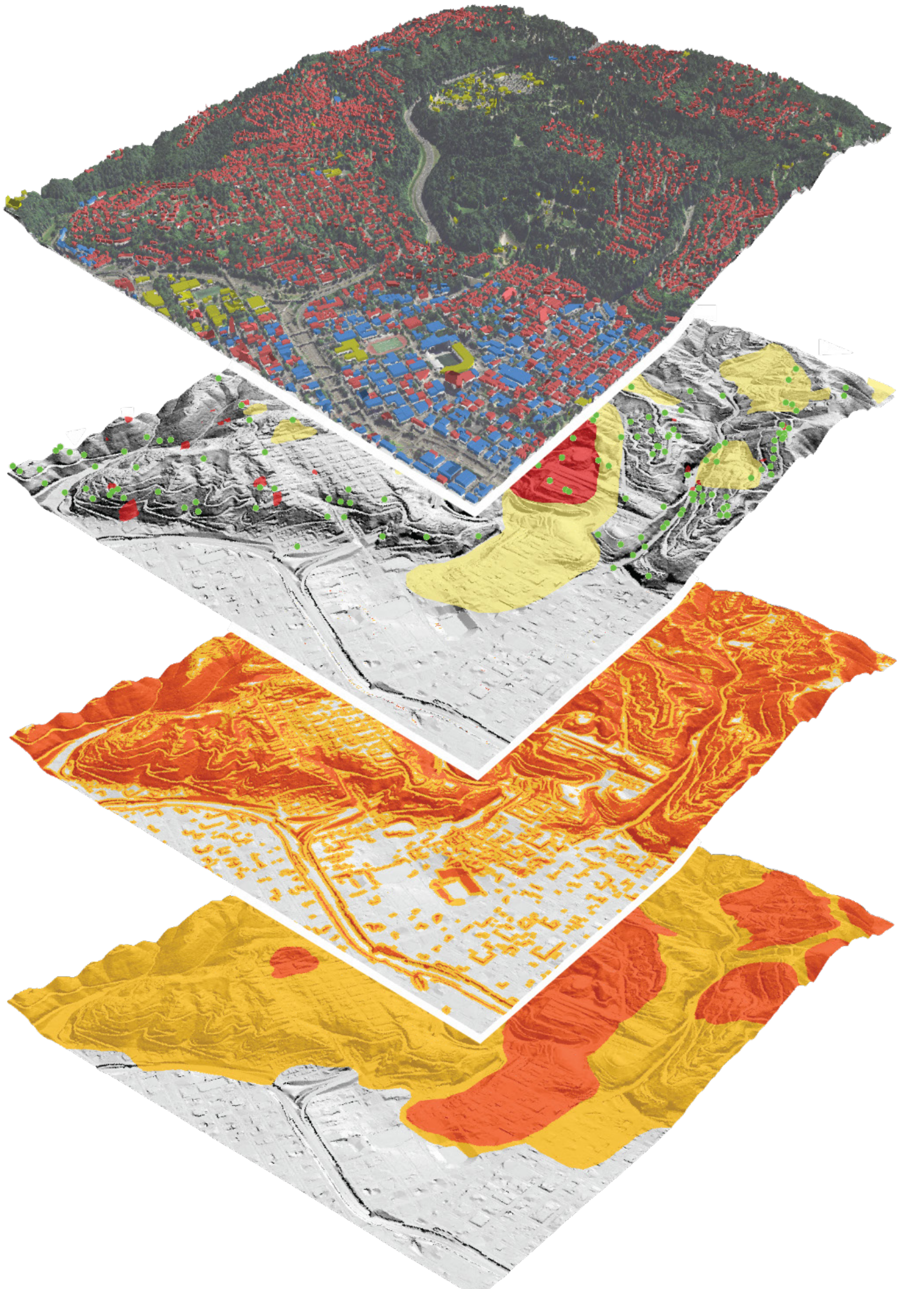
Landslide Hazard and Risk Study

Central and Western Multnomah County, Oregon



Interpretive Map 57

Oregon Department of Geology and Mineral Industries

Cover page: Landslide risk and hazards for a portion of the study area. Layers from top to bottom: Assets (buildings and transportation routes), landslide inventory, shallow landslide susceptibility, and deep landslide susceptibility.

State of Oregon
Oregon Department of Geology and Mineral Industries
Brad Avy, State Geologist

INTERPRETIVE MAP 57

LANDSLIDE HAZARD AND RISK STUDY OF CENTRAL AND WESTERN MULTNOMAH COUNTY, OREGON

by William J. Burns[1], Nancy C. Calhoun[1], Jon J. Franczyk[1], Kassandra O. Lindsey[2], and Lina Ma[1]

2018

[1]Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Suite 965, Portland, OR 97232
[2]Colorado Geological Survey, 1801 19th Street, Golden, CO 80401

DISCLAIMER

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For additional information:
Administrative Offices
800 NE Oregon Street, Suite 965
Portland, OR 97232
Telephone 971-673-1555
http://www.oregongeology.org
http://www.oregon.gov/DOGAMI/

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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.

Multnomah_Landslide_Inventory.gdb:

feature classes:

Deep_LS_Susceptibility (polygons)
Deposits (polygons)
Historic_LS_Points (points)
Scarps (polylines)
Scarps_Flanks (polygons)
Shallow_LS_Susceptiblity (raster)

Metadata in .xml file format:

Deep_LS_Susceptibility.xlsm
Deposits.xlsm
Historic_LS_Points.xlsm
Scarps.xlsm
Scarps_Flanks.xlsm
Shallow_LS_Susceptibility.xlsm

1.0 REPORT SUMMARY

At least 1,700 landslides have occurred within the City of Portland during the last 90 years (1928–2016). Of these landslides, approximately 830 occurred during the severe storms in 1996. From these historical data, we estimate an average of 20 landslides per year in the City of Portland. We estimate annual loss from landslides in the City of Portland ranges from $1.5M (million) to $3M. In years with extreme winter storms, this estimate can increase to approximately $64M to $81M. These historical data are a clear indication of a significant landslide risk and thus the need for continued landslide risk reduction.

In 2014, the Oregon Department of Geology and Mineral Industries (DOGAMI) submitted a grant application to Federal Emergency Management Agency (FEMA) and was granted funding to perform this study. The majority of the work on this project took place during 2015-2016. The purpose of the project was to assist the communities in the study area to better understand the landslide hazard and risk and to continue landslide risk reduction. Deliverables of the study include:

- This report text, appendices, and map plates
- Geographic Information System (GIS) datasets including:
  - landslide inventory—map of locations of landslides that have occurred at some time in the past
  - shallow landslide susceptibility—map of areas prone (low, moderate, high) to future shallow landslides
  - deep landslide susceptibility—map of areas prone (low, moderate, high) to future deep landslides
  - Landside risk analysis

The study area includes the Cities of Portland, Gresham, Fairview, Wood Village, Troutdale, and portions of Multnomah County and covers approximately 300 square miles. The city of Portland is divided into risk reporting areas roughly defined by the nine neighborhood coalitions. Nearly one quarter of the people living in Oregon (~4 million people), live in the study area (~724,000 people). These people live and work in approximately 230,000 buildings worth approximately $75B with an additional $45B in land value.

First, we compiled existing detailed, lidar-based landslide inventories. These data were created and published during 2010–2012 by following the protocol of Burns and Madin (2009). Then, we updated the historical landslide inventory inside the City of Portland with data provided by the City. We created new, generalized bedrock and surficial engineering geology datasets as part of this study as the foundation of new susceptibility maps. The new shallow and deep landslide susceptibility maps are appropriate for use in landslide risk reduction activates such as updates to building codes and evaluation of storm water systems.

We performed two types of risk analysis: 1) hazard and asset exposure, and 2) Hazus® earthquake-triggered landslide risk analysis. We found that approximately $1.65B (billion) in land and buildings and almost 6,700 people are located on existing landslides. Also, 29,000 people live in the high-susceptibility hazard zone for shallow landslides, and nearly 8,000 people live in the high-susceptibility hazard zone for deep landslides in the study area. The second type of risk analysis, with Hazus, a risk modeling software package developed by FEMA, can be used to model a variety of earthquake, flood, and wind probabilistic hazards and/or hazard event scenarios. Because there is no Hazus landslide module, we used the earthquake module with and without earthquake-induced landslide hazards. Then we subtracted the earthquake-without-landslides model from the earthquake-with-landslides model so that the earthquake-induced landslide damage and losses could be examined separately. We found in some communities up to 25% of the modeled damage is from landslides triggered by earthquakes.

Although we cannot predict when the next landslide events will occur or how big they will be, we were able to provide a detailed understanding of landslide events in the past, the estimated scale of a potential disaster, the areas susceptible to future landslides, and an estimate of what the damage and losses might be. All of these data confirm that landslide risk exists in the study area and thus that there is a strong need for continued landslide risk reduction. Landslide risk reduction can be performed in various ways. We provide recommendations and conclusions based on our findings. These recommendations are not comprehensive, but they should provide an adequate foundation for many of the risk management phases. The primary actions are related to awareness, regulations, and planning.

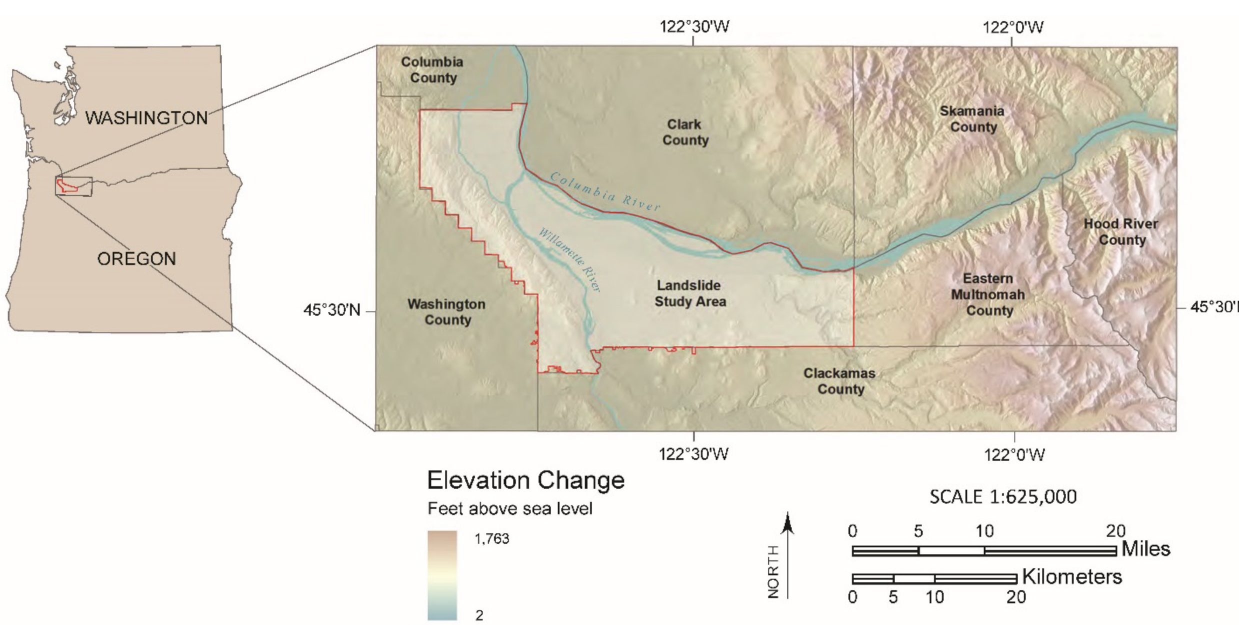
2.0 INTRODUCTION

Portions of central and western Multnomah County, Oregon, have significant landslide hazards (Burns and others, 1998). This region of the state also contains the most developed land in Oregon. The high landslide hazard combined with dense development results in high risk. The assessment of this risk is the primary reason for this study.

2.1 The Study Area

The study area is defined by the Multnomah County boundary with the exception of the eastern one third of the county (**Figure 2-1**).

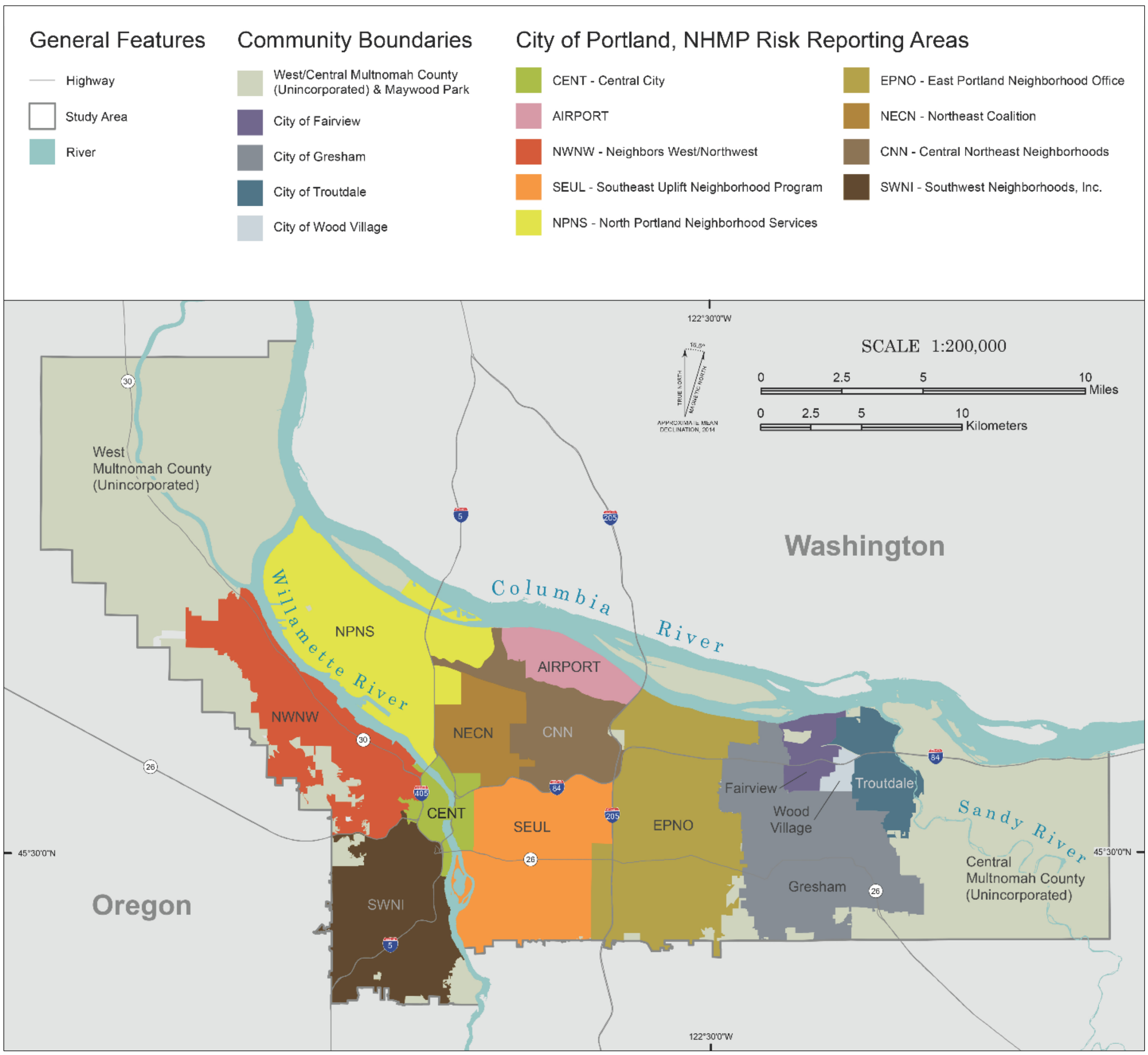
Figure 2-1. Map of the study area.



The study area includes the Cities of Portland, Gresham, Fairview, Wood Village, and Troutdale and covers 300.64 mi^2 (**Figure 2-2**). The City of Portland is divided into risk reporting areas roughly defined by nine neighborhood coalitions as listed in Portland's mitigation action plan (Tetra Tech, 2016); 723,895 people live in the study area (U.S. Census, 2010, https://www.census.gov/2010census/data/).

The Columbia River bounds the study area to the north; the Sandy River approximates the eastern boundary. The Willamette River runs through the study area. The topography is relatively flat except for the Tualatin Mountains (also known as the Portland Hills), locally steep slope-banks along the rivers, the Boring volcanoes (such as Rocky Butte, Powell Butte, and Kelly Butte, Mount Tabor, and Mount Scott), and in the eastern portion of the study area the Columbia River Gorge and the foothills of the Cascade Mountains (Plate 1).

Figure 2-2. Map of risk reporting areas/communities in the study area. NHMP is Natural Hazard Mitigation Plan.



The study area has a West Coast marine climate: 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 40 and 60 in/yr (Spatial Climate Analysis Service, 2000). The region is subjected to small to large magnitude earthquakes from three primary sources: 1) the Cascadia Subduction Zone, 2) intraplate, and 3) crustal.

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:

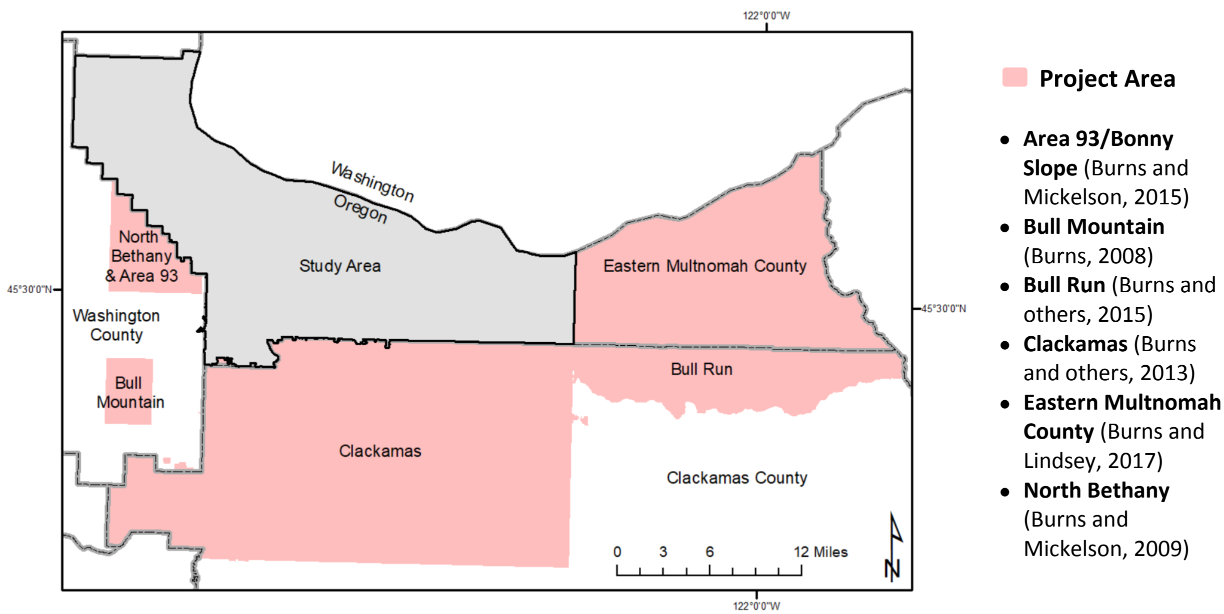
- compile existing data including previous geologic hazard reports and natural hazard mitigation plans
- create new geodatabases of landslide hazards including landslide inventory and susceptibility
- compile or create a database of critical facilities and primary infrastructure, generalized land occupancy (land use/zoning), buildings, and population distribution data
- 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 is defined here as capable of being affected by a specified action or process, and in this report the process is mass wasting by means 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 Landslide Hazard and Risk Projects

Recent landslide hazard projects and, in some cases, risk analysis projects have been completed adjacent to the study area (**Figure 2-3**). This study follows the same methods used for those projects.

Figure 2-3. Recently completed landslide hazard and risk analysis projects (pink areas) near the study area.



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 lithostratigraphical 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 described below. For additional information on the bedrock and surficial geology, see Ma and others (2009, 2012).

The oldest rocks belong to the basalt of Waverly Heights and consist of a sequence of subaerial basaltic lava flows deposited during the Eocene (~40 Ma; Ma and others, 2012; Beeson and others, 1989). Subsequently, sediments of the Scappoose Formation were deposited. The Scappoose Formation consists of marine sandstone, siltstone, and claystone deposited during the Miocene. Next, lava of the Columbia River Basalt Group erupted from vents in eastern Oregon, Washington, and western Idaho, and some lavas of the Wanapum Basalt as well as the Grande Ronde Basalt flowed into the Portland Basin.

On top of the Columbia River Basalt Group is a series of sedimentary deposits including the Springwater Formation and Troutdale/Sandy River Mudstone Formations. Sediments that make up these formations were deposited at the end of the Miocene into the Pleistocene and consist of a range of sedimentary types from volcaniclastic to conglomerate to mudstone (Ma and others, 2012). The rocks are slightly consolidated and generally lack cementation. During approximately the same time period, the Boring Volcanic Field was active in the Portland region (Ma and others, 2012). The lava from the Boring volcanoes is primarily basaltic lava flows but can include scoria and tephra. Many of the Boring deposits are highly weathered, especially near the surface. The weathered material consists of red clay rich soil with relict texture and gravel as well as boulder size weathered basalt corestone pieces.

During the Pleistocene, silt, sand, and gravel were deposited throughout the Portland region by cataclysmic floods (Allen and others, 2009). The Cordilleran ice sheet formed an ice dam along the Clark Fork River, which resulted in the formation of Glacial Lake Missoula. When the ice dam broke, huge floods traveled across eastern Washington, eroding the sediment and carrying it down the Columbia River channel to the Willamette River Valley. This process was repeated at least 40 times, resulting in deposits typically over 200 feet thick. After the floods, eolian silt (loess) was blown onto the Tualatin Mountains and Boring volcanoes. At the same time, large and small rivers in the area were eroding and depositing alluvium.

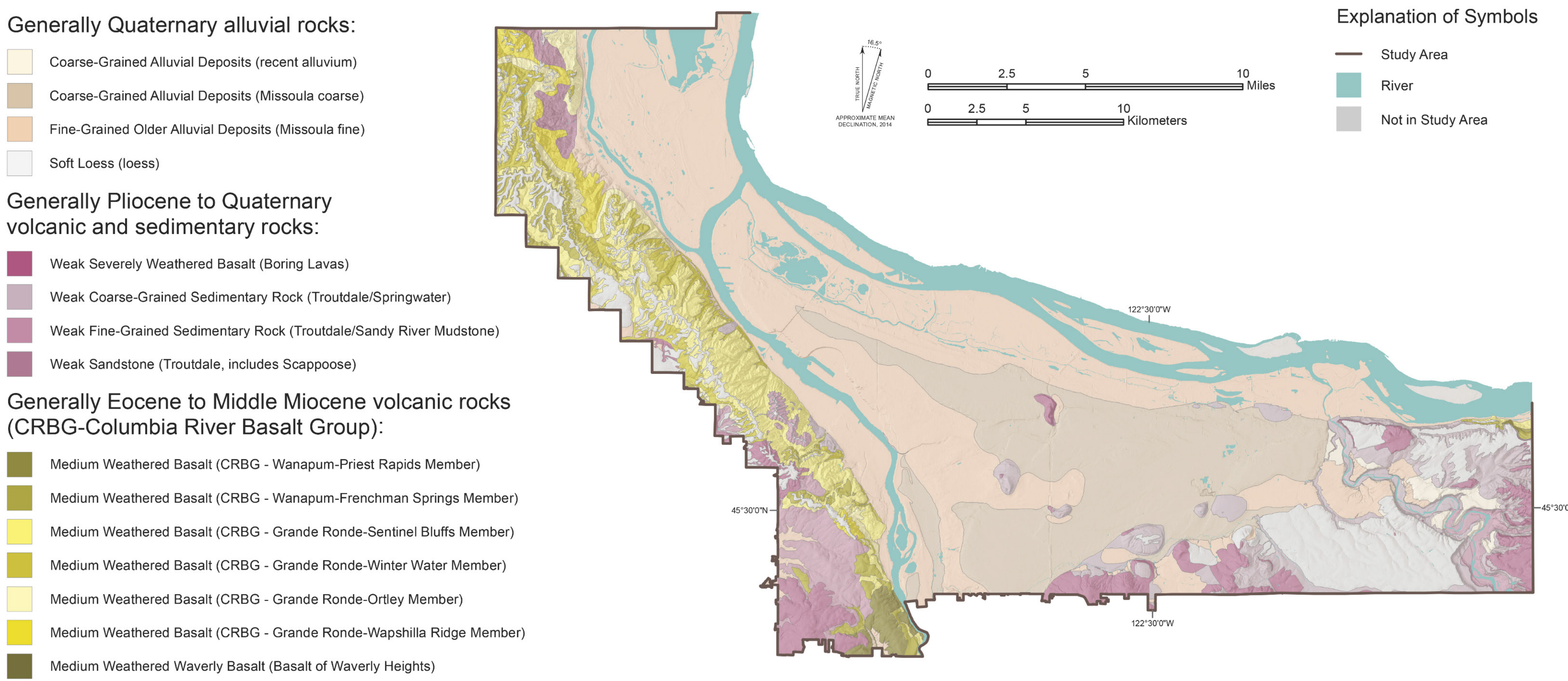
We simplified the geologic units in the study area into 15 bedrock engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 2-4**):

Generally Quaternary alluvial rocks:
Coarse-Grained Alluvial Deposits (recent alluvium)
Coarse-Grained Alluvial Deposits (Missoula coarse)
Fine-Grained Older Alluvial Deposits (Missoula fine)
Soft Loess (loess)

Generally Pliocene to Quaternary volcanic and sedimentary rocks:
Weak Severely Weathered Basalt (Boring Lavas)
Weak Coarse-Grained Sedimentary Rock (Troutdale/Springwater)
Weak Fine-Grained Sedimentary Rock (Troutdale/Sandy River Mudstone)
Weak Sandstone (Troutdale, includes Scappoose)

Generally Eocene to Middle Miocene volcanic rocks (CRBG–Columbia River Basalt Group):
Medium Weathered Basalt (CRBG – Wanapum-Priest Rapids Member)
Medium Weathered Basalt (CRBG – Wanapum-Frenchman Springs Member)
Medium Weathered Basalt (CRBG – Grande Ronde-Sentinel Bluffs Member)
Medium Weathered Basalt (CRBG – Grande Ronde-Winter Water Member)
Medium Weathered Basalt (CRBG – Grande Ronde-Ortley Member)
Medium Weathered Basalt (CRBG – Grande Ronde-Wapshilla Ridge Member)
Medium Weathered Waverly Basalt (Basalt of Waverly Heights)

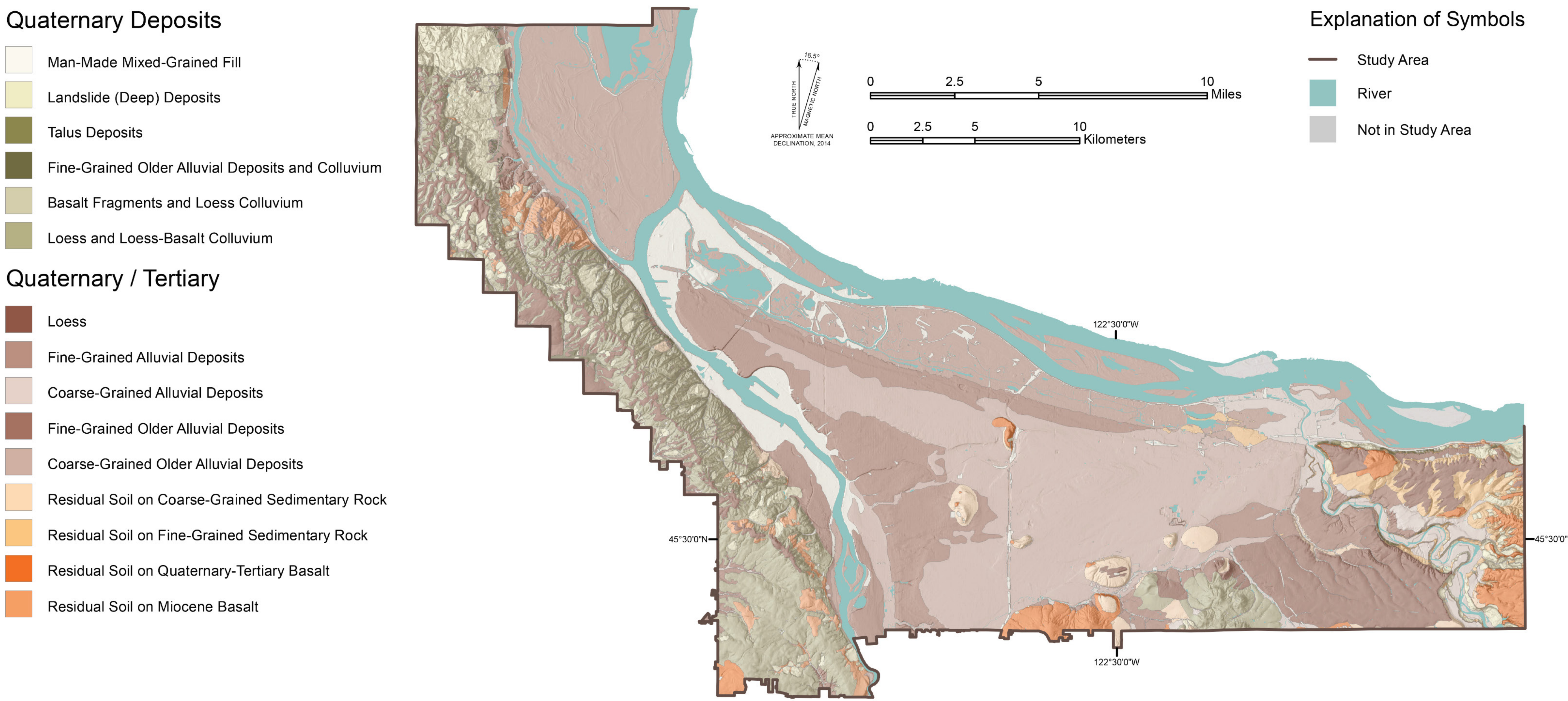
Figure 2-4. Map of generalized bedrock engineering geology in the study area.



We simplified the surficial geologic units in the study area into 15 surficial engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 2-5**). The units are listed below in generally increasing strength (weaker to stronger):

- Man-Made Mixed-Grained Fill
- Landslide (Deep) Deposits
- Talus Deposits
- Fine-Grained Older Alluvial Deposits and Colluvium
- Basalt Fragments and Loess Colluvium
- Loess and Loess-Basalt Colluvium
- Loess
- Fine-Grained Alluvial Deposits
- Coarse-Grained Alluvial Deposits
- Fine-Grained Older Alluvial Deposits
- Coarse-Grained Older Alluvial Deposits
- Residual Soil on Coarse-Grained Sedimentary Rock
- Residual Soil on Fine-Grained Sedimentary Rock
- Residual Soil on Quaternary-Tertiary Basalt
- Residual Soil on Miocene Basalt

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



2.5 Landslides

The Federal Emergency Management Agency (FEMA) issued 32 major disaster declarations for Oregon during the period 1953–2016 (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 frequently included landslides. During this time, at least seven Presidential Disaster Declarations for Multnomah County noted landslides as part of the reason for the declaration (FEMA Disaster Declarations Summary [Excel spreadsheet], accessed via https://www.fema.gov/media-library/assets/documents/28318):

- 1964 – FEMA DR-184, Oregon Heavy Rains and Flooding
- 1996 – FEMA DR-1099, Oregon Severe Storms/Flooding
- 2004 – FEMA DR-1510, Oregon Severe Winter Storms
- 2006 – FEMA DR-1632, Oregon Severe Storms, Flooding, Landslides, and Mudslides
- 2009 – FEMA DR-1824, Oregon Severe Winter Storm, Record and Near Record Snow, Landslides, and Mudslides
- 2011 – FEMA DR-1956, Oregon Severe Winter Storm, Flooding, Mudslides, Landslides, and Debris Flows
- 2016 – FEMA DR-4258, Oregon Severe Winter Storms, Straight-line Winds, 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 into areas with relatively higher landslide hazards.

There are many historic (<150 years ago) and prehistoric (>150 years ago) landslides in the study area, which increase the current landslide risk. In 2012, DOGAMI finished mapping the existing landslides following the method outlined by Burns and Madin (2009). There are 1,996 landslides, which cover 8% of the study area (Plate 1). There are 820 shallow and 781 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.

There are several well-known large deep landslides in the City of Portland including the Zoo Landslide (also known as the Ancient Highlands Landslide) and the Washington Park Landslide. The Oregon Zoo and the residential neighborhood to the west are located on the Zoo Landslide (Hammond and Vessely, 1998). Portions of this extensive prehistoric landslide have been reactivated during construction on Highway 26 in the 1950s and 1960s. In 1998, TriMet (the Oregon Tri-County Metropolitan mass transit operator) installed an elevator shaft through the Zoo Landslide to the light rail tunnel below (https://trimet.org/pdfs/history/railfactsheet-westside.pdf). A complex dewatering system was installed to reduce the likelihood of the Zoo Landslide from moving in the future and damaging the transportation system. The Washington Park Landslide (sometimes referred to as the Phenomenal Landslide) is located adjacent and west of the northwestern portion of downtown Portland (Clark, 1904). In the 1890s, the City of Portland constructed two drinking water reservoirs in Washington Park, which caused a portion of an existing landslide to reactivate (Cornforth, 2005). The landslide is described in detail by Clark (1904). The new lidar-based mapping revealed the extent of the original pre-historic landslide, which encompasses the historic Washington Park Landslide (Plate 1). In 1993, the M5.6 Scotts Mills Earthquake shook the region. This shaking caused the Washington Park Landslide to make a jump in the rate of movement

(Cornforth, 2005). Both landslides are examples of historic reactivation of a deep landslide within an older prehistoric landslide complex.

There are several well-known large deep landslides outside of the City of Portland but within the study area. These include the Wildwood and the Dutch Canyon Landslide Complexes in the northwestern portion of Multnomah County (Plate 1; Madin and Niewendorp, 2008). In the eastern portion of the study area, there are numerous large deep landslides along the Sandy River, especially where the weak sedimentary rocks of the Troutdale Formation crop out on the surface.

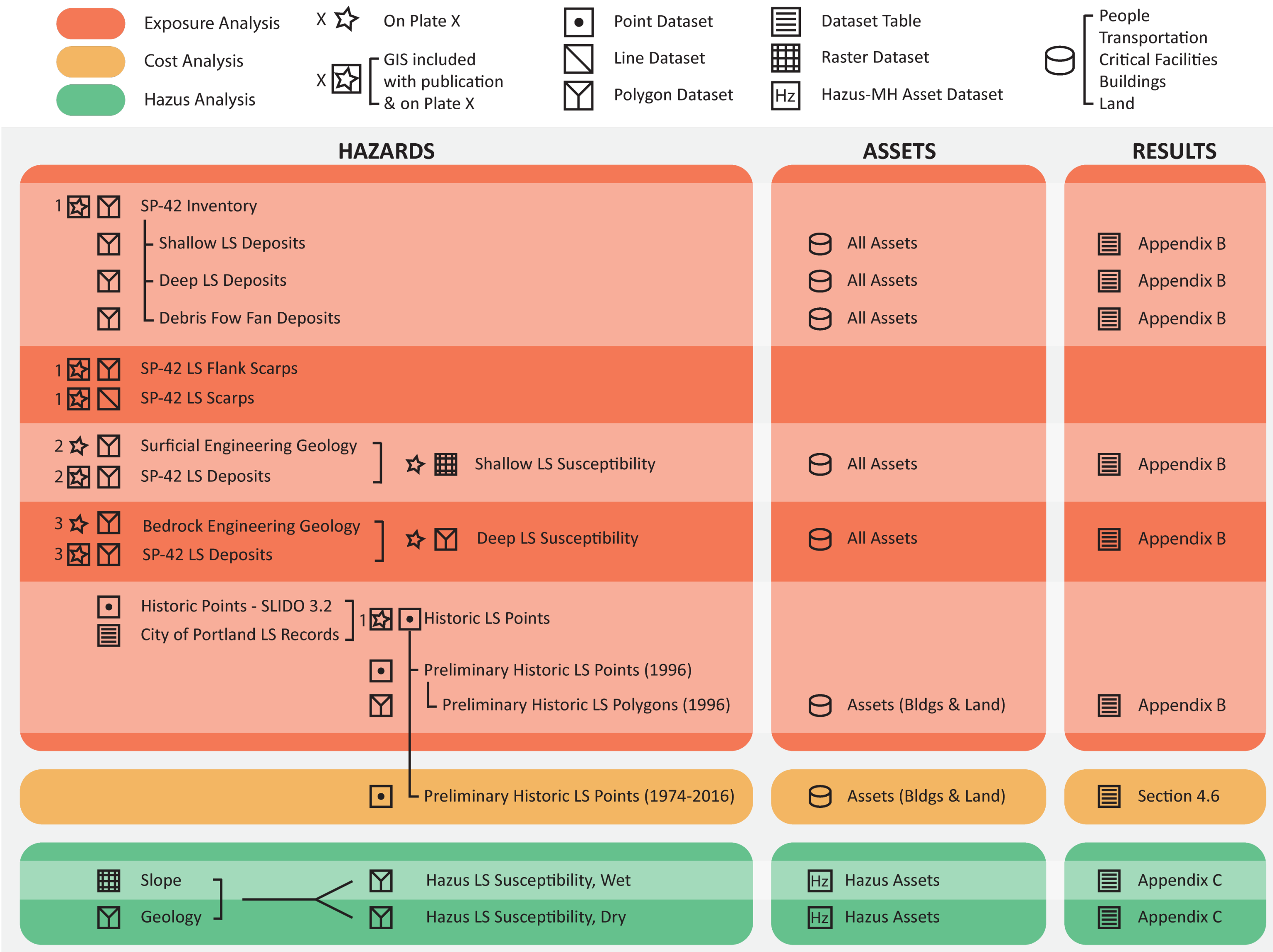
Several recent events have caused widespread landsliding in the study area. The most notable is the February 1996 storm event, a 100-year event (Burns and others, 1998). Burns and others mapped 705 landslides that occurred during this event and concluded that these landslides were concentrated in certain geological provinces, including the Tualatin Mountains (Portland Hills), steep bluffs along the rivers, the fine-grained Troutdale Formation area, and the valley bottoms. The landslide inventory and hazard regions map by Burns and others (1998) has been used by the City of Portland and others for two decades.

The combination of FEMA declared disasters, hundreds of prehistoric landslides, and hundreds of historic landslides provide good evidence of a significant level of landslide hazard and risk in the study area. Therefore, these data attest to the need to continue 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.

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 inside the City of Portland boundary. Because both 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 points 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) City of Portland historic landslide records. We began the compilation by extracting historic landslide points from SLIDO-3.2. The City of Portland historic landslide records were provided by Ericka Koss (written communication, 2016). The City of Portland landslide dataset consists of 1,481 records with dates ranging from 1928 to 2013 with a wide range of attributes including a street address, landslide dimensions, landslide type, and date. Additional data from 2014–2016 was also provided by the City of Portland. However, there was no spatial component (GIS) to these datasets, so a process combining GIS (tax lots, streets, lidar hillshade, aerial photos) and Google Earth® (street addresses, imagery) was followed to convert the City of Portland dataset into a GIS dataset (Appendix A). Also, it was discovered that many of the landslides in the SLIDO-3.2 dataset had duplicates in the City of Portland dataset, so a process combining GIS and address and other matching attributes was followed to remove duplicates (see Appendix A). The final version of this dataset is included with this publication and is referred to as *historic landslide points (***Figure 3-1)**.

A subset of the final combined *historic landslide points* inventory that occurred during 1996 has length and width attributes. These were used to create a dataset of rectangular polygons used to perform exposure analysis (section 3.3.1.1).

A preliminary version of the *historic landslide points* (*preliminary historic landslide points*) was used in this study to estimate losses from landslides (Burns and others, 2017). This previous study used the *preliminary historic landslide points* (**Figure 3-1)** dataset, which contains 1,806 landslide records from 1928 through the first half of 2016 located inside the City of Portland. Some of these 1,806 records were later deemed duplicates or non-landslide events and removed from the *historic landslide points* dataset included with this publication (Erika Koss, written communication, 2017).

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 2.3, we created a new surficial engineering geology map during this project. Instead of using existing generalized statewide values (Burns and others, 2012, Table 2), we created a new table of material properties (**Table 3-1**) for each of the primary surficial engineering geologic units in this specific study area. To calculate the FOS (component 2), we estimated new material properties from adjacent past studies including Clackamas, Bull Run, and North Bethany/Area 93 (**Figure 2-3**).

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 and Portland Water Bureau geotechnical engineers 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.

Primary Surficial Geologic Engineering Unit	Angle of Internal Friction (degrees)	Cohesion (lb/ft^2)	Unit Weight (Saturated lb/ft^3)	Slope Threshold For Stable (FOS > 1.5) (degrees)	Slope Threshold For Potentially Unstable (FOS > 1.25) (degrees)
Landslide (Deep) Deposits	28	0	115	9.0	10.5
Man-Made Mixed-Grained Fill	28	0	115	9.0	10.5
Basalt Fragments and Loess Colluvium	28	0	115	9.0	10.5
Loess and Loess-Basalt Colluvium	28	0	115	9.0	10.5
Talus Deposits	30	150	115	13.0	15.5
Fine-Grained Older Alluvial Deposits and Colluvium	28	0	115	9.0	10.5
Coarse-Grained Alluvial Deposits	32	0	115	10.5	12.5
Coarse-Grained Older Alluvial Deposits	34	0	115	11.0	13.5
Fine-Grained Alluvial Deposits	30	0	115	9.5	11.5
Fine-Grained Older Alluvial Deposits	30	150	115	13.0	15.5
Loess	30	150	115	13.0	15.5
Residual Soil on Coarse-Grained Sedimentary Rock	40	0	115	14.0	16.5
Residual Soil on Fine-Grained Sedimentary Rock	30	200	115	14.5	16.5
Residual Soil on Miocene Basalt	28	500	115	20.0	24.0
Residual Soil on Quaternary-Tertiary Basalt	28	500	115	20.0	24.0

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; SP-48; **Figure 3-1**). Deep landslides were defined by Burns and Madin (2009) as having a failure surface greater than 15 feet deep. 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 is geologic contacts. We have observed in Oregon, especially since we began mapping landslide inventories using lidar (Burns and Mickelson, 2016) that many landslides occur along a contact, especially when sedimentary or volcaniclastic rock is covered by hard volcanic rock. For example, large, deep landslides are located next to each other along the contact between the overlying basalt of the Weak Severely-Weather Basalt (Boring Lavas) and the underlying Weak Fine-Grained Sedimentary Rocks (Troutdale/Sandy River Mudstone) along the Sandy River in the eastern portion of the study area. Most of the failure surfaces of these landslides are almost completely within the Rhododendron Formation, so they are not failing or sliding along the "geologic contact" in the sense that the failure plane follows the contact below ground. It is more of a spatial relationship between the landslides and the contact surface trace in map view; this relationship is most likely caused by erosion or downcutting at the surface, which leads to exposure of the underlying weaker unit.

The third factor, slope angles, is very commonly correlated with landslide susceptibility. Most landslide susceptibility maps use slope as the primary factor or as at least one of the factors to predict future landslide locations. 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 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. Therefore we used the recorded direction of movement from the landslide inventory database as a proxy for dip direction or preferred direction of movement.

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

3.1.4 Landslide susceptibility for Hazus

We performed a type of risk analysis with Hazus, a risk modeling software package developed by FEMA (FEMA, 2011). The Hazus landslide susceptibility map (created for input into Hazus earthquake module, **Figure 3-1**) 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 (**Table 3-2**).

Table 3-2. 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

3.2 Asset Data Compilation and Creation Methods

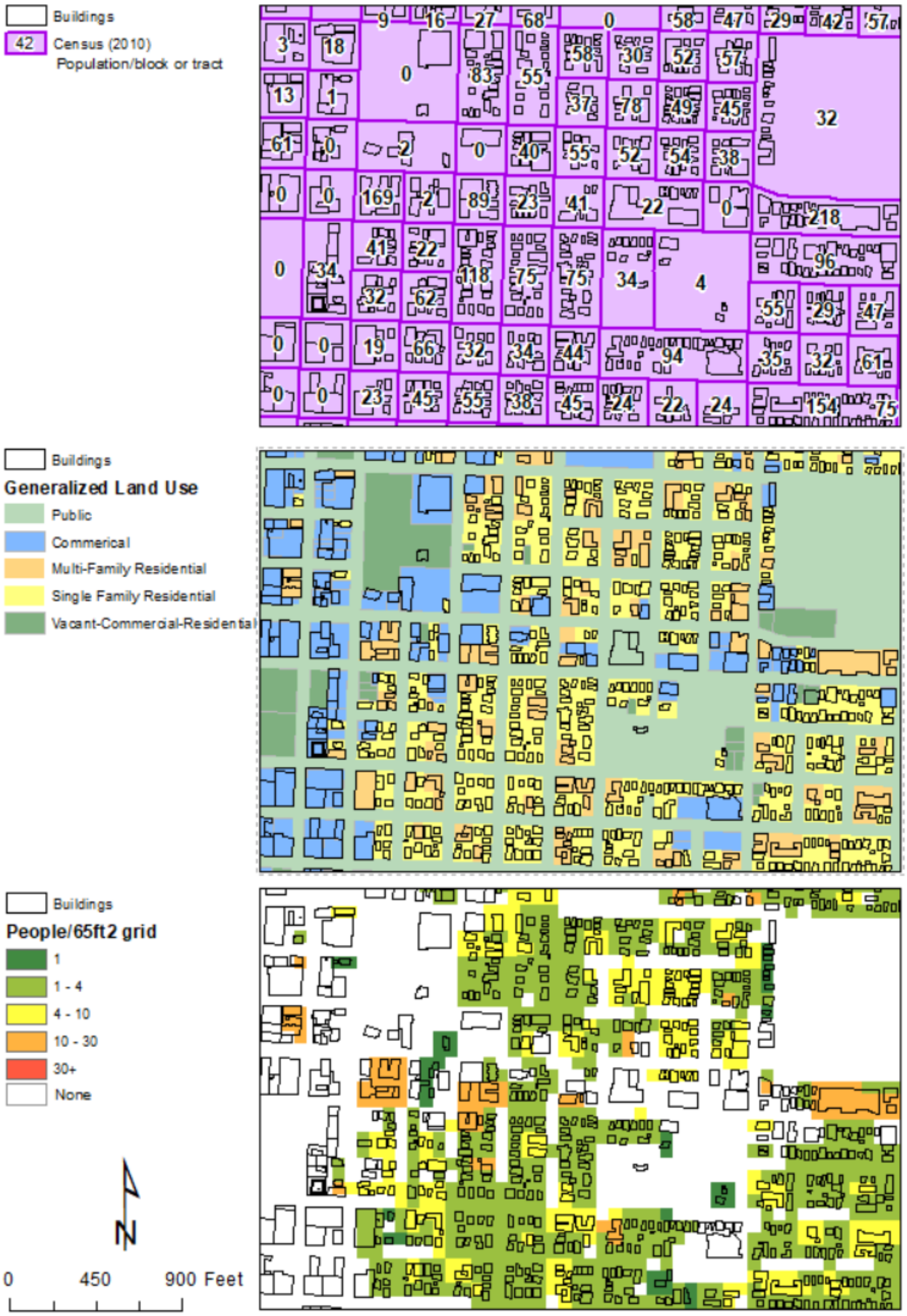
Next, we compiled and created asset datasets that included permanent population distribution, buildings and land, critical facilities, and roads. We overlaid these asset datasets along with the *SP-42 inventory* and shallow and deep landslide susceptibility datasets to evaluate exposure of the assets to the landslide hazard. We followed the same general methods to create and perform exposure outlined by Burns and others (2013) in Clackamas County.

3.2.1 Permanent population distribution dataset

Permanent population (resident) figures are needed to accurately estimate 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 3-2**). 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 more precisely map population over an area. To assess and geographically distribute permanent population within the study area, we created a dasymetric population grid (62ft^2). 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. We also used building footprints to determine the likely locations of people within those tax lots designated as residential (**Figure 3-2**).

Figure 3-2. Dasymetric population distribution map input data and result examples.



3.2.2 Buildings and land

DOGAMI acquired and edited building locations from Metro's (the Portland, Oregon, metropolitan area regional government) Regional Land Information System (RLIS; Metro, 2015). Parts of the study area were not covered by the RLIS 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 locate 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.

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 noticed 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 file for Multnomah County acquired from RLIS. Starting with the generalized zoning dataset, we then 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 (sometimes 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

Roads were divided into three categories:

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

We acquired the road and railroad data from RLIS (Metro, 2015). We found the railroad data to have significant spatial error when compared to the lidar-based imagery, so we did not include them in the analysis.

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). To better understand the risk, we also collected historic landslide data for the study area and estimated actual historic losses.

3.3.1 Exposure analysis

A building is considered to be exposed to the hazard if it is located within a selected hazard area. 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 3-3**). 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)
- 1996 landslide historic points converted to polygons in the City of Portland (see section 3.3.1.1)
- 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, 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

In other words, we used GIS to find which community assets fell in which hazard zones. For example, we superimposed the buildings layer for the study area on the deep-landslide high-susceptibility zone layer to determine which buildings are exposed to that level of hazard. 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.

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

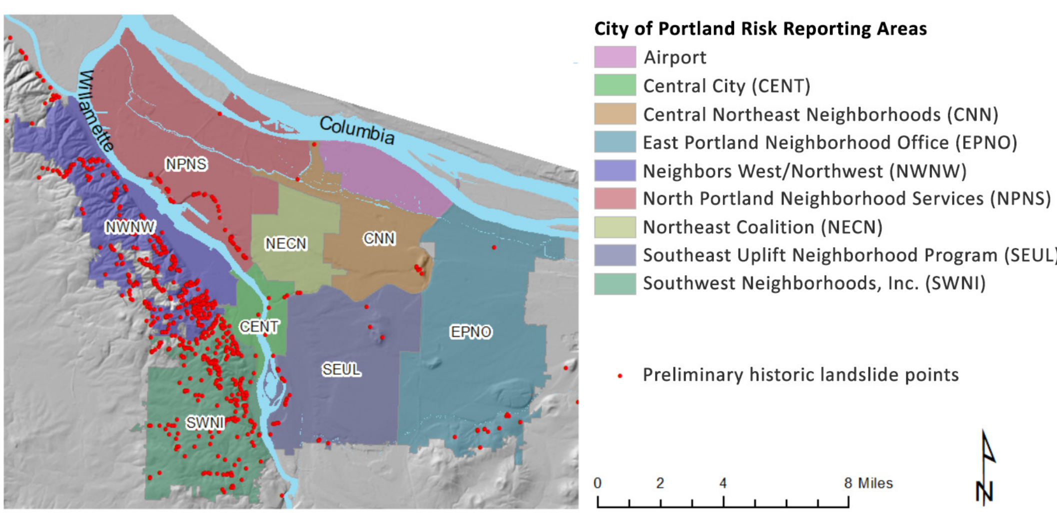
Community	Area (mi²)
Multnomah County (West/Central; Maywood Park)	121.7
City of Fairview	3.4
City of Gresham	23.5
City of Troutdale	6.1
City of Wood Village	0.9
City of Portland Neighborhoods	
Central City (CENT)	4.7
Airport	8.6
Neighbors West/Northwest (NWNW)	19.3
Southeast Uplift Neighborhood (SEUL)	21.1
North Portland Neighborhood (NPNS)	27.5
East Portland Neighborhood (EPNO)	29.0
Northeast Coalition Neighborhood (NECN)	7.2
Central Northeast Neighborhood (CNN)	10.5
Southwest Neighborhood (SWNI)	17.9
City of Portland (total)	145.7

3.3.1.1 Exposure analysis of City of Portland 1996 event landslide points converted to polygons

Point data cannot be used to perform exposure analysis, so we converted the points to polygons. The method used to calculate exposure on the 1996 event landslides was performed on the *preliminary historic landslide points* (Burns and others, 2017). As previously mentioned, the preliminary dataset has 1,806 landslide records from 1928 through the first half of 2016 (**Figure 3-3**).

The concentration of historic landslides in certain neighborhoods (**Figure 3-3**) is due to several geologic and geomorphic conditions. Northwest and southwest of the Willamette River (neighborhoods NWNW and SWNI) the surficial geologic conditions often consist of loess deposits overlying bedrock and steep topography created by the Portland Hills anticline (Evarts and others, 2009). The landslide pattern in the NPNS neighborhood follows the rivers bluff, a high-relief feature caused by the catastrophic Missoula floods.

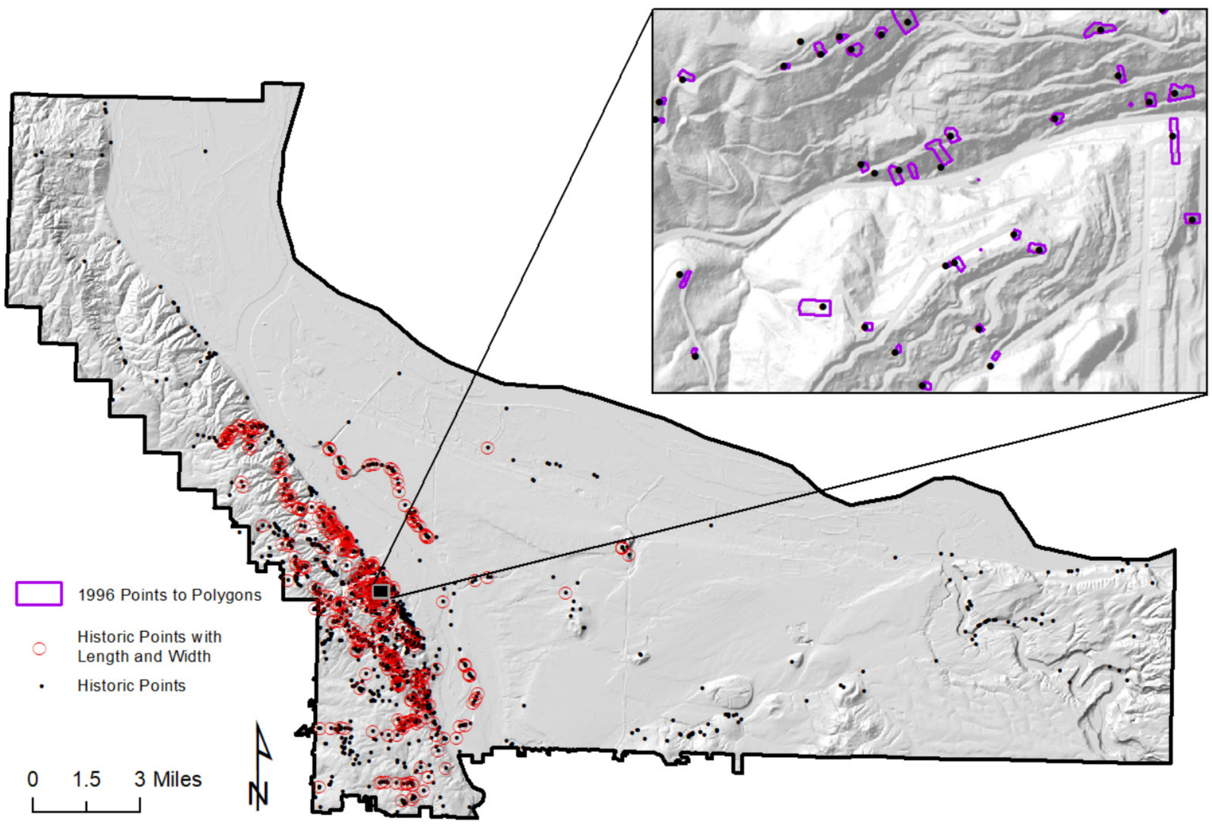
Figure 3-3. Map of the 1,806 preliminary historic landslide points (red dots) recorded for the period 1928–2016 (Burns and others, 2017).



The *preliminary historic landslide points* and *historic landslide points* include point location data, rather than a polygon that represents areal extent of a landslide. Records often contained limited or generic site information, such as only an address, which was not enough detail to create a polygon.

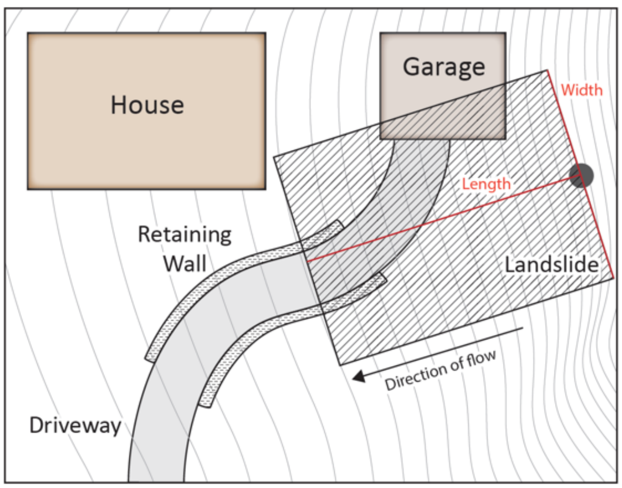
Of the 1,806 landslides, 831 occurred during 1996. Records often contained limited or generic site information, such as only an address, which was not enough detail to create a polygon. However, records for 457 of the 891 landslides (*preliminary historic landslide points*) that occurred during the 1996 event (**Figure 3-4**) included length and width data for the landslide. Drazba (2008) created simple polygons for some of these points; we augmented these with more simple polygons for application in exposure analysis (**Figure 3-5**).

Figure 3-4. Map showing locations of the 457 *preliminary historic landslide points* from the 1996 event that have landslide length and width data. Detail map shows some of the 1996 event points expanded to landslide polygons for exposure analysis.



Using the 457 *preliminary historic landslide points* converted to polygons, we calculated land and building exposure values by using the area of the generated landslide polygon. While examining the tax lot values, we noticed the significant lack of dollar values for public land. Of these 457 polygons, only 177 (39%) were located with more than 50 percent of their area overlapping private land. Therefore, we performed this exposure analysis on only the 177 landslides located predominantly on private tax lots. Instead of including the entire house value if touched by a landslide, as previously done in exposure analysis, we combined the building and land values and distributed the total value equally across the lot in the exposure calculation. We used this method to reduce inflated exposure when including the entire building value. Distribution of the structure value over the property also provides a proxy method to account for other exposed improvements such as driveways, retaining walls, and outbuildings, which are commonly damaged in landslides (**Figure 3-5**).

Figure 3-5. Schematic showing the difference in landslide exposure value for landslide point (solid black dot) data versus landslide polygon (hashed rectangle) data in the same parcel.



Land area =	8,000 ft^2
Land value =	$70,000
Improvements value (house garage, retaining wall, and driveway) =	$400,000
Total value =	$470,000
Average parcel value per ft^2 (land plus improvements)	$470,000/8,000 ft^2 = $58.75/ft^2
Area of landslide:	2,000 ft^2 (25% of land area)
Landslide exposure based on landslide polygon data:	2,000 ft^2 * $58.75/ft^2 **= $117,500**

Gray lines are elevation contours.

3.3.2 Hazus-MH analysis

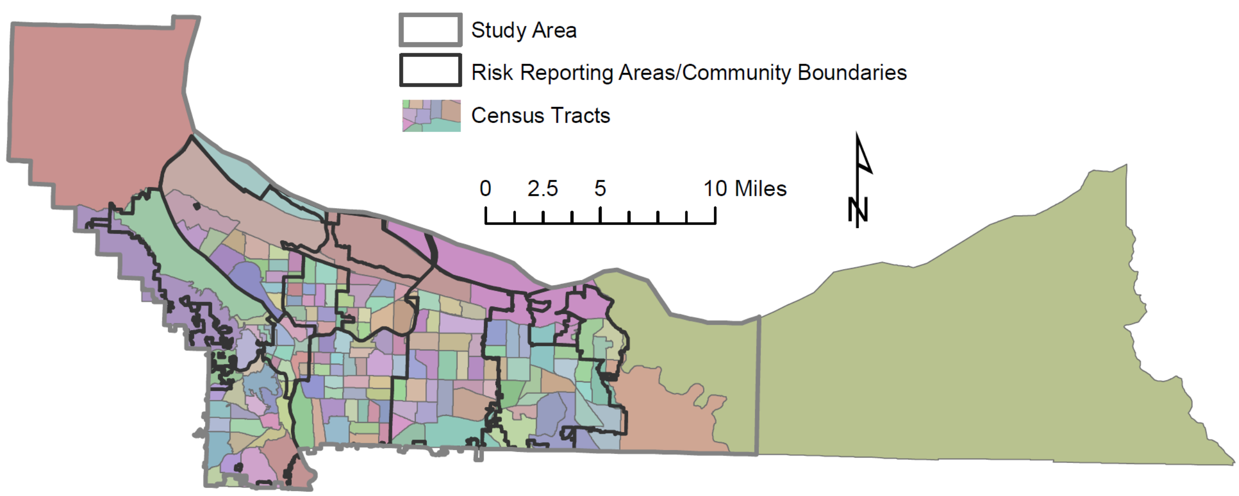
We performed the second type of risk analysis with Hazus-MH, a multi-hazard risk modeling software package developed by FEMA, the National Institute of Building Sciences (NIBS), and other public and private partners (FEMA, 2011). Hazus software can be used to model a variety of earthquake, flood, and wind probabilistic hazards and/or hazard event scenarios. Although Hazus-MH has limitations, we chose to use Hazus-MH as part of our risk analysis because it is the only widely and publicly available risk analysis program with data for the United States that can produce casualty and fatality estimates. We also 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-MH 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.

To work around the lack of a landslide scenario module in Hazus-MH, we used the earthquake module with and without earthquake-induced landslide hazards. Then we subtracted the earthquake-without-landslides model results from the earthquake-with-landslides model results so that earthquake-induced landslide damage and losses could be examined separately.

Default hazard and asset databases are included with the Hazus-MH program. Most data are based on national-scale information that generally does not accurately reflect local conditions. To better account for local variability, the software is designed to incorporate user-specific updates to the hazard and asset databases (FEMA, 2011). To update the asset database, detailed building-specific data must be collected.

The smallest areal extent allowed for analysis in the Hazus earthquake module is the census tract level. We selected the 171 census tracts that best represent the study area (**Figure 3-6**). Although the extent of the 171 tracts is in some places larger than the study area and in some places smaller, overall an analysis extent based on tract level best represented the study area. One limitation of Hazus is that census tract areas can be too coarse for small areas mapped as hazard zones.

Figure 3-6. Map of the 171 census tracts used in Hazus analysis, risk reporting areas/community boundaries, and study area.



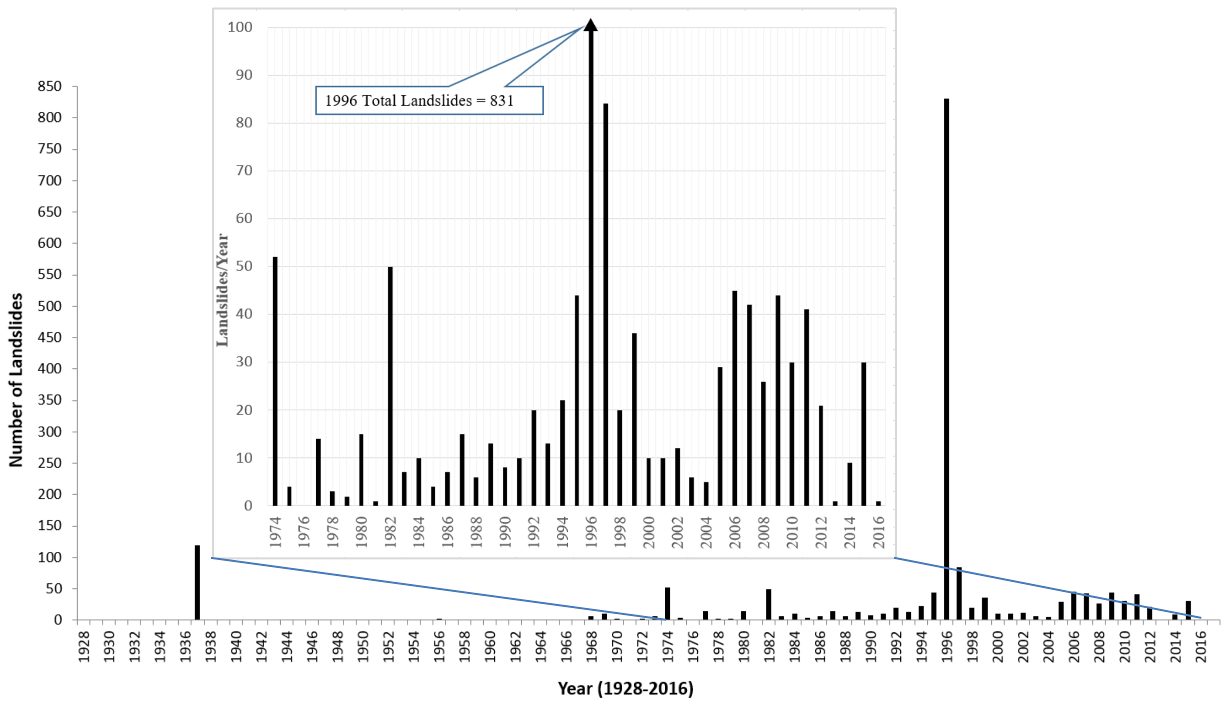
The goal for our Hazus analysis was to estimate damage and losses from two kinds of earthquakes (local crustal and Cascadia Subduction Zone), both with and without earthquake-induced landslides, so that we could examine the difference in damage and losses caused by just the earthquake-induced landslides. We also ran landslides in dry and wet conditions (see **Table 3-2**) for each scenario to make sure the changes were continuing above the analysis level (detailed landslides). This resulted in six different Hazus analyses (see Appendix C):

- Portland Hills Fault (local crustal)
  - No landslides
  - Landslides Dry
  - Landslides Wet
- Cascadia Subduction Zone
  - No landslides
  - Landslides Dry
  - Landslides Wet

3.3.3 Annualized loss

To better understand landslide risk, we used the *preliminary historic landslide points* dataset to estimate the annualized loss in the City of Portland. Of the 1,806 landslides in that dataset, 831 occurred during 1996 and are located in the City of Portland. Further examination of the data found incomplete records or lack of data collection from 1928 to 1973 (**Figure 3-7**). If the 831 landslides that occurred in the City of Portland in 1996 are excluded, records from 1974 to 2016 result in an average of 20 recorded landslides per year, providing a minimum annual estimate for the City of Portland (**Figure 3-7**, insert chart).

Figure 3-7. Chart of all *preliminary historic landslide points* in the City of Portland displayed as number of landslides per year from 1928–2016 and (inset chart) 1974–2016 (Burns and others, 2017).



This portion of the project was published with greater detail in the Third North American Symposium on Landslide conference proceedings, titled Estimating Losses from Landslide in Oregon, however a brief overview is provided below (Burns and others, 2017). All values in this paper were converted to 2016 dollars by using http://www.usinflationcalculator.com/. In this study, we performed the following tasks:

- Examined original loss estimates for the 1996 events from Wang and others (2002). This was mostly losses on public property.
- Performed exposure analyses with the City of Portland 1996 event landslide points converted to polygons on private property (see section 3.3.1.1 of this report).
- Compiled cost data from permits for landslide repair on private property (2000–2013)
- Compiled total loss data for landslides that occurred during the winter of 2015- 2016.

We examined the data listed above using simple statistics including mean and range. The results of this analysis are summarized in **Table 3-4**.

Table 3-4. Summary of annualized loss estimates (2016 dollar values).

Dataset	Estimated Mean Dollars per Landslide	Estimated Loss in Typical Year (20 Landslides)	Estimated Loss in Extreme Year
Public land (extrapolated from 1996 data)	$67,600[#]	$1.4M	$34M
Public land (extrapolated from 1996 data)	$102,500[##]	$2.1M	$34M
Private land exposure (1996 landslide polygons)	$144,000	$2.9M	$47M*
Private land (1996 permits)	$99,000	$1.9M	$32M*
Private land (permits 2000–2013)	$93,100	$1.9M	$30M*
Private and public land (2015-2016 season)	$67,500	$1.4M	$56M**

[#] 507 landslides; includes recreational land such as parks or greenspaces, which may have minimal infrastructure, or damageable property.

[##] 333 landslides; does not include recreation land.

* 324 landslides on private land multiplied by mean per landslide.

** 831 landslides on private and public land multiplied by mean per landslide.

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 (Burns and Duplantis, 2010) in the study area, 97 landslides areas (polygons) were mapped and included in SLIDO-1 (Burns and others, 2008). In contrast, the *SP-42 inventory* (Burns and Madin, 2009), used for the current project, includes 1,996 landslides in the study area. The surface area of these landslides covers approximately 25 square miles, or approximately 8 percent of the study area (300.6 mi^2; Plate 1). These landslides range in size from 250 square feet to more than 11 square miles. Of the 1,996 *SP-42 inventory* landslides, 820 are shallow and 781 are deep. The other 395 landslides are mostly debris flow fans (347) and rock fall talus. Details for each community are shown in **Table 4-1**.

Out of the 1,996 *SP-42 inventory* landslides, 1,288 are known or are estimated to have moved in the last 150 years. A very simplified historical constant rate of landslides would then be 8-9 landslides per year (1,288 landslides/150 years). However, as noted in this study and other studies (Burns and others, 2013; Wang and others, 2002), it is much more common in Oregon for tens to hundreds of landslides to occur during single large storm events with periods of no or very few landslides between storm events.

The updated *historic landslide points* inventory contains 1,700 landslide records from 1928 to 2016. Of the 1,700 landslides, 891 occurred during 1996 or are noted to have occurred during 1996-1997 or have a reactivation date including 1996. The *historic landslide points* dataset is displayed on Plate 1, and details for each community are shown in **Table 4-1**. Records for 457 of the 831 *preliminary historic landslide points* that occurred during 1996 included length and width data were used to create simple polygons (**Figure 3-4**). The 457-simple-polygon dataset allowed us to compare a known reoccurrence interval event (widespread 100-year rainfall event) to the new shallow landslide susceptibility map and perform exposure analysis.

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

Community	*SP-42 Inventory*	*Historic Landslide Points*
Multnomah County (West/Central)	1,115	205
City of Fairview	0	0
City of Gresham	55	7
City of Troutdale	44	2
City of Wood Village	1	1
City of Portland Neighborhoods		
Central City (CENT)	2	39
Airport	1	6
Neighbors West/Northwest (NWNW)	437	635
Southeast Uplift (SEUL)	18	41
North Portland (NPNS)	31	60
East Portland (EPNO)	42	49
Northeast Coalition (NECN)	3	5
Central Northeast (CNN)	9	11
Southwest (SWNI)	307	659
City of Portland (total)	847	1,505

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

4.2 Shallow Landslide Susceptibility Findings

We classified the entire study area into zones of low, moderate, and high susceptibility to shallow landslides. Approximately 63% of the study area is classified as low, 21% as moderate, and 16% as high susceptibility (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**).

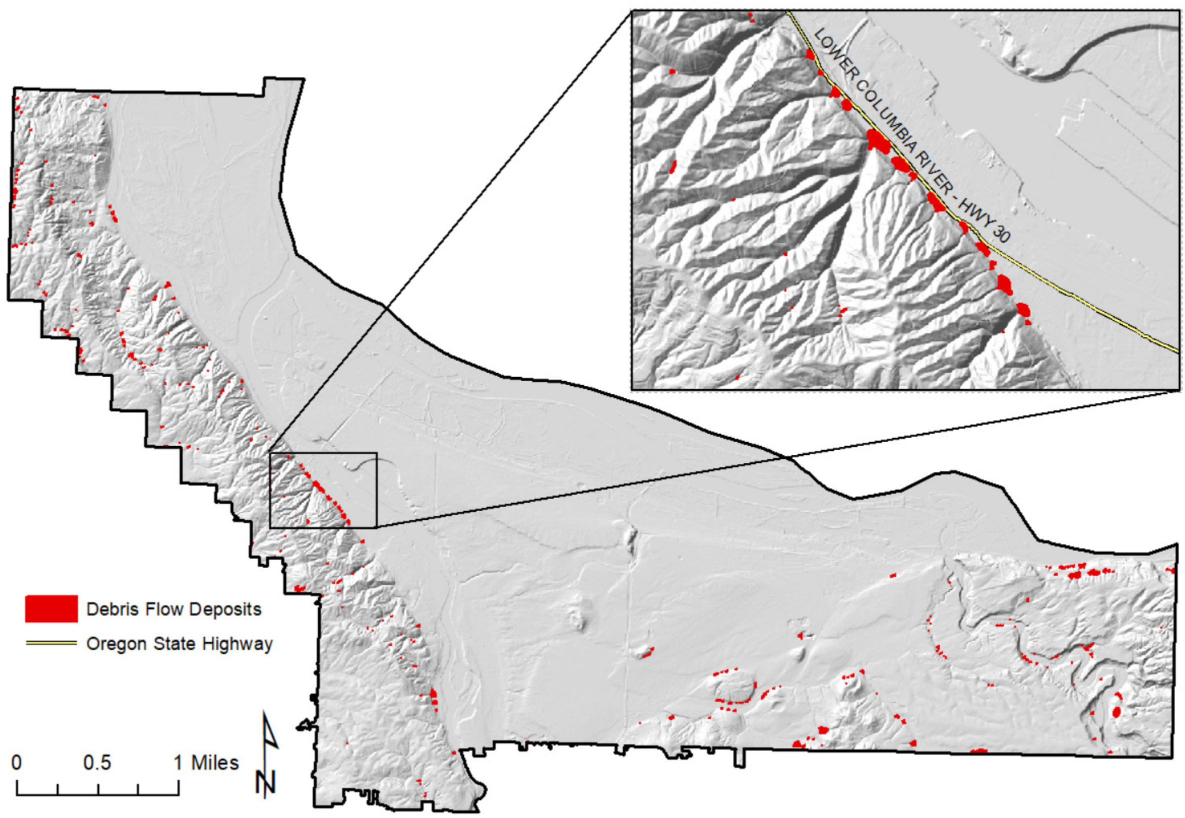
We draped the 457 simple polygons (created from the *preliminary historic landslide points* that occurred during 1996 including length and width data) over the shallow landslide susceptibility map in order to analyze spatial statistics. The ratio of area of the 457 landslide polygons to the shallow landslide susceptibility high zone was extrapolated to the total 831 to find approximately 0.5% of the area mapped as high in the City of Portland moved as landslides in the 1996, 100-year return event (1% probability of occurring in any year).

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

	Percentage by Zone		
Community	**Low**	**Moderate**	**High**
Multnomah County (West/Central)	56%	22%	22%
City of Fairview	74%	20%	6%
City of Gresham	70%	19%	11%
City of Troutdale	71%	20%	9%
City of Wood Village	77%	18%	5%
City of Portland Neighborhoods			
Central City (CENT)	78%	16%	4%
Airport	92%	7%	2%
Neighbors West/Northwest (NWNW)	27%	23%	53%
Southeast Uplift (SEUL)	78%	18%	3%
North Portland (NPNS)	81%	14%	5%
East Portland (EPNO)	80%	16%	5%
Northeast Coalition (NECN)	79%	19%	2%
Central Northeast (CNN)	78%	17%	5%
Southwest (SWNI)	32%	46%	24%
City of Portland (total)	67%	20%	13%
Total study area	63%	21%	16%

Although we did not model susceptibility to channelized debris flow transport and deposition, we did map 347 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 if 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 the channel gradient is reduced and the 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 78% of the study area is classified as low, 15% as moderate, and 7% as high (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 can be thought of as a worst-case scenario. This is because we included all deep landslides that have ever occurred throughout geologic time in the high susceptibility zone. However, we do not expect all deep landslides to be active at the same time throughout the watershed. This is the most conservative approach and therefore the worst-case scenario.

As with shallow landslide susceptibility, we calculated the area covered by deep landslide susceptibility within the communities (**Table 4-3**).

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

	Percentage by Zone		
Community	**Low**	**Moderate**	**High**
Multnomah County (West/Central)	65%	21%	14%
City of Fairview	100%	0%	0%
City of Gresham	95%	4.5%	0.5%
City of Troutdale	96%	2.5%	1.5%
City of Wood Village	100%	0%	0%
City of Portland Neighborhoods			
Central City (CENT)	98%	2%	1%
Airport	100%	0%	0%
Neighbors West/Northwest (NWNW)	30%	58%	12%
Southeast Uplift (SEUL)	100%	0%	0%
North Portland (NPNS)	100%	0%	0%
East Portland (EPNO)	98%	2%	0%
Northeast Coalition (NECN)	100%	0%	0%
Central Northeast (CNN)	99%	1%	0%
Southwest (SWNI)	64%	31%	5%
City of Portland (total)	86%	12%	2%
Total study area	78%	15%	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 10 hazard datasets/zones:

- shallow landslides (inventory polygons)
- deep landslides (inventory polygons)
- debris flow fans (inventory polygons)
- 1996 landslide historic points converted to polygons in the City of Portland
- shallow landslide susceptibility (low, moderate, and high)
- deep landslide susceptibility (low, moderate, and high)

and asset datasets: permanent population; critical facilities and roads; and land and buildings. Tables showing the all the results of this analysis are provided in Appendix B.

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 almost 6,700 people and approximately $1.65 billion 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	187	132	$25.8M	1,985	$34.9M	1.0	3
Deep landslides	6,129	2,196	$988.8M	4,023	$501.6M	44.8	2
Debris flow fans	371	342	$53.4M	900	$42.3M	2.9	0

Recall that records for 457 of the 831 *preliminary historic landslide points* that occurred during 1996 were used to create "simple" polygons. Of the 457, 177 (39%) had more than 50% area on private property, for a total exposure value of $25.5M and a mean value of $144,000 per landslide (private property in the City of Portland; Burns and others, 2017).

In order to approximate total private property exposure, 39% was applied to the total 831 landslides, equaling approximately 324 (831*0.39) landslides (private property in the City of Portland). To estimate the total exposure, the mean exposure value ($144,000 per landslide) was multiplied by the 324 private property landslides, resulting in approximately $47M in 1996 landslide exposure to private property (Burns and others, 2017).

The remaining 507 of the total 831 landslides are therefore on public land and caused approximately $34.3M in losses (Wang and others, 2002). However, these 507 landslides touched 174 pieces (34%) of recreational land, as classified in the tax lot data, that are considered parks or greenspaces, and so may have minimal infrastructure or damageable property. The remaining 66% of landslides on public land were not located on recreational land, and therefore this estimate included the majority of the $34.3M in public losses. This would equal an average of approximately $102,500 per landslide (on public property in the City of Portland). Together the total estimated losses from landslides in the City of Portland during 1996 on public land is $34.3M and exposure on private land of $47M, which is a total of approximately $81.3M (Burns and others, 2017).

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 $8.7 billion in land and building values are located in xxx. More than 29,000 people live in the shallow landslide high susceptibility hazard zone and nearly 8,000 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	552,707	261,617	$55,621.6M	204,855	$31,652.0M	2,356.4	326
Moderate	141,892	103,601	$72,223.1M	97,279	$9,359.2M	998.3	287
High	29,294	62,100	$3,631.6M	79,857	$3,201.4M	44.7	277
Deep Landslide Susceptibility							
Low	686,765	278,773	$70,320.5M	207,919	$40,282.5M	3,029.3	318
Moderate	29,240	12,489	$5,886.1M	14,753	$3,221.6M	301.2	17
High	7,901	3,020	$1,236.5M	3,674	$708.9M	69.1	2

4.5 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 C):

Crustal M6.8 earthquake scenario: Portland Hills 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 M6.8 Portland Hills 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 C. The results show that in a subduction zone event the earthquake-induced landslide hazard alone would result in economic loss to buildings of approximately $500M (**Table 4-6**) and in a local crustal earthquake approximately $3B. Hazus estimates a replacement value for buildings at approximately $86B for both scenarios, which is more than the taxable improvements (building) value of $75B we derived from tax lot data (Appendix C). 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.

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 1,344 or 4,992 buildings being moderately to completely damaged and 600 to 2,761 residents needing shelter (Appendix C). In Multnomah County, the loss ratio increased from 10% to 13% when landslides in a “wet” condition are added to the scenario. This is a 31% increase; overall, almost 25% of the damage comes from landslides. Similar increases in loss ratios are calculated in the Neighbors

West/Northwest (NWNW) and Southwest (SWNI) neighborhoods in the city of Portland. However, some communities had minimal increases. These include the Southeast Uplift (SEUL), Northeast Coalition (NECN), Central Northeast (CNN), and Airport neighborhoods.

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 C.

		Building Losses							
		Cascadia— No Landslide		Cascadia with Landslide (Dry)		Cascadia with Landslide (Wet)		Landslide (Wet) Only*	% of
	Total Building Value ($)	Loss ($)	Loss Ratio (%)	Loss ($)	Loss Ratio (%)	Loss ($)	Loss Ratio (%)	Difference in Losses ($)	Total Losses from Landslides
Multnomah County (west/central)	$1,832.8M	$177.9M	10%	$177.9M	10%	$232.7M	13%	$54.8M	24%
Cities of Troutdale, Wood Village, Gresham, Fairview	$11,626.8M	$597.2M	5%	$597.2M	5%	$617.3M	5%	$20.1M	3%
City of Portland Neighborhoods									
Airport	$1,234.8M	$246.6M	20%	$246.6M	20%	$246.6M	20%	$0	0%
Central City (CENT)	$11,000.8M	$3,990.3M	36%	$3,990.5M	36%	$4,122.8M	37%	$0.3M	3%
Central Northeast (CNN)	$5,210.9M	$288.0M	6%	$288.0M	6%	$288.0M	6%	$0	0%
East Portland (EPNO)	$11,539.3M	$695.6M	6%	$695.6M	6%	$695.9M	6%	$0.3M	0%
Northeast Coalition (NECN)	$5,683.4M	$447.6M	8%	$447.6M	8%	$447.6M	8%	$0	0%
North Portland (NPNS)	$7,477.2M	$1,269.6M	17%	$1,269.7M	17%	$1,294.1M	17%	$24.5M	2%
Neighbors West/Northwest (NWNW)	$5,271.5M	$424.9M	8%	$432.5M	8%	$530.9M	10%	$106.0M	20%
Southeast Uplift (SEUL)	$15,628.6M	$1,093.0M	7%	$1,093.0M	7%	$1,093.0M	7%	$0	0%
Southwest (SWNI)	$9,775.4M	$505.7M	5%	$505.7M	5%	$687.1M	7%	$181.4M	26%
City of Portland Total	$72,821.7M	$8,961.3M	12%	$8,969.1M	12%	$9,405.9M	13%	$444.6M	5%
Total study area	$86,281.3M	$9,736.4M		$9,744.3M		$10,255.9M		$519.5M	

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

4.6 Annualized Loss Results

On the basis of historical data, there is an average of 20 landslides per year in the City of Portland (**Figure 3-7**). Stormy, wet, or otherwise extreme landslide years, such as the 1996 winter, can cause hundreds of landslides. The number of landslides multiplied by the average loss estimates provides a preliminary estimate of losses per year. We found an average cost of $99,000 from building/construction permits and $144,000 per landslide on private property and $102,500 per landslide on public property in the City of Portland from exposure (**Table 3-4**). From these numbers, one can conclude that annual loss estimates from landslides in the City of Portland have ranged from ~$1.5M to ~$3M (in 2016 dollars) over the last 20 years. In extreme years, this annual estimate increased to approximately $34M for public and $47M for private property. Together, the estimated total ranges from approximately $64M to $81M. If the typical annual loss values are inferred over the 42 years (1974–2016), the total cumulative losses are likely in the range of \$84M to \$126M for the City of Portland. This indicates that losses from just one or two extreme landslide years are the equivalent of ~40 years' worth of typical losses (Burns and others, 2017).

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 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 describing the landslide hazards as well as community assets and the risk that exists where the two overlap.

Lidar-based landslide inventory mapping (Plate 1) using the SP-42 method found 1,996 landslides, which cover approximately 8% (~24 mi^2) of the study area. Land and buildings valued at approximately \$1.65B and almost 6,700 people are located on these existing landslides. Our new historic landslide points dataset has 1,700 records with dates ranging from 1928 to 2013 within the study area. We conclude that annual loss estimates from landslides in the City of Portland range from ~\$1.5M to ~\$3M; in extreme years (such as 1996), this increases to approximately \$64M to \$81M. We also found almost 8,000 people live in the deep landslide high susceptibility zone and approximately 29,000 live in the shallow landslide high susceptibility zone. We also found that the loss ratio for the Cascadia earthquake scenario without landslides increased approximately 25–35% when landslides were added in NWNW and SWNI neighborhoods in the city of Portland and Multnomah County. For example, in Multnomah County the loss ratio increased from 10% to 13%, which is a 30% increase.

Many of the historic and more recent landslides were reactivations of existing landslides. These younger landslides are located within and at the toe of older slides (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 deposits 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 appears to be the combination of weak rock and soil, steep slopes, riverine and glacial outburst flood erosion, possible outburst flood rapid water level drawdown, and exposure to high precipitation and earthquake shaking. The loess and loess colluvium in the Tualatin Mountains, the Missoula Flood deposits along the Willamette River and other stream banks, and most places where there are generally steeper slopes are susceptible to shallow landslides (Plate 1 and 2, Burns and others, 1998). The highly weathered Columbia River Basalts and the weak sedimentary rock in the Tualatin Mountains and in the eastern portion of the study area are generally susceptible to deep landslides (Plate 1 and 3).

We have discussed detailed study results in this report and have provided detailed data in appendices and on GIS-based map plates. Three 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 6,000 residents, more than 2,000 buildings, and a combined building and land value of almost $1.5B are affected.
- Annual historic landslide losses range from ~$1.5M to ~$3M; in extreme years (such as 1996), this increases to approximately $64M to $81M.
- Damage and losses from landslides alone, induced by a local crustal or a Cascadia Subduction Zone earthquake, may result in an estimated 1,344 to 4,992 buildings being moderately to completely damaged and 600 to 2,761 residents in need of shelter. In some communities, potential landslides triggered by the earthquakes could cause a 31% increase in damage and losses.
- 16% of the study area is classified as highly susceptible to shallow landslides.

These data indicate a significant landslide hazard and risk in the study area. When we examined the hazard and risk at the community scale, we found Multnomah County (west/central), Portland Neighbors West/Northwest, and Portland Southwest Neighborhood had consistently higher hazard and risk. However, there is some level of landslide hazard and risk in all the communities. This amount of landslide risk indicates a strong need for continuing landslide risk management. Landslide risk management can be performed in various ways. One way to conceptualize the risk management components is illustrated in **Figure 5-1**.

Figure 5-1. Landslide risk management diagram showing (written communication Wang, 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 13**. 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 land owners in the study area become aware of the parts they can play in readiness for hazardous events and risk reduction. Once the hazard is understood better, 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" (http://www.oregongeology.org/sub/Landslide/ger_homeowners_guide_landslides.pdf) and the DOGAMI fact sheet "Landslide Hazards in Oregon" (http://www.oregongeology.org/sub/publications/landslide-factsheet.pdf; DOGAMI, 2006).

City, county, neighborhood, and other local community leaders can implement awareness campaigns to educate neighborhoods, businesses, and individual home owners 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 very 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 to better understand when these events might happen through the development of a landslide warning system. 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, local rainfall thresholds could be developed for landslide initiation in the communities 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 with the potential for life safety issues are identified, such as the debris flow fans, 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 the inclusion of the data in this report into 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 areas. Additional planning can focus on maintenance of road-related grading, repeated asphalt overlays, or expanding roadways. Keeping good records of maintenance practices is another way to track risk reduction effects.

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

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 have requirements (usually) 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 to mitigate because they often have multiple land owners on an individual deep landslide. Mitigation may require cooperating effort from public and private entities (usually city or county and landowners) because the slides can span or even cross entire neighborhoods. To reduce the likelihood of a slide reactivation, a public awareness campaign could be undertaken to educate homeowners and landowners about landslide hazards in their areas and how to reduce their risk. Residents on mapped landslide areas should participate in a neighborhood risk reduction program where all affected entities help reduce the overall risk. Risk reduction measures should include:

- minimizing irrigation on slopes
- avoiding removing material from bases of slopes
- avoiding adding material or excess water to tops of slopes
- draining water from surface runoff, downspouts, and driveways well away from slopes and into storm drains or natural drainages
- consulting an expert to conduct a site-specific evaluation before considering major construction

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. Historic Landslide Inventory Methodology (PDF)

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

Appendix C. Hazus Analysis Results (PDFs):

Crustal M6.8 earthquake scenario: Portland Hills Fault

- No landslides (phf6_8_sl_no_cb.pdf)
- Dry scenario landslides (phf6_8_sl_dry_cb_gsreport.pdf)
- Wet scenario landslides (phf6_8_sl_wet_cb_run2_gsreport.pdf)

Subduction Zone M9.0 earthquake scenario: Cascadia Fault

- No landslides (cascadia9_0_no_gsreport.pdf)
- Dry scenario landslides (cascadia9_0_dry_cb_gsreport.pdf)
- Wet scenario landslides (cascadia9_0_wet_cb_gsreport.pdf)