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Brad Avy, State Geologist

INTERPRETIVE MAP 60

LANDSLIDE HAZARD AND RISK STUDY OF EUGENE-SPRINGFIELD AND LANE COUNTY, OREGON

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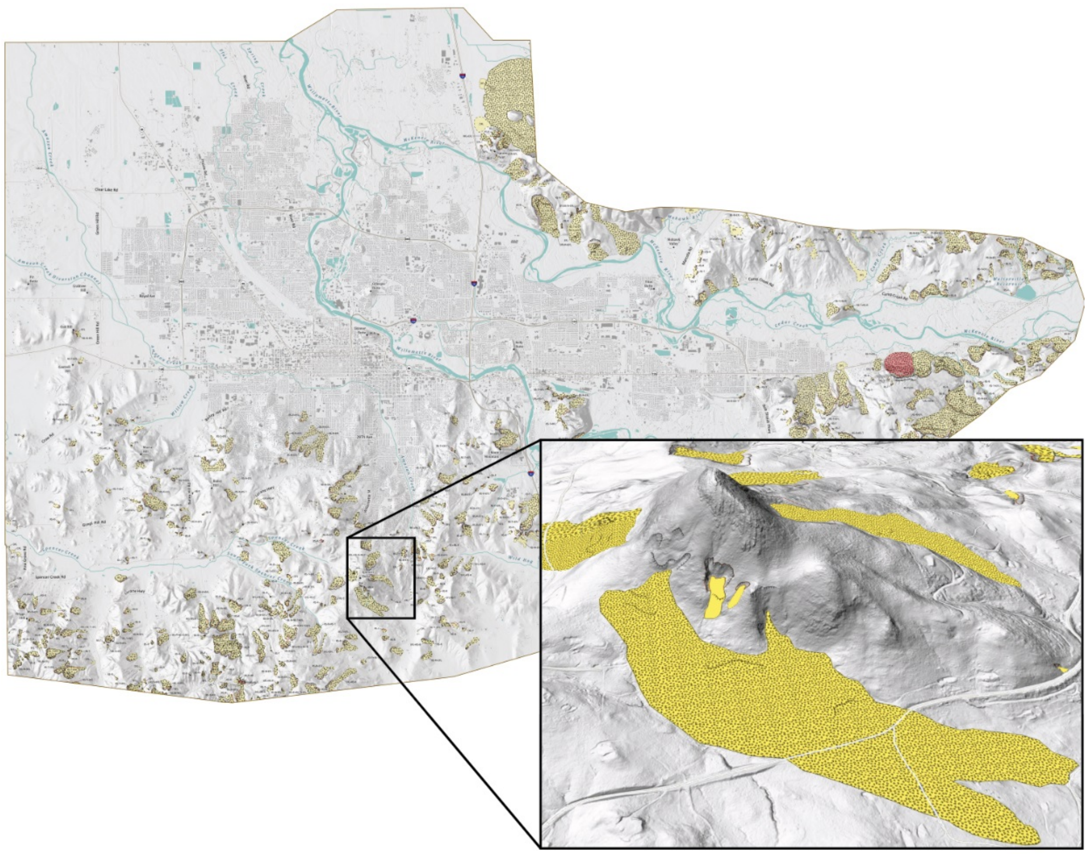

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Cover image: *Landslide inventory map of the Eugene-Springfield study area. Inset shows closeup of mapped landslides near Spencer Butte. See Plate 1 of this publication for more information.*

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GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files. Geodatabase is Esri® version 10.1 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

Eugene_Springfield_landslide_GIS_IMS_60.gdb:

Datasets:

- Buildings
  - building_footprints (polygons)
- Engineering_Geology
  - Eugene_Bedrock_Geo (polygons)
  - Eugene_Surficial_Geo (polygons)
- Landslide_Inventory
  - Deposits (polygons)
  - Historic_landslide_points (points)
  - Scarp_Flanks (polygons)
  - Scarps (polylines)
- Eugene_Deep_Susc (polygons)
- Eugene_Shallow_Susc (raster)

1.0 REPORT SUMMARY

This Eugene-Springfield landslide hazard and risk study was undertaken by the Oregon Department of Geology and Mineral Industries (DOGAMI) in order to create detailed, usable maps and analyses on the level and location of the landslide hazard and risk to infrastructure in the study area. This project was funded by the Federal Emergency Management Agency Risk MAP (Mapping, Assessment, and Planning) Program (EMW-2015-CA-00106). Lane County has experienced hundreds of landslides in the past 50 years. Many of these have been recorded in the Statewide Landslide Information Database for Oregon (SLIDO); however, no landslide hazard study has been conducted in the most populous portion of the county: the Eugene-Springfield metro area. The cities of Springfield and Eugene are growing at a rate of 5% to 7.7% annually (U.S. Census 2010) and, as this is the second most populated metro area in Oregon, understanding landslide hazards and risk from landslides is important for citizens and those addressing natural hazards in their organizations.

For this study we used the protocols established by DOGAMI for 1) making a landslide inventory; that is, mapping existing landslide deposits, 2) modeling deep and shallow landslide susceptibility in order to demonstrate where landslides may occur in the future, and 3) assessing landslide risk through exposure analysis and by using the FEMA Hazus-MH model. These established methods allow for a consistent scientific framework and comparison to other areas in Oregon to understand relative risk.

The study area is 230 mi^2 (595 km^2) centered on the Eugene-Springfield and Coburg urban growth boundaries with a buffer to include as much of the surrounding populated areas of Lane County as our project scope and available lidar coverage allowed. Our results include the following:

- There are over 700 existing landslides, including historic landslide points, covering 6% of the total study area.
- More than 4,500 residents live on existing deep-seated landslides.
- Approximately $476 M worth of buildings is located on existing deep landslides.

To better understand the results, we divided the study area into subsections, defined by communities. The landslide hazard is concentrated in a few communities. Notably, in the hills south of Eugene, southeast of Springfield, and throughout unincorporated Lane County, there is markedly more landslide hazard than in the dominantly flat, alluvial terrain in north-central and western Eugene, and in western Springfield along the McKenzie River and Willamette River.

The results led us to conclude that, overall, the study area experiences moderate landslide hazard and risk, with both concentrated in a few communities in the study area. We recommend:

- increasing private property owners' awareness of existing landslide hazards and taking precautions through risk reduction efforts at the individual lot level,
- incorporating landslide hazard maps and risk reduction strategies into community- and county-level planning efforts, and
- creating a landslide emergency response plan in order to best prepare and react in the case of a landslide occurrence.

The primary landslide hazard in the study area is exposure of existing structures to deep landslides. Substantive risk reduction activities for this type of landslide hazard include controlling the input of water onto slopes within the moderate and deep landslide susceptibility zones and on existing deep landslides, and avoiding adding material (weight) to the tops of susceptible slopes or, conversely, removing material from the bottoms of slopes (excavation or grading).

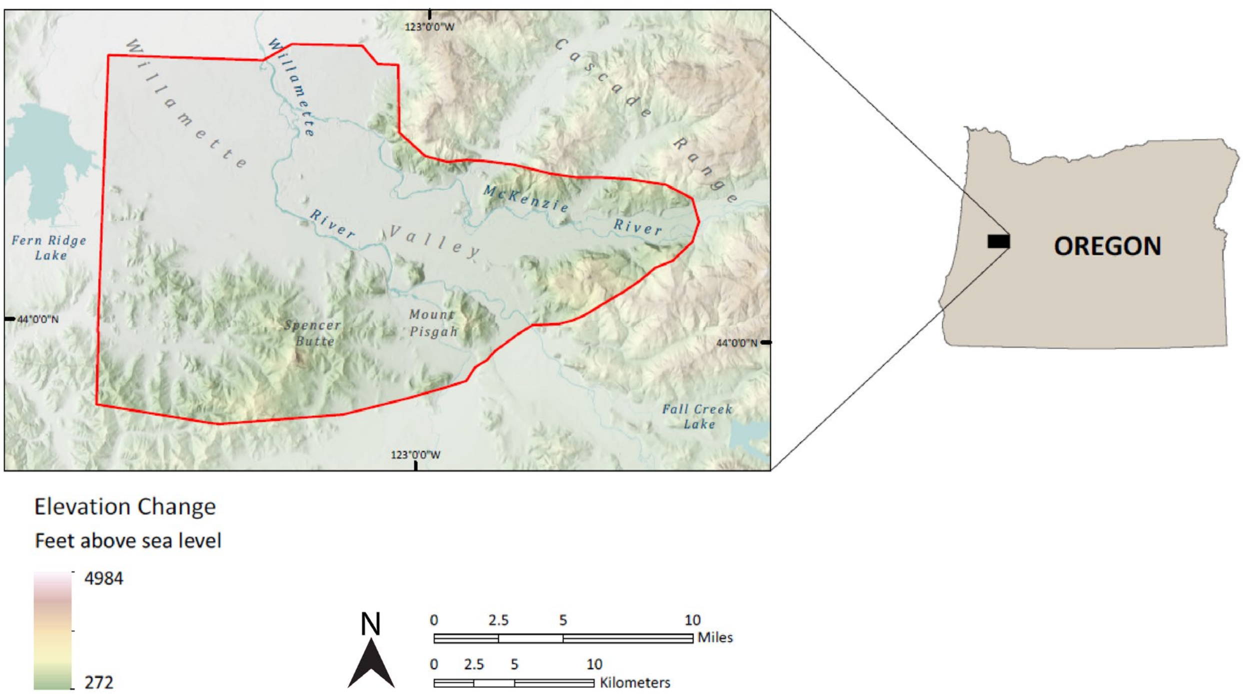
2.0 INTRODUCTION

Lane County has experienced many landslides in the last 50 years. Risk from landslides is not well-constrained for the most populated portions of the county. Assessing landslide risk is the primary reason for this study. In our work, we use DOGAMI protocols established by Burns and Madin (2009), Burns and others (2012), and Burns and Mickelson (2016). We also draw from the insights and results of Burns and others (2018).

2.1 The Study Area

The study area encompasses the population centers of the cities of Eugene and Springfield and includes within the project scope as much of the surrounding populated area as possible within available lidar-derived basemap coverage (**Figure 2-1**). We defined the southeastern boundary by available lidar coverage, and we used established quadrangle boundaries to define the western and northern boundaries.

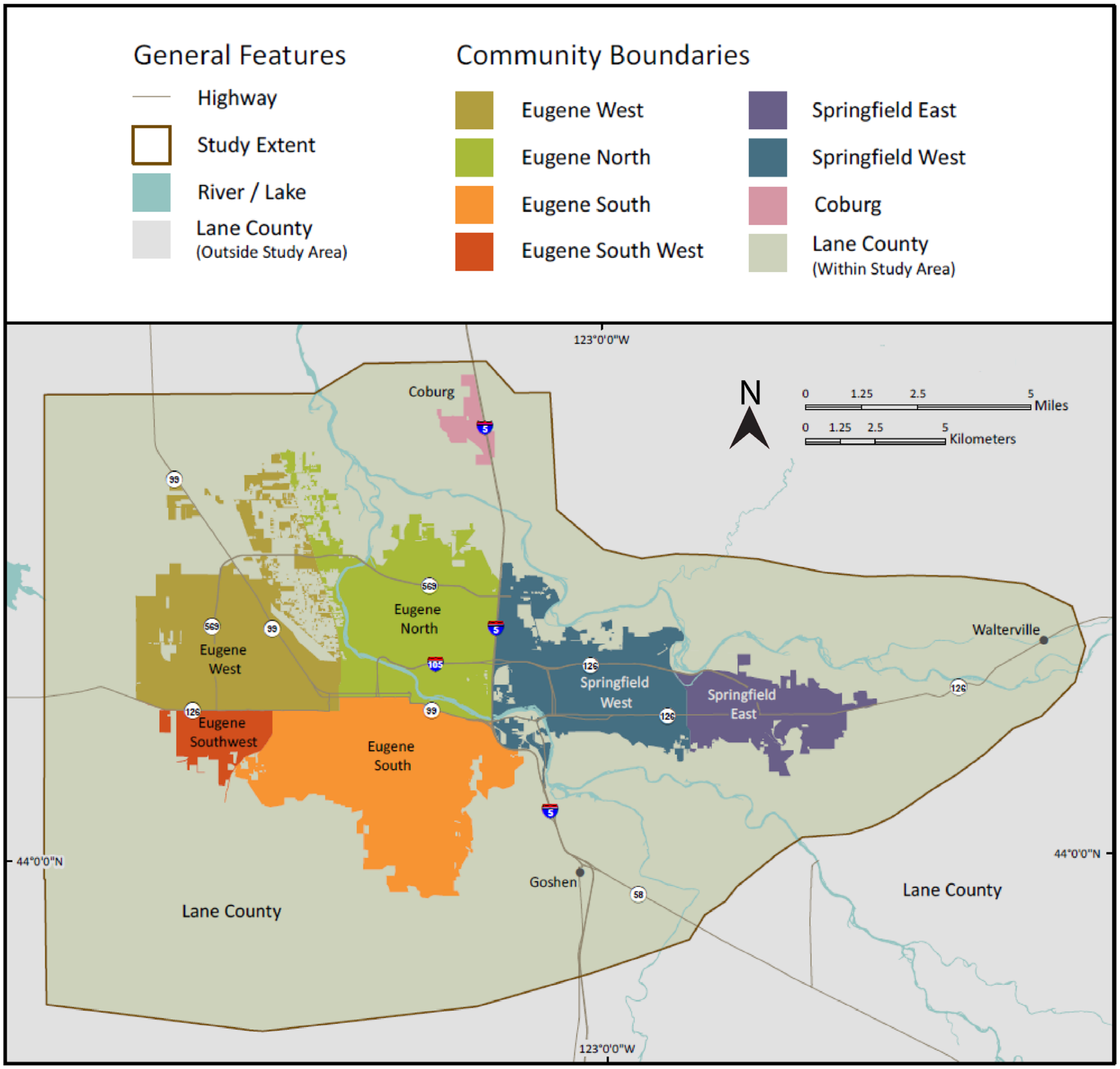
Figure 2-1. Map of the study area.



The study area includes the Cities of Eugene, Springfield, and Coburg, the unincorporated communities of Goshen and Walterville, and areas of unincorporated Lane County (**Figure 2-2**). The Cities of Eugene and City of Springfield are divided into risk reporting areas roughly defined by neighborhoods. The study area is the second most populous metro area in Oregon, with 256,278 people living within its boundaries (2010 U.S. Census, https://www.census.gov/2010census/data/).

The study area is centered on the southern terminus of the Willamette Valley, flanked by the Coast Range on the west and the Western Cascades on the east. The metro area includes the confluence of the Coastal Fork and Middle Fork of the Willamette River near Eugene's South Hills, as well as the confluence of the McKenzie River and the Willamette River just north of Eugene. These major rivers and the associated alluvial plains characterize the relatively flat topography along the valley floor. The subdued hills that comprise the South Hills of Eugene and more rugged mountains in the north and east of the study area define the terrain in the uplands surrounding the terminus of the Willamette Valley (Plate 1).

Figure 2-2. Map of risk reporting areas/communities in the study area.



The study area has a West Coast marine climate, with cool, wet winters and warm, dry summers. 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 30 and 60 inches per year (Spatial Climate Analysis Service, 2000).

The region is subjected to small- to large-magnitude earthquakes from three primary sources: 1) Cascadia Subduction Zone, 2) intraplate, and 3) crustal. The Cascadia Subduction Zone is approximately 100 miles to the west, off the coast. The source for intraplate earthquakes is related to the subducting Juan de Fuca plate movement deep below the area. Shallow, crustal earthquakes occur from geologic structures near the surface, with a variety of potential sources in the greater Willamette Valley area (McClaughry and others, 2010).

2.2 Purpose

The purpose of this project is to help communities in this region become more aware of and resilient to landslide hazards by providing the communities with accurate, detailed, and up-to-date information about these hazards and community assets at risk.

The main objectives of this study are to:

- compile existing data including previous geologic hazard reports and natural hazard mitigation plans,
- create new geodatabase of landslide hazards including landslide inventory and susceptibility,
- compile or create a database of critical facilities and primary infrastructure, generalized land occupancy (land use/zoning), buildings, and population distribution data, and
- perform exposure and Hazus–based risk analyses.

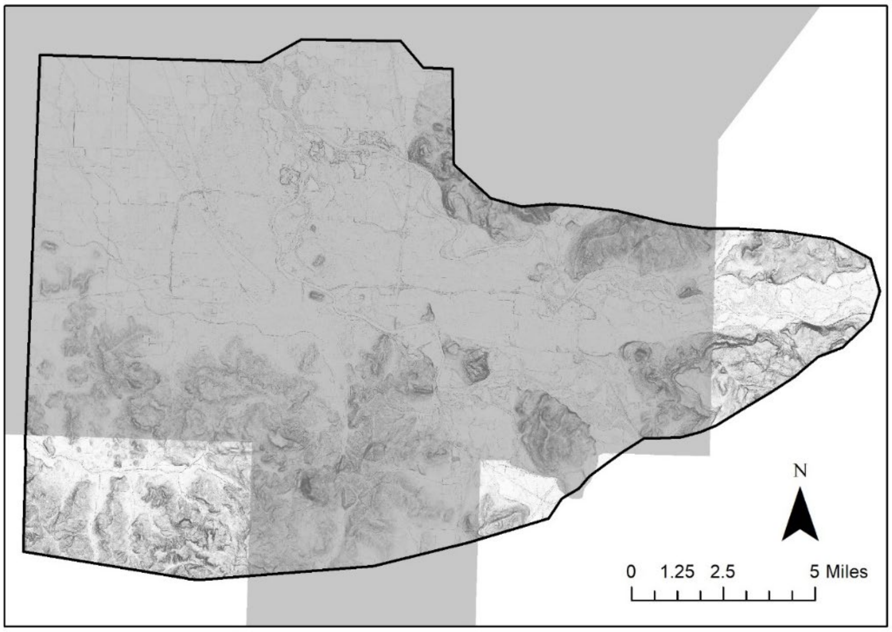
The body of this report describes the methods and results for these objectives. Throughout this report we use the engineering geology terms *hazard*, *susceptibility*, and *risk*. The term hazard is defined here as a possible source of danger, and in this report we are specifically referring to landslides as a hazard. The term susceptibility in this context is defined as a particular area being capable of slope failure or 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 (Burns and others, 2015).

2.3 Adjacent Past Geologic or Related Studies

There have been no specific landslide hazard studies or risk studies in the Eugene metro area recently. There have been several landslide studies in northern Willamette Valley, including parts of Clackamas and Multnomah Counties (Burns and others, 2013; Burns and others, 2018), which we can use to compare relative risk.

Recent, in-depth geologic mapping in this area used lidar for analysis and included interpreted landslide deposits. The Southern Willamette Valley study (McClaughry and others, 2010) identified 26 landslide polygons within the current study area. However, as seen in **Figure 2-3**, some parts of our current study area are outside the study area of McClaughry and others (2010).

Figure 2-3. Southern Willamette Valley geologic map coverage shown in grey (McClaughry and others, 2010).



2.4 Engineering Geology

We created bedrock and surficial engineering geologic maps of the study area as input datasets for the deep and shallow landslide susceptibility models described later in this report. Engineering geology maps are commonly based on geotechnical properties and engineering behavior derived from a standard lithostratigraphic geologic map (Dobbs and others, 2012). Such maps are commonly divided into bedrock engineering geology and surficial engineering geology (Keaton and DeGraff, 1996).

In general, we followed the methods of Burns and others (2012) and Burns and Mickelson (2016) to create the surficial and bedrock engineering geology maps. A brief geologic history of the study area is provided below. For additional information on the bedrock and surficial geology, see McClaughry and others (2010) and the Oregon Geologic Data compilation (OGDC, release 6 [Smith and Roe, 2015]).

Three distinct physiographic provinces, the Coast Range, the Western Cascades, and the Willamette Valley (after Walker, 1977), coalesce in the study area. This means a diverse assemblage of rocks and sediment, as well as diverse topography, define the Eugene-Springfield metro and surrounding area. The highest buttes, peaks, ridgelines, and plateaus reach 1,800 ft above sea level, while the majority of the Eugene-Springfield metro area along the alluvial plains of the Willamette and McKenzie Rivers is between 400 and 450 ft above sea level.

The majority of geologic units in the study area are a result of deposition and deformation along the Juan de Fuca plate and North American plate boundary, which is an active subduction zone (Niem and Niem, 1984; Orr and Orr, 2012; McClaughry and others, 2010). The geologic setting is a complex forearc basin east of the Cascadia subduction zone, with accumulation of ~23,000 ft of volcanic and sedimentary strata during the Cenozoic (last 65 million years). A major structural feature, the Eugene-Denio lineament, strikes northwest to southeast through the southern terminus of the Willamette Valley. Rocks range from mid-Eocene sedimentary rocks to late Eocene and Oligocene volcanic and volcaniclastic rocks. These are overlain locally by Quaternary sediments including landslides, fans, and alluvial plain deposits (McClaughry and others, 2010).

The oldest rocks in the study area are exposed in the hills southwest of Eugene and include sedimentary rocks that are part of the middle Eocene Spencer Formation (~48 Ma). The Spencer Formation is overlain by younger sedimentary rocks of the Eugene Formation and interlayered tuffs and volcaniclastic rocks of the Fisher Formation. Early Western Cascade Volcanics define the northeastern portion of the study area, with an eruptive center, the Mohawk River caldera, defining the ridgeline of the Coburg Hills (McClaughry and others, 2010).

We simplified the geologic units in the study area into 11 bedrock engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 2-4**):

Late Pliocene and Quaternary units:

- Alluvium (Holocene to late Pleistocene)
- Older terrace alluvium (late Pliocene to Pleistocene)

Lower Miocene to Middle Eocene sedimentary rocks:

- Weathered volcaniclastic conglomerate, breccia, and sandstone (Mehama Formation; lower Miocene to upper Eocene)
- Moderately weak, weathered marine sandstone (Eugene Formation; Oligocene and upper Eocene)
- Nonmarine undivided sandstone, conglomerate, breccia, siltstone, and tuff (Fisher Formation; upper and middle Eocene)
- Weakly weathered marine siltstone to sandstone to conglomerate (Spencer Formation; middle Eocene)

Lower Miocene to Eocene volcanic rocks of the early Western Cascades:

- Nonwelded to strongly welded tuff with clay alteration and zeolitization; intracaldera tuff facies (Mohawk River caldera; lower Oligocene)
- Medium weathered basaltic andesite intracanyon lavas, basalt lavas and basaltic andesite (Little Butte Volcanics; Oligocene)
- Erosion-resistant, intermediate to mafic intrusions (Oligocene)
- Deeply weathered to zeolitized basaltic andesite and basalt (basalt of Mount Tom; Eocene)
- Ash-flow tuff (tuff of Fox Hollow; middle Eocene)
- Deeply weathered basalt and basaltic andesite lavas (Fisher basalt; Eocene)

Figure 2-4. Map of generalized bedrock engineering geology in the study area.

Late Pliocene and Quaternary units:

- Alluvium (Holocene to late Pleistocene)
- Older terrace alluvium (late Pliocene to Pleistocene)

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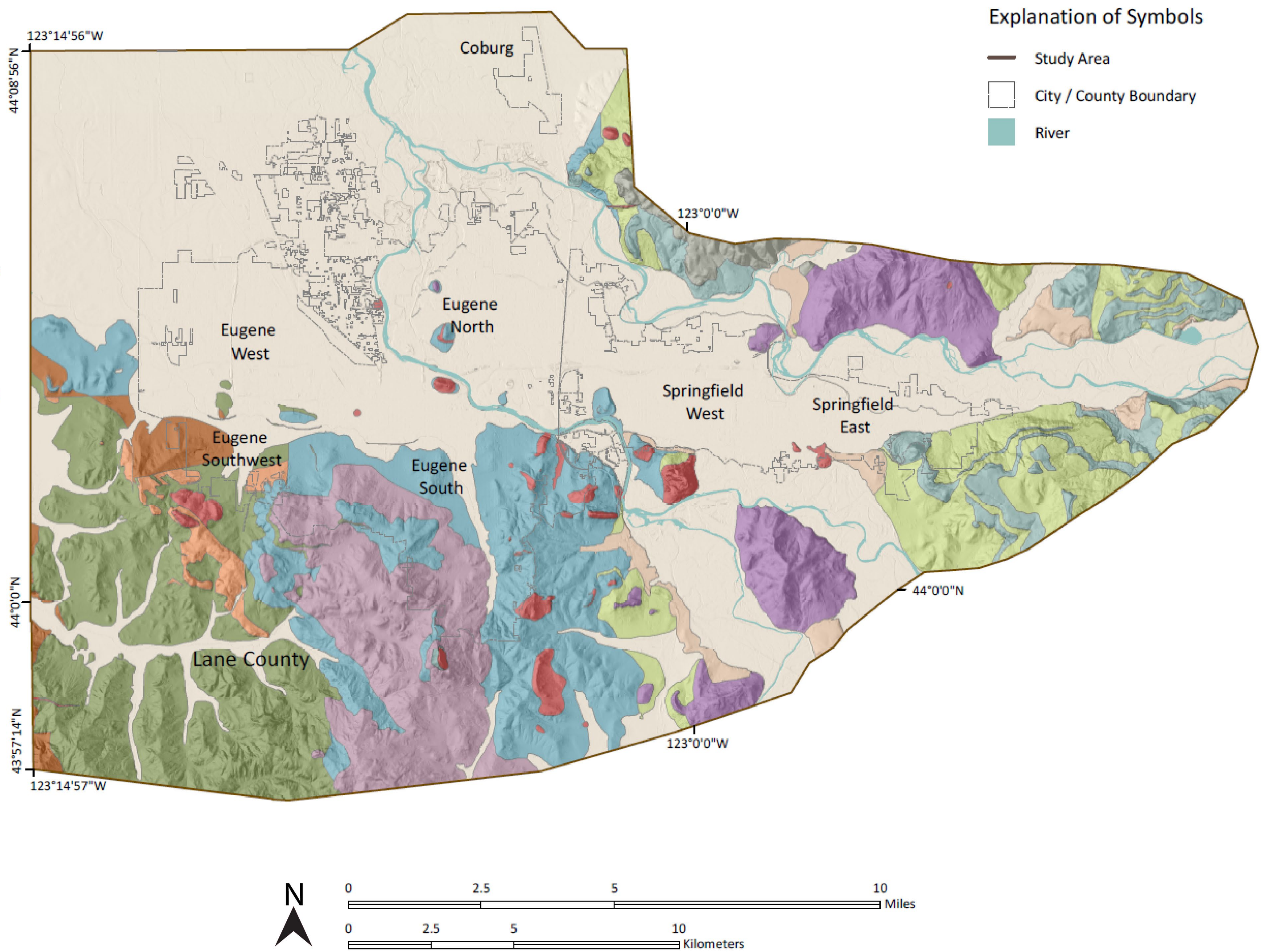
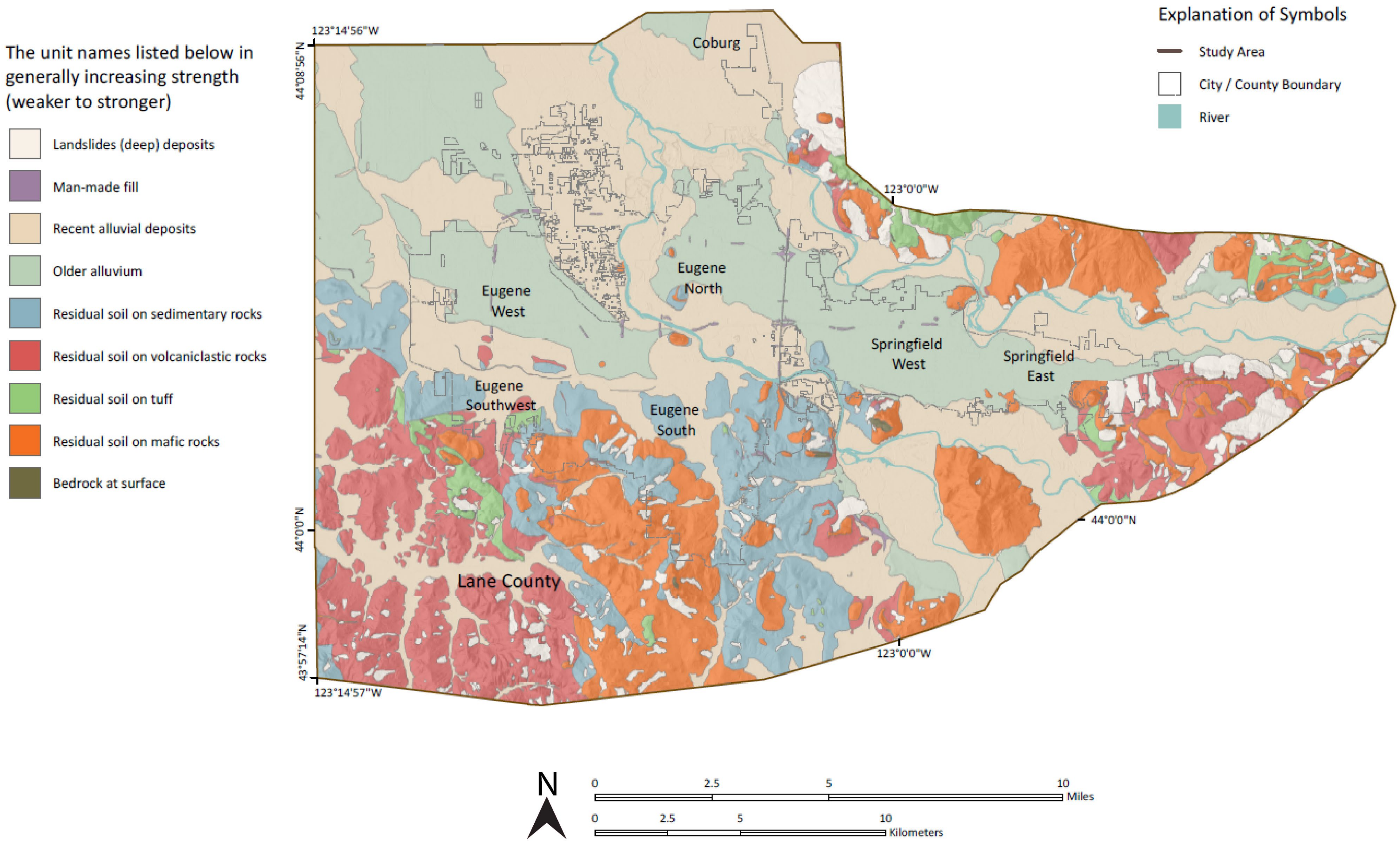


We simplified the surficial geologic units in the study area into nine surficial engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 2-5**). The surficial engineering geologic map takes into consideration descriptions of soils and materials at the surface (Patching, 1987). The units are listed below in generally increasing strength (weaker to stronger):

- Landslide (deep) deposits
- Man-made fill
- Recent alluvial deposits
- Older alluvium
- Residual soil on sedimentary rocks
- Residual soil on volcaniclastic rocks
- Residual soil on tuff
- Residual soil on mafic rocks
- Bedrock at surface

Figure 2-5. Map of generalized surficial engineering geology in the study area.



2.5 Landslides

The Federal Emergency Management Agency (FEMA) issued 50 major disaster declarations for Oregon during the period 1953–2017 (https://www.fema.gov/disasters/grid/state-tribal-government/88?field_disaster_type_term_tid_1=All). Most of these disasters were related to storm events that caused flooding and commonly included landslides. During this time, 15 declared disasters affected Lane County (FEMA Disaster Declarations Summary [Excel spreadsheet], accessed via https://www.fema.gov/media-library/assets/documents/28318), including:

- 1964 – FEMA DR-184, Heavy Rains and Flooding
- 1972 – FEMA DR-319, Severe Storms and Flooding
- 1974 – FEMA DR-413, Severe Storms, Snowmelt, and Flooding
- 1994 – FEMA DR-1036, The El Nino (The Salmon Industry) Fishing Losses
- 1996 – FEMA DR-1099, High Winds, Severe Storms, and Flooding
- 1996 – FEMA DR-1107, Severe Storms and High Winds
- 1996 – FEMA DR-1149, Flooding, Land, Mud Slides, High Winds, Severe Storms
- 1997 – FEMA-DR 1160, Severe Winter Storms, Land and Mudslides, Flooding
- 2002 – FEMA-DR 1405, Severe Winter Storm with High Winds
- 2004 – FEMA-DR 1510, Severe Winter Storms
- 2005 – FEMA-DR 3228, Hurricane Katrina Evacuation (Coastal Storm)
- 2012 – FEMA-DR 4055, Severe Winter Storm, Flooding, Landslides, and Mudslides
- 2014 – FEMA-DR 4169, Severe Winter Storm
- 2015 – FEMA-DR 4258, Severe Winter Storms, Straight-Line Winds, Flooding, Landslides, and Mudslides
- 2016 – FEMA-DR 4296, Severe Winter Storm and Flooding
- 2017 – FEMA-DR-4328 Severe Winter Storms, Flooding, Landslides, and Mudslides

The increase in declared disasters in recent decades is likely due to a combination of 1) improved reporting, recording, and communications because of the onset of digital technology during this time period and 2) development in areas with relatively higher landslide hazards. Not all of the above declared disasters for Lane County included landslides or included the immediate study area for this project.

There are many historic (<150 years ago) and prehistoric (>150 years ago) landslides in the study area, which increase the current landslide risk. It is important to note that not all landslides that occurred in the past 150 years have been recorded or are accessible. For this study, DOGAMI mapped the existing landslides following the method outlined by Burns and Madin (2009). There are 634 landslides in the study area, covering 6% of the study area (Plate 1). There are 252 shallow and 335 deep landslides. These landslides were one of the primary inputs into the models used for the current project to create the shallow and deep landslide susceptibility maps.

One landslide was studied in more detail prior to this study. Known as the 67th Street landslide and labeled in our landslide inventory as Eugene_348, this landslide was mapped during geological mapping by Walker and Duncan (1989), Yeats and others (1996), Hladky and McCaslin (2006), and McClaughry and others (2010), with slightly different extents interpreted by the mappers. A geotechnical boring drilled and logged by DOGAMI in 1996 identified about 18 ft of breccia, interpreted to be landslide debris, overlying volcanic tuff, confirming the geological mapping interpretations (Oregon Water Resources Department well log LANE 51916, https://apps.wrd.state.or.us/apps/gw/well_log/Default.aspx).

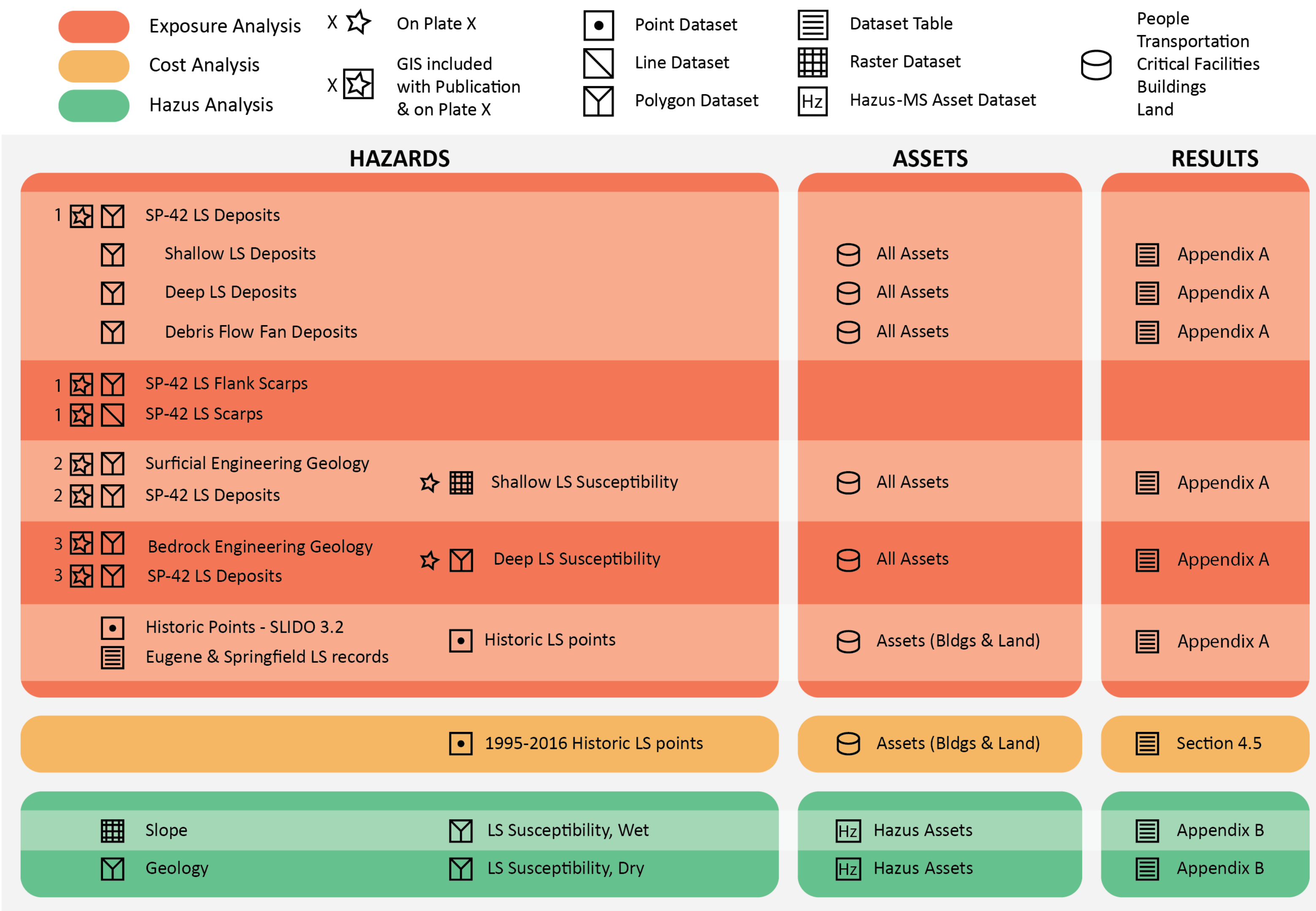
In the winters of 1996 and 1997 9,582 landslides (Hofmeister, 2000) were recorded across Oregon (FEMA Disaster Declarations 1099, 1107, 1149, and 1160). Lane County experienced 24% (2,280) of these 1996-1997 landslides.

The combination of FEMA declared disasters, hundreds of prehistoric landslides, and many historic landslides provides evidence of a moderate level of landslide hazard and risk in the study area. Therefore, these data attest to the practicality of continuing landslide risk reduction in this area.

3.0 METHODS

To evaluate the landslide hazard and risk for the study area, we performed three primary tasks: 1) compiled and created landslide hazard data including landslide inventory and susceptibility, 2) compiled and created asset data including critical facilities, roads, generalized land occupancy (land use/zoning), buildings, and population distribution data, and 3) performed risk analysis including exposure and Hazus-based risk analysis. **Figure 3-1** summarizes the hazard and asset datasets needed for the risk analyses and where the results of the analyses can be found in this publication.

Figure 3-1. Input datasets and results. SP-42 is Special Paper 42 (Burns and Madin, 2009). LS is landslide. SLIDO 3.2 is Statewide Landslide Information Database for Oregon, release 3.2 (Burns, 2014). Hazus-MH is Hazus-MH, version 2.1, loss estimation data (FEMA, 2011).



3.1 Landslide Hazard Evaluation Methods

First, we compiled the detailed lidar-based landslide inventory. Lidar data are from laser imaging of the ground surface from an airplane. Lidar data provide high-accuracy elevation imagery of the ground surface without vegetation and buildings, which makes mapping landslide scarps and morphology much easier (Burns, 2007). Then, we updated the historic landslide inventory within Eugene, Springfield, and areas of unincorporated Lane County within the study area. Because both of these datasets are landslide inventories but are different types of landslide inventories, we will refer to the lidar-based polygon inventory as the *SP-42 inventory* (**Figure 3-1**; DOGAMI Special Paper 42; Burns and Madin, 2009) and the historic point inventory as the *historic landslide point inventory* throughout this paper. Next, we used models to create shallow and deep landslide susceptibility. The methods we used to perform analysis with and create these datasets are described in detail in the following sections of this report and are the same methods DOGAMI uses for landslide hazard mapping projects throughout Oregon.

3.1.1 Landslide inventories

The SP-42 inventory was compiled from existing publications following the methodology of Burns and Madin (2009) to create the landslide inventory at a recommended use scale of 1:8,000. The data were extracted from the Statewide Landslide Information Database for Oregon (SLIDO), release 3.2 (Burns, 2014).

The historic landslide point dataset was created by compiling two existing datasets: 1) SLIDO-3.2 and 2) locally-held historic landslide records. We began the compilation by extracting historic landslide points from SLIDO-3.2. The City of Eugene and City of Springfield records were provided by several Bureau of Maintenance and Public Works staff members, in an open-format data gathering meeting. The final version of this dataset is included with this publication and is referred to as *historic landslide points* (**Figure 3-1)**.

Before this study, 51 historic landslide points had been recorded within the study area. Many of these records were from a post-1996 storm season damage survey carried out by FEMA and Oregon's Office of Emergency Management (FEMA, 1996). Others still were compiled by DOGAMI in the aftermath of the 1996 and 1997 winter storms (Hofmeister, 2000). In this compilation study, Lane County reported 24% of all landslides in Oregon recorded in the three 1996 and 1997 disaster declarations. Other historic landslide points were recorded by ODOT for failures along their roadways.

We identified 44 new historic landslides in this study on the basis of records gathered from City of Eugene and City of Springfield Public Works and Maintenance staff, as well as aerial photo surveys.

3.1.2 Shallow landslide susceptibility

We created the shallow landslide susceptibility map by following the shallow landslide susceptibility (**Figure 3-1**) mapping methodology of Burns and others (2012). 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 (to reduce overprediction),
4) creating buffers to add susceptible areas missed in a grid-type analysis (to reduce underprediction), and
5) combining the four components into final susceptibility hazard zones.

The first component was 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 2.4, we created a new surficial engineering geology map during this project. We created a table of material properties, based in part on local geotechnical reports and in part on existing, generalized statewide values (Burns and others, 2012, Table 3-2), for each of the primary surficial engineering geologic units in this specific study area (**Table 3-1**). Many of the values were based on local geotechnical reports submitted to the City of Eugene planning department as a part of the development requirements (Branch Engineering Inc., 1995; B2CC Construction Consulting, 2000; Professional Service Industries, Inc., 2000; Geomax, Inc., 2001; Redmond and Associates, 2003; Geoscience, Inc., 2006; Branch Engineering, Inc., 2012). Several reports included laboratory and/or field measurements of material strength. To calculate the FOS (component 2), we estimated new material properties from these local geotechnical reports and from past studies in the northern Willamette Valley including Clackamas, Multnomah County, and City of Portland (Burns and others, 2013, 2018), for geologic units that were not measured locally.

After we acquired the material property values either directly from past studies or through correlations for each surficial geologic unit, we averaged each set of values by geologic unit. DOGAMI staff then reviewed these ranges of values and the averaged values in order to decide the final material properties to be used for this study. These properties are listed in **Table 3-1** and were 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).

Table 3-1. Summary of geotechnical material properties for primary surficial geologic engineering units in the study area, based on Burns and Mickelson, 2016.

Primary Surficial Geologic Engineering Unit	Angle of Internal Friction (degrees)	Cohesion (lb/ft^2)	Unit Weight (Saturated lb/ft^3)	Threshold* for Stable Slopes (FOS > 1.5) (degrees)	Threshold* for Potentially Unstable Slopes (FOS > 1.25) (degrees)
Landslide (deep) deposits	28	0	115	9.0	10.5
Man-made fill	30	0	115	9.5	11.5
Recent alluvial deposits	30	0	115	9.5	11.5
Older alluvium	34	0	115	11.5	13.5
Residual soil on sedimentary rock	30	250	115	15	18
Residual soil on volcaniclastic rocks	28	500	115	20	24
Residual soil on tuff	28	500	115	20	24
Residual soil on mafic rocks	28	500	115	20	24
Bedrock at surface	40	750	115	30	36

*Slope angle thresholds are the boundaries calculated for three FOS ranges: 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 (to reduce overprediction—component 3) and to add susceptible areas missed in a grid-type analysis (to reduce underprediction—component 4), we created buffers as described in detail by Burns and others (2012). 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. This could include features like road ditches. One disadvantage of a slope stability analysis using a raster or grid-type infinite slope equation is that the analysis looks at each raster cell independently. The FOS is calculated in the same way regardless 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, DOGAMI developed these two buffers to help reduce underprediction.

3.1.3 Deep landslide susceptibility

We created the deep landslide susceptibility map by generally following the methodology of Burns and Mickelson (2016; **Figure 3-1**). Deep landslides were defined by Burns and Madin (2009) as having a failure surface greater than 15 feet in depth. 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:
    a. susceptible geologic units
    b. susceptible geologic contacts
    c. susceptible slope angles for each engineering geology unit polygon
    d. susceptible direction of movement for each engineering geology unit polygon
4) combining components 1–3 into final susceptibility hazard zones

For each component and factor we made separate 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, commonly, 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 types are more or less prone to landslides. This is generally due to the properties of the rock or soil, such as the material strength or bedding planes.

The second factor, geologic contacts, is something we have noted in Oregon, especially since we began mapping landslide inventories using lidar (Burns and Mickelson, 2016). Many landslides occur along a contact, particularly when sedimentary or volcaniclastic rock is in contact with hard intrusive or volcanic rock. For example, large, deep landslides are located next to each other along the interlayered units of Mehama volcaniclastic rocks and basaltic andesite in the plateau area southeast of Springfield. 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 angle, 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 to include the other three factors (geologic units, geologic contacts, and direction of movement).

Finally, the fourth factor is the direction of movement, which is recorded as an attribute for every landslide in our landslide inventory. 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 in the study area. Therefore we used the recorded direction of movement from the landslide inventory database as a proxy for dip direction or preferred direction of movement, and, where available, we included dip and dip direction measurements from digitized geologic maps (McClaughry and others, 2010).

We added together the four GIS data layers made from the factors to delineate the line between the moderate and low hazard zones (Plate 3). Then we combined the four component GIS layers to create the deep landslide susceptibility map with low, moderate, and high hazard zones.

In this particular study area, we observed several existing deep landslides along the southern valley wall of the McKenzie River (hills southeast of Springfield) whose toes protruded far onto the flat river valley bottom. The landslide "runout," or distance traveled from head scarp to final depositional zone, varies for different landslides, and some landslides exhibit long runouts that exceed the expected length of movement.

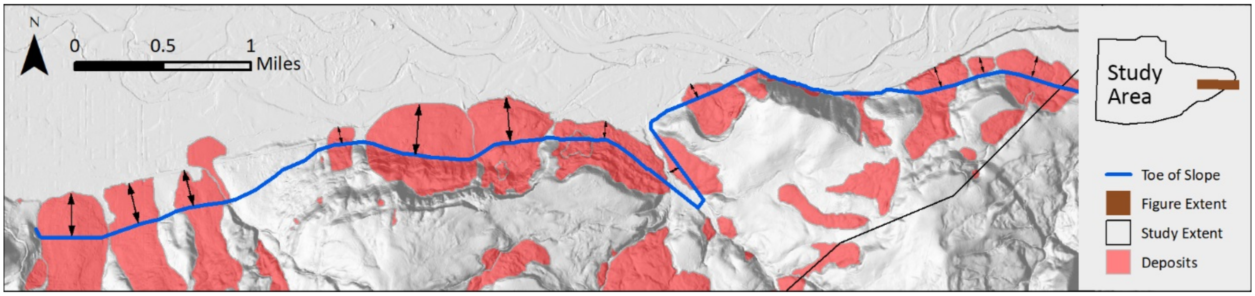
During landslide inventory mapping, we observed landslides that reached beyond the toe of the slope in the hills southeast of Springfield. This area more than any other in the study area exhibited many deep landslides along a relatively uniform slope with similar underlying geology and orientation. Using a simple method, we wanted to capture the area along similar, nearby slopes beyond the toe of slope that a landslide may be able to reach, based on what has occurred sometime in the past. We incorporated a mean runout length and added this area to the moderate deep landslide hazard zone.

In the hills to the southeast of Springfield (seen in study area inset map in **Figure 3-2**A), 13 deep landslides descend from the plateau onto the McKenzie River Valley. For each landslide, a polyline was drawn, estimating the toe of the slope, extrapolated beneath the landslide deposits, as shown in **Figure 3-2**A. The closest upslope bedrock slope angle was projected onto the river valley below, approximating where the toe of the slope might be without landslide or other surficial deposits obscuring the base of the slope. This was approximated along the north side of the plateau, beneath interbedded volcanic and volcaniclastic units forming distinct benches above the river plain. Unfortunately, recent precise geologic mapping is unavailable for the majority of this area of the study.

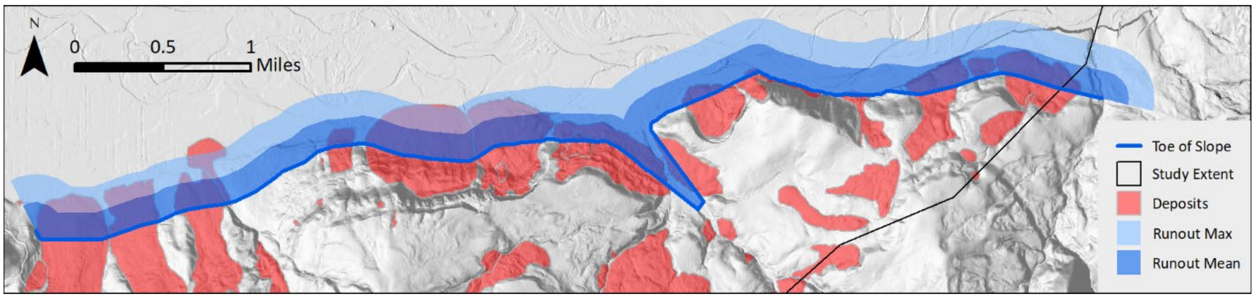
From this polyline, we measured the distance to the furthest extent of the landslide deposit (**Figure 3-2**A). We calculated the mean from these thirteen local landslides with varying runout distances, and found the mean runout of the landslide from the toe of the slope was 815 ft. We then buffered the polyline with this length (**Figure 3-2**B). This polygon was included in the moderate zone, extending the moderate hazard zone to include where landslides with extended runouts may occur. In instances along this valley-wall, existing landslide deposits extend farther than the mean runout distance, and the existing high and moderate hazard zones supersede this additional moderate zone factor (**Figure 3-2**C, D).

Figure 3-2. Method for determining mean runout along the southern wall of the McKenzie River valley.

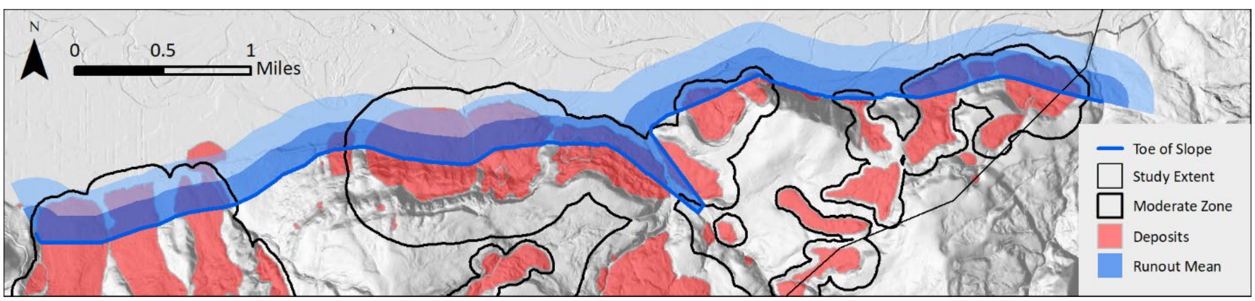
(A) Toe of slope in blue; horizontal runout length measurements shown via arrows, representing runout. Inset map depicting subset of study area for which this exercise was completed.



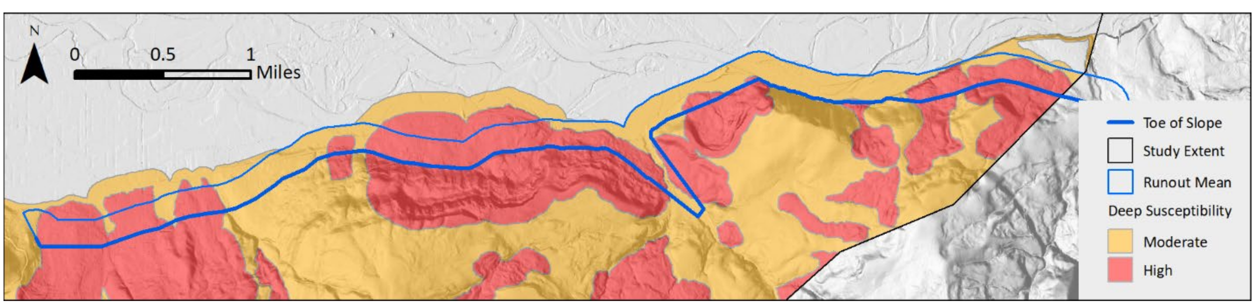
(B) Toe of slope line, with runout mean and runout max zones.



(C) Runout mean zone delineated and deep landslide deposits shown with a minimal moderate buffer, based on their head scarp heights (SP-48).



(D) Deep landslide susceptibility shown, with mean runout incorporated into the moderate zone.



Runout of landslides is not a well-constrained metric for deep landslides, and there are many different methods to map landslide runout, without scientific consensus. Coe and others (2016) pointed out the difficulty of inferring landslide velocity from existing landslide deposits. Long runout of landslides can be difficult to predict. We encourage more work on landslide runout that can be used for hazard mapping in the future.

3.2 Asset Data Compilation and Creation Methods

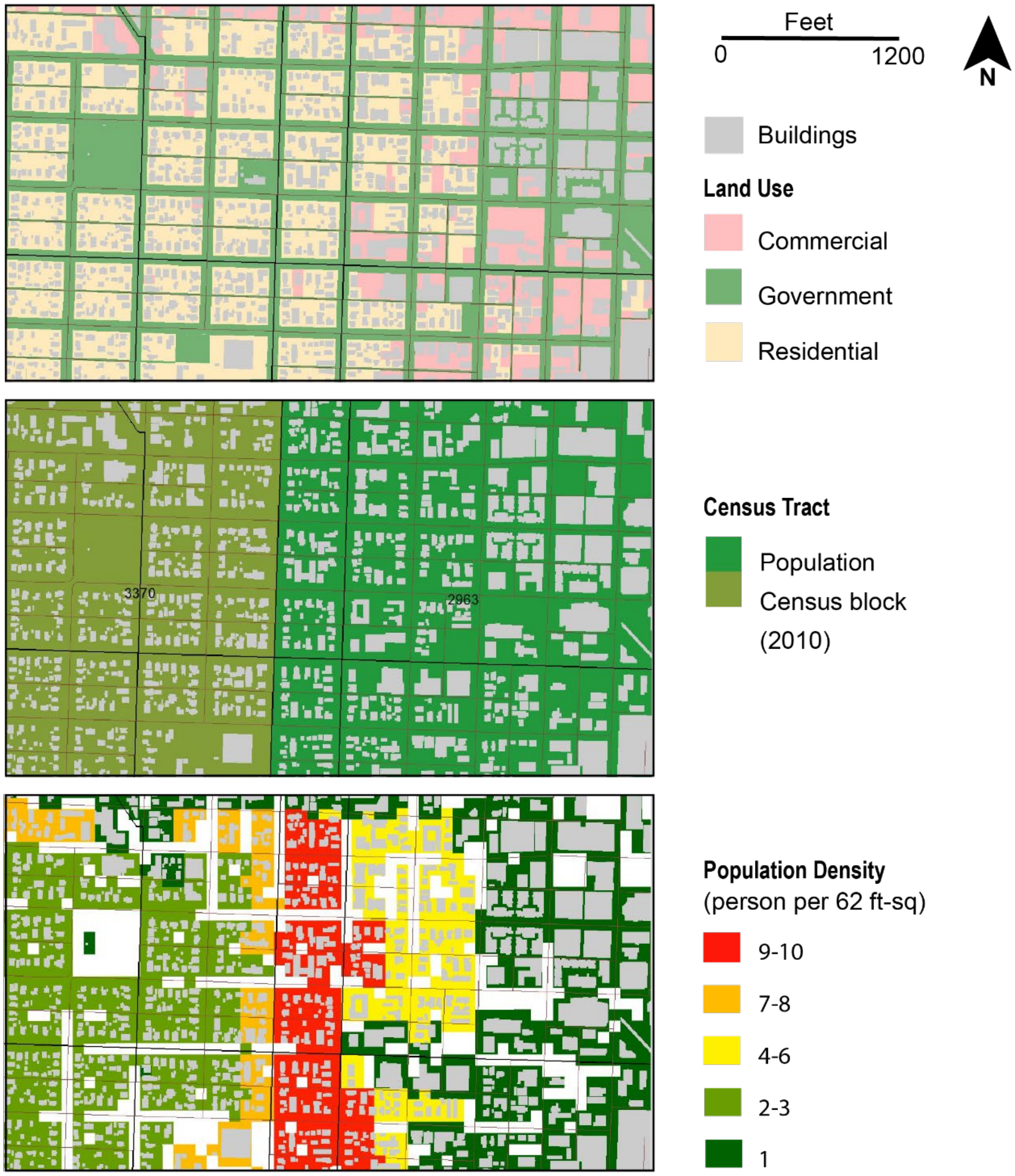
Next, we compiled and created asset datasets that included permanent population distribution, buildings and land, critical facilities, and roads. These asset datasets along with the SP-42 inventory and shallow and deep landslide susceptibility datasets were overlaid to evaluate exposure of the assets to the landslide hazard. We followed the same general methods to create and perform exposure outlined by Burns and others (2018) in Multnomah County.

3.2.1 Permanent population distribution dataset

Permanent population (resident) figures are needed to estimate accurately losses from disasters. However, it is challenging to map this asset because people tend to travel on yearly, seasonal, monthly, daily, and hourly bases.

In the study area, U.S. Census population data are organized in spatial units called census block-groups. Block-groups are statistical divisions of census tracts and generally contain between 600 and 3,000 people. Blocks can be as small as 125 acres (50 hectares) and are typically bounded by streets, roads, or creeks. In urban areas census blocks are small, usually defined by one city block, while in rural areas with fewer roads, blocks are larger and can be bound by other geographic and geomorphic features. Within each block-group the census provides no information on the spatial distribution of population. The census provides only one population number per block-group (**Figure 3-3**). To estimate the size and distribution of permanent population for most of the study area, we used the dasymetric mapping method developed by the U.S. Geological Survey (Sleeter and Gould, 2007). Dasymetric mapping is a process that allocates population data to residential units. Datasets like land cover and census data are used in the dasymetric process to map more precisely the population over an area. To assess and geographically distribute permanent population within the study area, we created a dasymetric population grid with 62 ft^2 cells. In order to make improvements to the population distribution we also used tax lots, which differentiate lots that generally have people living on them from those that do not, such as residential versus industrial. We also used building footprints to determine the likely locations of people within those tax lots designated as residential (**Figure 3-3**).

Figure 3-3. Dasymetric population distribution map input data and result examples from within the City of Eugene.



3.2.2 Buildings and land

DOGAMI acquired and edited previously digitized building footprints from LCOG, the Lane Council of Governments. Parts of the study area were not covered by the LCOG data, so DOGAMI staff digitized the buildings in those areas. To do this, we converted digital elevation models (DEMs, derived from lidar first returns) to hillshade imagery and used these together with orthophotos to identify building locations.

After we finalized the generalized land-use GIS layer, we transferred the improvement values and generalized land-use categories from the tax lot dataset into the building dataset (see Appendix C for more information).

Zoning refers to the permitted land use designation such as agricultural, industrial, residential, recreational, or other land-use purposes. Zoning data are commonly included in tax lot databases along with land-use designations. Data from tax lot databases also include information about the dollar value of the land and any improvements, such as houses. To evaluate land assets for this project, we combined county and city tax lot databases to create a layer that identifies generalized land use (residential, commercial, or public) information for each piece of property. While creating the generalized tax lot dataset, we noted the lack of dollar value for most public land and therefore recommend all public values be considered underestimates.

We created the generalized tax lot dataset with available property tax code data for Lane County acquired from LCOG. Starting with the generalized zoning dataset, we assigned each tax lot a generalized use of residential, commercial, or public. We classified generalized use classes from the parcel's defined chief zoning and land-use of the property. This methodology potentially introduces errors where the tax code for a parcel might not reflect real infrastructure or use at time of publication. We classified selected property that had no ownership information or property tax code according to occupancy class seen in or estimated from orthophotos. We classified government and education occupancy parcels from existing critical facility datasets. Community (generally jurisdictional) boundaries were manually populated, so that parcel counts were not duplicated during inventory/exposure analysis. In scenarios where parcels crossed multiple community boundaries, we selected the community to which the parcel appeared to be most appropriately associated.

3.2.3 Critical facilities

Critical facilities are typically defined as emergency facilities such as hospitals, fire stations, police stations, and school buildings (FEMA, http://www.fema.gov/national-flood-insurance-program-2/critical-facility). We used the definitions and data created for the DOGAMI Statewide Seismic Needs Assessment (SSNA; Lewis, 2007) to identify the critical facilities. The critical facilities included in this project are schools, police stations, fire stations, and hospitals. We extracted critical facilities as points from the SSNA. These points were buffered into polygons, which were used to complete the exposure analysis.

3.2.4 Roads

We acquired the road data from LCOG. Roads were divided into three categories:

- freeways, highways, and major arterials
- minor arterials and collectors/connectors
- local streets

3.3 Risk Analysis Methods

When landslides affect assets, landslides become natural hazards. Natural hazard risk assessment is the characterization of the overlap of natural hazards and assets. Risk analysis can range from simple to complicated. In this project we selected two types of regional risk analysis: 1) hazard and asset exposure, and 2) Hazus-MH analysis. Hazus-MH is a multi-hazard (MH) analysis program that estimates physical, economic, and social impacts of a disaster (FEMA, 2011). In order to understand better the risk, we also collected historic landslide data for the study area and estimated actual historic losses.

3.3.1 Exposure analysis

A building, or other asset, is considered to be exposed to a hazard if it is located within that particular hazard area. To find which community assets fell in which hazard zones, we performed exposure analysis with Esri ArcGIS software. We determined exposure through a series of spatial and tabular queries between hazards and assets. We then summarized the results by community (**Table 3-2**). Landslide hazard datasets used in the exposure analysis are:

- shallow landslides (inventory polygons; see section 3.1.1)
- deep landslides (inventory polygons; see section 3.1.1)
- debris flow fans (inventory polygons; see section 3.1.1)
- shallow landslide susceptibility (low, moderate, and high – see section 3.1.2)
- deep landslide susceptibility (low, moderate, and high – see section 3.1.3)

Asset data (section 3.2) used in the exposure analysis are:

- population (people per 62 ft^2)
- buildings and land in three generalized use classes: residential, commercial, and public
    - buildings reported by count, count percent of total, and value (dollars)
    - land reported by count, count percent of total, area (square feet and acres), area percent of total, value (dollars)
- critical facilities buildings: fire stations, police stations, hospitals, and school buildings
    - buildings reported by count, count percent of total, and value (dollars)
- roads: freeways, highways, and major arterials — lines
    - report by length (feet and miles), and percent of total

For example, we superimposed the buildings layer for the study area on the deep-landslide inventory layer to determine which buildings are exposed to that type of hazard, as demonstrated in **Figure 3-4**. The result of this analysis is both a map of the community assets exposed to the hazard and a table with the corresponding numbers of community assets exposed (full results in Appendix A).

Figure 3-4. Exposure examples from the study area: generalized land use (left), deep landslide deposit (center), and exposure of assets to a deep landslide (right).

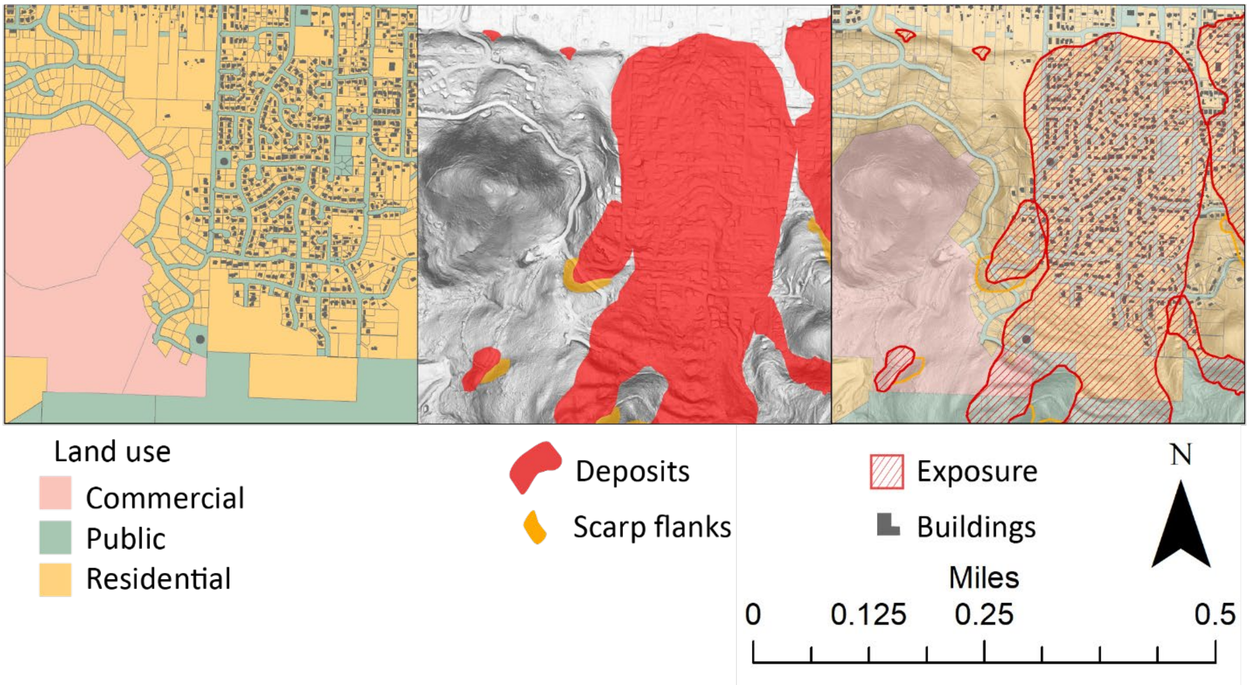


Table 3-2. Communities for exposure reporting. Community extents are shown in Figure 2-2.

Community	**Area (mi^2)**
Lane County	170
City of Springfield (East)	5.5
City of Springfield (West)	10.3
City of Coburg	1.0
City of Eugene neighborhoods	
Eugene North	13.2
Eugene South	15.4
Eugene Southwest	2.5
Eugene West	12.9
City of Eugene (total)	44

3.3.2 Hazus-MH analysis

We performed risk analysis with Hazus-MH, a risk modeling software package developed by FEMA (2011). Hazus requires a specific landslide susceptibility map, which is different than either the shallow or deep landslide susceptibility maps created as part of this project. The Hazus landslide susceptibility map (created for input into the Hazus earthquake module only) follows a specific method outlined in the Hazus technical manual (FEMA, 2011). We created both "dry" and "wet" Hazus landslide susceptibility maps for the study area, in which we used the surficial and bedrock engineering geologic information from **Figure 2-4** and **Figure 2-5** (**Table 3-3**).

Table 3-3. Landslide susceptibility of geologic groups (Hazus-MH 2.0, Table 4-15 [FEMA, 2011])

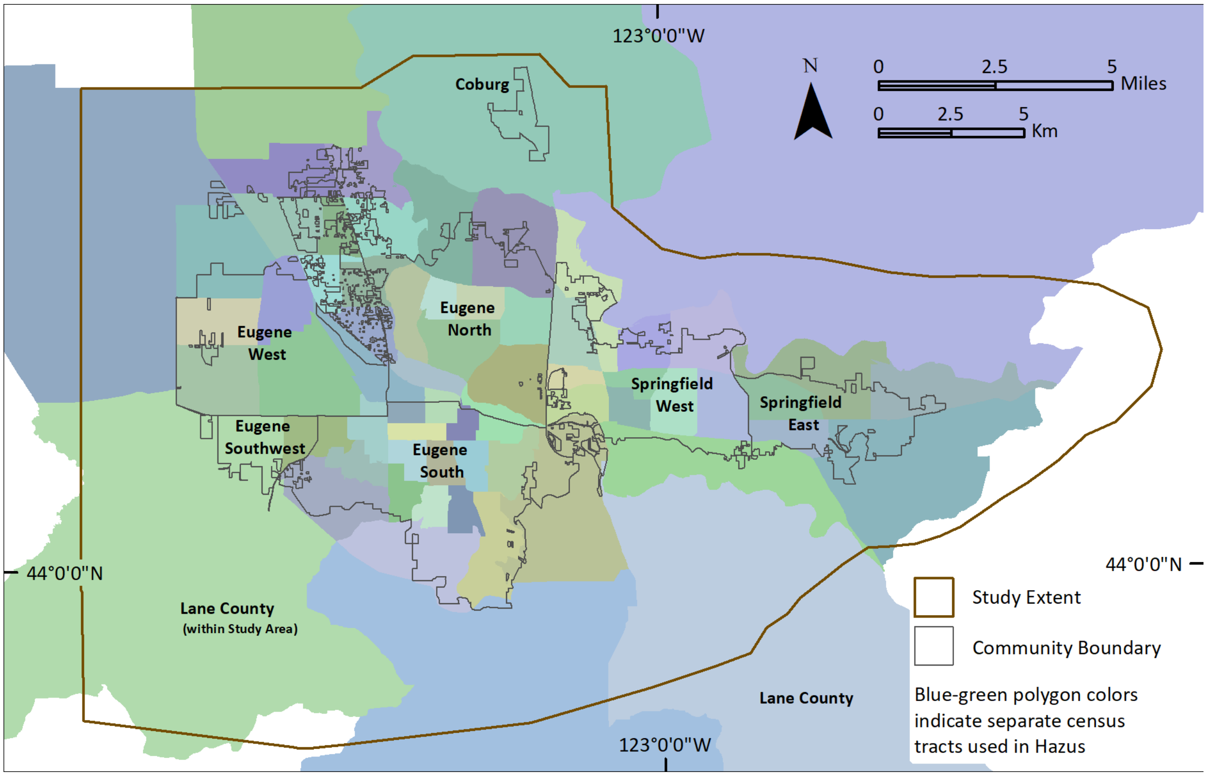
		Slope Angle, degrees					
	Geologic Group	**0–15**	**10–15**	**15–20**	**20–30**	**30–40**	**>40**
	(a) Dry (groundwater below level of sliding)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' = 300 psf, ϕ' = 35°)	none	none	I	II	IV	VI
B	Weakly Cemented Rocks (sandy soils and poorly cemented sandstone, c' = 0, ϕ' = 35°)	none	III	IV	V	VI	VII
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' = 0, ϕ' = 20°)	V	VI	VII	IX	IX	IX
	(b) Wet (groundwater level at ground surface)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' = 300 psf, ϕ' = 35°)	none	III	VI	VII	VIII	VIII
B	Weakly Cemented Rocks (sandy soils and poorly cemented sandstone, c' = 0, ϕ' = 35°)	V	VIII	IX	IX	IX	X
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' = 0, ϕ' = 20°)	VII	IX	X	X	X	X

Hazus software can be used to model a variety of earthquake, flood, and wind probabilistic hazards and/or hazard event scenarios. Although Hazus has limitations, we chose to use Hazus as part of our risk analysis because it is a widely and publicly available risk analysis program with data for the United States.

Default hazard and asset databases are included with the Hazus program. Most data are based on national-scale, general information that does not accurately reflect local conditions. We focused on loss ratios rather than absolute numbers, because we know that absolute numbers can be inaccurate at the local scale. For example, instead of examining the absolute count of buildings at various levels of damage, we looked at the ratio of the estimated damaged buildings to the total buildings in the Hazus database. Although the absolute numbers may be inaccurate, the ratios are very likely in the realistic range and could be applied to the much more accurate local database to obtain a realistic absolute number.

In the Hazus earthquake module, the census tract level is the smallest areal extent allowed for analysis. One limitation of Hazus is that census tract areas can be too coarse for small hazard zones. Although the extent of the 65 tracts is in some places larger than the study area and in some places the tracts are smaller, the chosen analysis extent, when constrained to census tracts, best represents the study area (**Figure 3-5**).

Figure 3-5. Map of the 65 census tracts used in Hazus analysis.



The goal for the Hazus analysis was to estimate damage and losses from two kinds of earthquakes (local crustal and Cascadia Subduction Zone), both with and without earthquake-induced landslides, so that we could examine the difference in damage and losses caused by just the earthquake-induced landslides. We subtracted the earthquake-without-landslides model results from the earthquake-with-landslides model results so that earthquake-induced landslide damage and losses results could be examined separately. We also analyzed landslides in dry and wet conditions (see **Table 3-2**) for each scenario to simulate the differences between an earthquake occurring when it is generally dry (summer) versus when it is generally wet (winter).

For the Cascadia Subduction Zone magnitude 9.0 earthquake scenario, Madin and Burns (2013) obtained synthetic bedrock ground motions from Arthur Frankel (U.S. Geological Survey, written communication, 2012); we used the same bedrock ground motion data for this project. We used the surficial engineering geology map from this study, created for the shallow landslide susceptibility, as the basis to create a seismic site class map, which was used to amplify the bedrock ground motions for the CSZ and the local crustal fault earthquake.

There is no known active mapped local crustal fault within 20 miles of the study area. Consequently, we examined the background seismicity in the U.S. Geological Survey deaggregation report for the Eugene-Springfield area (https://earthquake.usgs.gov/hazards/interactive/) and Burns and others (2008) to select an arbitrary fault with the potential to produce a magnitude 6.5 earthquake. We called this scenario the Arbitrary Eugene Fault.

While performing the Hazus analysis we discovered some software bugs associated with the Lane County data when using the CSZ ground motion input data. Hazus would not accept the tract (building) values we entered, so we were forced to analyze the tract data separately from the rest of the assets in

Hazus. The Hazus global reports provided in Appendix B include both sets of results, and we have obscured in each report the sections that should not be used.

These choices resulted in eight different Hazus analyses (Appendix B):

- M9 Cascadia Subduction Zone
  - No landslides
  - Landslides Dry – Tract results
  - Landslides Dry – Non-Tract results
  - Landslides Wet – Tract results
  - Landslides Wet – Non-Tract results
- M6.5 Arbitrary Eugene Fault
  - No landslides
  - Landslides Dry
  - Landslides Wet

In order to examine the coseismic landslide damage and loss only, we subtracted the "No Landslides" results from the dry and wet landslide results.

3.3.3 Annualized loss

To better understand the landslide risk, we used the historic landslide point inventory in conjunction with previous research related to landslide losses in Oregon (Burns and others, 2017). There are limited records of landslides in this study area, but landslide location points gathered from ODOT, Lane County Public Works, and damage survey reports from FEMA and OEM after the February 1996 storms and associated disasters (FEMA, 1996; Hofmeister, 2000), are recorded as historic landslide points in SLIDO. We identified other landslides by using aerial imagery and records from Lane County Public Works.

Six landslide-associated permits in the City of Eugene records cited landslides as reason for repairs to residential private property. These permits are associated with a known historic landslide in the vicinity. Repairs included foundation repairs, installation of helical piers, or replacing decks. The total cost of stated for work for landslide repairs was $67,500 for six unique landslide events, with a mean of $11,250 per landslide.

We combined these permit data with more data from other parts of Oregon. The best available data, gathered from a recent landslide study for western Multnomah County and the City of Portland (Burns and others, 2018), included dozens of landslides of a range of sizes and amounts of damage. When a permit is required to repair landslide damage, the City of Portland has a record of the monetary damage done to private infrastructure from landslide impact. A compilation of permits for landslide repairs, as well as loss estimates made immediately post-1996 on damage to public entity infrastructure, allowed an average landslide cost to be calculated from both public and private landslide loss data. The range of losses per landslide from these sources is $67,500 to $144,000 (Burns and others, 2017). These are our best available estimates for cost per landslide in the state of Oregon.

Our assumption is that damage from landslides in other places has similar economic loss impacts as calculated in the Burns and others (2017) study. We acknowledge that different landslide types in different geologic units may cause different amounts and types of damage and that differences in housing and property values may cause differences in damage and losses amounts. However, given the limited scope of this project, we were unable to factor in these differences.

A total of 75 landslide points from 1979 to 2016 are included. There may have been landslides in the past 150 years in the area that were not observed or recorded.

4.0 RESULTS

We produced three detailed hazard maps from data collected and analyzed in this study. Plate 1 is a landslide inventory, Plate 2 shows shallow landslide susceptibility, and Plate 3 shows deep landslide susceptibility. We combined the hazard maps with asset data to complete a landslide risk analysis.

4.1 Landslide Inventory Findings

Before the use of lidar to map existing landslides in the study area, 230 landslides areas (polygons) were mapped and included in SLIDO-3.4 (excluding talus/colluvium and fans; Burns and others, 2014). In contrast, the SP-42 inventory (method of Burns and Madin, 2009) created for the current project includes 634 landslides in the study area. The combined surface area of these landslides covers approximately 14.2 square miles (37 square kilometers), or approximately 6 percent of the study area (230.5 square miles; 595 square kilometers; Plate 1). These landslides range in size from 660 square feet (61 square meters) to more than 3 square miles (8 square kilometers). Of the 634 SP-42 inventory landslides, 252 are shallow and 335 are deep. The other 47 landslides are mostly debris flow fans (44) and rock fall talus. Inventories for each community are shown in **Table 4-1**.

The updated historic landslide point inventory contains 75 landslide records from 1979 to 2016. The historic landslide point dataset is displayed on Plate 1, and inventories for each community are shown in **Table 4-1**.

Table 4-1. Summary of landslide inventories for each community.

Community	SP-42 Inventory*	Historic Landslide Point Inventory
Lane County**	575	38
City of Springfield (East)	20	7
City of Springfield (West)	2	4
City of Coburg	0	0
City of Eugene neighborhoods		
Eugene North	1	1
Eugene South	63	24
Eugene Southwest	0	0
Eugene West	0	1
City of Eugene (total)	64	26

*Some landslides overlap community boundaries, so totals will not equal total landslides in study area.

**Unincorporated Lane County included in study.

4.2 Shallow Landslide Susceptibility Findings

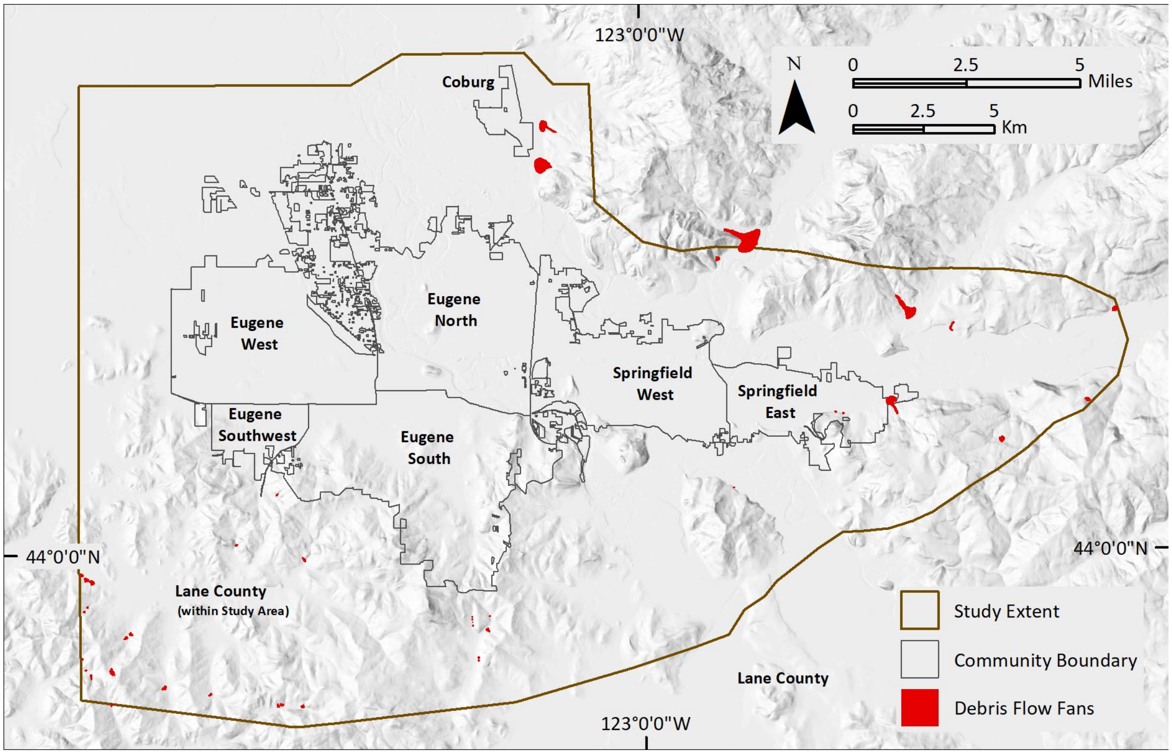
We classified the entire study area into zones of low, moderate, and high susceptibility to shallow landslides. Approximately 68% of the study area is classified as low, 24% as moderate, and 6.9% as high susceptibility (**Table 4-2**; Plate 2). It is important to remember that the shallow landslide susceptibility map can be thought of as a worst-case scenario. We produced the worst-case scenario by setting the groundwater table level to the ground surface throughout the study area. This worst-case scenario would be unlikely to occur everywhere at the same time. However, without better spatial and temporal information about groundwater this is a choice that we were forced to make. We chose a worst-case scenario as the best and most conservative approach. To further examine shallow landslide susceptibility, we examined the study area by the community (**Table 4-2**).

Table 4-2. Summary of shallow landslide susceptibility by community.

	Percentage by Zone		
Community	**Low**	**Moderate**	**High**
Lane County	65%	27%	8%
City of Springfield (East)	76%	18%	5%
City of Springfield (West)	89%	9%	2%
City of Coburg	93%	6%	0.7%
City of Eugene neighborhoods			
Eugene North	87%	10%	2%
Eugene South	63%	29%	7%
Eugene Southwest	88%	10%	1%
Eugene West	93%	5.6%	0.9%
City of Eugene (total)	77%	18%	4%
Total study area	68%	24%	6.9%

Although we did not model susceptibility to channelized debris flow transport and deposition, we did map 44 existing debris flow fans as part of the landslide inventory (**Figure 4-1**). Areas identified as highly susceptible to shallow landsliding are the most likely areas for initiation of debris flows (Plates 1 and 2). A possible method to identify whether or not a particular drainage is susceptible to debris flows is the presence of a fan at the mouth of the drainage developed by past debris flow events. The fan is usually formed by a sequence of debris flows depositing material where channel gradient is reduced and channel confinement is lost.

Figure 4-1. Map of channelized debris flow fans in the study area.



4.3 Deep Landslide Susceptibility Findings

We classified the entire study area into areas of low, moderate, and high susceptibility to deep landslides. Approximately 70% of the study area is classified as low, 23% as moderate, and 7% as high (**Table 4-3**; Plate 3). As previously mentioned, we noted that some historic deep landslides occurred within existing prehistoric landslides. It is important to remember that the susceptibility map is a conservative approach that can be thought of as a worst-case scenario. This is because we included all deep landslides that have been mapped in the high susceptibility zone. However, we do not expect all deep landslides to be active at the same time throughout the study area. 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 communities (**Table 4-3**).

Table 4-3. Summary of deep landslide susceptibility by community.

	Percentage by Zone		
Community	**Low**	**Moderate**	**High**
Lane County	64%	27%	9%
City of Springfield (East)	80%	10%	9%
City of Springfield (West)	98%	1.3%	0.3%
City of Coburg	100%	0%	0%
City of Eugene Neighborhoods			
Eugene North	100%	0%	0%
Eugene South	68%	27%	5.7%
Eugene Southwest	100%	0%	0%
Eugene West	100%	0%	0%
City of Eugene (total)	85%	12.5%	3%
Total study area	70%	23%	7%

4.4 Risk Analysis and Loss Estimation Results

We performed two types of risk analysis: 1) hazard and asset exposure and 2) Hazus earthquake-triggered landslide risk analysis.

4.4.1 Exposure analysis results

We performed hazard and community asset exposure analysis on the nine hazard datasets/zones:

- shallow landslides (inventory polygons),
- deep landslides (inventory polygons),
- debris flow fans (inventory polygons),
- shallow landslide susceptibility (low, moderate, and high), and
- deep landslide susceptibility (low, moderate, and high)

and five asset datasets:

- buildings,
- land,
- transportation,
- critical facilities, and
- permanent population.

Tables showing the results of this analysis are provided in Appendix A.

As noted previously, while performing the exposure analysis we noticed the significant lack of dollar values for public land in the tax lot data. Therefore, for public land we consider the exposure analysis values as minimum values.

Table 4-4 is a summary of the exposure of select assets to the three landslide types. We found that about 4,600 people and approximately $1.13B in land and buildings are located on existing landslides.

Table 4-4. Summary of the exposure of select assets to three existing landslide types.

Landslide Type	Permanent Population	Buildings	Building Value	Land Parcels	Land Value	Roads (Miles)	Critical Facilities
Shallow landslides	33	31	$4.43M	316	$114M	0.37	0
Deep landslides	4,506	2,592	$476M	3,250	$493M	41.25	0
Debris flow fans	76	64	$9.40M	132	$30.3M	1.31	0

Table 4-5 is a summary of exposure of select assets to the six landslide susceptibility classes from the deep and shallow susceptibility maps. We found approximately $5.1B in land and buildings are located in the combined shallow and deep high susceptibility zones. More than 4,600 people live in the shallow landslide high susceptibility hazard zone, and more than 5,200 people live in the deep landslide high susceptibility zone.

Table 4-5. Summary of exposure of select assets to shallow and deep landslide susceptibility zones.

Susceptibility Class	Permanent Population	Buildings	Building Value	Land Parcels	Land Value	Roads (Miles)	Critical Facilities
			Shallow Landslide Susceptibility				
Low	220,560	100,246	$16,300M	83,430	$9,540M	1,218	84
Moderate	31,068	15,080	$3,880M	28,752	$1,740M	357	12
High	4,649	8,350	$4,560M	23,342	$361M	7	22
			Deep Landslide Susceptibility				
Low	231,433	111,213	$22,240M	76,888	$10,215M	1,350	117
Moderate	19,613	9,474	$1,925M	10,915	$1,122M	184	1
High	5,232	2,989	$561M	3,694	$308M	48	0

The amount of damage is concentrated in a few neighborhoods in the study area, as is clear from results in Appendix A. The damage from landslides is focused predominantly in Eugene South and Lane County communities, which are also the two largest communities by area. The unincorporated Lane County community makes up 74% of the total study area, some of which includes steep terrain with relatively weak rocks. Over 35% of Lane County is in the moderate to high susceptibility zones for both deep and shallow landslides, equaling 38,500 acres, the most of the communities included. Eugene South has a similar proportion of its area located in moderate to high susceptibility zones. Lane County also is the least densely populated of the communities, so has an associated 4,500 people living in moderate to high susceptibility zones, while Eugene South has between 18,000 and 20,000 people living in moderate to high susceptibility zones. Springfield East has the highest proportion of its buildings and land in the deep landslide high susceptibility zone (9% for each).

Several of the communities in this report have little to no exposure to existing landslides and have almost no land in the deep or shallow susceptibility zones. The communities of Eugene Southwest, Eugene West, Springfield West, Eugene North, and Coburg all have 0–10 cumulative percent of buildings exposed to any landslide hazard class, including existing landslides and moderate to high susceptibility zones, for both shallow and deep landslide susceptibility models.

4.4.2 Hazus analysis results

To examine the estimated damage and losses from future landslides triggered by an earthquake, we performed three different Hazus analyses on each of two earthquake scenarios (Appendix B):

Crustal M6.5 earthquake scenario: Arbitrary Eugene Fault

- No landslides
- Dry scenario landslides
- Wet scenario landslides

Subduction Zone M9.0 earthquake scenario: Cascadia Fault

- No landslides
- Dry scenario landslides
- Wet scenario landslides

These two scenarios were selected because the crustal M6.5 Arbitrary Eugene Fault earthquake represents a less likely but worst-case scenario and the M9.0 Cascadia Subduction Zone earthquake represents the more likely but less damaging scenario.

Hazus reports for each of the six analyses are provided in Appendix B. The results show that in a subduction zone event the earthquake-induced landslide hazard alone would result in economic loss to buildings of approximately $89.7M and in a local crustal earthquake approximately $454M. Hazus estimates a total replacement value for buildings at approximately $29B for both scenarios, which is more than the taxable improvements (building) value of $24.8B we derived from tax lot data (Appendix A). The reason for the difference in total building value between our database and the Hazus database is unclear and points to the need to update the Hazus general building stock inventory data with more accurate local data in future earthquake risk analysis studies. Another difference, in particular, between exposure results and Hazus results is apparent in the town of Coburg. There is little to no exposure calculated for Coburg's assets; however, due to the nature of the census tracts, the tract in which Coburg is situated has landslide deposits outside of the study area and town limits that are included in the Hazus results.

Total economic loss values are likely either over- or underestimates due to the low quality of the standard Hazus asset data, especially the critical facilities and infrastructure data. However, loss ratios are likely to be better estimates than the absolute numbers.

The analysis estimates damage by landslides alone triggered in a Cascadia or crustal earthquake will result in an estimated 2,770 buildings being moderately to completely damaged and more than 580 residents needing shelter (Appendix B). In Lane County, the loss ratio increased from 8% to 10% when landslides in a "wet" condition are used in the scenario. Overall, 1.5% of the damage of a Cascadia earthquake comes from landslides in the study area.

As can be seen in **Table 4-6**, Springfield East has 20% of total losses from a Cascadia-Subduction Zone earthquake damage occurring from landslides. Eugene South also has a high dollar value associated with coseismic landslide damage, with $34M worth of building damage estimated.

For the modeled damage for Cascadia – With Dry Landslides scenario, there was no additional damage compared to Cascadia – With No Landslides scenario. The ground motions from the Cascadia Subduction Zone earthquake alone did not overcome the Hazus-defined slope failure threshold within dry conditions. However, within wet ground conditions (Cascadia – With Landslides (Wet)), while ground motions were the same, slope failure was modeled to occur.

Table 4-6. Summary of Hazus analysis results for the Cascadia Subduction Zone M9.0 earthquake scenario: building dollar values only. Other results are included in Appendix B.

		Building Losses							
	Total Building Value ($)	Cascadia—No Landslide Loss ($)	Cascadia—No Landslide Loss Ratio (%)	Cascadia with Landslide (Dry) Loss ($)	Cascadia with Landslide (Dry) Loss Ratio (%)	Cascadia with Landslide (Wet) Loss ($)	Cascadia with Landslide (Wet) Loss Ratio (%)	Landslide (Wet) Only* Difference in Losses ($)	Percent of Total Losses from Landslides
Coburg	$870M	$137M	16%	$137M	16%	$137M	16%	$0M	0%
Lane County	$4,990M	$421M	8%	$421M	10%	$516M	10%	$95M	1.5%
Springfield East	$2,357M	$163M	7%	$163	7%	$204M	9%	$41M	20%
Springfield West	$6,798M	$583M	9%	$583M	9%	$583M	9%	$0	0%
City of Eugene Neighborhoods									
Eugene North	$9,030M	$1,329M	15%	$1,329M	15%	$1,329M	15%	$0	0%
Eugene South	$13,760M	$1,998M	14%	$1,998M	14%	$2,032M	15%	$34.4M	1.7%
Eugene Southwest	$847M	$96M	11%	$96M	11%	$99M	12%	$2.77M	3%
Eugene West	$9,132M	$1,204M	13%	$1,204M	13%	$1,208M	13%	$3.79M	0%
City of Eugene total	$32,769M	$4,627M	14%	$4,627M	14%	$4,668M	14%	$40.9M	<1%
Total study area	$47,787M	$5,931M	12%	$5,931M	12%	$6,108M	13%	$177M	1.5%

* "Landslides (Wet) Only" is the difference between "Cascadia – No Landslide" and "Cascadia Landslide Wet" values.

4.5 Annualized Loss Results

On the basis of historical data, one to three landslides occur per year on average in the study area. Stormy, wet, or otherwise extreme landslide years, such as the 1996 winter, can cause hundreds of landslides and millions of dollars' worth of damage (Wang and others, 2002). The number of landslides multiplied by the average loss estimates provides a preliminary estimate of losses per year. In a previous study, Burns and others (2017, Table 4), found from exposure analysis for the City of Portland an average cost of $99,000 per landslide based on building permits, $144,000 exposed on private property per landslide, and $102,500 public property exposed per landslide. Although landslides in the Eugene-Springfield metro area may differ in type, style, and amount of damage as compared to landslides that have caused damage in the City of Portland, the Portland loss data are the best available and can be useful for landslide loss estimates in the Eugene-Springfield area.

A total of 75 landslide points from 1979 to 2016 are included in this study's historic landslide points. There may have been earlier historic landslides in the area; however, they were not recorded or were not recorded in a way that we were able to find. There are very few landslide records before 1996. From the years 1996 to 2016, there were 54 landslides; there are 15 landslides with unknown or undetermined years of occurrence and 6 records prior to 1995. Therefore, there are approximately 2-3 landslides per year on average, in the past 20 years; however, 37 of these 75 historic landslide points occurred in the record-setting rainy years of 1996 and 1997 winter. Omitting an extreme landslide occurrence year from the mean, there is approximately 1 landslide per typical year, although 37 were recorded in an exceptionally rainy year.

Therefore, based on the best available data the range of losses from landslides in a typical year is $99,000 to $306,000. The range of losses in an exceptional year, such as 1996, is $3.6M to $5.3M.

5.0 CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

This study was initiated to alert communities in the study area of the need to be prepared for landslides. Although we cannot predict when landslide events will occur or how big they will be, we have provided a detailed understanding of landslide events in the past, the estimated scale of a potential disaster, the areas more or less susceptible to future landslides, and an estimate of what the damage and losses might be. We note that the portion of Oregon included in this study has high average annual precipitation as well as high 24-hour-duration precipitation related to storm events. The area also has a relatively moderate to high seismic hazard. Both high precipitation and large earthquakes are primary triggers for new landslides and the reactivation of existing landslides. Human activities can also trigger landslides. The main purpose of this project was to help communities in the study area become more resilient to landslide hazards by providing detailed, new digital databases locating the landslide hazards as well as community assets and the risk that exists where the two overlap.

A summary of findings includes:

- Lidar-based landslide inventory mapping (Plate 1) using the SP-42 method found 634 landslides, which cover approximately 6% (~14 square miles; 36 square kilometers) of the study area.
- About 4,500 people and land and buildings valued at approximately $1.1B are located on these existing landslides.
- Our new historic landslide point dataset has 75 records with dates ranging from 1979 to 2016 within the study area.
- Annual loss estimates from landslides in the study area are expected to be between $99,000 and $306,000 in a typical year; in extreme years (such as 1996), this increases to $3.6M to $5.3M.
- Almost 5,200 people live in the deep landslide high susceptibility zone and approximately 4,600 live in the shallow landslide high susceptibility zone.

Most of the existing historic landslide points are within both the deep and shallow moderate to high landslide susceptibility zones (Plate 3). Although we did not create a channelized debris flow susceptibility map, the combination of the shallow susceptibility map and the landslide inventory map showing debris flow fans could be used to identify where these types of landslides might initiate and where they might deposit. In addition, DOGAMI Interpretive Map 22 (Hofmeister and others, 2002) could be used with these other datasets to evaluate potential channelized debris flow hazards. In many cases, debris flow fan areas have the potential for life safety risk, and therefore we recommend extra caution is taken in these areas.

The main reason for the landslide hazard in the current study area appears to be the high relief and steep topography combined with susceptible geologic units and contacts in the northeast and southeast of the study area. The interpreted Mohawk River caldera rim northeast of the City of Eugene contains many large, deep landslides, many along contacts within the volcanic units. There are many more mapped to the north beyond this study area by McClaughry and others (2010), indicating there are widespread landslides within the Mohawk volcanic series.

An area only partly included in the McClaughry and others (2010) geologic study is the plateau southeast of Springfield. This area has susceptible geologic contacts and units, and nearby unfailed slopes with similar slope angles and direction of previous deep failures. There are 33 deep landslides with similar slope, direction, and underlying geology along the south wall of the McKenzie River valley. Within this area, we chose to add an extra deep landslide susceptibility buffer factor to accommodate the runout length typified by these 33 deep landslides. However, on the north side of this valley there are fewer and smaller deep landslides, though with similar geological makeup. This difference is likely due to underlying structural controls, such as dip direction, although we have limited structural geologic data in this particular area.

The other area with widespread moderate to high deep landslide susceptibility is in the South Hills area, south of Eugene. This area is characterized by weathered marine sedimentary and volcaniclastic rocks, with increased landslide susceptibility along contacts. Overall, the majority of the South Hills have a moderate susceptibility, with the existing landslides the likely place for reactivation of deep landslides. Shallow susceptibility, on the other hand, is strongly dictated by slope and strength of geologic material. The South Hills have some susceptibility to shallow landslides; however, susceptibility is concentrated along isolated steep slopes and narrow zones, particularly compared to the far southeast and northern hills with high concentrations of high susceptibility.

Compared to areas covered by previous studies that used the same methodologies, the Eugene-Springfield area as a whole has a low to moderate landslide hazard. This study area has a landslide density, or percent landslide inventory deposit coverage of the total area, of 5.2%, which is less than that of areas covered by previous studies using the same methodologies (**Table 5-1**). Some of these previous studies are centered in mountainous, entirely steep terrain, making a direct comparison to a mean landslide density slightly misleading, as the hazard locally can have a considerable range.

Table 5-1. Landslide density reported from past studies in Oregon.

	Percent Landslide Inventory Deposit Coverage	Relative Overall Hazard Classification Concluded in Report
Astoria (Burns and Mickelson, 2013)	27%	High
North Fork Siuslaw Watershed (Burns and others, 2012)	37%	High
Coastal Curry County (Burns and others, 2014)	25%	High
Bull Run Watershed (Burns and others, 2015)	15%	Moderate to High
Clatskanie (Mickelson and Burns, 2012)	25%	High

The deep landslide susceptibility of the Eugene-Springfield study is comparable to several other studies in Oregon, namely northwestern Clackamas County. The results for this study were also divided into communities, some with no (0%) deep landslide susceptibility, ranging to 8.2% of the areas of a community within the high deep landslide susceptibility. The City of Portland also exhibits a range by community, from 0% of some communities ranging to 14% of a community. Therefore, the Eugene-Springfield study area has a variable but significant deep landslide susceptibility range, comparable to that of northwestern Clackamas County.

We have discussed detailed study results in this report and have provided detailed data in appendices and on GIS-based map plates. Four primary conclusions of the project are:

- Large, deep landslides are a primary threat in the study area, and asset exposure to these landslides is significant. More than 4,500 residents, more than 2,500 buildings, and a combined building and land value of about $950 million are affected.
- 8,350 buildings are located in the high shallow landslide susceptibility zone, with close to $5B worth of land and buildings exposed.

- Annual historic landslide losses range from $99,000-$306,000; in extreme years (such as 1996), this increases to several million.
- Damage and losses from landslides alone, induced by a local crustal or a Cascadia Subduction Zone earthquake, may result in an estimated 2,770 buildings being moderately to completely damaged and close to 600 residents in need of shelter. In most communities, <5% of earthquake damage would come from landslides. However, in some communities, potential landslides triggered by the earthquakes could cause a 20% increase in damage and losses.

These data indicate moderate landslide hazard and risk in the study area. When we examined the hazard and risk at the community scale, we found Lane County, Eugene South, and Springfield East had consistently higher hazard and risk than the other, predominantly low-risk communities. This amount of landslide risk indicates an opportunity for proactive landslide risk management. Landslide risk can be managed in various ways. One way to conceptualize risk management components is illustrated in **Figure 5-1**.

Figure 5-1. Landslide risk management diagram (Y. Wang, written communication, 2010).

We provide the following recommendations to communities in the study area for continued work on landslide risk management. These recommendations are not comprehensive, but they should provide an adequate foundation for many of the risk management phases shown in **Figure 5-1**. The primary actions are related: awareness, regulations, and planning.

5.1 Awareness

Awareness of local hazards is crucial to understanding associated dangers and how to prepare for them. One of the main purposes of this report and maps is to help residents and landowners in the study area become aware of the parts they can play in readiness for hazardous events and risk reduction. Once the hazard is better understood, residents and landowners can work on risk reduction. To increase awareness, we will post this report and the map plates on the DOGAMI website. Helpful flyers can be linked from DOGAMI websites and/or distributed to help educate landowners of activities individuals can initiate to reduce landslide risk. Helpful flyers include the "Homeowners Guide to Landslides" (https://www

.oregongeology.org/Landslide/ger_homeowners_guide_landslides.pdf) and the DOGAMI fact sheet "Landslide Hazards in Oregon" (https://www.oregongeology.org/pubs/fs/landslide-factsheet.pdf).

City, county, neighborhood, and other local community leaders can implement awareness campaigns to educate neighborhoods, businesses, and individual homeowners about the locations of local hazards and how to reduce risk. For example, homeowners unintentionally increase their own risk through discharge of stormwater onto slopes that are susceptible to landslides. Landslides resulting from this type of discharge were observed after the 1996 events (Burns and others, 1998). Just knowing which slopes are susceptible can provide the impetus to switch from unknowingly increasing risk to actively reducing risk through cost-effective methods such as extending stormwater discharge pipes beyond the high hazard zone.

5.2 Warnings

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 and losses from specific hazard events. This was done at a regional scale during this project. Another way to prepare is through the development of a landslide warning system, which would help better understand when these events might happen. Oregon has a general statewide landslide warning system; when the National Weather Service (NWS) initiates warnings, several Oregon state agencies (Oregon Emergency Management [OEM], Oregon Department of Transportation [ODOT], and DOGAMI) disseminate the warnings. The current warning system could be used by the communities in the study area. In the future, a monitoring system that tracks rainfall thresholds at which landslides can be expected to initiate could be developed by monitoring precipitation and resulting slide activity. Knowing when there will be periods of increased landslide potential will help communities prepare, respond, and recover, should landsliding occur. If known very high hazard areas, such as debris flow fans, with the potential for life safety issues are identified, evacuation could be considered, recommended, or required.

5.3 Development and Infrastructure Planning

Planning is an effective method to work on risk reduction and can be initiated in a variety of ways using the maps and data produced in this project. Two types of planning that engage leaders, residents, and landowners in planning are 1) focus on future development, and 2) focus on existing infrastructure.

These new hazard data should be used in long-term planning. The data should also be included in assessments when discussing expansion of urban growth boundaries. Another long-term planning tool is including data from this report in comprehensive plans, which most cities and counties use to identify community goals. Some planning could result in the avoidance of proposed development in high-hazard areas and even public buyouts in very high or life-threatening hazard areas. Additional planning can focus on maintenance of road-related grading, repeated asphalt overlays, or expanding roadways. Keeping specific records of maintenance practices is a good way to track risk reduction effects.

Stormwater runoff routing must be done carefully so that water is not directed onto or into unstable slope areas. Planning of the public stormwater system, for example, should include culvert outlets in order to evaluate any discharge onto highly susceptible zones. Planning could focus on private landowner education and awareness in order to gain landowner partnership in the control of stormwater.

5.4 Regulation

Connecting landslide inventory and susceptibility maps and data to regulations such as development codes and ordinances can be very effective. Such regulations use landslide hazard maps to identify proposed development and grading or other activities that may increase landslide risk in high hazard areas. These regulations typically have requirements to perform site-specific geotechnical analysis and mitigation design. Regulations can also reduce grading-related landslides. For example, relatively shallow grading activities can unintentionally cause slope failures, especially in conditions where existing landslides or slopes in high susceptibility zones may be only marginally stable. Placing debris 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.

5.5 Large Deep Landslide Risk Reduction

Large, deep landslides are commonly harder and more expensive to mitigate because a single deep landslide may affect multiple landowners, including private, city, county, state, and federal landowners. Mitigation may require cooperating effort from public and private entities (generally, city or county and landowners) because the slides can span or even cross entire neighborhoods. This study accomplished parts one (hazard identification) and two (risk assessment) of landslide management illustrated in **Figure 5-1**. The critical next step is number three, engaging stakeholders (**Figure 5-1**). A public awareness campaign could be undertaken to educate homeowners and landowners about the landslide hazard and risk in their areas and prioritize future risk reduction actions. Residents on mapped landslide areas should participate in a neighborhood risk reduction program where all affected entities help reduce the overall risk.

There are many actions to reduce risk on large deep landslides. Risk reduction measures should include these as a minimum:

- Water
    - minimize or eliminate irrigation on landslide
    - intercept and collect surface water above landslide area to reduce natural water infiltration into the landslide
    - collect surface water runoff from within the landslide area from impervious surfaces, for example: roof downspouts, streets, and driveways, and
    - reduce any onsite storm water retention and inflation within the landslide area.
- Grading
    - Avoid grading within the landslide area unless a detailed geotechnical evaluation has been performed including recommendations on how and when to perform grading safely.
- Consult a geotechnical engineer and engineering geologist to conduct a site-specific evaluation to develop further site-specific risk reduction activities.

Some mitigation actions are more affordable and easier to accomplish than others. Large-scale mitigation activities for deep landslides commonly include engineered retaining structures and underground dewatering drainage systems. These activities will need to be prioritized by the community based on funding and acceptable level of risk for the community. A Geologic Hazard Abatement Districts (GHAD) designation may be a useful mechanism to fund and implement some landslide risk reduction actions (Curtin and Zovod, 2005). The report by Curtin and Zovod (2005) is a useful resource to understand GHADs specifically as they relate to landslide risk reduction.

5.6 Emergency Response

Finally, we recommend that neighborhoods and communities create landslide emergency response plans before the next disaster. One component of the plan should include identifying local engineering geologists and geotechnical engineers and establishing working relationships with them so they can be asked to evaluate landslides or areas during and directly after the next disaster. Their evaluations would help determine the immediate actions required following the disaster. For example, they would determine if a neighborhood should be evacuated or if the area is stable enough to perform an emergency response.

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8.0 APPENDICES

Appendices are available as separate documents in the digital file set.

Appendix A. Exposure Analysis Results (Microsoft® Excel® spreadsheet and Adobe® PDF formats)

Appendix B. Hazus Analysis Results (Adobe PDF format)

Eugene Crustal

Crustal M6.5 earthquake scenario: Arbitrary Eugene Fault

- No landslides (M6.5_Arbitrary_Eugene_acrustal2_no_ls.pdf)
- Dry scenario landslides (M6.5_Arbitrary_Eugene_acrustal3_dry_ls.pdf
- Wet scenario landslides (M6.5_Arbitrary_Eugene_acrustal4_wet_ls.pdf)

Subduction Zone M9.0 earthquake scenario: Cascadia Fault

  - No landslides (CSZ_no_ls.pdf)
- Detailed
  - Dry scenario landslides (CSZ_ls_dry_non_tract_Redacted.pdf)
  - Wet scenario landslides (CSZ_ls_wet_non_tract_Redacted.pdf)
- Tract
  - Dry scenario landslides (CSZ_tract_ls_dry_Redacted.pdf)
  - Wet scenario landslides (CSZ_tract_ls_wet_Redacted.pdf)

Appendix C. Building Digitization and Tax Lot Association Methods (Adobe PDF format)