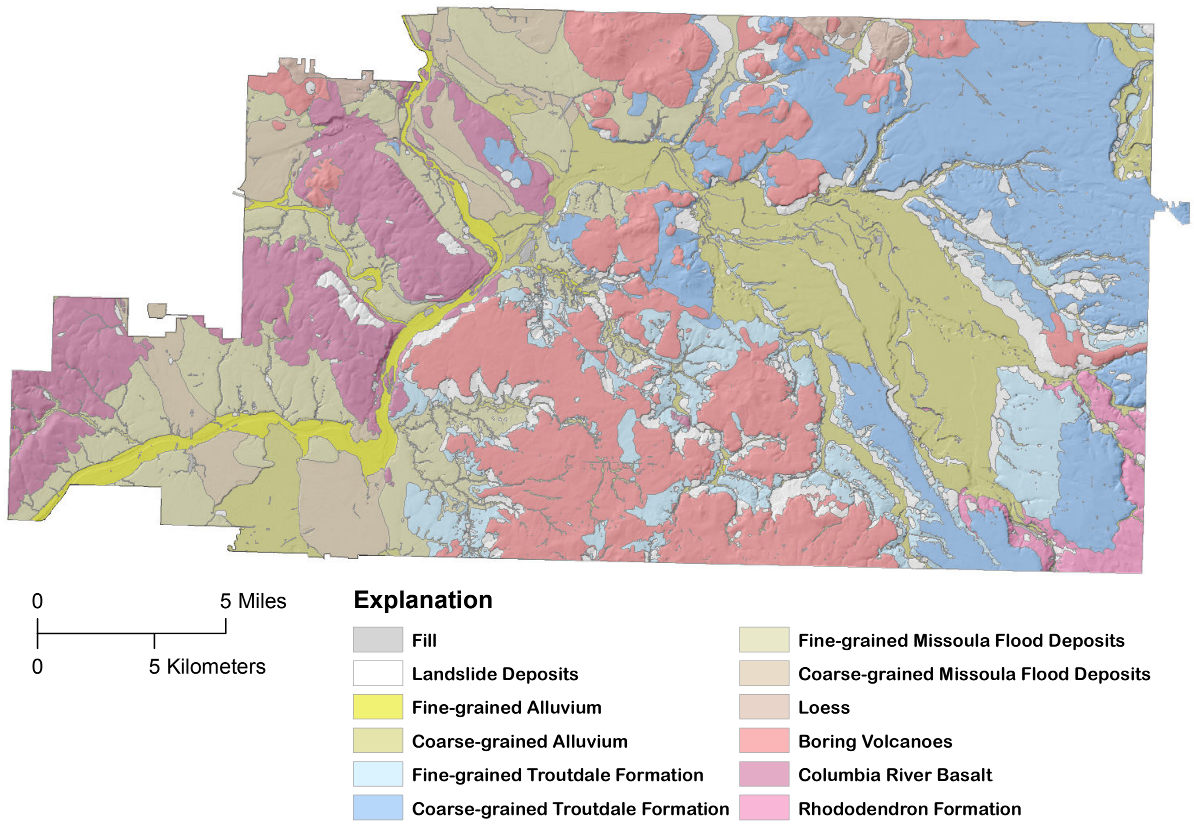

Figure 8. New digital surficial geology/material properties map for the study area.

make the map, we merged and simplified the previously mapped geologic units into 12 surficial geology/material properties units, except for landslide deposits taken directly from the landslide inventory.

5.2.3 Deep-landslide susceptibility

Deep landslides tend to be larger than shallow landslides and tend to move relatively slowly (sometimes less than an inch per year) but can lurch forward if shaken by an earthquake or if disturbed by removing material from the toe, by adding material to the head scarp, or by the addition of water into the slide mass. Reactivation often is focused upslope near the landslide head scarp and at the landslide toe (Turner and Schuster, 1996). To determine deep-landslide susceptibility in the study area, we followed and built on the method described by Burns (2008).

The method we used to identify areas susceptible to deep landslides combines several factors, many of which are derived from the deep landslides extracted from the SP-42 inventory (Burns and Madin, 2009). We assign each factor a relative score and then combine them into a final data set, which we use to assign areas to low, moderate, or high susceptibility zones. The contributing factors are:

- High susceptibility zone
  - landslide deposits
  - head scarp–flank polygons
  - head scarp–flank polygons 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
  - minimal landslide deposits and head scarp–flank polygon buffers
- Low susceptibility zone
  - areas not identified in the high or moderate

We created a standardized, blank Esri ArcGIS version 10.1 geodatabase called Deep_Landslide_Susceptibility_Clackamas_10_1.gdb to store working and final data. The geodatabase had the following working feature data sets, which can be thought of as subdatabases of the geodatabase:

- A_Landslide_Inventory
- B_Head_Scarp_Flank
- C_Geologic_Units
- D_Geologic_Contacts
- E_Slopes
- F_Direction

To explain the components of the method, we will use throughout this text images of the northwestern quarter of the U.S. Geological Survey Oregon City 7.5-minute quadrangle (Figure 9; Plate 52) The GIS method details are included in Appendix E.

5.2.3.1 High-susceptibility zone

In order to create the high-susceptibility zones, we needed a complete landslide inventory. We created this inventory by using the DOGAMI protocol (Burns and Madin, 2009). An example DOGAMI landslide inventory map made using this protocol is shown in Figure 9 (left).

We first queried all of the deep landslide deposit polygons from the inventory database and saved the data into the A_Landslide_Inventory feature data set in the Deep Landslide Susceptibility.gdb. We then converted this data set to a raster data set named High_Deposits and saved it in the same geodatabase. A portion of the raster data set is shown in Figure 9 (right).

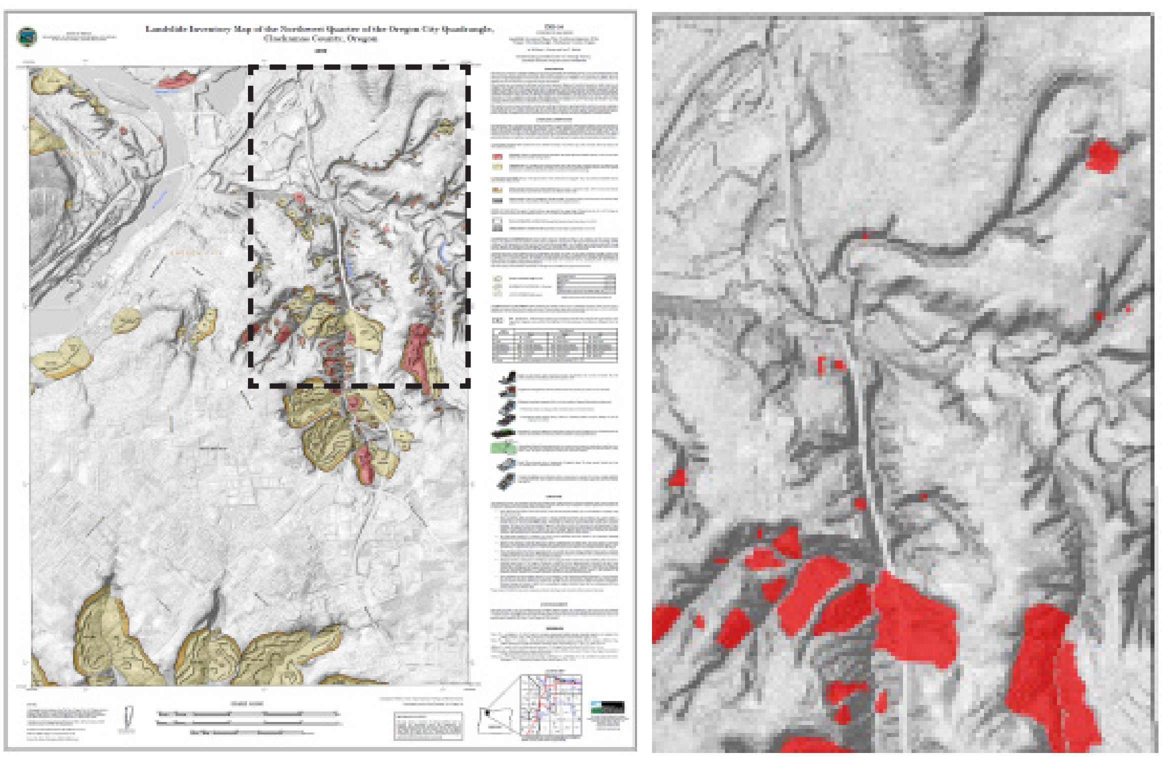

Figure 9. (left) Example of a lidar-based landslide inventory map (Burns and Mickelson, 2010). Dashed line indicates extent shown in figure on the right. (right) Example of deep landslide deposits converted to high-susceptibility zone (red areas on map) (Burns and Mickelson, 2010).

5.2.3.2 Head scarp–flank polygons and buffers

We queried out all deep head scarp–flank polygons from the inventory database and saved the data into the B_Head_Scarp_Flank feature data set in the Deep Landslide Susceptibility.gdb. We then considered these head scarp–flank polygons to be areas of high susceptibility and included them as part of the head scarp–flank polygon buffers, discussed next. Because the head scarp–flank areas are included in the buffer file, we did not process them individually.

There are many unknowns due to the lack of spatial geological data and spatial data with depth values involved in regional deep landslide susceptibility mapping, so to account for some of these unknowns we applied two buffers to the high-susceptibility zone: 1) 2H:1V buffer on all head scarp–flanks and 2) head scarp–flank retrogression buffer.

We applied these buffers to all deep head scarp–flank polygons from the landslide inventory. In most cases the head scarp–flank polygon buffer results in a minimal buffer distance, and the head scarp retrogression buffer results in the maximal buffer distance. In all cases we used the greater of the two distances as the buffer value.

5.2.3.2.1 Head scarp–flank polygon 2H:1V buffer

Most landslides tend to leave a near-vertical head scarp above the failed mass (Turner and Schuster, 1996). Commonly, this head scarp area fails retrogressively or a separate landslide forms above the head scarp, because of the loss of resisting forces. Generally, the area above the head scarp has a relatively low slope angle, possibly indicating a low susceptibility to future failure. In many cases, however, the opposite is true; that is, the flat area directly above the head scarp (crown) is highly susceptible to failure. In order to account for the increase in susceptibility of this area above the head scarp, which may be missed by using the slope alone or in case a particular deep landslide has no internal down-dropped blocks, we apply a 2H:1V head scarp buffer (Figure 10). This buffer is different for each head scarp and is dependent on head scarp height. For example, a head scarp height of 16.5 ft has a 2H:1V buffer equal to 33 ft.

The 2 horizontal to 1 vertical ratio (2H:1V) is commonly used in geotechnical engineering because the slope angle of a 2H:1V slope is equal to 26° (Figure 11) (Burns and others, 2013). This is important because most natural, intact (non-landslide) geologic units have an angle of internal friction or equivalent shear strength of at least 26°.

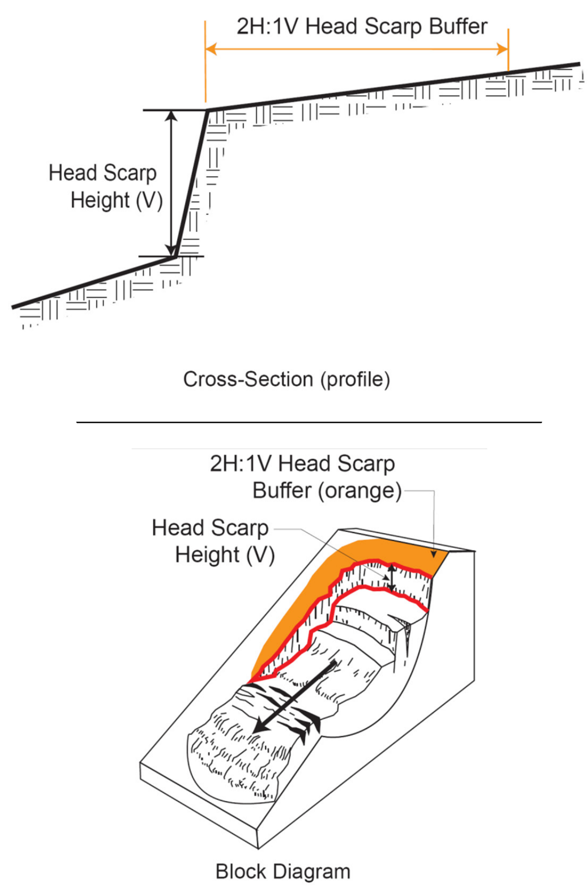

Figure 10. Diagram of the 2 horizontal to 1 vertical (2H:1V) head scarp buffer (orange on block diagram).

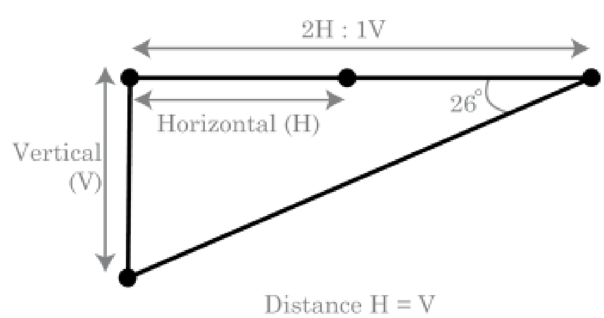

Figure 11. Diagram of the 2 horizontal to 1 vertical (2H:1V) ratio.

5.2.3.2.2 Head scarp–flank polygon retrogression buffer

Many deep landslides move repeatedly over hundreds or thousands of years, and many times the continued movement is through retrogressive failure (continued upslope failure) of the head scarp into the crown. In order to account for this potential upslope hazard, we applied a buffer to all the head scarp–flank polygons as shown in Figure 12. In order to calculate the head scarp retrogression buffer, we measure the horizontal distance of each of the internal down-dropped blocks (assumed to be previous retrogression failures) and use the average. The second buffer is also different for each head scarp and is dependent on the average of the horizontal distance between internal scarps.

After we created both buffers, we combined them and then converted them to a raster data set named High2 (see Appendix E) saved in the Deep Landslide Susceptibility.gdb. The finished data set is shown in Figure 13.

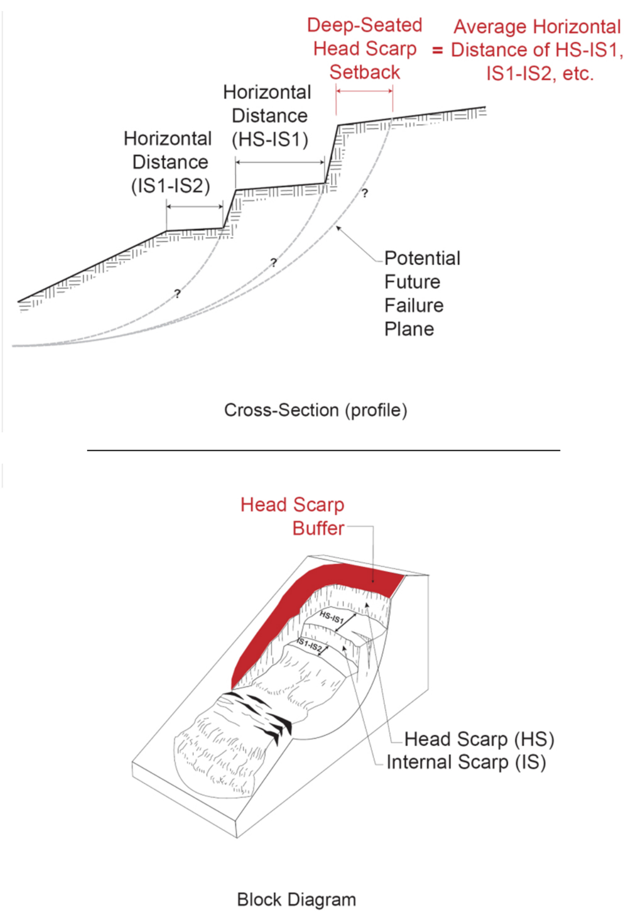

Figure 12. Head scarp retrogression buffer.

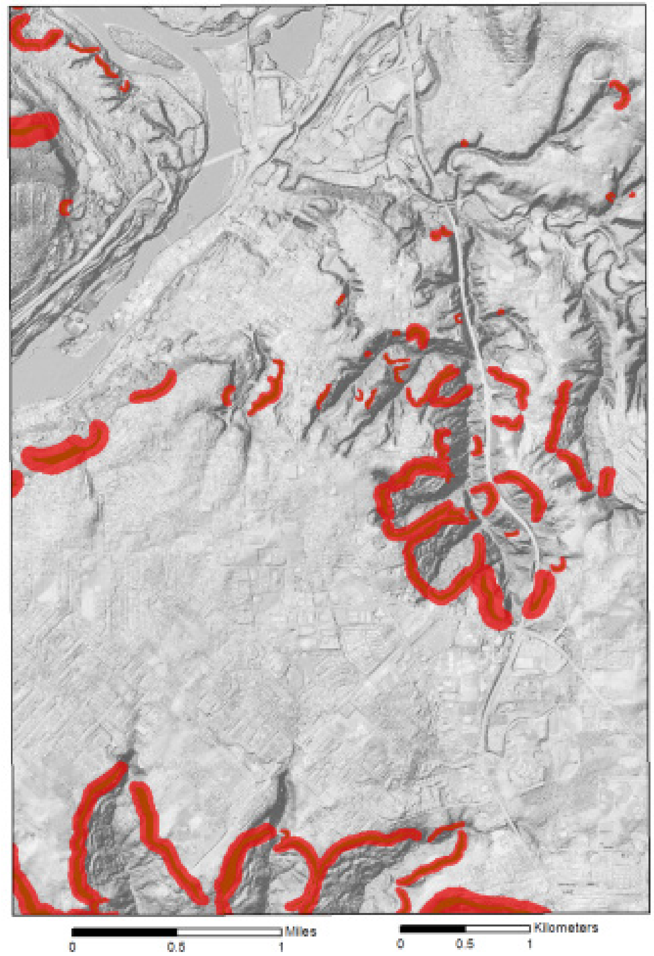

Figure 13. Example of the buffered deep-landslide head scarp–flank polygons converted to high-susceptibility zone (red areas on map). Brown areas are the mapped head scarp-flank polygons.

5.2.3.3 Moderate susceptibility zone

We created the moderate susceptibility zone by combining four maps made from four susceptibility factors described below and a minimal buffer around landslide deposits and head scarp–flank polygons. We used the four susceptibility factors and buffer to determine the boundary between the moderate and low susceptibility zones. (The high-susceptibility zone was defined in section 5.2.3.1.) 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 factors have been used or recommended by others to predict future landslide locations and/or susceptibility (Wilson and Keefer, 1985; Giraud and Shaw, 2007; Baum and others, 2008; Soeters and van Westen, 1996; Sidle and Ochiai, 2006; Schulz, 2007). We selected each of these factors for reasons explained below.

The first factor, geologic unit, has a relatively widespread correlation with surficial processes. For example, it is very common that certain geologic formations or units are more or less prone to landslides. This is generally due to the properties of the unit, such as material strength or planes of weakness within the unit.

The second factor, geologic contacts, we found to be significant in Oregon, especially after we started mapping landslide inventories using lidar. Many landslides occur along a contact, especially when a sedimentary unit is overlain by an igneous unit. For example, large, deep landslides are located next to each other along the contact between the Troutdale Formation and the Boring Lava (a sedimentary unit below an igneous unit) in the study area (Figure 14). Although it commonly appears that landslide failure occurs at the surface trace (that is, at the contact of the two units in plan view), the failure actually occurs entirely within the Troutdale Formation rather than along the plane between the two units. Very likely, in the distant past, the overlying Boring Lava covered and protected the Troutdale Formation. With time, streams eroded through the Boring Lava and into the Troutdale, exposing the Troutdale and creating low places in the topography (stream canyons) for Troutdale material to slide into. As Troutdale material formed landslides, in some places overlying Boring Lava material was dragged down slope along with the underlying Troutdale.

The third factor, slope angle, is commonly correlated with landslide susceptibility. Most landslide susceptibility maps use slope as the primary or as at least one of the factors to predict future landslide locations. For example, shallow landslides are commonly directly associated with steeper slopes. Deep landslides appear to have less of a direct correlation with slope steepness, which is one reason we included the other three factors (geologic unit, geologic contact, and direction of movement).

The fourth factor, direction of movement, is probably the least commonly used, likely because it is rarely recorded in landslide inventories. 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 bedding planes or other planes of weakness and in the direction of the dip of those planes. Because we do not have extensive dip and dip direction measurements, we decided to use the recorded direction of movement from the landslide inventory database as a proxy for dip direction or what we are calling preferred landslide direction of movement.

In order to create these four factor data sets, a geologic map is needed. We started with the best available geologic map, and then combine the units into engineering geologic units or units with similar engineering properties. We added a new field and assigned the new engineering geologic unit names, for example "Coarse Terrace Deposits" and saved result into the C_Geologic_Units feature data set in the Deep_Landslide_Susceptibility_Clackamas_10_1.gdb. The Oregon City portion of the final engineering geologic data set is shown in Figure 14.

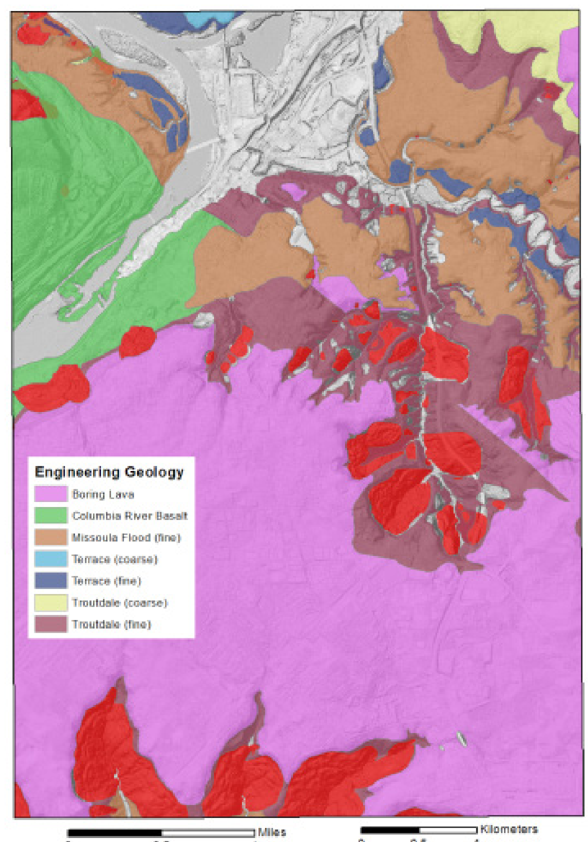

Figure 14. Engineering geology map of the Oregon City portion of the study area.

5.2.3.3.1 Susceptible geologic units

Next, we joined the landslide inventory to the engineering geology. We achieved this spatial join by matching the landslide location with the closest engineering geology unit polygon and matching each landslide one to one with a geologic polygon (see Appendix E). Then we calculated the number of landslides that joined to each engineering geologic unit (Figure 15).

We then used the frequency data to calculate the mean and standard deviation for each unit (Figure 16). We assigned a score of 0, 1, or 2 to each unit:

- score = 0, if less than the mean
- score = 1, if less than mean plus 1 standard deviation and greater than the mean
- score = 2, if equal or greater than mean plus 1 standard deviation

The Oregon City portion of the final map is displayed to Figure 17.

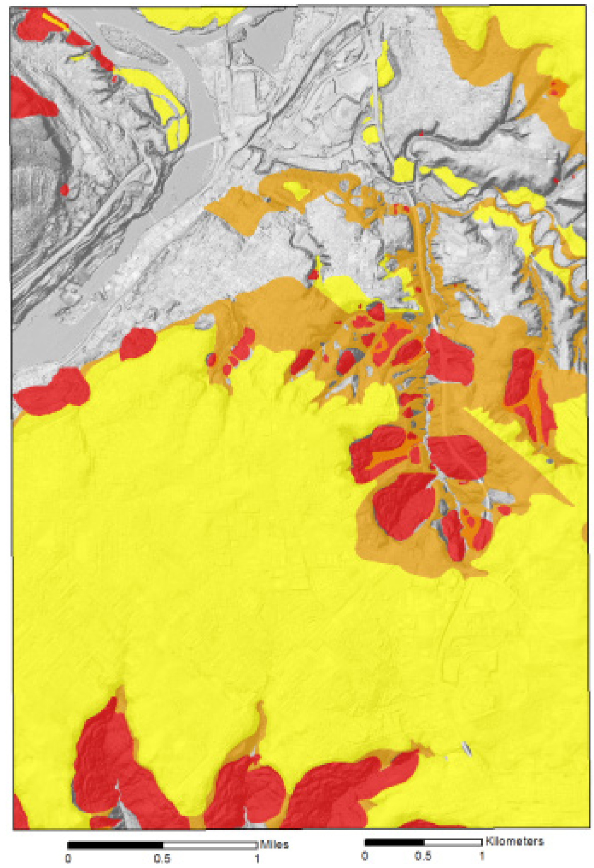

Figure 17. Map of susceptible geologic units factor with scores of zero (no color, gray), one (yellow), and two (orange). Red areas are landslide deposits.

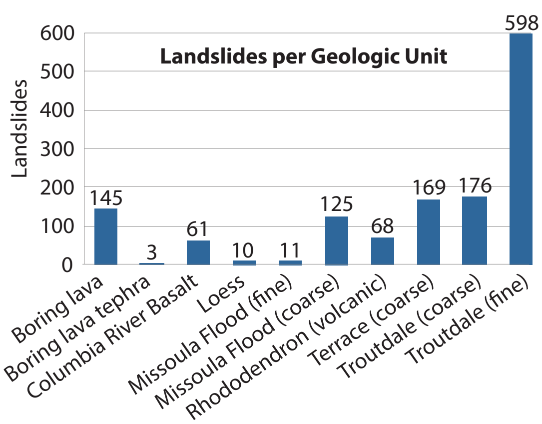

Figure 15. Landslides in each geologic unit in the study area.

Raw Statistics	
Mean	137
Standard Error	55
Median	97
Mode	N/A
Standard Deviation (STD)	175
Sample Variance	30,641
Kurtosis	6
Skewness	2
Range	595
Minimum	3
Maximum	598
Sum	1,366
Count	10

Score Derived from Raw Statistics			
Mean + 1 STD	312	equal or greater	2
Mean + 1 STD	312	or less	1
Mean	137	equal or greater	1
Mean	137	or less	0

Score Applied to Engineering Geology Unit		
Frequency	Engineering Geology	Score
145	Boring lava	1
3	Boring lava tephra	0
61	Columbia River Basalt	0
10	Loess	0
11	Missoula Flood (fine)	0
125	Missoula Flood (coarse)	1
68	Rhododendron (volcanic)	0
169	Terrace (coarse)	1
176	Troutdale (coarse)	1
598	Troutdale (fine)	2

Figure 16. Frequency data summary statistics.

5.2.3.3.2 Susceptible geologic contacts

The first step was to identify geologic contacts in the study area that have landslides along them (Figure 14). We selected the units on each side of the contact used the overlapping area of the two polygons to create a new susceptible contact line. We then used this contact line to select landslides that touch or are near the contact (Figure 18). We saved the selected landslides to the D_Geologic_Contacts feature data set in the Deep_Landslide_Susceptibility_Clackamas_10_1.gdb.

After the landslides are selected and saved to a separate file, we executed the minimum bounding geometry (MBG) tool in the Esri ArcGIS™ version 10.1 3D Analyst™ or Spatial Analyst™ extension on the selected landslide file. One of the calculated outputs of this tool is the landslide (MBG) rectangle width, which is normally the length of the landslide from the head to the toe. The mean and standard deviation of the MBG width can be easily calculated for each set of landslides correlated to a particular contact (Figure 19).

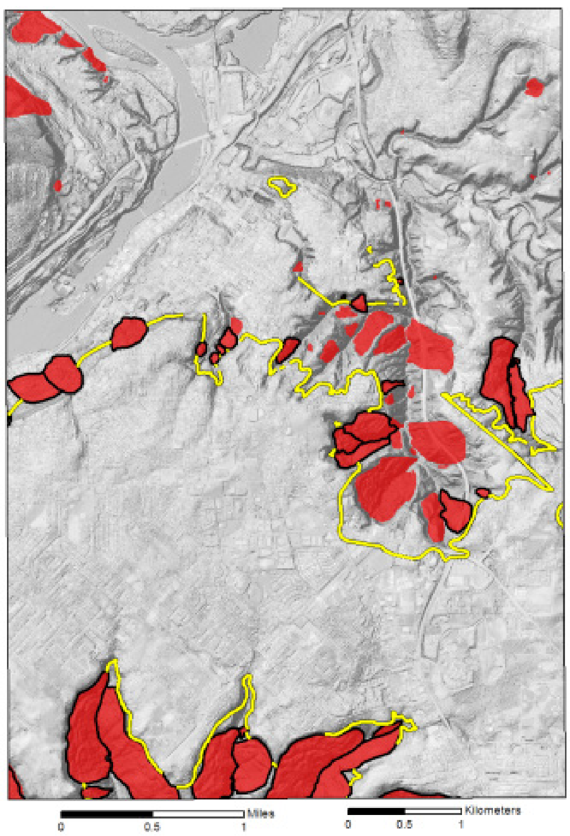

Figure 18. Map of the contact between Boring Lava and fine-grained Troutdale Formation (yellow line) showing landslide deposits (red) and the landslides that touch and are along the contact (red and outlined in black).

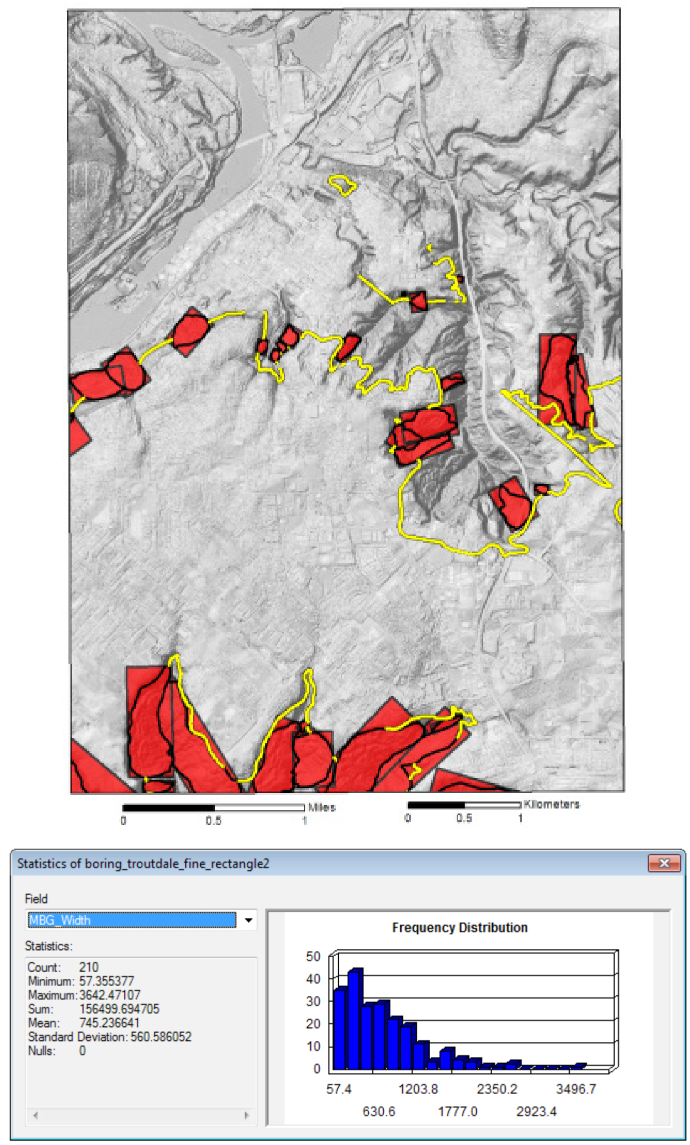

Figure 19. (top) Map of the minimum bounding geometry (MBG) rectangles (black outline and red fill) derived from landslide polygons (black outline inside rectangles). (bottom) Summary statistics of the minimum bounding geometry (MBG) width of landslides with along the contact between Boring Lava and Troutdale Formation.

We then used the mean MBG width distance to create a buffer around the contact line. We assigned this new buffer polygon a score of 2. We used the mean + 1 standard deviation MBG width distance to create a second buffer and we assigned this new polygon a score of 1 (Figure 20).

We repeated this same process or all susceptible contacts and then merged the results into a final susceptible contact factor score file.

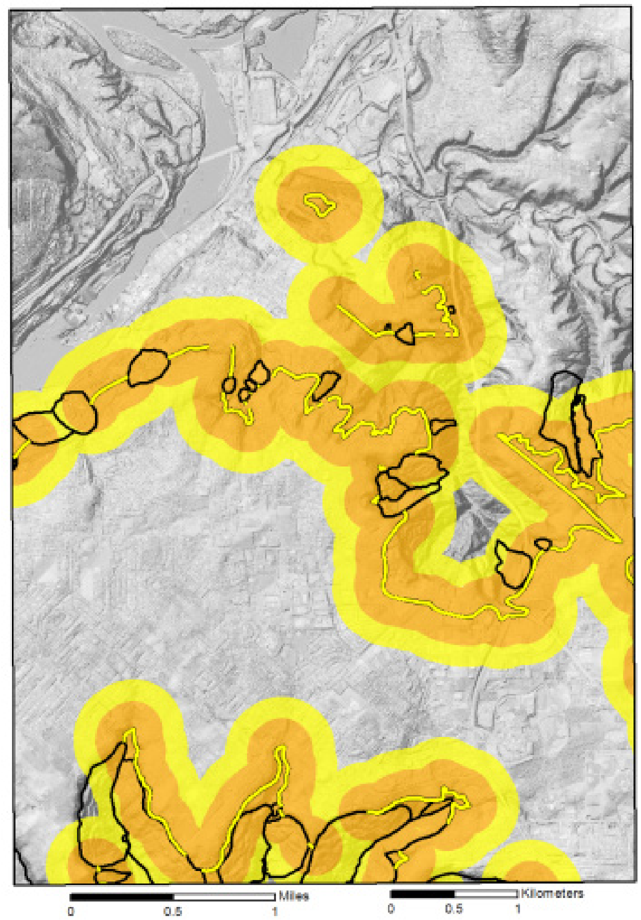

Figure 20. Map of the susceptible contact factor with scores of zero (no color, gray), one (yellow), and two (orange). The contact between the Boring Lava and fine-grained Troutdale Formation is the yellow line, and landslide deposits are outlined in black.

5.2.3.3.3 Susceptible slopes

Slope angles commonly correlate with landslide susceptibility. In the landslide inventory, the pre-failure slope angle is estimated at each landslide. We used these data to establish slope angle thresholds that have greater potential for future landslides within each engineering geology polygon. We started with the file of joined landslides and engineering geology from section 5.2.3.3.1 (Susceptible Geologic Units). Next we ran the summary statistics tool in ArcGIS and calculated the mean and standard deviation of each susceptible engineering geologic unit. We then joined this table back to the engineering geology file and converted the engineering geology table to a raster of mean slope (Figure 21) and a raster of mean slope plus two standard deviations.

We used the Esri ArcGIS raster calculator to evaluate where on the map the following situations occurred and to assign the following scores:

- score = 2, if slope greater than or equal to landslide mean slope
- score = 1, if slope greater than landslide mean slope and slope greater than mean minus 2 standard deviations slope

The two rasters were added together so that a final susceptible slope factor map is created (Figure 22).

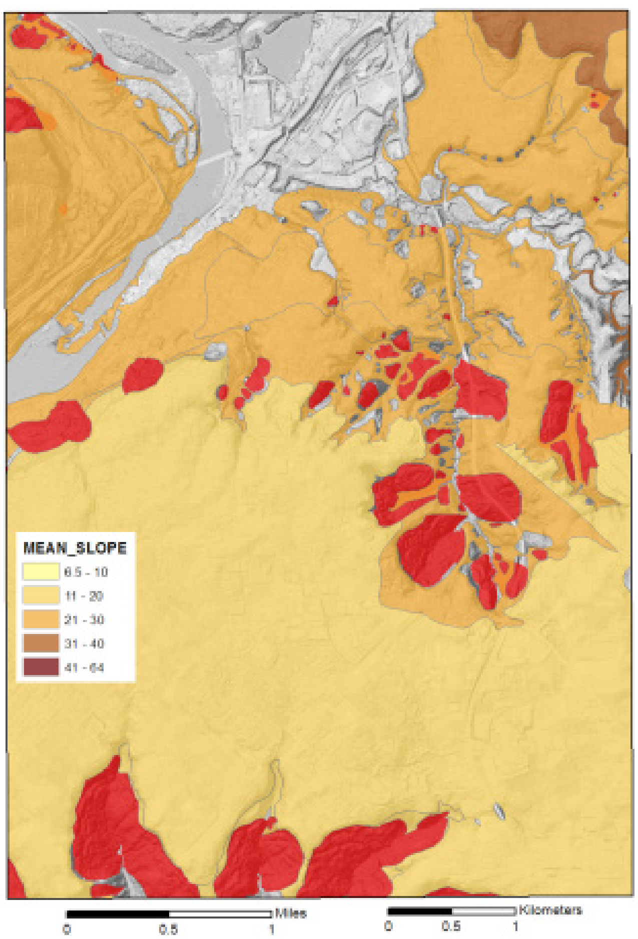

Figure 21. Map of the mean slope angle of each engineering geology polygon derived from landslides (red) located within each polygon.

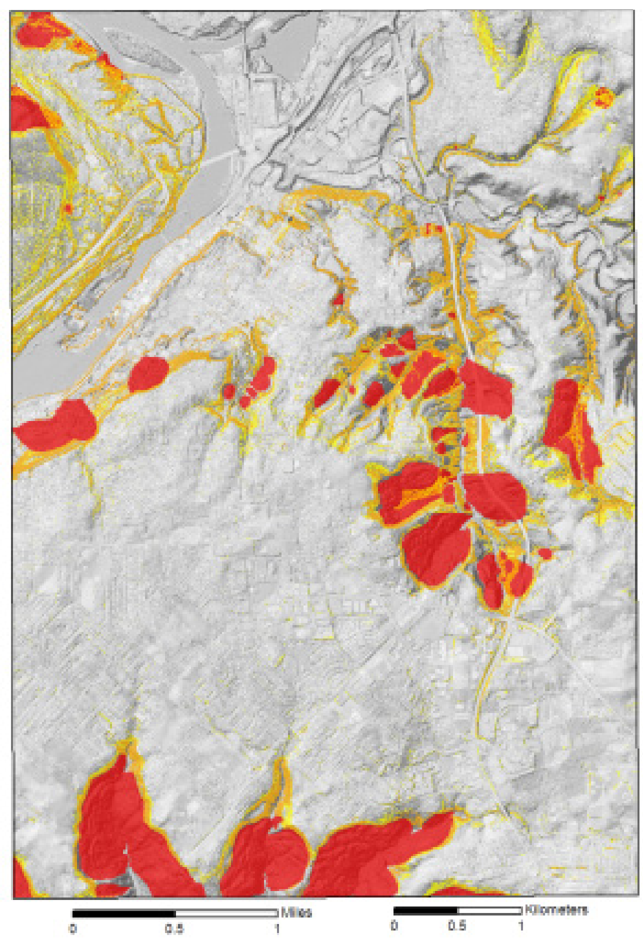

Figure 22. Map of the susceptible slopes factor with scores of zero (no color, gray), one (yellow), and two (orange). Landslides are shown in red.

5.2.3.3.4 Preferred direction of movement

Many deep landslides are partially controlled by subsurface geologic structure. However, structure is rarely factored into modeling due to the lack of detailed spatial understanding of the structure. We recorded the direction of movement at every landslide in our landslide inventory and recommend using these data as a proxy for the geologic structure or preferred direction of movement.

We first converted each landslide area to a grid of points with the direction attribute at each point. Next, we used the file described in section 5.2.3.3.2 (Susceptible Geologic Contacts) with the MBG width to establish the mean width for all landslides within the study area. Then, we interpolated a raster surface from these points using an inverse distance weighted (IDW) technique with a maximum distance set to the MBG width mean. Finally, we created a slope aspect file from the lidar DEM (Figure 23).

We then used the raster calculator to evaluate where on the map the following situations occur and assign the following scores (see Appendix E):

- score = 2, if [slope aspect less than or equal to (IDW direction of movement plus 22.5)] and [slope aspect greater than or equal to (IDW direction of movement minus 22.5)]
- score = 1, if [slope aspect less than or equal to (IDW direction of movement plus 45)] and [slope aspect greater than or equal to (IDW direction of movement minus 45)]

Because the slope aspect map is very detailed due to the lidar DEM and the map of interpolated landslide direction is very simplified (Figure 23), we decided to use a range

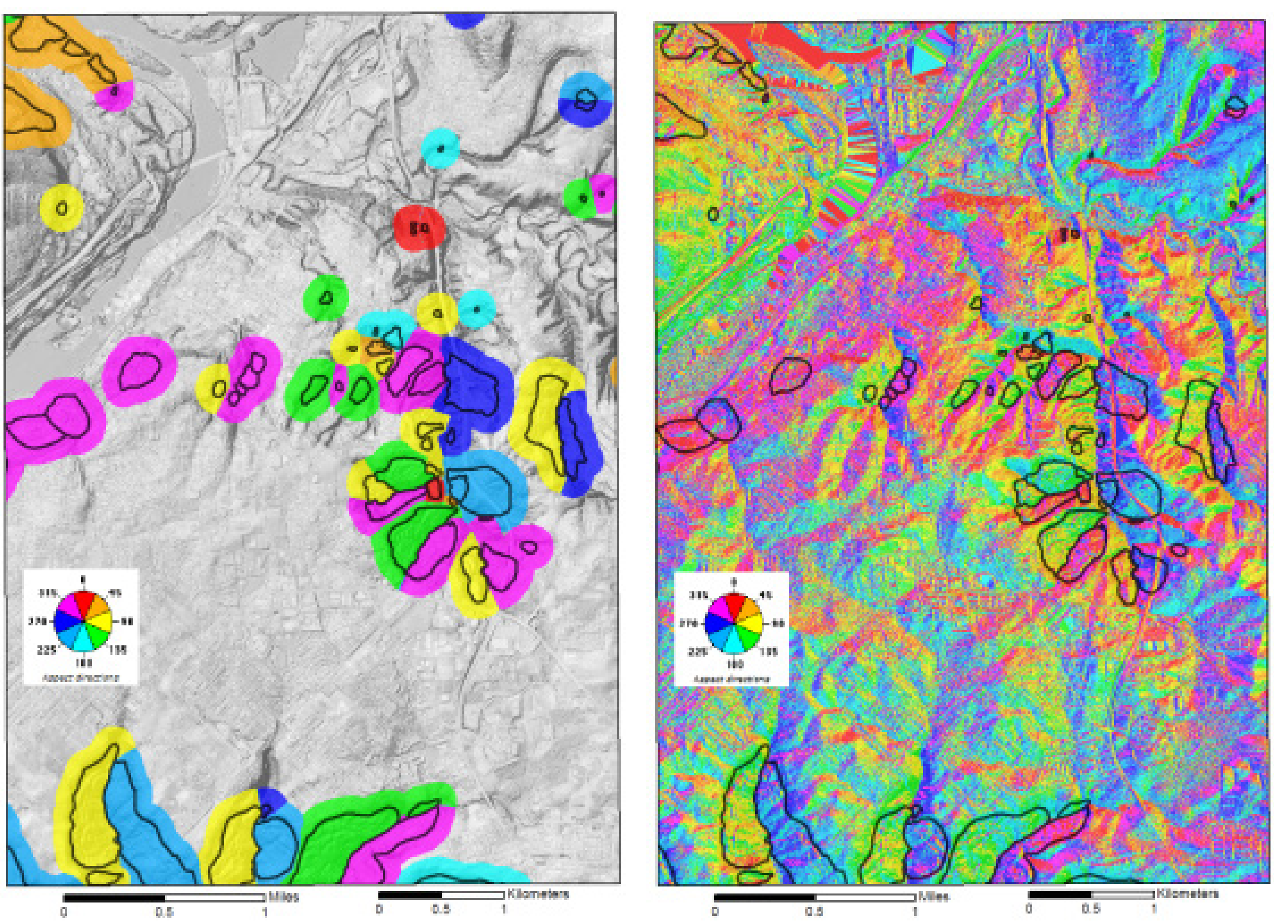

Figure 23. (left) Map of the interpolated landslide direction of movement. (right) Map of slope aspect derived from the lidar DEM. Landslides are outlined in black.

of slope direction. In the case of the higher score (2), any slope within ±22.5 degrees (45 degrees total) of the interpolated slope is identified. Twice this amount, or ±45 degrees (90 degrees total), is used for the medium score (1). We then added the two rasters together to create a final susceptible preferred direction factor map (Figure 24).

5.2.3.4 Combined moderate factors score

We then combined the four factor maps (geologic units, geologic contacts, slope angles, and direction of movement). Each factor map is made up of raster cells and each cell has a score of 0, 1, or 2, so the final combined map has a range of values from 0 to 8. A score of zero means none of the factors were present at a particular site, and a score of 8 means the maximum value for all four factors was present (Figure 25).

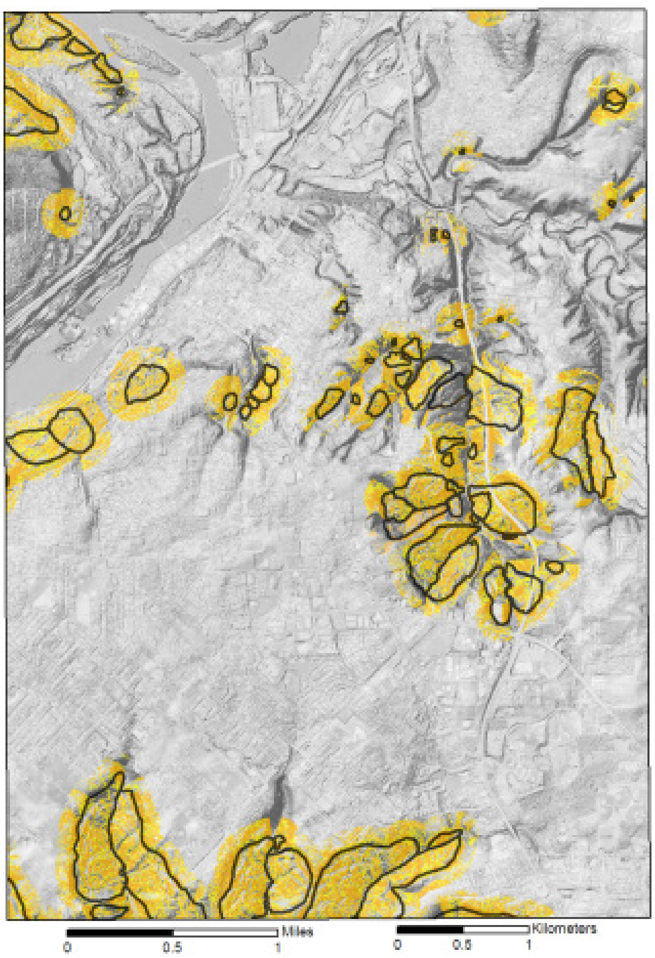

Figure 24. Map of the susceptible preferred direction factor with scores of zero (no color, gray), one (yellow), and two (orange). Landslides are outlined in black.

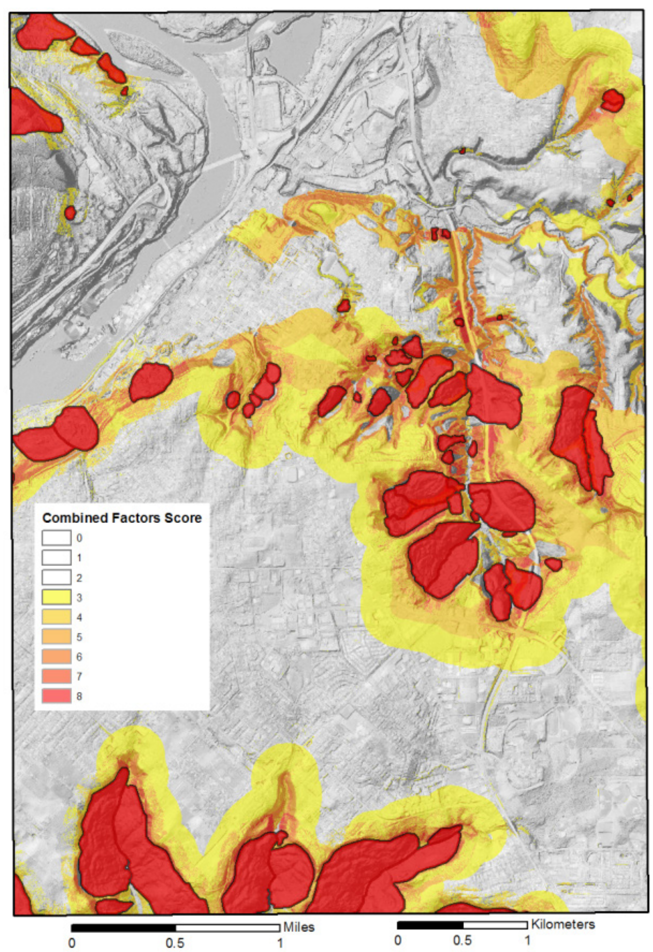

Figure 25. Map of the combined moderate factor scores with total scores ranging from zero (no color, gray) to eight (red). The high-susceptibility zone defined in section 5.2.3.1 is shown in red outlined in black.

5.2.3.5 Minimal landslide deposits and head scarp–flank buffers

To establish a minimal moderate susceptibility zone around the landslide deposits and head scarp–flank polygons, we multiplied the head-scarp height by two, just as we did in section 5.2.3.2 (Head scarp–flank polygons and buffers). This establishes a minimal distance for each landslide on the basis of individual landslide attributes (Figure 26, left).

5.2.3.6 Delineation of the moderate susceptibility zone

We used the minimal moderate susceptibility zone and the combined moderate factors map to delineate the line between the moderate and the low susceptibility zone. We used a minimal combined factor score threshold between 3 and 5 along with educated judgment to delineate the boundary between the low and moderate zones (Figure 26, right).

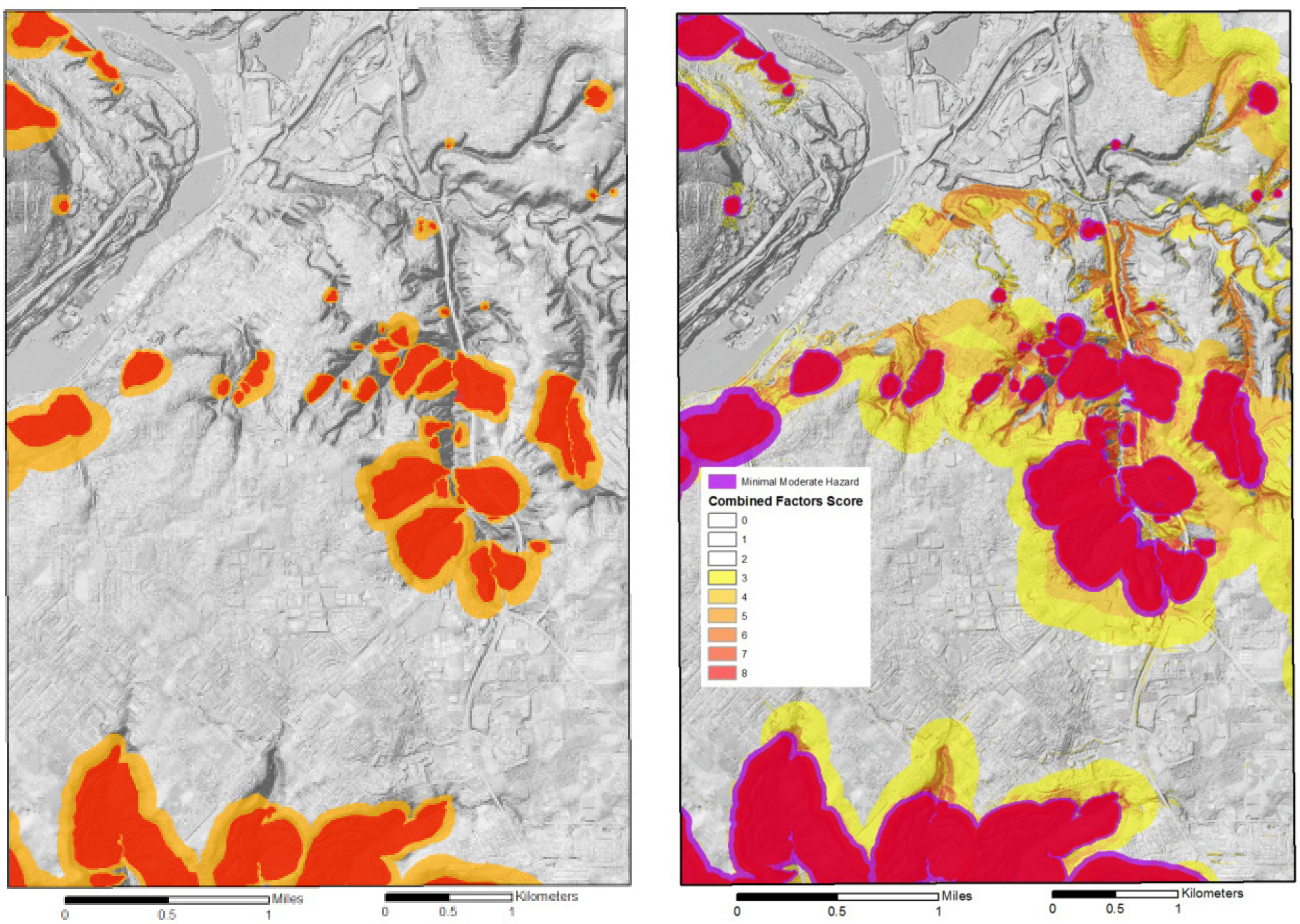

Figure 26. (left) Map of the minimal moderate susceptibility zone (orange) and landslide deposits (red). (right) Map of the high susceptibility zone (red), the combined moderate factors score (yellow to orange areas), and the minimal moderate zone (purple).

An example of educated judgment can be seen in the northwest portion of Figure 267. This area lacks moderate factors and minimal moderate zone; however, a known Columbia River Basalt soil interbed in this area called the Vantage Horizon is exposed at the surface. Just to the west of this area a large landslide, which very likely failed along the Vantage Horizon, occurred.

5.2.3.7 Final deep-landslide susceptibility zones

The final deep landslide susceptibility zones are a combination of contributing factors discussed in the previous section 5.2.3 and combined as shown in Table 2 (Figure 27).

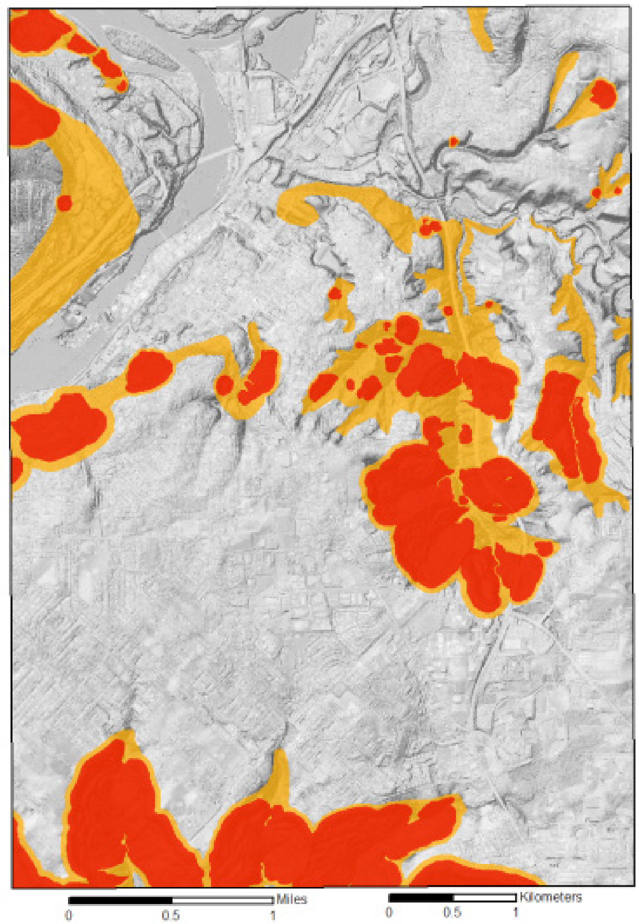

Figure 27. Map of high (red), moderate (orange), and low (no color, gray) deep-landslide susceptibility zones.

Table 2. Final deep-landslide hazard zone matrix.

Contributing Factors	Final Hazard Zone		
	High	Moderate	Low
Landslides, Head Scarp–Flanks, Buffers	included	—	—
Geologic Factors, High Zone Buffer	—	included	—
Minimal Geologic Factors	—	—	included

5.2.3.8 Deep-landslide susceptibility map

We developed a map template as part of the protocol described here. The map template provides a way to display deep-landslide susceptibility data in a consistent manner for any area in Oregon. An example of this template is shown in Figure 28.

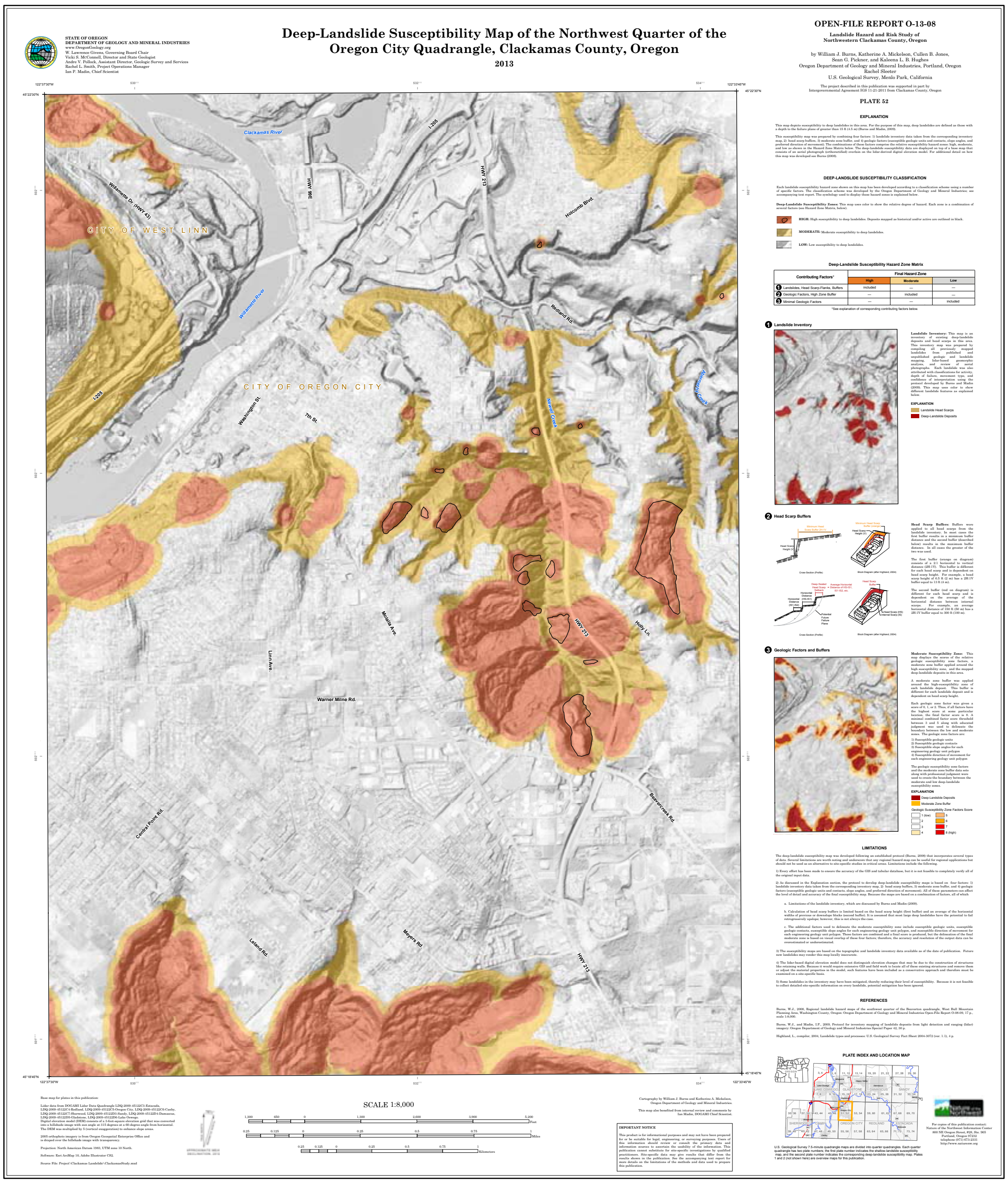

Figure 28. Example of the deep-landslide susceptibility map of the northwest quarter of the U.S. Geological Survey Oregon City 7.5-minute quadrangle, Clackamas County, Oregon (Plate 52).