36	17%
Laughing Water Creek	1.2	0.1	8%	0.02	2%	0.1	12%	0.06	5%
Deer Creek	1.9	0.2	8%	0.05	3%	0.0	2%	0.09	5%
Bull Run Watershed Total Miles² Percent	140	37 (26%)		29 (21%)		26 (19%)		21 (15%)	

5.3 Deep Landslide Susceptibility

We classified the entire watershed into areas of low, moderate, and high susceptibility to deep landslides. Approximately 66 percent of the watershed is classified as low, 15 percent as moderate, and 19 percent as high (Figure 25; Plate 3). As previously mentioned (Figure 17), we noted that many historic deep landslides occurred within existing prehistoric landslides. This relationship can be clearly seen in Figure 26 and in Plates 1 and 3. It is important to remember that the susceptibility map can be thought of as a worst case scenario. This is because we included all deep landslides that have ever occurred throughout geologic time in the high susceptibility zone. However, we do not expect all deep landslides to be active at the same time throughout the watershed. This is the most conservative approach and therefore the worst case scenario.

As with shallow landslide susceptibility, we calculated the area covered by deep landslide susceptibility within the 27 subwatersheds (Table 3). In general, the subwatersheds with the greatest areas of high susceptibility to deep landslides include Bedrock Creek, Blazed Alder Creek, Upper Bull Run River, Falls Creek, the West Branch Falls Creek, Fir Creek, Cedar Creek, Middle Bull Run River, South Fork Bull Run River, Lower Bull Run River, and Little Sandy River. All of these had greater than 0.5 square miles (1.3 km) of area classified as having high susceptibility to deep landslides.

5.4 Surface Hydrography

The new surface hydrography data consist of three primary file types: stream lines (flow lines), waterbody polygons, and watershed polygons (HU [hydrologic units]) (Plate 5).

Our final dataset has 3,432 stream line segments; 67 percent of these have National Hydrography Dataset (NHD) reach codes, and the rest are new stream lines that were not in the existing NHD and will need new codes established during the NHD update process. Thirty-seven percent of the streams were classified as intermittent, 51 percent as perennial, and 11 percent as artificial paths.

Our final waterbody dataset has 92 waterbodies that cover 1.9 percent of the watershed. Seventy-seven percent of these have NHD reach codes, and the rest are new waterbodies that were not in the existing NHD and will need new codes established during the NHD update process. Twenty-seven waterbodies are classified as swamp/marsh areas that cover 0.3 percent of the watershed, and 65 waterbodies are classified as lakes/ponds that cover 1.6 percent of the watershed. The current and updated NHD does not classify any of the waterbodies as reservoirs.

The final redefined Bull Run Watershed boundary is a single HUC10 boundary as defined in the NHD. The lower limits of this boundary are at the confluence of the Bull Run River and the Sandy River. This new watershed boundary, which we delineated by using the new (3 ft^2 grid) lidar-derived bare-earth DEM, has an area of 3,901,012,315 ft^2 (362,416,227 m^2) [140 mi^2 (362 km^2)]. Six HUC12 (defined in the NHD as a subwatershed) boundaries subdivide the HUC10 boundary. These watershed and subwatershed boundaries are displayed on Plate 5.

We understand the PWB is interested in using these datasets to update the NHD. Although the new, detailed hydrography dataset is in place, some work remains before the NHD can be updated. We recommend forming a committee consisting of at least the following entities: Portland Water Bureau, U.S. Geological Survey (USGS) NHD Stewardship State Region I, USGS Oregon Geospatial Liaison, U.S. Forest Service (USFS) Mount Hood, Bureau of Land Management (BLM) Oregon State Office, and DOGAMI.

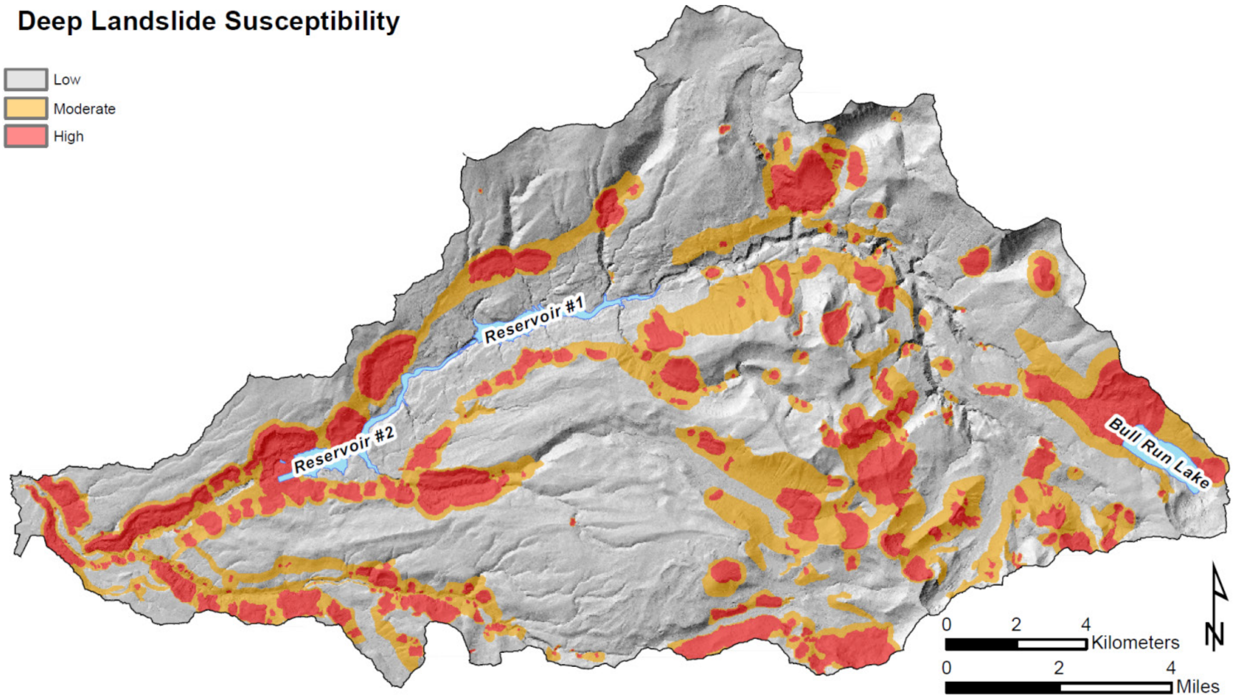


Figure 25. Map of deep landslide susceptibility for the Bull Run Watershed. Also see Plate 3.

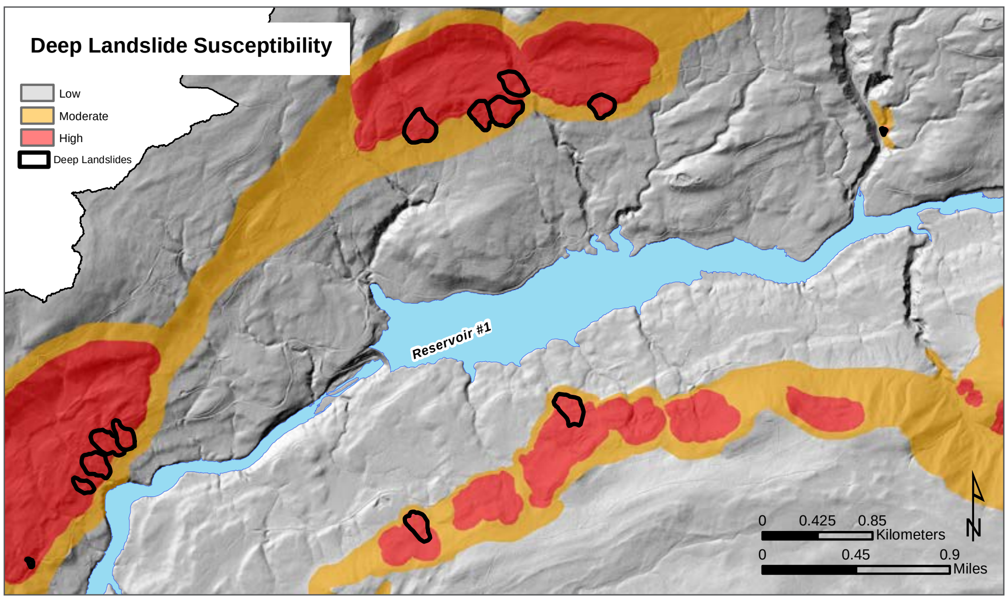


Figure 26. Map of the spatial relationship between historic deep landslides (black outline) and the moderate and high deep landslide susceptibility (orange and red areas) for the central portion of the watershed. Note that the high susceptibility areas are mostly prehistoric landslide deposits.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Although we cannot predict where and when the next landslide events will occur in the Bull Run Watershed or how big they will be, we were able to provide detailed maps of where landslide events occurred in the past and areas that are more or less susceptible to future landslides. We note that this portion of Oregon has high average annual precipitation as well as high 24-hour-duration precipitation related to storm events. The area also has relatively moderate to high seismic hazard. Both high precipitation and large earthquakes are primary triggers for new landslides and reactivation of existing landslides. Human activities can also trigger landslides. The information we presented in this report along with the map plates and GIS datasets fulfills the objective of the project, which is to assist PWB in making its system more resilient to landslide hazards.

Approximately 15 percent of the Bull Run Watershed is underlain by existing landslides; 0.1% shallow landslides; 11% deep landslides; 3.9% debris flows, etc.). Two-hundred twenty-six, or about 20 percent, of the 1,068 landslides found in the landslide inventory are known or are estimated to have moved during historic times (less than 150 years ago). Tens of these 226 landslides have resulted in damage including turbid water, road fill embankment failures, and significant damage to infrastructure such as bridges and the primary water conduits connecting the Bull Run Watershed to the City of Portland.

Our landslide susceptibility modeling found 21 percent of the watershed is highly susceptible to shallow landslides and 15 percent is highly susceptible to deep landslides. The deep landslide inventory correlates well with the deep landslide high susceptibility zone (11% deep landslide inventory/15% high susceptibility to deep landslides). However, the shallow landslide inventory covers only 0.1 percent of the watershed, while 21 percent of the watershed is highly susceptible to shallow landslides. This is likely because shallow landslides tend to become eroded and/or filled in by colluvium relatively quickly, compared to deep landslides; that is, shallow landslides fill in within hundreds of years rather than within the thousands or even tens of thousands of years needed to erode or fill in large deep landslide areas. Thus, the shallow landslide inventory does not correlate well with the shallow susceptibility.

We conclude that the Bull Run Watershed, when compared with similarly sized watersheds and with areas examined in similar studies throughout western Oregon, has a similar level of landslide hazard. For example, in a recent, similar study for the City of Astoria (Burns and Mickelson, 2013), we found almost one third (27 percent) of the area within city limits was underlain by existing landslides. In a recent study of several watersheds in the central portion of the Oregon Coast Range (Burns and others, 2012d), we found that over one third of the total watershed area was underlain by existing landslides. For the Bull Run Watershed, the landslide hazard is approximately 18 percent (using the values of 15 percent landslide inventory; 21 percent high susceptibility to shallow landslides; 19 percent high susceptibility to deep landslides). Therefore, 82 percent of the watershed has a moderate to low susceptibility to landslide hazard.

The primary reason for the landslide hazard appears to be the combination of weak rock and soil, steep slopes, riverine and glacial erosion, and exposure to high precipitation and earthquake shaking. Our statistics show that some geologic units in the watershed are more prone than others to landslides. These include the Rhododendron Formation, Troutdale Formation, and the basalt of the Bull Run Watershed. However, it is likely that many landslides associated with the basalt of the Bull Run Watershed are actually failing within and caused by the underlying Rhododendron Formation (Figure 15). The Troutdale and Rhododendron Formations are both basically sedimentary units (mudstone/sandstone and volcaniclastic), which have lower strengths than the hard basaltic lava flows interbedded in them. Also, sedimentary rocks in general have more interconnected pore space than lavas, allowing water to saturate the rock, thereby increasing weight and pore pressures, both of which cause a decrease in slope stability. Therefore, we conclude that the Rhododendron and Troutdale Formations are the two geologic units most highly susceptible to landslides within the Bull Run Watershed. It appears that some sort of mass erosion event or events in the past resulted in the extensive exposure of both of these formations, especially along the Bull Run River (Figure 14). The resulting steep slopes in these two units correlate with most slides in the area.

We found that many of the historic and/or more recent landslides were reactivations of existing landslides. These younger landslides are located within and at the toe of older slides (Figure 17). Many reactivated slides caused damage to roads and other infrastructure (Table 2).

Although there is a relationship between shallow landslide susceptibility and debris flow fans (Figure 23), most existing fans in the Bull Run Watershed are not at the mouths of the primary streams (e.g., North Fork, Falls Creek, Cougar Creek, South Fork). We found most existing fans are located at the mouths of intermittent streams and/or side drainage channels that lead into the primary streams. This is likely related to the drainage gradient. For example, the small intermittent drainages/channels leading into the North Fork Bull Run River have a mean slope of 18 degrees with a standard deviation of 9.5 degrees (approximate range of 10 to 30 degrees). However, the North Fork Bull Run River has a mean drainage gradient of 5 degrees with a standard deviation of 5 degrees (approximate range of 0 to 10 degrees). From the studies described in section 5.1.4, we conclude that the mean slope of 5 degrees characteristic of primary streams like the North Fork Bull Run River is well within the 3 to 15 degrees threshold below which there is a decreasing debris flow transport potential.

Other primary streams had similar mean slope gradients (e.g., Falls Creek, 7 degrees; Cougar Creek, 7 degrees; South Fork Bull Run River, 4 degrees). Therefore, we conclude that it is not very likely that debris flow transport will occur down these primary streams from relatively small shallow landslides or relatively small, erosion-induced debris flows. There is undoubtedly erosion and sediment transport down these streams, but not likely as small debris flows. This is true unless the volume of the initiation is unusually large. For example, if a large deep landslide with a large volume transformed into a debris flow, the flow would likely continue for a significant distance even at these low channel gradients; this is likely what happened to the 1972 North Fork slide.

Large deep landslides appear to be the primary threat in the Bull Run watershed for several reasons. First, large deep landslides can move large volumes of sediment, leading to significant turbidity in the system, possibly for weeks to years. The large volume can also transform into large debris flows, which can then reach the main Bull Run River and reservoirs directly. Large deep landslides can and have caused significant damage to infrastructure, for example, to water conduits and roads.

All these data indicate that a significant landslide risk exists in the Bull Run Watershed and thus that there is a strong need for continuing landslide risk management. Landslide risk management can be performed in various ways. One approach is illustrated in Figure 27. If PWB follows this risk management approach, then the current project has already achieved task I (Hazard Identification; Figure 27).

We provide the following recommendations to the City of Portland Water Bureau for continued work on landslide risk management. These recommendations are not complete, but they should provide a good foundation.

Future improvements. When planning future development within the watershed, for example, expansion or relocation of existing roads, new roads, infrastructure improvements, and grading or storm water control, use the landslide inventory and susceptibility maps to identify areas of increased landslide potential. If landslide issues are identified and considered as part of the design phase of the project, the end result should be an increase in slope stability.

Maintenance. Review maintenance practices in light of the new landslide information. For example, repeated removal of ditch debris and sloughed or eroded soil and/or any type of relatively shallow grading activities can unknowingly cause slope failures (Figures 20 and 21), especially in conditions where existing landslides may be only marginally stable. The placement of storm debris and/or soil in the wrong location, for example, near the heads of existing landslides, can also unknowingly cause slope failure simply by adding more weight to the slope. Finally, storm water runoff routing must be done carefully so that water is not directed onto or into unstable slope areas. Keeping good records of maintenance practices is another way to track effects.

Figure 27. Landslide risk management diagram (modified after Wang, 2010).

Risk analysis. Risk is defined here as the intersection of hazard and assets. The new hazard data are ideal for analyzing and re-analyzing risk. For example, the Cornforth Consultants (2003) Bull Run conduit corridor study could easily be repeated with the new landslide hazard data, especially since the data are in GIS format. Along with the conduits, the City could examine the roads, electric system, and communications system for vulnerability to landslide hazards. The new landslide hazard and hydrography data also present the opportunity to reevaluate water quality risk. Risk data are fundamental for engaging stakeholders and prioritizing risk reduction and mitigation projects. Once the risk analysis is complete, a risk management plan can be developed and implemented.

Emergency response. Preparing for emergency situations, such as storm events and earthquakes can be done in several ways. One can assess the level of readiness and preparedness to deal with a disaster before disaster occurs by estimating damage from specific hazard events (before or after a disaster hits). Another way to prepare is to better understand when these events might happen through the development of a landslide warning system. The State of Oregon has a very general statewide landslide warning system that is initiated by the National Weather Service (NWS) and disseminated by several Oregon State Agencies (OEM, ODOT, and DOGAMI). The NWS system could be used by PWB initially; however, we recommend that PWB develop rainfall thresholds for slide initiation in the watershed by monitoring precipitation and resulting slide activity. Knowing when there will be periods of increased landslide potential will help PWB prepare, respond, and recover.

Landslide monitoring. With accurate, consistent GIS data for the entire Bull Run Watershed, landslide monitoring is the next step. Landslide monitoring provides quantitative data that are essential for evaluation of remediation alternatives, including engineering solutions. The two primary ways to accomplish landslide monitoring are regional and on-the-ground site-specific techniques. We recommend both. A regional approach might include collecting new lidar datasets and performing change analysis similar to that of Burns and others (2010) for landslide terrain in western Oregon. This type of regional analysis could be performed periodically (e.g. every 5 years) and would help the PWB understand which large landslides are moving and perhaps where sediment is coming from and going. This should be coupled with on-the-ground, site-specific monitoring. Current practices include standard surveying and resurveying of markers, ground-based lidar scanning, and installation of inclinometers and extensometers. Acoustic-flow monitor (AFM) seismometers can automatically detect large debris flows. For example, the U.S. Geological Survey Cascade Volcano Observatory has a system using AFMs on Mount Rainier (http://volcanoes.usgs.gov/activity/methods/hydrologic/lahardetection.php).

Specific landslides. While performing this study, we noted several landslides that might have significant enough risk to warrant further investigation. The landslide coupled with Dam Number 2 and the landslide that dams Bull Run Lake are both associated with impoundment of significant volumes of water. Landslides located directly adjacent to the reservoirs have the potential to directly enter the waterbodies and cause water displacement. In addition, there are many areas with existing landslides along the North Fork Bull Run River, South Fork Bull Run River, Cougar Creek, and Fir Creek. These rivers/creeks drain directly into reservoirs and could contribute significant sediment. We understand the PWB performs regular evaluations of infrastructure. We recommend that this new information be incorporated into future studies.

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APPENDIX A. SUPPLEMENTARY MATERIAL FOR CREATING LANDSLIDE INVENTORY DATA

Appendix A consists of:

I. Report text from DOGAMI Special Paper 42, Landslide protocol for inventory mapping of landslide deposits from light detection and ranging (lidar) imagery (Burns and Madin, 2009).
—See the digital publication folder for this PDF.

II. Appendix A: 1998 database table excerpted from Landslide assessment and monitoring project, Bull Run conduit corridor, Bull Run, Oregon (Landslide Technology, 2003).
—The table is reproduced below and is also provided as a PDF in the digital publication folder.

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1998 Database Table - Historically Active Landslides

Slide Name	Documented Activity	Potential Impact	Type	Remediation / Slope Hazard Rating*	I[1]	References
Slope north of powerhouse (Dam No. 2)	Ongoing	Diversion Pool	Rockfall			• Shannon & Wilson, 1981 • Cornforth Consultants, Jan. 1994 • Cornforth Consultants, Dec. 1996
Lab Building Slides (north of river)	1990s	River	Debris flow			• Interview, G. Mickelson, Feb. 1998
Headworks Bridge Slide	November 28, 1995	Conduits 2 & 4	Slump and flow	Rock infill / Low	✓	• Landslide Technology, Nov. 30, 1995 • Landslide Technology, Feb. 1996 • Cornforth Consultants, Dec. 1996
Slope south of spillway pool	1960, smaller slide in 1970s	Plunge pool	Slump	Grouted rock infill, slope flattening / Moderate	✓	• Shannon & Wilson, 1963, 1981 • The Perron Partnership, May 20, 1974 • Cornforth Consultants, Jan. 1994
West Spillway Slumps		River	Slump			
South Slope Complex		Conduit 3	Debris flow			
Quarry debris flow	1995-96	Road	Debris flow	Removal of debris / Moderate		• Interview, G. Mickelson, Feb. 1998 • Cornforth Consultants, reconnaissance, 1998
S-10 Bridge Slide East		Conduits 2 & 4	Translational and flow			
S-10 Bridge Slide		Conduits 2 & 4	Translational and flow			
East Larson Bridge Slide		-	Slump			
Larson Bridge Slide	Early 1960s 1955	Conduits 2 & 4	Slump and flow	Removal of debris, regarding / High		• DOGAMI, Geological Hazard of the Bull Run Water Shed, 1974 • Interview, G. Mickelson, Feb. 1998

*See Report Section 3 for discussion of slope hazard rating
[1]I = Investigation, ✓ = Geotechnical Investigation, ✓✓ = Instrumentation

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1998 Database Table - Historically Active Landslides (cont'd)

Slide Name	Documented Activity	Potential Impact	Type	Remediation / Slope Hazard Rating*	I(1)	References
West Larson Bridge Slide Complex		Conduits 2, 3 & 4; Road	Slump and flow, debris flow			
Little Sandy River Slide Complex		Conduits 2, 3 & 4; Road	Slump, debris flow			
Little Sandy River Slide	February 1956	Conduit 2, Road	Slump, debris flow	Bin wall with rockfill / Moderate	✓	• Shannon & Wilson, Apr. 1965 • DOGAMI, Geologic Hazard of the Bull Run • Water Shed, 1974 • Elliott, 1989
Soapstone Slide Complex		Conduits 3 & 4	Translational			
Bowman Bridge Slide	March 18, 1997	Conduits 2, 3, & 4; Road and Bridge	Debris flow	Rock infill / Low	✓✓ ✓	• Landslide Technology, Mar. 1997 • Landslide Technology, Apr. 4, 1997
West Bowman Bridge Slide	March 18, 1997 Previous	Conduit 3, Road	Slump, possible flow years earlier	Rock infill / Low	✓✓ ✓	• Interview, G. Mickelson, Feb. 1998 • Landslide Technology, Apr. 10, 1997
East Soapstone Slide	1974	Conduit 3	Translational	Trench drains / High		• The Perron Partnership, Mar. 18, 1974
Soapstone Hill Slide	Pre-1965	Road	Debris flow?	Bin walls with rockfill / High	✓	• Shannon & Wilson, Apr. 1965 • DOGAMI, Geologic Hazard of the Bull Run Water Shed
River Bend Slide		Conduits 2 & 4	Slump, debris flow			
Phelps Road Slide	Mid-1990s		Debris flow	Rockfill / Low		• Interview, G. Mickelson, Feb. 1998

*See Report Section 3 for discussion of slope hazard rating
(1)I=Investigation, ✓=Geotechnical Investigation, ✓✓=Instrumentation

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1998 Database Table - Historically Active Landslides (cont'd)

Slide Name	Documented Activity	Potential Impact	Type	Remediation / Slope Hazard Rating*	I(1)	References
Ditch Camp Slide	1890s	Damage to Conduit 1				• DOGAMI, Geologic Hazard of the Bull Run Water Shed, 1974
	1965	Conduits 2 & 4, Road, 1½ feet of movement	Translational	Rockfill to replace road excavation	✓ ✓✓	• Shannon & Wilson, Apr. 1965
	1985	Conduit 4 break	Translational	Special pipeline couplings	✓	• Cornforth Consultants, Nov. 1985 Landslide Technology, Jan. 1989
	1995-96	Conduits 2 & 4	Translational	Horizontal drains 1997-98 / Moderate	✓ ✓✓	• Landslide Technology, unpublished
Penstock Slide	1961-65	1 inch of movement			✓	• Shannon & Wilson, 1965
	January 1980	Break in penstock, 0.11 feet of movement	Translational	Minor regrading, special pipeline couplings / Moderate	✓ ✓✓	• Shannon & Wilson, Aug. 1980 • Portland General Electric, 1998
Bull Run River Road Slides	1990s	Conduit 3	Slump and flow			• Cornforth Consultants reconnaissance, 1998
Camp Namanu Road Slide	1995-96	Conduit 3	Slump and debris flow		✓ ✓✓	• Cornforth Consultants, Dec. 20, 1996
West Camp Namanu Road Slide	1995-96	Conduit 3	Debris flow			• Cornforth Consultants, reconnaissance, 1998
North Bull Run River Slide		Conduit 3	Translational			
Lusted Road culvert	Ongoing	Conduits 2, 3 & 4	Culvert outlet erosion			• Fujitani Hilts & Associates, Jul. 1991

*See Report Section 3 for discussion of slope hazard rating
(1)I=Investigation, ✓=Geotechnical Investigation, ✓✓=Instrumentation

APPENDIX B. SUPPLEMENTARY MATERIAL FOR CREATING SHALLOW LANDSLIDE SUSCEPTIBILITY DATA

Appendix B consists of:

I. Report text from DOGAMI Special Paper 45, Protocol for shallow-landslide susceptibility mapping (Burns and others, 2012c).
—See the digital publication folder for this PDF.

II. Raw geotechnical material properties data created by the authors.
—See the digital publication folder for this Microsoft® Excel® spreadsheet.

III. Raw factor of safety calculations created by the authors.
—See the digital publication folder for this Excel® spreadsheet.

APPENDIX C. SUPPLEMENTARY MATERIAL FOR CREATING DEEP LANDSLIDE SUSCEPTIBILITY DATA

Appendix C consists of:

I. Deep landslide susceptibility mapping method; 14 pages extracted DOGAMI Open-File Report O-13-08, Landslide hazard and risk study of northwestern Clackamas County, Oregon (Burns and others, 2013)
—See the digital publication folder for this PDF.

II. Deep landslide susceptibility: Geographic Information System (GIS) method
—The results are shown below and are provided as a PDF in the digital publication folder.

III. Raw results of the deep landslide susceptibility analysis for Bull Run Watershed
—The method is shown below and is provided as a PDF in the digital publication folder.

II. Deep-Landslide Susceptibility: Geographic Information System (GIS) Method

The method we used to identify areas of susceptibility to deep landslides combines several factors, most of which are from or are derived from the deep landslides identified and extracted from the data in SP-42 inventory (Burns and Madin, 2009). Each of the factors is assigned a relative score value and then the factors combined into a final dataset, which is used to assign areas of low, moderate, and high susceptibility. The contributing factors are:

High Susceptibility Zone:
- landslide deposits
- head scarp-flank polygons
- head scarp-flank polygon buffers

Moderate Susceptibility Zone:
- susceptible geologic units
- susceptible geologic contacts
- susceptible slope angles for each engineering geology unit polygon
- susceptible direction of movement for each engineering geology unit polygon

Low Susceptibility Zone
The low susceptibility zone consists of areas that are neither high nor moderate.

The method to identify areas of susceptibility to deep landslides is as follows.

Create an Esri® File Geodatabase

1. Create a new file geodatabase with the following feature datasets:

- A_Landslide_Deposits
- B_Head_Scarp_Flanks
- D_Geologic_Units
- C_Geologic_Contacts
- E_Slopes
- F_Directions

2. Extract all deep landslide deposits from the landslide inventory, name Deep_Landslide_Deposits, and save into the A_Landslide_Deposits feature dataset. Delete extra fields from Deep_Landslide_Deposits.
3. Extract all deep landslide head scarp-flank polygons from the landslide inventory deposits, name Head_Scarp-Flanks, and save into the B_Head_Scarp_Flanks feature dataset.
4. Start with the best available geology map. Combine the units into like engineering geology units. Add text field "general_g" and assign the new generalized engineering geology unit names, for example "Coarse Alluvium". Clip to study extent. Delete all the extra fields, name Engineering_Geology, and save into the C_Geologic_Units feature dataset. Add a field called Polygon_ID to the Engineering_Geology.
5. Compute a slope map from the lidar-derived bare-earth DEM using the Slope tool and name Slope.img.
6. Compute an aspect map from the bare-earth DEM using the Aspect tool and name Aspect.img.

Define the High Susceptibility Zone

Landslide deposits factor

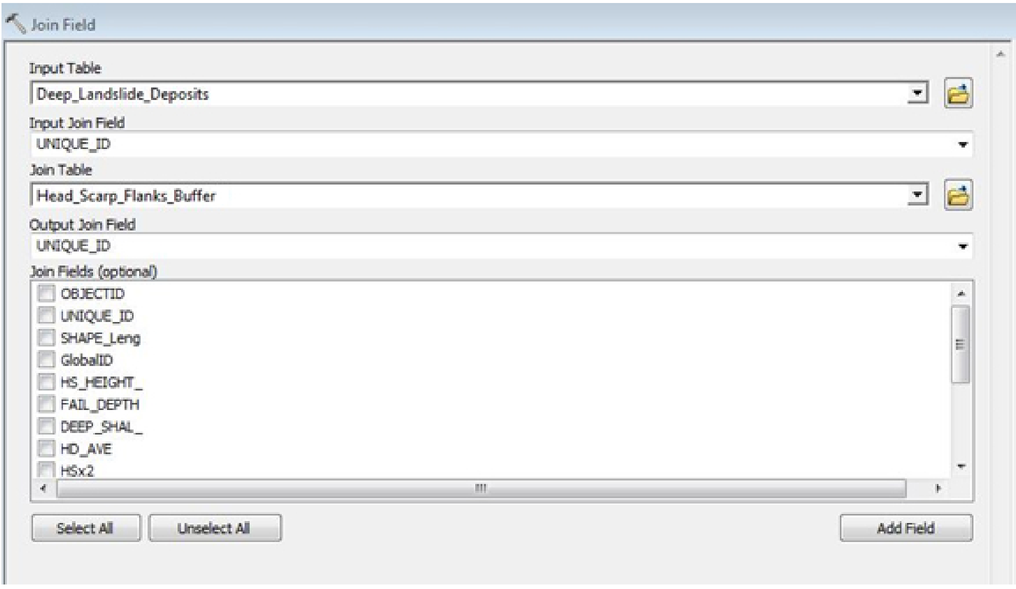
1. Add two fields to Deep_Landslide_Deposits: Relative (text field, 25) and Relat_Susc (short integer), and assign all landslides Relative = "High" and a Relat_Susc = 3.
2. Convert the polygons to raster using the Feature to Raster tool with the field = Relat_Susc and the cell size = 3. Save the raster into the geodatabase and name High_deposits (values = 0, 3, where 3 = high final deep susceptibility zone).

Head scarp-flank polygons and buffers factors

1. In Head_Scarp_Flanks, add two fields: HSx2 (short integer) and Buffer (short integer). Attribute the HSx2 field with HS_HEIGHT field × 2. Attribute the Buffer field with the larger value from either the HD_AVE or the HS_HEIGHT field.
2. Create the buffered file using the Buffer tool with the Head_Scarp_Flanks file, with field set to the Buffer, side type = full and dissolve type = none. Name the output file Head_Scarp_Flanks_Buffer. Add two fields: Relative (text field, 25) and Relat_Susc (short integer) to the Head_Scarp_Flanks_Buffer, then save it in the B_Head_Scarp_Flank feature dataset. Assign all buffered head scarps Relative = "high" and Relat_Susc = 3.
3. Convert the polygons to raster using the Feature to Raster tool with the field = Relat_Susc and the cell size = 3. Save the raster into the geodatabase and name High_HSBuffer (values = 0, 3, where 3 = high final deep susceptibility zone).

Define the Moderate Susceptibility Zone

1. Create a moderate buffer zone around the buffered head scarps and landslide deposits. Use the Join Field tool to join the "Buffer" field from Head_Scarp_Flanks_Buffer to the Deep_Landslide_Deposits.



2. Export the Deep_Landslide_Deposits and name the output Moderate_buffer. Copy all the features from the Head_Scarp_Flanks_Buffer into Moderate_buffer.
3. Use the Buffer tool with the Moderate_buffer file, with field set to the Buffer, side type = full, and dissolve type = all. Name the output file Moderate_zone. Add two fields: Relative (text field, 25) and Relat_Susc (short integer), to the Moderate_zone and save it in the geodatabase. Assign Relative = "moderate" and Relat_Susc = 2.

The moderate susceptibility zone is created through the combination of four factors. These factors are used to determine the boundary between the moderate and low susceptibility zones. The four factors are:
- susceptible geologic units
- susceptible geologic contacts
- susceptible slope angles for each engineering geology unit polygon
- susceptible direction of movement for each engineering geology unit polygon

These four factors will be turned into four raster datasets with scores ranging from 0 to 2 and then added together to create a final moderate zone factors layer.

Susceptible geologic units factor

1. Save the Engineering_Geology file and the Deep Landslide Deposits into the C_Geologic_Units feature dataset and name them Engineering_Geology1 and Deep_Landslide_geolpoly.
2. Create a new field called "Polygon_ID" in the Engineering_Geology file and give every different unit a unique number (1, 2, 3, …). Make sure the Engineering_Geology file is "exploded," as merged units will affect the spatial join.

3. Use the Feature to Point tool to turn the landslides into singular points. Save the points as Deep_landslide_points.

4. Spatial Join the Engineering_Geology1 to the Deep_landslide points:
   - Target = Deep_landslide points
   - Join = Engineering_Geology1
   - Output = Deep Landslide Deposit_Geolpts
   - Join operation = one to one
   - Keep all target = no
   - Match option = Closest

5. Review that the correct engineering geology has been associated with each point. Make edits to the associated geology if necessary.

6. Use the Join Field tool to join the "Polygon_ID" field from the Deep_landslide points to Deep_Landslide_geolpoly based on the Unique_ID field. Merge the Deep_Landslide_geopoly to remove overlapping landslide polygons and save as Deep_Landslide_geopolys_merge. Intersect the Deep_Landslide_geopolys_merge and the combined (merged) Engineering_Geology. Save file as Deep_Landslide_Deposit_Geolpoly_intersect

7. Use the Export to Dbase tool and save Deep Landslide Deposit_Geolpoly_intersect in the folder (the export will not save in the geodatabase). Save the file as an Excel® format table. In the Excel file, create a new worksheet and copy the two columns of area data into the worksheet. In the new worksheet, calculate the landslide area/unit area, then convert to percent as shown below.

Engineering Geology Unit Area (miles 2)	Lands lide Area Per Unit (miles 2)	Lands lide Area / Unit Area (%)
69.01	0.65	0.94%
1.13	0.00	0.04%
36.37	1.27	3.49%
2.81	0.12	4.27%
45.98	2.35	5.11%
20.46	0.26	1.27%
5.95	0.40	6.72%
38.43	5.42	14.10%
0.93	0.00	0.11%
64.73	1.42	2.19%
30.46	11.79	38.71%

8. In Excel®, run the Data Analysis Descriptive Statistics tool on the landslide area/unit area percent. Find the mean and standard deviation.

9. In Esri® ArcMap™, add one field: Score (short integer) to the Engineering Geology1. Assign all units greater than or equal to mean + 1STD a Score = 2 and assign all units less than mean + 1STD and greater than or equal to mean a Score = 1.

10. Convert the polygons to raster using the Feature to Raster tool with the field = Score and the cell size = 3. Save the raster into the geodatabase and name Geology (values = 0, 1, 2).

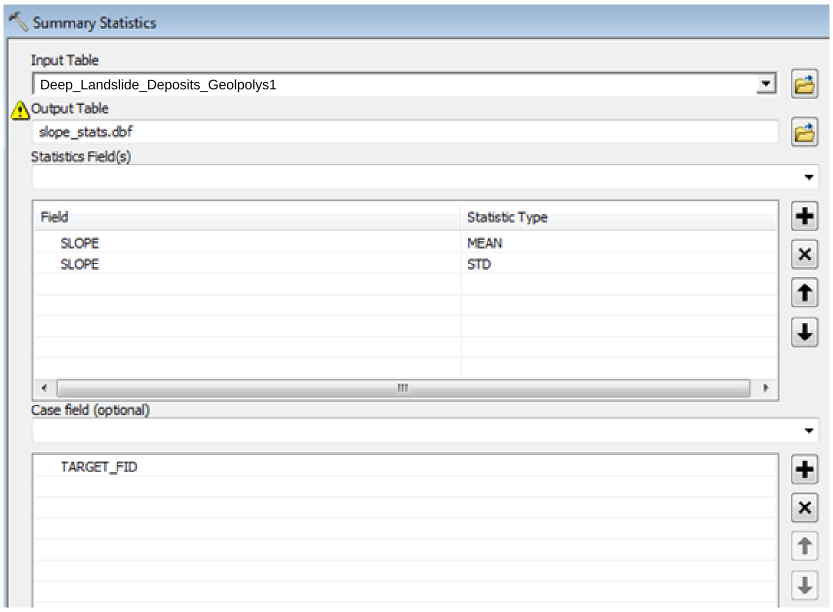
Susceptible geologic contacts factor

1. Use Engineering_Geology to select two units with slides located along their contact (example: Boring Lava and Troutdale fine). Export output each to two different shapefiles and save into C_Geologic_Contacts. Run the Intersect tool with the two units (two files) as the two input features. Output type = line. Save the file as, for example, boring_troutdale_fine_intersect.
2. By using the Select By Location tool with the relationship "are within a distance of the source feature," select all deep slides from the Landslide Inventory Deep Map file that touch the new line file and apply a search distance of 100 ft. Export the selected slides to a new feature class and name it boring_troutdale_fine_ls.
   Run the Minimum Bounding Geometry tool on this file with geometry type = rectangle by width and name boring_troutdale_fine_rectangle. Examine the new field called MBG_width and find the mean and the standard deviation using statistics.
3. Make a ring buffer using the Ring Buffer tool on the boring_troutdale_fine_intersect file of the mean MBG_width and the mean +1 STD MBG_width as the two buffers and name file boring_troutdale_fine_buffer. Add one field: Score (short integer) to the boring_troutdale_fine_buffer, and save it in the C_Geologic_Contacts feature dataset. Assign all mean buffers Score = 2 and mean + 1STD Score = 1.
4. Repeat for all susceptible contacts. Then merge all buffers to a single file and name Susceptible_Geologic_Contacts.
   Note: If contacts overlap in Susceptible_Geologic_Contacts, merge all Score = 1 and all Score = 2 in the Score field.
5. Select all Score = 2 and use the Clip tool in the Editor toolbar to clip all Score = 1 out from underneath.
6. Add a polygon of the study area boundary to Susceptible_Geologic_Contacts and assign the boundary a score of 0. Clip the 1s and 2s from the boundary.
7. Convert the polygons to raster using the Feature to Raster tool with the field = Score and the cell size =3 ft. Save the raster into the geodatabase and name Contacts.

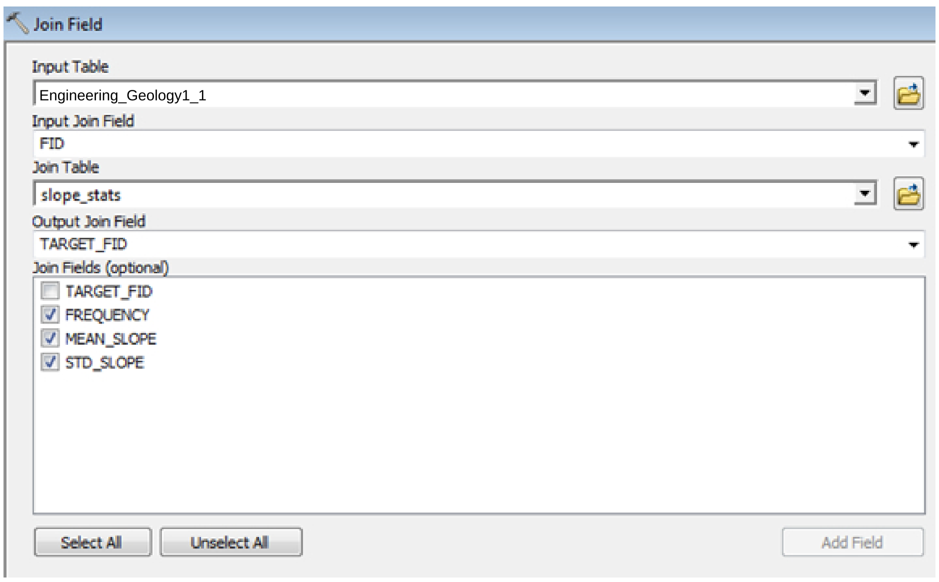
Susceptible slope angles for each engineering geology unit polygon factor

1. Copy and paste the Deep_Landslide_Deposits_Geolpolys1 and Engineering_Geology1 (from C_Geologic_Units) into E_Slopes.

2. Run the Summary Statistics tool on the joined file Deep_Landslide_Deposits_Geolpolys1:
   - Output table: slope stats.dbf
   - Slope = Mean
   - Slope = STD
   - Case Field = Polygon_ID



3. Join field slope stats.dbf to Engineering_Geology1_1 using the Polygon_ID field.



4. Add a field called Mean_2STD to Engineering_Geology1_1. Use the Field Calculator to calculate and populate that field with the Mean field minus 2 STDs.

5. Convert Engineering_Geology1_1 to a raster using the Feature to Raster tool. Field is Slope Mean = value. Output cell size is 3 ft. Output Raster is Slope_Mean (0-90).

6. Use the Raster Calculator with equation Slope => Slope Mean. Output raster is Slope_High (0,1). Use Reclassify to turn the value = 1 to value = 2 and leave value = 0; output raster = Slope_Highr.

7. Convert Engineering_Geology1_1 to a raster using the Feature to Raster tool. Field is Mean_2STD = value. Output cell size is 3 ft. Output Raster is Slope_Mean2S (0-90).

8. Use the Raster Calculator with equation (Slope < Slope_Mean) and (Slope > Slope_Mean2S). Output raster is Slope_Mod (0,1).

9. Use the Raster Calculator tool with equation Slope_Mod + Slope_Highr. Raster dataset name with extension = slope_mod_high.

10. Reclass no data values to zero and name the file Slopes.

Susceptible direction of movement for each engineering geology unit polygon factor

1. Copy and paste the Deep_Landslide_Deposits_Geolpolys1 into F_Direction.

2. Run the Minimum Bounding Geometry tool on Deep_Landslide_Deposits_Geolpolys1 with geometry type = rectangle by width; add the geometry characteristics as attributes to output and name Deep_Landslide_Deposits_Geolpolys1 _Rectangle.

3. Run Summary Statistics to get mean MBG_width.

4. Convert Deep_Landslide_Deposits_Geolpolys1 to a raster using the Feature to Raster tool with 3-ft cell size and the direction as the value; name the raster Landslide_dir.

5. Convert the raster cells to points using the Raster to Points tool with value and name Landslide_Dir_points.

6. Run IDW interpolation tool on the points:
    - Z value field = grid
    - Output raster = Direction_IDW
    - Power = 2
    - Search Radius = Variable
    - Number of Points = blank
    - Maximum Distance = MBG_Width mean
    - Input Barrier = Blank

    Note: If polygons in IDW_Direction raster are cut, place the extra points outside of study area.

7. Use the Raster Calculator to select all values with 360 from the IDW_Direction file and save as IDW_Direction360. Use the Reclassify tool to turn value = 0 to No Data and leave value = 1. Output raster is IDW_Direction360r.

8. Use the Raster Calculator with equation (Aspect =< 22.5) and IDW_Direction360r. Output raster is Dir_High_360. Use the Reclassify tool to turn value = 1 to value = 2 and value=0 to No Data. Output raster = Dir_Highr_360.

9. Use the Raster Calculator with equation (Aspect =< 45) and IDW_Direction360r. Output raster is Dir_Mod_360. Use the Reclassify tool to turn value = 0 to No Data and leave value = 1. Name the output raster Dir_Modr_360.
10. Use the Raster Calculator to select all values with 337.5 from the IDW_Direction file and save as IDW_Direction3375. Use the Reclassify tool to turn value = 0 to No Data. Name the output raster IDW_Direction3375r.
11. Use the Raster Calculator with equation (Aspect =< 22.5) & IDW_Direction3375r. Output raster is Dir_Mod_3375. Use Reclassify value = 0 to No Data and leave value = 1. Name the output raster Dir_Modr_3375.
12. Use the Mosaic to New Raster tool with raster files listed in the following order:
    - Dir_Highr_360
    - Dir_Modr_360
    - Dir_Modr_3375
13. Change Mosaic Operator to FIRST. Raster dataset name with extension = mod_high_3603375 (1, 2).
14. Use the Raster Calculator with equation (Aspect =< (IDW_Direction + 22.5)) and (Aspect => ((DW_Direction – 22.5)). Output raster is Dir_High. Use the Reclassify tool to turn value = 1 to value = 2 and leave value = 0. Name the output raster Dir_Highr.
15. Use the Raster Calculator with equation (Aspect =< (IDW_Direction + 45)) and (Aspect => (IDW_Direction – 45)). Name the output raster Dir_Mod (0, 1).
16. Use the Raster Calculator Dir_Highr + Dir Mod. Output raster is Mod_high (0, 1, 3). Use the Reclassify tool to turn value = 3 to 2. Name the output raster Mod_highr.
17. Use the Mosaic to New Raster tool with raster files listed in the following order:
    - mod_high_360375
    - Mod_highr
18. Change Mosaic Operator to FIRST. Raster dataset name with extension = Direction (0, 1, 2).
19. Use the Reclassify Direction tool to turn value = no data to 0. Output raster is Direction_r.

Final Moderate Zone factors layer

1. Use the Raster Calculator to add Geology + Contacts + Slopes + Direction_r. Name the file Moderate_Factors. The Score field ranges from 0 to 8.
2. Set scores 0–3 with no color. Use values 4–8 as a guide to draw the moderate zone in on the Moderate_zone file created above.

Define the Low Susceptibility Zone

The low susceptibility zone consists of areas that are neither high nor moderate. To determine the low susceptibility zone, clip the study extent area with the high and moderate zone shp file polygons.

III. Raw results of the deep landslide susceptibility analysis for Bull Run Watershed

Susceptible geologic units

In order to determine which geologic units were susceptible to deep landsliding, we first spatially joined the engineering geology and deep landslides to determine the number of landslides occurring in each geologic unit. To perform a one-to-one join, we converted each landslide to a singular point at the landslide's center. We did this because a single landslide polygon may cross several geologic units. We inspected the centralized point of each landslide after the spatial join to confirm that the appropriate geologic unit was selected. We then re-joined these points to the deep landslide polygons in order to attribute each landslide with the correct geologic unit.

Number of landslides occurring in each geologic unit in the Bull Run Watershed

Geologic Unit	Landslide Frequency	Landslide Area/ Geologic Unit Area
Aschoff Buttes cinder cone	1	16.2%
basalt of the Bull Run Watershed	142	9.6%
Columbia River Basalt Group (Wanapum Basalt)	36	8.6%
andesites of Zigzag Mountain and Lolo Pass	23	13.3%
Pliocene lava flows, undivided	1	5.4%
Troutdale Formation	116	24.8%
basaltic andesite of Aschoff Buttes	2	1.1%
Columbia River Basalt Group - (Grande Ronde Basalt)	9	3.8%
andesite of Hiyu Mountain	8	2.6%
Boring Lava	4	0.5%
Rhododendron Formation	151	34.9%

Next, we determined the mean and standard deviation for Landslide Area/Geologic Unit Area.

Mean and standard deviation of landslide frequency per geologic unit

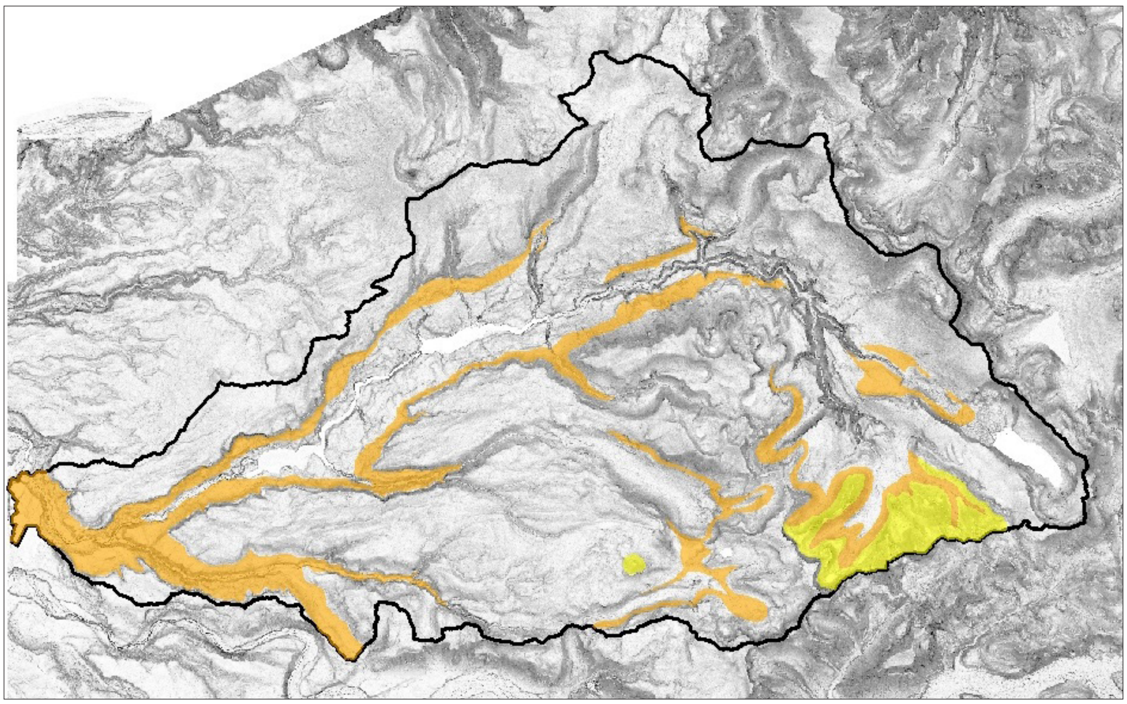
Mean	10.98
Standard Deviation	10.79

We assigned scores ranging from 0 to 2 to each geologic unit. We assigned a score of 0 to any unit with a Landslide Area/Geologic Unit Area less than the mean. We assigned a score of 1 to any unit with Landslide Area/Geologic Unit Area greater than or equal to the mean and less than the mean plus one standard deviation. We assigned a score of 2 to any unit with Landslide Area/Geologic Unit Area greater than or equal to the mean plus 1 standard deviation. Using criteria listed above, we assigned a score of 2 to two geologic units, a score of 1 to two geologic units, and a score of 0 to all other units.

Relative scores assigned to each geologic unit based upon landslide frequency and criteria listed above.

Geologic Unit	Score
cinder cone/small volcano	1
basalt of the Bull Run Watershed	0
Columbia River Basalt (Wanapum and Frenchman Springs Members)	0
andesites of Zigzag Mountain and Lolo Pass	1
Cascade Platform lavas	0
Troutdale Formation	2
basaltic andesite of Aschoff Buttes	0
Columbia River Basalt - (Grande Ronde Member)	0
andesite of Hiyu Mountain - Quaternary andesite	0
Boring Lava	0
Rhododendron Formation	2

Map showing susceptible geologic units with scores of 0 (no color, gray), 1 (yellow), and 2 (orange) in the Bull Run Watershed (thick black line).



Susceptible geologic contacts

In order to determine which contacts were susceptible to deep landsliding, we compared the engineering geology and deep landslide databases. We overlaid landslides on the geology dataset to see how many landslides intersect with the boundary between two geologic units. We performed a query for each possible geologic contact to determine the frequency of landsliding. For example, where the Rhododendron Formation contacts the basalt of the Bull Run Watershed, a total of 122 landslides intersect. We exported all associated landslides for each susceptible geologic contact into new, separate datasets.

We selected for further analysis those geologic units with the highest number of landslides occurring on their contacts and their associated landslides. We did not select any contact with 5 or fewer intersecting landslides.

Geologic contacts with in the Bull Run study area and the number of landslides that intersect each contact.

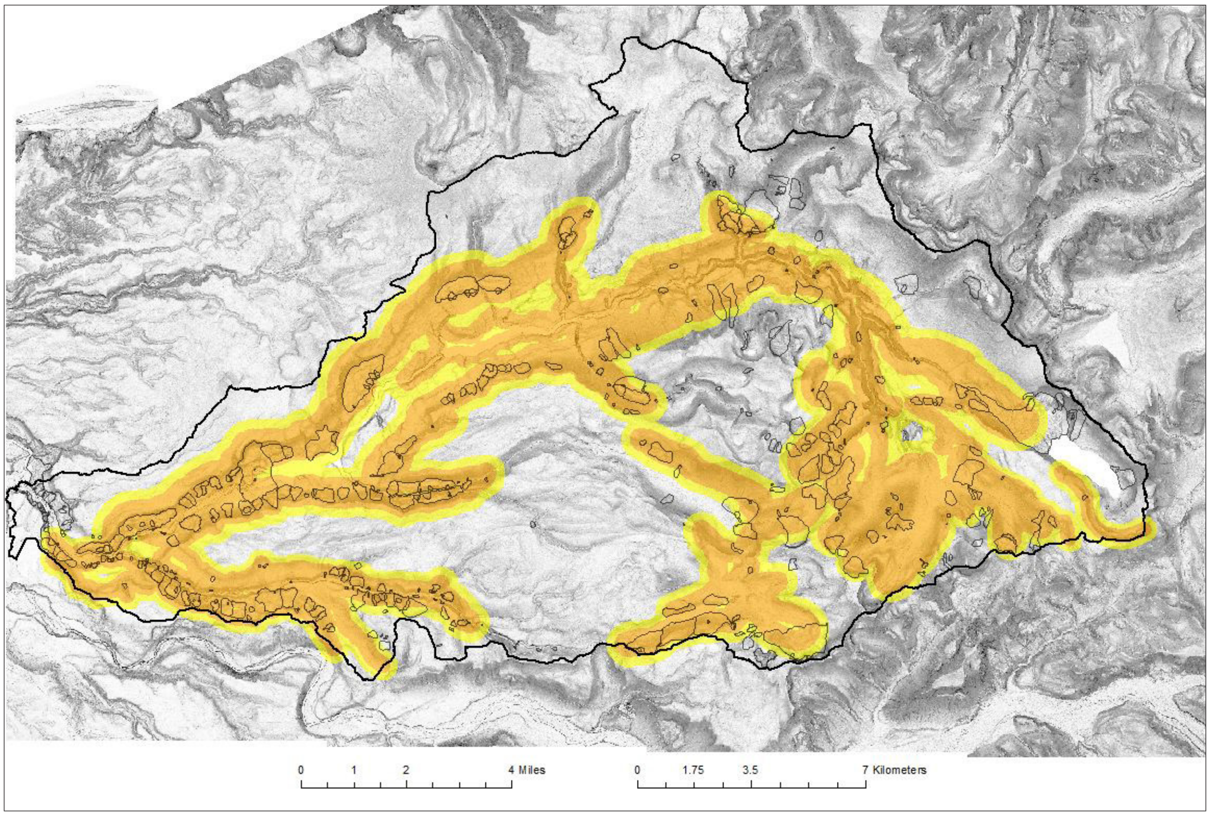
Contact	Landslides
Basalt of Bull Run - Rhododendron	122
Basalt of Bull Run - Troutdale Formation	28
Rhododendron Formation - Toutdale Formation	45
RhododendronFormation - Boring Lavas	14
Rhododendron Formation - Columbia River Basalt (Wanapum and Frenchman Spring Members)	73
Rhododendron Formation - Columbia River Basalt (Grande Ronde Member)	7
Rhododendron Formation - Andesite of Zigzag Mountain and Lolo Pass	13
Columbia River Basalt (Wanapum and Frenchman Spring Members) - Columbia River Basalt (Grande Ronde Member)	18
Cascade Platform Lavas - Andesite of Hiyu Mountain	11

We determined the mean and standard deviation of the associated landslides for each susceptible geologic contact. We performed statistical analysis on each landslide dataset to determine the mean landslide width and standard deviation. We created two buffers around each susceptible geologic contact using the mean landslide width distance and the mean + 1 standard deviation. We assigned the mean buffer a value of 2 and the mean + 1 standard deviation a value of 1.

Contact	Mean Landslide Width (ft)	Standard Deviation	Mean + 1 Standard Deviation
Basalt of Bull Run - Rhododendron	1028	814	1842
Basalt of Bull Run - Troutdale Formation	837	570	1470
Rhododendron Formation - Toutdale Formation	743	562	1352
RhododendronFormation - Boring Lavas	1581	967	2548
Rhododendron Formation - Columbia River Basalt (Wanapum and Frenchman Spring Members)	1153	959	2112
Rhododendron Formation - Columbia River Basalt (Grande Ronde Member)	1175	353	1528
Rhododendron Formation - Andesite of Zigzag Mountain and Lolo Pass	1146	604	1750
Columbia River Basalt (Wanapum and Frenchman Spring Members) - Columbia River Basalt (Grande Ronde Member)	832	1251	2083
Cascade Platform Lavas - Andesite of Hiyu Mountain	700	511	1211

We then merged all geologic contact buffers into one file to be used in the final moderate susceptibility mapping.

Map showing susceptible geologic contacts with scores of 0 (no color, gray), 1(yellow), and 2 (orange) in the Bull Run Watershed (thick black line). Landslides are outlined in black.

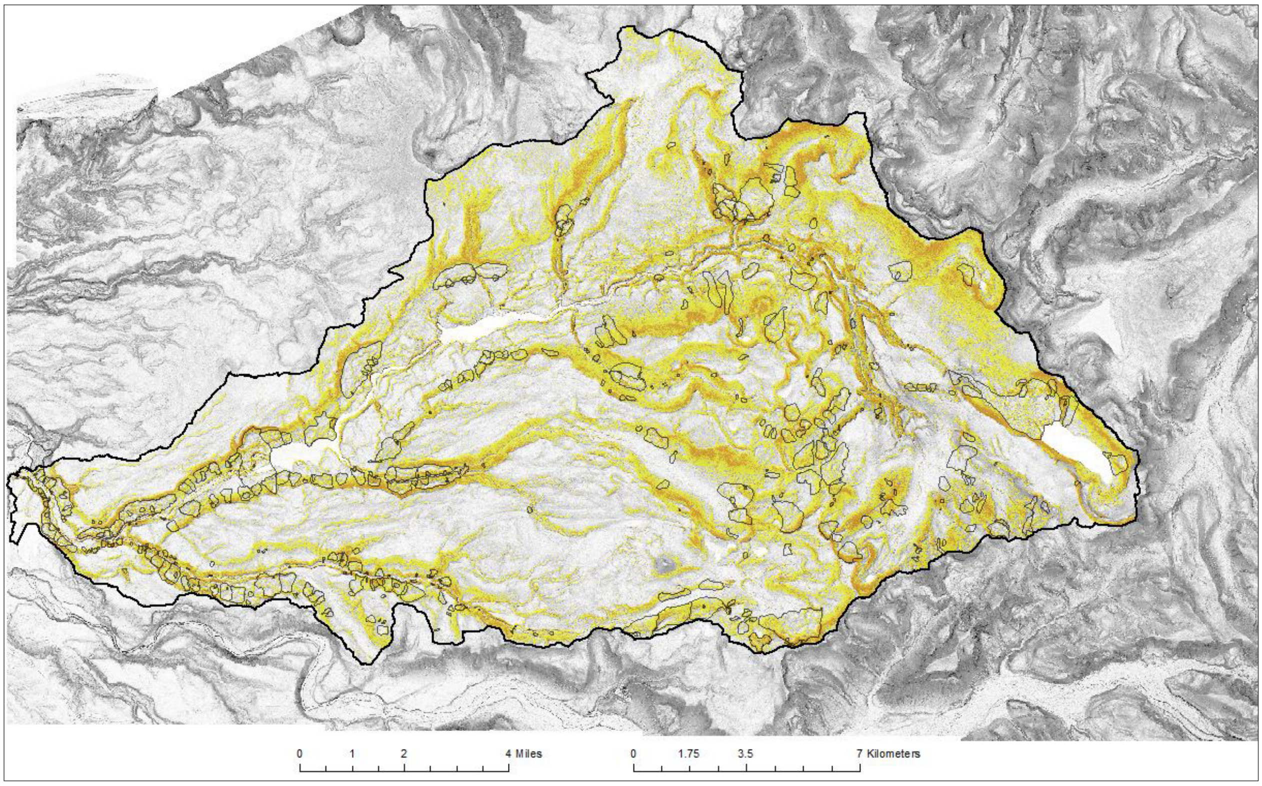


Susceptible slopes

The deep landslide polygons used in this analysis are the same polygons that were joined with the engineering geology in the Susceptible Geologic Units section. We ran summary statistics on the deep landslides polygons to determine the slope mean and standard deviation. The output of summary statistics produces a table. We then joined this table to the engineering geology so that each engineering geology unit would have an associated mean landslide slope. In addition to the mean landslide slope, we added a new field to each geologic unit. Within this new field, we calculated the mean minus two times the standard deviation.

We then performed queries with the slope raster based on the mean and the mean minus two times the standard deviation fields. Anywhere where the slope raster equaled the slope mean of a particular geologic unit, we assigned the cell a value of 2. Anywhere where the slope raster was less than the slope mean and greater than the mean minus two times the standard deviation of a particular geologic unit, we assigned the cell a value of 1.

Map showing susceptible slopes with scores of 0 (no color, gray), 1 (yellow), and 2 (orange) in the Bull Run Watershed (thick black line). Landslides are outlined in black.

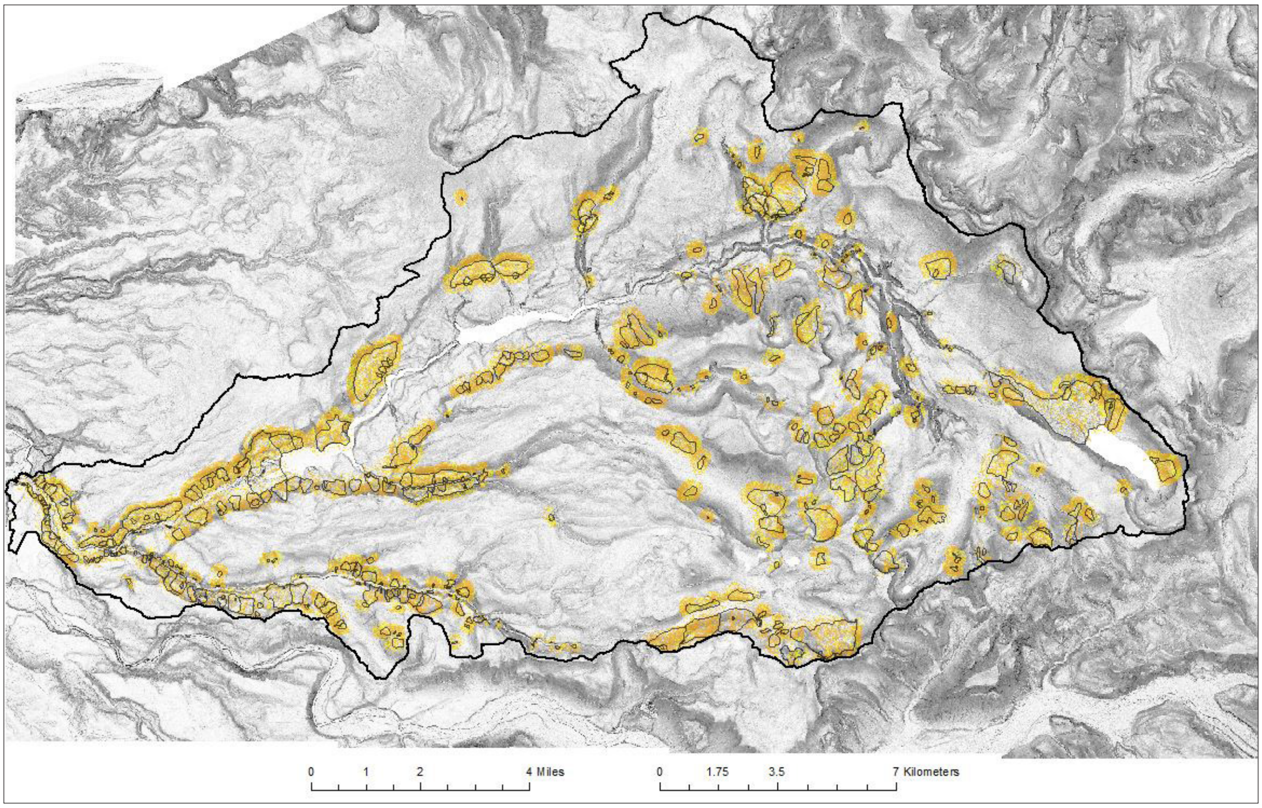


Preferred direction of movement

We converted the landslide polygons to a raster by using attributed landslide direction. We then converted the raster to points. We created an interpolated raster surface from these points using an inverse distance weighted (IDW) method with a maximum distance set to the mean landslide width (660 ft).

We then performed queries with the aspect raster and the interpolated IDW raster. Anywhere where the aspect raster was less than or equal to the IDW raster plus 22.5 and where the aspect raster was greater than or equal to the IDW raster minus 22.5, we assigned a value of 2. Anywhere where the aspect raster was less than or equal to the IDW raster plus 45 and where the aspect raster was greater than or equal to the IDW raster minus 45, we assigned a value of 1.

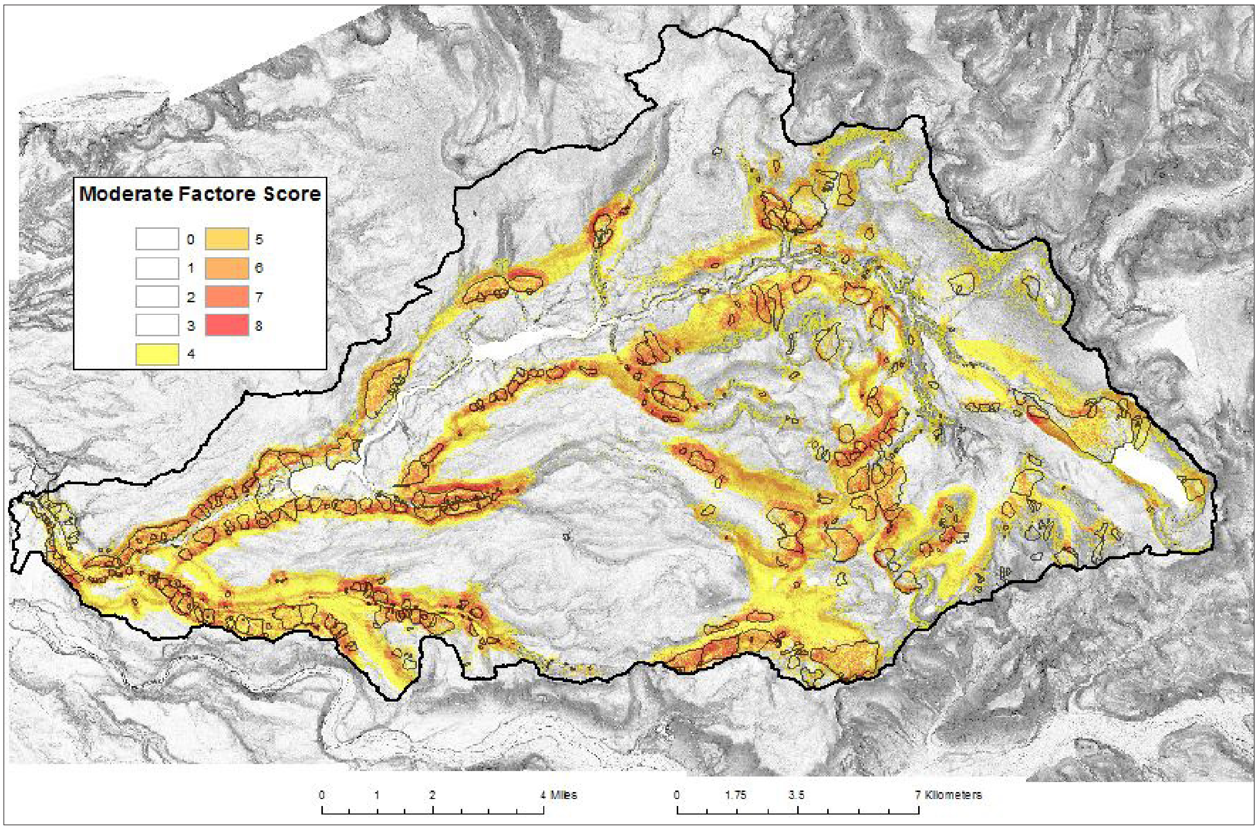
Map showing preferred direction of movement with scores of 0 (no color, gray), 1 (yellow), and 2 (orange) in the Bull Run Watershed (thick black line). Landslides are outlined in black.



Combined moderate factors score

We then added the final geologic unit, geologic contacts, slopes, and preferred direction rasters together to create a combined moderate factor score. These rasters have values of 0, 1, and 2, so the final raster has values ranging from 0 to 8. A score of zero mean that none of the factors were present; a score of 8 means that all four factors were present, each with a score of 2.

Map showing combined moderate factor scores ranging from 0 to 8 in the Bull Run Watershed (thick black line). Landslides are outlined in black.



APPENDIX D. PROCESS USED TO CREATE THE SURFACE HYDROGRAPHY GEODATABASE

Lakes and other waterbodies

1. We started with the Portland Water Bureau Lakes GIS file, which consisted of three waterbodies: Bull Run reservoirs #1 and #2 and Bull Run Lake. We have not altered these features except for a very small part of Bull Run Reservoir #2 at the spillway to make the edge straight.
2. We enhanced the Lakes feature class with U.S. Geological Survey National Hydrography Dataset (NHD; U.S. Geological Survey, 2012a) derived features for NHD feature codes (Fcode) 390 and 466 (feature Type [Ftype] Lake/Pond and Swamp/Marsh, respectively).
3. We enhanced the Lakes feature class with DOGAMI' lidar-derived features for Lake/Pond and Swamp/Marsh that are not in the NHD.
4. We added appropriate NHD-like attribute columns to the Lakes feature class.
5. We used the Spatial Adjustment toolbar in Esri® ArcGIS® to set up Attribute Transfer from the NHDWaterbody feature class to the Lakes feature class.

NOTE: Non-NHD based waterbodies have NHD Fcode and Ftype attributes only. We hope to add more features in a future update of the NHD for this area.

Modeled streams

1. We converted the "modeled stream-centerline" shp file provided by the Portland Water Bureau to a feature class.
2. We copied modeled streams to a separate feature class for editing purposes. This new feature class is named BRWFlowline.
3. We added appropriate NHD-like attribute columns to the BRWFlowlines feature class.
4. We edited BRWFlowlines at their junctions with roads at assumed culverts and to what the lidar revealed. This action was taken to correct radical shifts of the BRWFlowlines along roads.
5. We edited BRWFlowlines within lakes and reservoirs so the BRWFlowlines broke at waterbody edges and assumed a reasonably straight path. These lines became what the NHD terms "Artificial Path." Artificial Paths are assumed centerlines within a waterbody and provide network continuity within the NHD framework. A main flowline such as the Bull Run River through the Bull Run reservoirs will traverse the waterbodies near the centers, but this is not a hard-and-fast rule. All incoming side streams to the waterbody become Artificial Paths at the waterbody edge and then assume a reasonably straight path to the main flowline within the waterbody. The Artificial Path corrections are the most noticeable change to the modeled streams provided Portland Water Bureau.
6. We used the Spatial Adjustment toolbar in ArcGIS® to set up Attribute Transfer from the NHDFlowline feature class to the BRWFlowline feature class.

NOTE: Major discrepancies exist between the modeled flowlines, BRWFlowline, and NHDFlowline feature classes. The two feature classes do not correspond one-to-one. As a result, many of the BRWFlowlines cannot be given NHD attributes. In an update to the NHD, these non-attributed BRWFlowlines would become new features to the NHD.