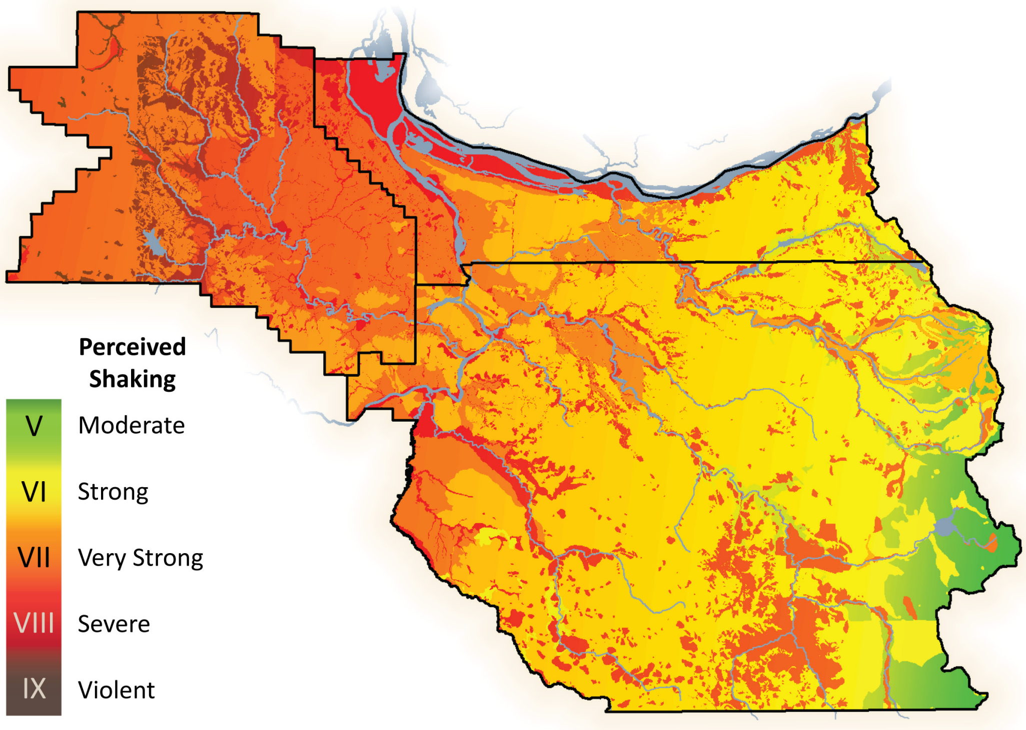
State of Oregon
Oregon Department of Geology and Mineral Industries
Brad Avy, State Geologist

OPEN-FILE REPORT O-18-02

EARTHQUAKE REGIONAL IMPACT ANALYSIS FOR CLACKAMAS, MULTNOMAH, AND WASHINGTON COUNTIES, OREGON

by John M. Bauer[1], William J. Burns[1], and Ian P. Madin[1]



2018

[1]Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Suite 965, Portland, OR 97232

DISCLAIMER

This product is for informational purposes and may not have been prepared for or be suitable for legal, engineering, or surveying purposes. Users of this information should review or consult the primary data and information sources to ascertain the usability of the information. This publication cannot substitute for site-specific investigations by qualified practitioners. Site-specific data may give results that differ from the results shown in the publication.

Cover Image: Perceived shaking for a simulated magnitude 9.0 Cascadia Subduction Zone earthquake in Clackamas, Multnomah, and Washington Counties, Oregon, using updated National Earthquake Hazard Reduction Program site classifications and bedrock ground motion data developed for the 2013 Oregon Resilience Plan. See Appendix E, Plate 6.

Oregon Department of Geology and Mineral Industries Open-File Report O-18-02
Published in conformance with ORS 516.030

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF MAP PLATES

See Appendix E

LIST OF TABLES

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

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

Metadata in .xml file format:
Each feature class, table, and raster listed below has an associated, standalone xml file containing metadata in the Federal Geographic Data Committee Content Standard for Digital Geospatial Metadata format.

RDPO_Earthquake_Impact_Analysis_Phase1.gdb:

Feature dataset: *Phase1*

Feature classes:

Building_Footprints
Electrical_Transmission_Structures
Emergency_Transportation_Routes
Jurisdictions
Neighborhood_Units
Population_and_Building_Density

Tables:

Loss_Jurisdiction_CSZ_M9p0_dry
Loss_Jurisdiction_CSZ_M9p0_wet
Loss_Jurisdiction_PHF_M6p8_dry
Loss_Jurisdiction_PHF_M6p8_wet
Loss_Neighborhood_Unit_CSZ_M9p0_dry
Loss_Neighborhood_Unit_CSZ_M9p0_wet
Loss_Neighborhood_Unit_PHF_M6p8_dry
Loss_Neighborhood_Unit_PHF_M6p8_wet

RDPO_GroundMotion_GroundFailure_Phase1.gdb:

Feature class:

PHF_M6p8_bedrock_groundmotion

Rasters:

CSZ_M9p0_pga_site
CSZ_M9p0_pgv_site
CSZ_M9p0_sa03_site
CSZ_M9p0_sa10_site
CSZ_M9p0_PGD_landslide_dry
CSZ_M9p0_PGD_landslide_wet
CSZ_M9p0_PGD_liquefaction_wet
CSZ_M9p0_Prob_landslide_dry
CSZ_M9p0_Prob_landslide_wet
CSZ_M9p0_Prob_liquefaction_wet
PHF_M6p8_pga_site
PHF_M6p8_pgv_site
PHF_M6p8_sa03_site
PHF_M6p8_sa10_site
PHF_M6p8_PGD_landslide_dry
PHF_M6p8_PGD_landslide_wet
PHF_M6p8_PGD_liquefaction_wet
PHF_M6p8_Prob_landslide_dry
PHF_M6p8_Prob_landslide_wet
PHF_M6p8_Prob_liquefaction_wet

EXECUTIVE SUMMARY

This report was prepared for the Regional Disaster Preparedness Organization (RDPO), with funding provided by the Urban Areas Security Initiative Program. The report provides damage and casualty estimates to buildings, people, and key infrastructure sectors resulting from a major earthquake in the Portland metropolitan region by using updated local geologic information and recent advances in loss estimation methods. Damage and casualty estimates are tabulated at county, jurisdiction, and neighborhood levels, providing actionable information for further use in emergency planning, earthquake mitigation, public awareness, and post-earthquake response and recovery.

The RDPO is a bi-state partnership of local and regional government agencies, non-governmental organizations, and private-sector stakeholders representing the Portland metropolitan region that collaborate to increase the region's resiliency to disasters. The region spans Clackamas, Columbia, Multnomah, and Washington Counties in Oregon and Clark County in Washington. In 2016 the RDPO Steering Committee identified a need for updated, region-wide, detailed loss estimates from a major earthquake and engaged the Oregon Department of Geology and Mineral Industries (DOGAMI) to conduct this study. Previously, earthquake damage estimates in large portions of the Portland metropolitan region were limited to studies conducted in the 1990s, when understanding of the Cascadia Subduction Zone (CSZ) risk was nascent. Since then, advances have occurred in several areas, including loss estimation tool capabilities, subduction zone science, and local geologic mapping in the Portland metropolitan region. The RDPO commissioned this study to harness such advances, thereby enabling local, regional, state, and federal planners and policy makers to apply the results in their efforts to mitigate risk and building seismic resilience and to prepare for response and recovery. DOGAMI and RDPO divided the project into two phases, with the first phase focused on methodology refinement and application of those methods to evaluate impact of a major earthquake in Clackamas, Multnomah, and Washington Counties (Oregon). Phase 2 will apply the same methods in Columbia County, Oregon, and Clark County, Washington.

The Portland metropolitan region is vulnerable to regional and local earthquakes. We modeled damage for two earthquake scenarios: a magnitude 9.0 CSZ earthquake, and a magnitude 6.8 Portland Hills fault earthquake, a local crustal fault situated at the foot of the Tualatin Mountains. In order to better understand the range of possible losses, our analysis quantified impacts during saturated and dry soil conditions—the former are more likely to have earthquake-induced landslides and liquefaction; the latter may have some earthquake-induced landslides, but little occurrence of liquefaction. We derived our damage estimates primarily from Hazus®, a geographic information system (GIS)-based tool and set of methods for loss estimation from natural hazards. Hazus is developed and supported by the Federal Emergency Management Agency (FEMA).

Our project consisted of several major efforts:

- **Building and infrastructure databases**: completion of a region-wide building footprint database, a building database containing detailed descriptions of each building, and an electric power transmission structure database
- **Geotechnical mapping updates:** earthquake-induced landslide susceptibility, liquefaction susceptibility, and soil classification, using recently published high-resolution geologic mapping
- **Ground motion and ground deformation updates:** local ground motion and ground failure data for two earthquake scenarios using the geotechnical mapping updates
- **Earthquake damage estimates:** quantifying impacts to buildings and the people that occupy them, to the region's designated emergency transportation routes, and to the electrical grid

A GIS database containing building footprints, population density grids, detailed casualty, debris, and building loss estimates by jurisdiction and neighborhood, key infrastructure sectors with loss estimates, and updated ground motion and ground deformation data accompanies this report. A separately published report describes the geologic mapping updates for the three-county area, consisting of National Earthquake Hazards Reduction Program (NEHRP) soil types, and earthquake-induced landslide and liquefaction susceptibility.

A Cascadia Subduction Zone (CSZ) magnitude 9.0 earthquake will have a severe impact on the three-county area, with building repair costs amounting to between 23.5 and 36.7 billion dollars (9% and 14% of the total building replacement cost, **Table ES-1**). Although damage estimates vary widely throughout the study area, no community will be unharmed. Depending on the time of day an earthquake occurs, casualties may be in the thousands or low tens of thousands. The earthquake will generate several millions of tons of debris from damaged buildings. Damage and casualty estimates resulting from a magnitude 6.8 Portland Hills fault earthquake are more than twice compared to a CSZ earthquake, primarily because of the Portland Hills fault location below densely populated and heavily developed areas (**Table ES-1**). However, the likelihood of a Portland Hills fault earthquake is considerably less than a Cascadia Subduction Zone earthquake.

Table ES-1. **Loss estimate summary for two earthquake scenarios in the Portland metropolitan area. Lower value: dry soil conditions. Upper value: saturated soil conditions.**

County	U.S. Census Population Estimate (2010)	Number of Buildings	Building Value ($ Billion)	Building Repair Cost ($ Billion)	Building Loss Ratio	Debris (Millions of Tons)	Long-Term Displaced Population (Thousands)	Total Casualties* Daytime Scenario (Thousands)	Total Casualties* Nighttime Scenario (Thousands)
Cascadia Subduction Zone magnitude 9.0 earthquake									
Clackamas	375,992	179,164	62.4	3.2–4.6	5%–7%	1.7–2.1	1.9–10.1	2.0–2.8	0.5–1.1
Multnomah	735,334	255,577	114.0	13.3–20.5	12%–18%	7.7–10.4	9.7–37.5	11.4–16.7	2.8–5.6
Washington	529,710	181,111	82.7	7.0–11.6	8%–14%	3.4–4.8	5.2–37.7	4.9–7.7	1.1–3.7
Total	1,641,036	615,852	259.1	23.5–36.7	9%–14%	12.8–17.3	16.8–85.3	18.3–27.2	4.4–10.4
Portland Hills fault magnitude 6.8 earthquake									
Clackamas	375,992	179,164	62.4	12.9–16.4	21%–26%	4.9–6.0	25.2–50.8	8.9–10.9	3.3–5.2
Multnomah	735,334	255,577	114.0	32.3–42.7	28%–37%	15.7–19.3	50.8–120	28.9–36.3	9.3–15.3
Washington	529,710	181,111	82.7	15.4–24.3	19%–29%	6.0–8.6	19.6–86.0	10.0–15.8	3.2–8.5
Total	1,641,036	615,852	259.1	60.6–83.4	23%–32%	26.6–33.9	95.6–257	47.8–63.0	15.8–29.0

* Casualty estimates include minor injuries, injuries requiring hospitalization, and fatalities.

The damage estimates are significantly higher than those given in previously published studies for the area, primarily due to usage of an updated building inventory that more accurately reflects the region's building code history with respect to seismic resiliency, and usage of updated soils and liquefaction susceptibility data.

This study addressed a major need for consistent, updated earthquake damage estimates in the Portland metropolitan region. The data are intended not as an end in themselves, but as a platform for counties, jurisdictions, and communities to better understand their needs to prepare for, respond to, and recover from a major earthquake. We conclude our report with recommendations supported by findings in this study that can reduce the region's vulnerability, shorten recovery time, and improve emergency operations.

1.0 INTRODUCTION

1.1 Overview

Casualty and loss estimates for a modeled earthquake provide planners with actionable data for pre-earthquake preparations and mitigation and for post-earthquake recovery efforts. The Regional Disaster Preparedness Organization (RDPO), a bi-state partnership of local and regional government agencies, non-governmental organizations, and private-sector stakeholders representing the Portland Metropolitan Region, collaborate to increase the region's resiliency to disasters, including earthquakes. The Portland Metropolitan Region spans Clackamas, Columbia, Multnomah, and Washington Counties in Oregon, and Clark County in Washington (**Figure 1-1**).

Figure 1-1. Regional Disaster Preparedness Organization counties, spanning Oregon and Washington. Phase 1 study area in tan, proposed Phase 2 study area in lavender. County seats shown as dots.

One of RDPO's guiding principles is ensuring equity and fairness in adopting regional policies, and from an earthquake planning perspective, that principle requires loss estimates that are developed using consistent methods and data across the region. Prior to this study, loss estimates from earthquakes in the Portland Metropolitan Region were derived from several studies, each done at different times, using different datasets (Wang, 1998; Hofmeister and others, 2003; FEMA, 2004; Tetra Tech, 2016a). Technologies and data available for earthquake impact analysis have improved since these studies. RDPO requested that Oregon Department of Geology and Mineral Industries (DOGAMI) develop—using the best tools and methods, updated local geological data, and detailed building and infrastructure data—updated loss estimates from a major earthquake for the five-county RDPO area.

We divided the project into two phases. **Phase 1** focused on methodology refinement and application of those methods to evaluate impact of a major earthquake in **Clackamas**, **Multnomah**, and **Washington Counties** (Oregon)—the "study area." Phase 2 will apply the same methods in Columbia County, Oregon, and Clark County, Washington. This report documents our Phase 1 work.

The three-county study area is home to 44% of Oregon's total population. It continues to experience significant growth, with population increasing from 1.45 million people in 2000, to 1.64 million people in 2010, to 1.78 million people in 2016 (Portland State University Population Research Center, 2016, https://www.pdx.edu/prc/population-reports-estimates). By 2030, the study area's total population is projected at 2.10 million people (Oregon Office of Economic Analysis, 2013, http://www.oregon.gov/das/OEA/Pages/forecastdemographic.aspx). The area hosts 894,000 jobs, or 50% of all jobs in Oregon, with total annual wages estimated at $50.5 billion (Oregon Employment Department, 2016). The area includes an infrastructure hub that houses all of Oregon's major liquid fuel port terminals, and Port of Portland facilities that include the state's largest airport. Most of the population in the study area is concentrated in cities (76%), but all three counties contain large tracts of unincorporated suburban development. All three counties have broad areas of dispersed rural development.

Geology in the 3,076-square-mile study area varies widely, influenced by local and regional processes (Evarts and others, 2009). It includes Columbia River basalts, alluvial deposits, volcanic outcrops, loess deposits, dredge and fill material placed on top of former riverine wetlands, and large areas of fine-grained to coarse-grained Missoula flood deposits (Ma and others, 2012). The geological diversity creates significant local variations in earthquake ground motion and in ground failure from earthquake-induced landslides and liquefaction.

1.2 Earthquake Scenarios and Earthquake Loss Estimation

An earthquake scenario tells the story of a defined earthquake and its potential impacts to a community, presenting narratives and data that can help planners and community members better understand the earthquake and plan for the future (Earthquake Engineering Research Institute [EERI], 2006). Scenarios use the best scientific information available on fault placement, rupture frequency, and earthquake magnitude. Because the loss estimate data are used for planning purposes, scenarios incorporate the upper end of predicted magnitude when modeling a specific earthquake. Full earthquake scenario exercises incorporate experts from multiple backgrounds and responsibilities, such as transportation and utilities. Past examples include the Seattle Fault (EERI, 2005) and the Wasatch Fault (EERI, 2015) scenarios.

Our study is more limited in scope compared to the two example scenarios; we focus on damage to buildings and the people that occupy them, and to two key infrastructure sectors. In this report, our use of the term *scenario* refers to a specific combination of a particular earthquake and one or more additional variables. In order to provide planners a more complete picture of the range of potential impacts from a large earthquake, we modeled two distinct earthquakes: a Cascadia Subduction Zone and a Portland Hills fault. Each earthquake was modeled with a *wet* (saturated) and a *dry* soil condition, and each earthquake was modeled at two different times of the day, at "2 AM" and at "2 PM."

In western Oregon and Washington, soil moisture conditions vary widely throughout the calendar year. Soil moisture conditions influence the likelihood of an earthquake-triggered landslide or liquefaction. An earthquake occurring during wet (saturated) soil conditions is much more likely to induce landslides and liquefaction. Some earthquake-induced landslides may occur in dry soil conditions, but liquefaction is much less likely.

Throughout a typical day, people move between various buildings such as residences, schools, work facilities, and commercial facilities. Some buildings, due to their basic structural system, are more likely to sustain significant damage from an earthquake and, thus, depending on how many people are occupying the building at the time of the earthquake, cause more casualties.

Past earthquakes along the 600-mile Cascadia Subduction Zone fault (**Figure 1-1**) have occurred at highly variable intervals, from decades to centuries, and have ranged widely in magnitude (Oregon Seismic Safety Policy Advisory Commission [OSSPAC], 2013). At least 40 large-magnitude earthquakes have occurred along the fault in the past 10,000 years. The most recent earthquake, estimated at magnitude 9.0, occurred on January 26, 1700 A.D. Studies of the geologic record suggest that a Cascadia Subduction Zone earthquake of magnitude 9.0 has a 10% to 14% chance of occurring within the next 50 years (Petersen and others, 2002; Goldfinger and others, 2012). For the central and northern Oregon coast, recent research suggests the chance of occurrence within the next 50 years may be 15% to 20% (Goldfinger and others, 2017).

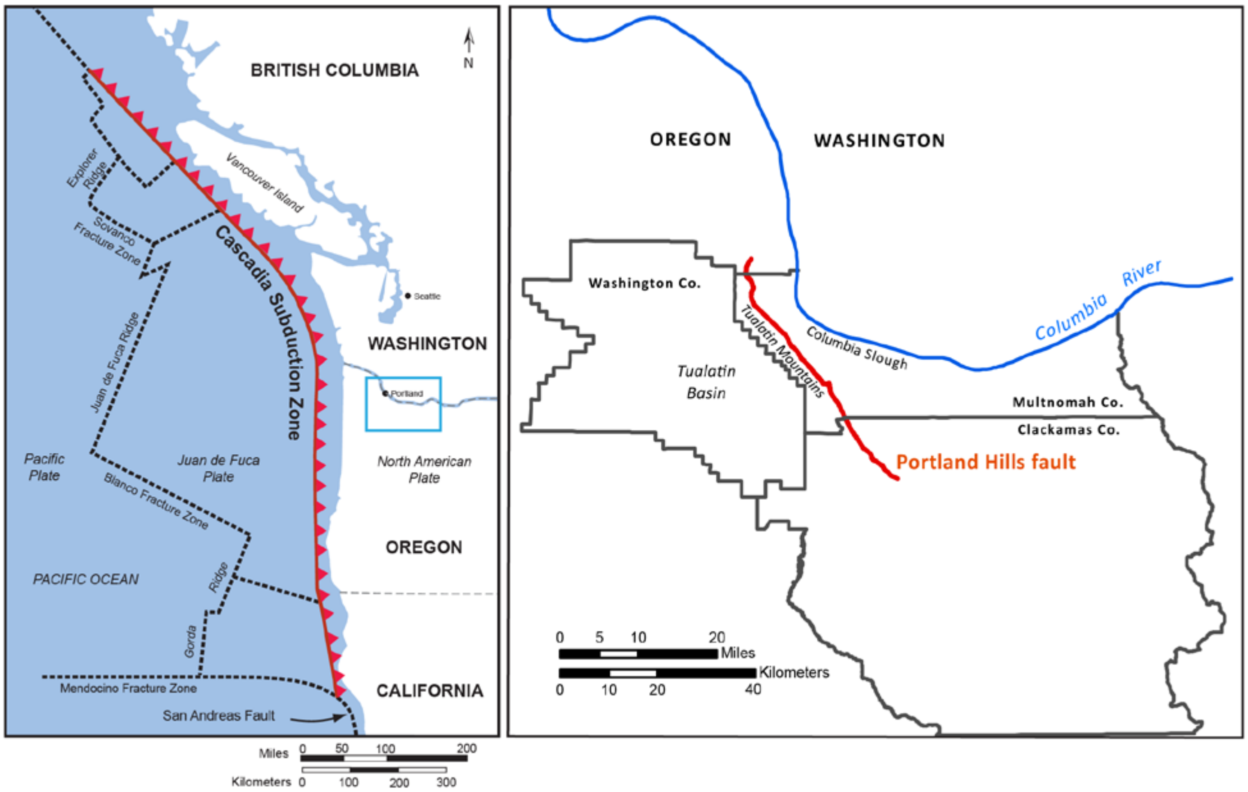
Although the Cascadia Subduction Zone fault has garnered significant attention, active local crustal faults should also be evaluated in an earthquake impact analysis. Wong and others (2001) concluded that the Portland Hills fault (**Figure 1-2**) might be seismogenic, with evidence suggesting two ruptures in the past 15,000 years (Liberty and others, 2003). Other active crustal faults exist in the Portland Metropolitan Region, but a rupture on the Portland Hills fault would be the most impactful, given its position directly underneath downtown Portland and the population centers of Clackamas County.

Hazus is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses geographic information system (GIS) technology to estimate physical, economic, and social impacts of disasters (FEMA, 2011). FEMA developed the earthquake model in cooperation with the National Institute of Building Sciences (Schneider and Schauer, 2006). Hazus damage and loss functions for generic model building types are considered to be reliable predictors of earthquake effects for large groups of buildings (FEMA, 2010). However, good estimates require accurate, updated data inputs.

The first Hazus-based study conducted in Oregon used a magnitude 8.5 model of a Cascadia Subduction Zone earthquake as it was understood at the time (Wang, 1998). The study was intended to provide an overall initial understanding of potential earthquake impacts across Oregon. Further, the Hazus tool at that time did not incorporate liquefaction or landslide information. Subsequent Hazus-based studies were limited to portions of the study area. The City of Portland had two Hazus-based studies (FEMA, 2004; Tetra Tech, 2016a), and Clackamas County had one Hazus-based study (Hofmeister and others, 2003). However, no studies have been conducted for Multnomah County (excluding the City of Portland) and Washington County since Wang (1998).

All previous Hazus-based earthquake studies in the study area were conducted at the census tract level—a spatial unit designated by the U.S. Census Bureau (https://www.census.gov/geo/reference/gtc/gtc_ct.html) that was chosen in the formative days of Hazus tool development out of computational necessity, but one that oversimplifies the building, seismic, and geologic heterogeneity within the census tract (Price and others, 2010). In the past five years, advances in Hazus tools and methods have enabled modeling earthquake damage using detailed data that incorporate local geologic variations and individual building seismic design characteristics. The advancements in the tools and methods provide more accurate loss estimates and permit analysis at a finer, neighborhood-scale level, rather than at the coarser census tract level. The updated methods require that considerable effort be expended on dataset development, including building and infrastructure inventory and local geological data. In Section 2, we provide background on the asset development, which includes all buildings and key infrastructure sectors in the study area. Further background on the key infrastructure sectors is in the following subsections.

Figure 1-2. Cascadia Subduction Zone fault (left) and Portland Hills fault (right) locations. Blue rectangle in left figure is shown in right figure.



1.2.1 Critical Infrastructure Sectors

The Cities of Eugene and Springfield Multi-Jurisdictional Natural Hazards Mitigation Plan (2014) identified three critical infrastructure sectors fundamental to the operation, maintenance, and restoration of all other infrastructure sectors—namely, electricity, transportation, and fossil fuels. Given the challenges of enumerating the numerous interdependencies among various sectors and of quantifying potential earthquake damage to the components of those sectors, we determined that by limiting our analysis to the key sectors identified in that plan, we could establish a basis upon which to build future infrastructure studies and interdependencies.

In the Portland Metropolitan Region, fossil fuel supply seismic resiliency has been analyzed by Wang and others (2013), with a focus on the Critical Energy Infrastructure (CEI) Hub in northwest Portland. Tetra Tech (2016b) quantified damage estimates to the CEI Hub's fuel storage structures for a Cascadia Subduction Zone and for a Portland Hills fault earthquake scenario, and DOGAMI provided a substantive review of the report. We did not see a need to revisit damage estimates to the nonbuilding structures contained in the CEI Hub. Nonbuilding structures include water towers, storage tanks, piers, dams, and carports, and where human occupancy is incidental (FEMA, 2012b).

A Hazus-based study of the City of Portland (FEMA, 2004) included an analysis of an earthquake impact to electric substations and the transportation network. Although it used best available liquefaction and landslide data, the study was limited to the City of Portland, and its spatial data were not made available for further analysis.

1.2.1.1 Electric Power Transmission

Electric power infrastructure consists of power generation and distribution, including dams, substations, transmission network, and local transformers. Within the network, substation components are typically the most likely to fail given strong ground motion (Fujisaki and others, 2014). Transmission structures (towers and poles) generally perform well under strong ground motion but can fail due to lateral movement from liquefaction or earthquake-induced landslides (Good and others, 2009). Hazus provides a simplified damage model from ground motion and ground failure for substations as a whole unit, but the model may be overly conservative (Kongar and others, 2014), and a more accurate model should consider individual substation components.

From our literature review we determined that our project should 1) provide updated ground motion and ground failure data for local utilities to better quantify their substation seismic resiliency, and 2) address the risk to the transmission network between substations by quantifying potential ground failure at the transmission structures. An example of earthquake-induced ground failure impact on a transmission structure is shown in **Figure 1-3**. Our approach builds on the previous exposure analysis of electric transmission structures to mapped landslides established by Burns and others (2011, 2013).

Figure 1-3. Example of ground failure underneath a transmission tower, 1999 İzmit earthquake (Turkey). Photographic credit: University of California, Irvine Consortium of University for Research in Earthquake Engineering Archives.

1.2.1.2 Emergency Transportation Routes

Functioning transportation networks are essential for emergency response and post-earthquake recovery. Regional planners have identified a subset of arterials in the study area as routes essential for providing emergency services. Understanding which routes may be impacted from an earthquake can permit planners to consider alternative routes or how to distribute services in a more dispersed manner. An example of earthquake-induced ground failure impact on a surface road is shown in **Figure 1-4**. A complete analysis would include a seismic analysis of the bridges and overpasses used by the emergency transportation routes, but such an analysis requires detailed field-gathered information (e.g., Wang, 2017) and was beyond the scope of this project.

Figure 1-4. Damaged road due to liquefaction-induced lateral spreading, 2001 Nisqually, Washington earthquake. Photographic credit: DOGAMI Archives.

1.3 Study Limitations

Hazus-based risk analyses often include damage estimates to various assets such as buildings, buried utilities, above ground utilities, and essential facilities. Such analyses typically use the inventory data that accompany Hazus. Out of necessity, the Hazus inventory data are constructed from readily available nationwide datasets, and often capture a portion of the non-building assets in an area. Users can supplant the inventory with more detailed information, but at significant development cost. Given the constraints on time and budget for this project, and the challenges of obtaining more detailed and accurate local data, we limited our analysis to buildings and the people that occupy them, and the two key infrastructure sectors previously discussed. Specifically, we did not analyze earthquake impacts to communication networks or towers, storage tanks, dams, levees, hazardous material facilities, and buried utilities conveying natural gas, potable water, oil, stormwater, and wastewater.

We did not identify or individually analyze specific buildings that may be considered essential or critical facilities. As discussed in the Recommendations section (Section 7), we maintain that the identification of such facilities should be community driven, and that an earthquake impact analysis of such facilities should be done by using the Rapid Visual Screening method (FEMA, 2015a) rather than a Hazus-based method using generic building models.

The Critical Energy Infrastructure (CEI) Hub along the Willamette River in northwest Portland was not analyzed in this report. A recent analysis conducted by Tetra Tech (2016b) provided a detailed damage assessment of the infrastructure from the same earthquake scenarios we used for this study. We did not include the hub's nonbuilding structures, such as oil tanks, in our building database.

Our economic loss estimates were limited to the direct cost of repairing a damaged building or replacing a severely damaged building with an equivalent structure. Our model assumes standard labor and material costs and availability of capital and credit. It does not factor in any demand surge. We did not model income losses such as wage and rental income, as we maintain that the impacts of a regional earthquake will fundamentally alter the local economy, rendering the basic assumptions used in the current Hazus model moot.

Our study focused on loss to buildings, which includes damage from earthquake-induced landslides and liquefaction. We did not quantify permanent loss of use, and thus value, of the land due to the ground failure. Such loss of use can add to the overall indirect economic loss.

2.0 ASSET DATABASE DEVELOPMENT

In this study we limited our analysis, and thus our asset database, to three components: buildings and the people occupying them, the electric power transmission infrastructure, and emergency transportation routes. A building is defined as a structure containing a roof and walls and occupied by people. Nonbuilding structures include water towers, storage tanks, piers, dams, and carports, and where human occupancy is incidental (FEMA, 2012b). We excluded nonbuilding structures from our building database. The electrical transmission network is limited to the towers and poles that supply power to the distribution substations (Appendix E, **Plate 1**). The surface transportation network is limited to a subset of highways, arterials, and roads identified as Emergency Transportation Routes (Appendix E, **Plate 10**).

2.1 Building Database

A Hazus-compatible building database contains a record for each distinct building, with each record containing required information for estimating damage to the structure and potential harm to the building's occupants (**Table 2-1**). Information associated with the building record, commonly referred to as attributes in a GIS context, is populated primarily from county assessor records or, where better data are available, from other ancillary datasets. Examples of such datasets are provided in **Table 10-1**.

Table 2-1. Building information required by Hazus earthquake model.

Hazus Attribute	Example	Purpose
Location of building	latitude, longitude	Extract ground motion and ground deformation data
Building usage	Single-family Residential; Retail Commercial	Repair/replacement cost; Number of people per building
Building material	wood; steel	Response to ground motion; debris
Year built	1968	Seismic design level: response to ground motion
Number of stories	2	Response to ground motion
Square footage	2250	Repair/replacement cost; debris
Daytime occupancy+	2.1	Casualty estimate
Nighttime occupancy+	3.4	Casualty estimate

+Daytime and nighttime occupancy amounts at the individual building level are based on proration of aggregated population data using the building's square footage, thus are typically fractional.

2.1.1 Building Footprint Development

A building footprint is a GIS polygon representation outlining the shape of the building. It defines a record in the building database. The building footprint establishes the location of the building, thereby placing the building relative to a natural hazard.

Because building footprints define the building record, our first task was to complete a building footprint database for the study area. Building footprints were obtained from Metro Regional Land Information System (http://rlisdiscovery.oregonmetro.gov/, downloaded February 2016) and from two DOGAMI publications (Burns and others, 2011, 2013). Large portions of western Washington County and southwestern Clackamas County had no building footprint data. In these areas we digitized building footprints following the methods described by Mickelson and Burns (2012, Section 3.2.3). Where lidar data were not present, we used 2016 orthoimagery from the National Agricultural Imagery Program (https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/index). Our digitization effort included removing obsolete building footprints (teardowns) and modifying existing building footprints where additions had been made or other digitization errors were noted.

We did not digitize structures less than 400 square feet in area, as such features are assumed to be non-building structures, such as kiosks, or are not reasonable to model within Hazus, such as portable storage sheds. Structures obtained from previous digitization efforts that were less than 400 square feet were retained in the building footprint database but were attributed as not modeled.

Nonbuilding structures include developments such as water towers, billboards, docks, dams, piers, and hoop houses. Outlines of such structures are often included in a building footprint database. Our study focuses on estimating damage from an earthquake to buildings and the people that reside in them. Many of the nonbuilding structures have no damage model or an overly simplified damage model within the Hazus framework. We identified such structures using orthoimagery and tax lot database queries, and we attributed them as not modeled.

Floating structures such as houseboats do not directly experience seismic shaking. We identified such structures using orthoimagery, attributed them as floating structures, and excluded them from our analysis. As with nonbuilding structures, we retained the building footprint of floating structures in the database. We note that floating structures may be damaged from seismic seiches (Jones and others, 2008).

In the building footprint database obtained from Metro RLIS, building complexes that contain two or more distinct, contiguous buildings were commonly digitized as a single building. Such buildings typically occur in downtown areas and can be identified by several methods, including their spanning multiple tax lots with unique owners, and distinct building heights derived from lidar elevation models. Seismic design level, building usage, and construction material can vary between such contiguous buildings, each of which can influence the damage estimate. We determined that dividing such polygons into individual buildings would result in a more accurate representation of the built infrastructure. Orthoimagery and street-level imagery further clarified whether a building footprint needed further partition. Building footprints digitized as part of this project factored in the guidelines for contiguous buildings.

Although parking garages are by definition nonbuilding structures, Hazus considers them as buildings in its occupancy class library (FEMA, 2011, Table 3.2). We retained that modest inconsistency in our building database by including parking garages in our damage assessment.

2.1.2 Assessor Database Processing

County assessor databases form the basis for assigning Hazus-required information for individual buildings, as the databases have information for most to all of the tax lots in the study area. We obtained detailed tabular data from the three county assessor offices. We used the tax lot spatial data from the Metro RLIS database to associate assessor tabular data with specific buildings, and we extracted information from the assessor tabular data to assign values to the appropriate attributes (**Table 2-1**). For example, Oregon Administrative Rules (OAR 150-308.215) require that county assessors assign a 3-digit property code for all tax lots in Oregon. We constructed a reference table to translate the tax lot property code into one of 36 Hazus occupancy classes, and we assigned that value to the particular buildings occupying that particular tax lot.

Assessor tabular data provided direct or easily-derived information for the following attributes: year built, square footage, number of stories, and building usage. None of the three county assessor databases had consistent information on building type (e.g., wood, steel).

2.1.3 Usage of Ancillary Data

We used a supersedence paradigm, overriding the assessor-derived data with more accurate data where available (Appendix A, Section **10.1**). For example, Lewis (2007) provided detailed information on square footage and building type for public buildings, such as schools, in Oregon. Other examples include the Metro RLIS spatial data on single-family and multi-family residential buildings, and the locations of educational, fire, and police buildings. Appendix A, Section **10.1** provides a complete list of other datasets used to populate the building database.

2.1.4 Building Type

The Hazus building type attribute specifies the basic structural system of a building. For example, a steel-framed building can be categorized as a steel light frame or a steel moment frame. The Hazus Advanced Engineering Building Module (AEBM) tool provides building damage functions for 36 generic building types (FEMA, 2010), and the FEMA Rapid Visual Screening handbook (FEMA, 2015a) provides qualitative descriptions of each building type. We classified all buildings in the study area into one of the 36 generic building types. Although Hazus AEBM permits one to create a unique performance model for individual buildings, such an effort was well outside of this project's scope, given its three-county scale.

We could not find any information in any of the three county assessor databases that provided consistent information on the building's primary construction material. Building types for a portion of the buildings were available from several sources, and we incorporated these into our building database. Lewis (2007) provided building types for public schools, fire, and police buildings. The most valuable dataset was the Metro Area Disaster GIS (MADGIS) database (Metro, 1998), with 40,000 buildings spread across all counties in the study area, categorized into Hazus-compatible building types.

For buildings that had no information on their primary construction material, we assigned a value based on the building's occupancy class, year built, and number of stories. We used an in-house tool that implements the statistical distributions listed in Tables 3.A1–3.A10 of the Hazus Earthquake Technical Manual (FEMA, 2011).

2.1.5 Building Replacement Value

We used the RSMeans valuation method for estimating a building's replacement cost (Charest, 2017), multiplying the building square footage by a standard cost per square foot. We used values from Hazus SQL database tables ([dbo].[hzReplacementCost] and [dbo].[hzRes1ReplCost]) that incorporated the RSMeans valuation to compute the replacement cost. We made no inflation or regional adjustments to the tabular data, for the following reasons. The Hazus tables were based on 2014 RSMeans national values. Because the Consumer Price Index difference between 2014 and 2017 was minimal, we made no further adjustment. The RSMeans location factor adjusts for regional differences in labor and material costs. Portland area's location factor of 0.98 for residential construction (Charest, 2017) was, for simplicity, rounded to 1.0, and thus we did not adjust cost; the commercial construction location factor at 1.0 also resulted in no adjustment.

Building replacement cost is not the same as a property's assessed value. For analysis purposes, we assume repair or replacement costs to damaged structures will be charged at standard construction rates and are independent of a building's age or the land on which the building is placed. Assessed value takes into account the land's value, which may fluctuate greatly depending on real estate markets, and for improvements, assessors typically factor in the building's depreciation into the assessed value.

An abnormal shortage of skilled labor or materials can occur after a large-scale disaster. Demand surge is a process resulting in a higher cost to repair building damage after large disasters than to repair the same damage after a small disaster (Olsen and Porter, 2011). Adjusting repair/replacement costs due to a likely demand surge was beyond the scope of this project.

2.1.6 Design Level Assignment

The design level assignment in the Hazus-MH earthquake model allows a user to specify, for the given building type, its seismic performance level. Oregon initially adopted seismic building codes in the mid-1970s (Judson, 2012). The established benchmark years of code enforcement are used in determining a "design level" for individual buildings. The design level attributes (pre-code, low-code, moderate-code, and high-code) are then used in the Hazus earthquake model to determine what damage functions are applied to a given building. The year built and the year of the most recent seismic retrofit are the main considerations for an individual design level attribute. We used the benchmark years listed in **Table 10-2** to assign a design level to each building. We are not aware of any building codes adopted at the local or county level that supersede, from a seismic design perspective, building codes established by the Oregon Building Codes Division.

In the past 20 years, many property owners, including private, public, and institutional, have implemented building seismic retrofits—modifications that improve building's seismic resilience. Ideally, we would obtain and incorporate such information into our database, instead of assigning a seismic design level based on the structure's original year of construction. However, such information was not available in any centralized, usable form from any of the county's permitting or assessor offices. The City Club of Portland's analysis (2017) identified a lack of reliable data, in part because permits are not often filed with seismic upgrades, or the seismic upgrades to a building may be part of a larger renovation. We found only one source of data for such information—the Unreinforced Masonry Building database maintained by the City of Portland (2017). Buildings identified as upgraded, 290 total, were assigned Reinforced Masonry (RM1), moderate code building type and design level values, respectively. The dataset was limited to the City of Portland. City Club of Portland's report (2017) found no other source of data for identifying locations of unreinforced masonry buildings in the region.

2.1.7 Daytime and Nighttime Population

In order to calculate casualties and displaced persons, we estimated the number of people occupying each building under two commonly implemented temporal scenarios: daytime and nighttime, commonly referred in a Hazus context as a "2 PM" and a "2 AM" scenario. The nighttime population assignment assumes that at least 95% of the people are in their primary residences and that nonresidential buildings have some level of occupancy, depending on their function. Fire stations, for example, are occupied by a nighttime shift. The daytime scenario assumes a typical weekday in a school year, with population distributed across schools, work facilities, and homes. The population assignments are primary driven by U.S. Census population data, the building's specific usage (i.e., its Hazus-designated occupancy class), and the building's square footage. We did not implement a "5 PM" scenario, as that requires assumptions on road occupancy and bridge failure models, and an evaluation of bridge and overpass seismic design performance was beyond the scope of this project.

For assigning permanent resident population quantities to residential buildings, we pro-rated the U.S. Census Bureau 2010 permanent population value for a given U.S. Census Bureau-defined census block group across the residential buildings, excepting the RES4 (hotel/motel) type, on a square footage basis. We determined that the census block geometries are often imprecise relative to building footprints, creating frequent scenarios where a census block has one or more residential buildings and zero permanent residents, or zero residential buildings and one or more permanent residents. The census block group's geometries are generally along arterials or physiographic features. Although pro-rating at the census tract was a possible alternative, we decided the finer resolution of the census block group provided the best estimate of residential building occupancy, one that reflected varying demographics within a larger census tract. We retained a *permanent resident* population field, and we populated the *nighttime population* for residential buildings by multiplying the permanent resident population by 0.95—slightly less than the 99% suggested by FEMA (2011, Table 13.2), and one that accounts for night shift employment and recreational and business travel.

For daytime population in nonresidential buildings, we considered the suggested peak population density numbers published in the Hazus Tsunami Model Technical Guidance (FEMA, 2017c, Table 3.14), but we observed that the daytime population was at least 3 times the permanent population of the study area. We determined that such a ratio was unreasonably high, as we assume that at least 75% of the working population in the study area reside within the study area. Instead, we computed people-per-square-footage (ppsf) values by using the estimated commercial, industrial, and educational population estimates by Census Tract in the Hazus SQL database table [dbo].[hzDemographicsT], and our own building stock square footage summaries, and then used the ppsf values and the individual building's square footage to assign people per building.

We assigned daytime populations for residential buildings and nighttime populations for nonresidential buildings by using the Day to Night ratios provided by FEMA (2017c, Table 3.14).

Permanent resident figures per residential building were based on the April 1, 2010 U.S. Census numbers and the 2010 U.S. Census Block Group boundaries. The study area has seen significant growth since then, with the most recent estimate (July 1, 2016 Certified Population Estimates, Portland State University Population Research Center, https://www.pdx.edu/prc/population-reports-estimates) showing an 8.4% increase from 2010. Several jurisdictions have had boundary adjustments via annexations since 2010. Planners may wish to adjust the displaced population and nighttime casualty estimates using the percentages shown in **Table 2-2**. Given the larger uncertainty with the daytime population assignments compared to nighttime population assignments, we do not recommend adjusting daytime casualty numbers.

Table 2-2. Population changes in the study area, 2010 to 2016. Limited to cities with 2010 population of 20,000 or more people and with no to minimal annexations between 2010 and 2016. Certified Population Estimate: Portland State University Population Research Center.

County or Jurisdiction	2010 U.S. Census Population	Certified Population Estimate July 1, 2016	Percentage Increase
Study Area	1,641,036	1,779,245	8.4%
Clackamas County	375,992	404,980	7.7%
Multnomah County	735,334	790,670	7.5%
Washington County	529,710	583,595	10.2%
Portland	583,776	627,395	7.5%
Gresham	105,594	108,150	2.4%
Lake Oswego	36,619	37,425	2.2%
Oregon City	31,859	34,240	7.5%
Tualatin	26,054	26,840	3.0%
West Linn	25,109	25,615	2.0%

2.2 Electric Power Transmission

We constructed a transmission pole and tower point file database from several data sources, including Burns and others (2011, 2013), spatial data obtained from Portland General Electric Company (PGE, written communication, 2016), and where large gaps occurred, from our own digitization. Gaps in the transmission network were highlighted using the transmission line corridors and substations dataset downloaded from the Homeland Infrastructure Foundation-Level Data (HIFLD; U.S. Department of Homeland Security, 2017). The linear corridor data were used as a backdrop to digitize additional poles and towers, following the method established by Burns and others (2011). We did not distinguish between the type of structure (e.g., lattice tower or wood) or the voltage carried on the wires. To keep the problem tractable, we limited our analysis to the high-voltage network from power generation facilities up to the neighborhood distribution substations.

We identified a total of 18,098 poles and tower locations. The transmission network is incomplete, however, as we did not complete digitization of poles and towers in portions of North Portland, and data were not made available from the local utility. Electric power transmission distribution in North Portland is typically conveyed on single poles, which are difficult to distinguish using lidar-derived imagery or orthoimagery.

2.3 Emergency Transportation Routes

We obtained a GIS shapefile representing the Metro Emergency Transportation Routes (ETR) from Portland Bureau of Emergency Management (L. Bruno, written communication, 2017). Though the Metro Data Resource Center has not maintained the dataset for at least 10 years (S. Erickson, written communication, 2017), it is still considered operative at the regional level. The ETR extends into all five counties within the RPDO (**Figure 1-1**), but our analysis was limited to our three-county study area (Appendix E, **Plate 10**). Multiple transportation agencies have responsibility for various components of the ETR, and as outlined in a 2005 Memorandum of Understanding (Emergency Transportation Route Post-Earthquake Damage Assessment and Coordination Portland, Oregon/Vancouver, Washington Regional Area; State of Oregon Misc. Contracts & Agreements No. 21,273):

> (Terms of Agreement #1): ODOT, WSDOT and Agencies have identified the ETR. […] The ETR have been identified as "critical infrastructure" by the parties to the Memorandum of Understanding. ODOT, WSDOT and Agencies would give their jurisdictional ETR the highest priority for assessment of road and bridge conditions during an earthquake emergency […]
> (Exhibit A, I. Purpose [p. 8]): An Emergency Transportation Route or ETR is defined as a route needed during a major regional emergency or disaster to move response resources such as personnel, supplies, and equipment to heavily damaged areas.

The road network consists of GIS polylines placed at the road centerline and includes highway ramp and detailed highway intersection information. For our analysis purposes, polylines are not as useful as polygons, as we need to quantify the amount of ground deformation to a road that has some width. In order to prepare the road network for analysis, we first buffered the road centerlines by 50 foot, and then we dissolved the geometries. This typically generalizes highway areas, such as the I-5 corridor, into a single polygon. The dissolved polygon file was then manually edited to create a segment/node model, with segments beginning and ending at intersections. However, major intersections, such as the I-5—I-205 intersection, were treated as a single segment instead of a node. We identified 238 road segments and gave each a unique key for analysis purposes.

3.0 NATURAL HAZARD DATA DEVELOPMENT

3.1 Bedrock Ground Motion

The Hazus model requires four descriptors of ground motion at a building's location: peak ground acceleration (pga), peak ground velocity (pgv), spectral acceleration at 1.0 second (sa10), and spectral acceleration at 0.3 second (sa03). Peak ground acceleration and peak ground velocity are the largest acceleration and velocity that can be expected at a particular site due to an earthquake. Peak ground acceleration is a widely used measure of ground shaking for a range of geotechnical and structural engineering applications. Spectral acceleration definitions and usage are given by the U.S. Geological Survey (USGS) at https://earthquake.usgs.gov/hazards/learn/technical.php.

For the Cascadia Subduction Zone magnitude 9.0 earthquake, Madin and Burns (2013) obtained synthetic bedrock ground motions from Arthur Frankel (USGS, written communication, 2012); we used the same bedrock ground motion data for this project. Bedrock ground motions for a synthetic Portland Hills fault magnitude 6.8 earthquake (firm rock conditions, V_{s30} = 760 m/s) were provided by Arthur Frankel (written communication, 2016) of the USGS at 0.01 degree intervals and are included in the accompanying geodatabase.

3.2 Site Ground Motion

The intensity of ground shaking during an earthquake depends on the geotechnical properties of the soil or bedrock at a particular site. The National Earthquake Hazard Reduction Program (NEHRP) provisions (FEMA, 2015b) specify, for each ground motion descriptor, level of bedrock ground motion, and NEHRP soil classification, a multiplication factor for calculating the ground motion at the surface (also known as the site) where buildings and infrastructure are placed. The NEHRP soil classification for a site is based on the average shear wave velocity within 30 meters of the ground surface. NEHRP classifications and general descriptions of the bedrock and soil material are as follows:

- site class A—hard rock
- site class B—rock
- site class C—very dense soil and soft rock
- site class D—stiff soil
- site class E— soft soil
- site class F—soils susceptible to potential failure

For our site ground motion data, we used updated NEHRP soil classification mapping that we completed as part of this project (Appleby and others, in preparation). Sites classified as "F" were, for amplification purposes, reclassified as "E". This is a conservative but commonly implemented assumption for loss estimation purposes. We overlaid the bedrock ground motion data with the NEHRP soil classification polygons, and we applied the appropriate amplification to derive the site ground motion. Further details on the site ground motion dataset development are provided in Appendix B.

The site ground motion from the synthetic earthquakes in our two scenarios differ dramatically across the study area, with the Portland Hills fault exhibiting significantly higher ground motion proximal to the fault (Appendix E, **Plate 5**). The technical descriptions of earthquake ground motion, such as depicted on Plates 4 and 5 (Appendix E), can be challenging to interpret, so we developed damage potential maps using the Modified Mercalli Intensity (MMI) scale (Appendix E, Plates 6 and 7). The MMI scale is an empirical scale that describes the building damage and felt effects experienced from ground shaking in an earthquake. For the MMI categories, we used our site peak ground velocity ground motion data and the relationships used by USGS ShakeMap products (Wald and others, 2006, Figure 2.5).

What is not depicted in such maps is the duration of the earthquake. A local crustal fault will likely result in strong ground motion for up to 60 seconds, whereas a megathrust earthquake typically results in strong ground motion for 3 to 5 minutes. The Hazus building damage model uses the magnitude of the earthquake as a surrogate for duration, categorizing the earthquake as short, medium, or long duration (FEMA, 2011, Section 5.4), with a longer duration producing more building damage for a given ground motion. The Cascadia Subduction Zone magnitude 9.0 earthquake was modeled in Hazus as long duration, and the Portland Hills fault magnitude 6.8 earthquake was modeled in Hazus as medium duration.

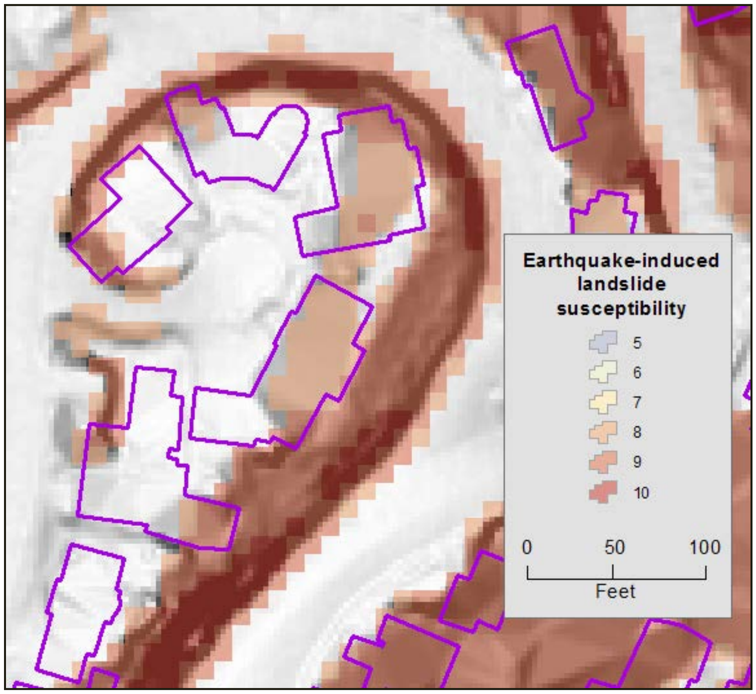
3.3 Liquefaction and Landslide Susceptibility

For our Hazus building damage model, we provided a liquefaction and landslide susceptibility value for each building record, thereby allowing the Hazus model to calculate the amount of ground deformation and probability of ground deformation. The Hazus building loss model incorporates that calculated information into its overall building damage estimate.

A Hazus-based liquefaction susceptibility rating for each building record was obtained by using a simple overlay of the liquefaction susceptibility polygons developed for this project (Appleby and others, in preparation). Because the liquefaction susceptibility polygons are at a coarser scale relative to the building footprints, we determined that assigning the liquefaction susceptibility value at the building centroid was sufficient.

We developed a high-resolution, 10-foot Hazus-based landslide susceptibility grid for this project (Appleby and others, in preparation), following the methods specified in the Hazus®-MH 2.1 Technical manual, Earthquake model (FEMA, 2011, Chapter 4), for both a wet (saturated) and a dry scenario. We calculated landslide susceptibility zonal statistics for each building footprint by using the Esri® Spatial Analyst Zonal Statistics as Table tool. The arithmetic mean of the landslide susceptibility, rounded to the nearest integer, was then assigned to the building record. Such an assignment more accurately captures the earthquake-induced landslide hazard across the entire building footprint area, compared to a simple building centroid sampling approach (**Figure 3-1**).

Figure 3-1. Example: Capturing the variability of landslide susceptibility within building footprints (magenta polygons). Landslide susceptibility values use the Hazus landslide susceptibility 0 through 10 scale. Areas of no shading: minimal to no landslide susceptibility. Earthquake-induced landslide susceptibility data from Appleby and others (in preparation).



Liquefaction requires saturated soil conditions. Hazus permits a user to specify, on a per-building basis, the depth of the water table, and adjusts the ground failure estimates accordingly. However, there currently exists no region-wide groundwater mapping information. Water tables vary significantly throughout the year, and even if such information were available, the use of an average water table level could significantly underestimate liquefaction occurrence during peak moisture conditions. We were aware of a regional groundwater study (Snyder, 2008) but noted that it covered only a portion of the study area. We chose to mimic the "wet" (saturated soil) and "dry" landslide scenarios by setting water depth to two distinct values: 0 feet and 1,000 feet, respectively. Thus, each of the two synthetic earthquakes was run with "wet" and "dry" soil moisture conditions, for a total of four unique scenarios.

3.4 Permanent Ground Deformation

Permanent ground deformation (PGD) data include an estimate of the amount of lateral spreading due to liquefaction and ground failure due to earthquake-induced landslide, along with a probability of their occurrences. We provided the liquefaction and landslide susceptibility data from Appleby and others (in preparation) and the site ground motion data for both earthquakes developed in Section **3.2** as input to the tool developed by Sharifi-Mood and others (M. Sharifi-Mood, M. J. Olsen, D. T. Gillens, and I. P. Madin, Complementary ground motion, ground deformation, and damage potential maps for deterministic scenarios of Cascadia Subduction Zone earthquake events, manuscript in preparation). The tool implements the methods for ground deformation estimation described by Madin and Burns (2013, Section 4), and provides raster grids describing the PGD amount and probability of occurrence, using the Hazus ground deformation models described in the Hazus-MH 2.1 Technical manual (FEMA, 2011).

Because the tool is currently constrained to calculating liquefaction lateral spreading at a fixed water depth, we generated liquefaction ground deformation (lateral spreading) data for only the “wet” (saturated soil) scenario. We calculated earthquake-induced landslide ground failure data for both wet and dry soil condition. The PGD and probability of occurrence data are in the accompanying geodatabase. Further details on the dataset development are documented in Appendix B, Section **11.2**.

To quantify impacts to infrastructure, we combined the grids from the two ground failure mechanisms, obtaining the maximum PGD and maximum probability of occurrence across the area for a given earthquake and soil moisture scenario. Although liquefaction and landslide are two distinct physical mechanisms, the specific cause of the ground failure is not important for our key infrastructure sector analysis purposes.

4.0 LOSS ESTIMATION METHODS

4.1 Impacts to Buildings and People

4.1.1 Building Repair Cost and Casualties

We used the Hazus Advanced Engineering Building Module (AEBM) (FEMA, 2010) included in Hazus-MH v4.0 to calculate individual building repair costs and casualties and to obtain parameters needed to calculate debris and displaced population. Although the AEBM permits a user to specify unique building profiles, including adjusted individual capacity curve or fragility curve parameters, we instead used the generic building profiles provided in the Hazus SQL database table [dbo].[eqAebmProfile]. The particular AEBM profile for an individual building in the building database is constructed from its occupancy class, building type, and seismic design level. The building's square footage, replacement cost, daytime occupants, and nighttime occupants were also supplied to the Hazus AEBM model.

The Hazus AEBM model was run for a given user-supplied seismic scenario, with site ground motions supplied in polygon form. The model returns a building repair cost and casualty estimate for each building, along with five probability of damage state (PDS) values, each, for the structural, nonstructural drift, and nonstructural acceleration components. We used the PDS values to calculate debris and displaced population and to estimate the total number of red-tagged and yellow-tagged buildings.

The Hazus AEBM model first calculates a building's structural and nonstructural probability of damage state values from the ground motion and liquefaction/landslide data provided to the model. It then uses the PDS values to calculate casualties, based on the number of user-specified people occupying the building and the building type. The methodology is based on the assumption of a strong correlation between building damage and number and severity of casualties (FEMA, 2011). Casualties are classified into four levels (**Table 4-1**). Levels 2 and 3 are generally interpreted as "injuries requiring hospitalization."

Table 4-1. Hazus casualty level descriptions (taken from FEMA, 2011). The broad description of each category is shown in boldface.

Injury Severity Level	Injury Level Description
Level 1: **Minor Injuries**	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self-treated are not estimated by Hazus.
Level 2: **Injuries Requiring Hospitalization**	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration, or exposure.
Level 3: **Life-Threatening Injuries**	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Level 4: **Deaths**	Instantaneously killed or mortally injured.

4.1.2 Building Debris Estimation

The Hazus AEBM does not provide a debris estimate for a damaged building. We manually calculated debris by first calculating the total weight of each building, in tons, using the total square footage of the building, the type of building (e.g., steel frame or wood frame), and the per-square-footage weight estimates listed in the Hazus SQL database table [dbo].[eqDebrisAnalParms]. Debris was then calculated based on the methods outlined in the Hazus Earthquake Technical Manual (FEMA, 2011, Equation 12-3), by using the structural and nonstructural drift probability of damage states obtained for the individual building from the Hazus AEBM.

The debris estimate is limited to buildings. We did not estimate debris tonnage from landslides, damaged bridges, buckled roads, sand and silt ejecta caused by liquefaction (Villemure and others, 2012), or damaged nonbuilding structures.

4.1.3 Displaced Population and Shelter Needs

Unlike the Hazus General Building Stock tool, Hazus AEBM does not calculate displaced households or displaced population. We adapted the methods outlined in the Hazus Earthquake Technical Manual (FEMA, 2011, Chapter 14), but instead of calculating displaced households we calculated displaced population. Displaced population is more direct to calculate given the methods discussed previously for assigning people, and not households, to distinct multi-family and single-family residential buildings (Section **2.1.7**). We followed the guidance provided by FEMA (2011, Table 14.1) that was based on the work of Perkins and Chuaqui (1998), but we altered the weight factor for multi-family residential building type, W_{MFE}, by setting it to zero. The displaced population then becomes a simple computation: the number of permanent residents in the building times the building's probability of *complete* structural damage state, with the latter factor directly obtained from the Hazus AEBM output.

We equated the red tag term used in a post-earthquake building safety evaluation context (ATC, 1989) with the Hazus "complete" structural damage state, following the guidance of FEMA (2010, Table 6.1). Similarly, yellow tag was associated with "extensive" damage state, and green tag with buildings in a none, slight, or moderate damage state. We recognize that alternate mappings of Hazus damage states or repair costs to ATC-20 tag levels exist (e.g., MMI Engineering [2012] presents two such definitions).

The Hazus displaced population computation assumes the building has been categorized into one of the three ATC-20 tags. In practice, the post-earthquake building inspection process is estimated to take weeks, if not months (EERI, 2015; p. 25). Thus, what is being computed is an estimation of *post*-inspection, longer-term displaced population. Our summary tables use the term *Long-term Displaced Population* to emphasize the point.

The topic of displaced population and shelter needs is involved, and estimates can vary throughout the response and recovery phases based on numerous factors, including psychological, sociological, and economic considerations. For example, some portion of the population may occupy a damaged building until it is officially inspected and red tagged, at which point they must vacate. An owner of a moderately damaged (green-tagged) apartment building may decide to replace the structure rather than repair it. For this project, we provide detailed information on permanent residents per building damage state, thereby allowing a basis from which to estimate Day 1, Day 7, and Day 30 displaced population and shelter needs (Appendix C, **Table 12-4** through **Table 12-7**). A portion of the displaced population may need long-term publicly provided shelter while residences are repaired or replaced (FEMA, 2011, Section 14.3). We determined that the ethnic, racial, and income level factors listed in Hazus Earthquake Technical Manual (FEMA, 2011, Equation 14.2) were too assumption-laden, and thus we did not calculate shelter requirements with such factors. For reference purposes, past Hazus runs for a Cascadia

Subduction Zone earthquake that used these assumptions calculated the portion of displaced population needing temporary shelter/housing solutions between 20% and 30% (Wang, 1998; Hofmeister and others, 2003; EERI, 2015, p. 34).

4.1.4 Aggregation Unit

Although the inputs into the Hazus model are individual buildings with occupants, loss estimates from the model are statistically meaningful only at an aggregated level. As Pinter and others (2016) emphasized, Hazus-calculated damages are estimates appropriate for comparison and planning purposes, particularly when pooled among a group of structures. Hazus-calculated damages are not appropriate for individual building analysis. We considered various aggregation units, including city neighborhoods and fire districts. Several jurisdictions in the study area have well-defined neighborhoods, but most do not. Further, unincorporated areas have no formal or usable neighborhood definitions. For example, we considered fire districts in unincorporated areas, but we determined they were too coarse to be useful for community level planning.

We chose the census block group (CBG), a U.S. Census Bureau-designated geographical unit that is between the census tract and the census block, as the basic mapping aggregation unit for damage estimates. Census block groups typically have between 600 and 3,000 people, but the number of buildings can vary widely, depending on the type of buildings and the number of multi-family residential structures within a CBG. Where warranted, we combined contiguous CBGs to create a larger unit encompassing at least 300 buildings. The process resulted in reducing the study area's 1,041 CBGs into 876 *neighborhood units.*

To provide a larger-scale perspective across the study area, we also aggregated loss at the jurisdictional level, with all buildings associated with a particular city, designated community, or unincorporated county. The jurisdiction layer combined city jurisdictional boundaries published by Metro RLIS (Metro, 2016), along with hamlet and village designations by Clackamas County (2017). Given the City of Portland's size relative to surrounding cities, we used the Portland Bureau of Emergency Management's (PBEM) Risk Reporting Areas (Tetra Tech, 2016a, Section 4.4, Table 4.4) as subdivisions for aggregation. All buildings not associated with a jurisdiction were designated as unincorporated.

4.1.5 Seismic Design Level Improvement Modeling Exercise

Most of the buildings in the study area were constructed with minimal consideration given to seismic resilience (**Table 10-3**). Seismic retrofits to more vulnerable buildings can reduce damage to the building and casualties to the building occupants when an earthquake occurs. Our Hazus model can be used to generate an overall benefit estimate for seismic retrofitting. Levi and others (2015) performed such an analysis for Israeli building inventory, where at least 25% of the building inventory was designed with minimal resistance to earthquakes.

We ran two alternative loss scenarios, wherein we upwardly adjusted seismic design levels within our building database. For the moderate scenario, all buildings with a seismic design level of pre code or low code were updated to moderate code, and all unreinforced masonry buildings were altered to RM1 (reinforced masonry) building type. Buildings with high code were left unchanged. For the high scenario, the seismic design level was set to high code for all buildings, with all unreinforced masonry buildings altered to RM1 (reinforced masonry) building type. We then ran Hazus AEBM, using the same ground motion, liquefaction/landslide susceptibility, and building population occupancy, and tabulated loss estimates (see Section 5.3.1). Our analysis was limited to the Cascadia Subduction Zone earthquake scenario, and run for both wet (saturated) and dry soil conditions.

4.2 Electric Power Transmission

Using the ground deformation estimates, we calculated the mean lateral spread within a 10-meter buffer of each transmission structure for the Cascadia Subduction Zone earthquake and Portland Hills fault earthquake, for wet (saturated) and dry soil moisture conditions. The mean permanent ground deformation at each point was then classified into three categories: less than 1 meter, 1 to 2 meters, and greater than 2 meters. For all points with greater than 1-meter permanent ground deformation, the probability of occurrence is between 20% and 30% (Appendix E, **Plate 13**).

4.3 Emergency Transportation Routes

The Hazus tool provides an analysis of linear features such as roads, but we determined it inadequately captures the range of variability of permanent ground deformation throughout the length of the segment. Currently, the tool samples only at the linear feature segment's endpoints and at its midpoint. We take a conservative approach in our evaluation of earthquake impact on surface transportation by considering the possibility of permanent ground deformation across the entire length of the road segment. A road segment is considered failed if any portion of that road segment exceeds an amount of ground deformation and a probability of occurrence.

Ground deformation and probability estimates were available in a 10-foot raster grid format (Section **3.4**). We combined the landslide and liquefaction PGD grids using Esri Spatial Analyst Cell Statistics function to obtain the maximum value per pixel. For our analysis purposes, the mechanism of the ground failure is not relevant; the amount and probability of lateral spread is of primary concern. Following the methods outlined by Mahalingam and others (2015), we then generated a new grid based on focal statistics of the ground deformation within a 100-foot window (10 pixel × 10 pixel; a pixel is 10 ft). Inclusion of surrounding areas adjacent to the road segment is a more conservative approach, because we wanted to include potential landslides slightly distant from the road. We then classified the maximum value of the ground deformation within each road segment into four bins, using Esri Spatial Analyst Zonal Statistics as Table tool: less than 0.5 meters, 0.5 to 1.0 meters, 1.0 to 2.0 meters, and greater than 2.0 meters. The process was repeated for the CSZ dry soil conditions scenario and the PHF wet (saturated) and dry soil conditions scenarios, with the results stored in the accompanying geodatabase. Appendix E, Plates 10 and 11 represent the impacts of ground failure per segment under a Cascadia Subduction Zone earthquake, given the two soil moisture scenarios. For another perspective, Appendix E, **Plate 12** highlights the maximum potential permanent ground deformation at specific locations throughout the segment.

4.4 Model Limitations

Our damage estimates were primarily derived from the Hazus AEBM. Limitations and uncertainties are inherent in any loss estimation methodology. They arise in part from incomplete scientific knowledge concerning earthquakes and their effects on buildings and facilities.

4.4.1 Geological Models

An actual earthquake may vary significantly in ground motion and site amplification compared to the synthetic data we provided the model in this study. Our analysis used the best available information for a subduction zone fault and a local crustal fault. We used the upper bound for the earthquake magnitude, recognizing that an actual earthquake may rupture on only a portion of its fault. Further, the

NEHRP site classification is a simplification of complex surficial geology, and local site amplification effects within a given NEHRP site class may be at significant variance with the standard ground motion amplification model.

We did not model damage from aftershocks. Wein and others (2017) presented scenario examples and the consequences of such earthquakes. The impact of aftershocks on slightly damaged buildings has be modeled in a Hazus context (Seligson and others, 2015), but we did not have aftershock scenarios available, nor was such modeling within the scope of our project.

Although our loss model includes the impact of earthquake-induced landslides on buildings, we do not model the impact of large landslide flows on structures downhill from the source. Such flow can wreak significant damage to buildings and people (Daniell and others, 2017), but such modeling capability is not available with existing tools.

4.4.2 Building Damage Models

Limitations and uncertainties also result from the approximations and simplifications that are necessary for comprehensive analyses. Although we gave extensive effort to correctly attributing each of the 615,852 individual buildings in this study, we recognize that misclassifications are present, and we made statistical distribution assumptions on building type when attribution information was not otherwise available.

We used the generic building damage models provided by the Hazus tool. These models simplify the vast variability present in existing building construction, such as vertical irregularities, plan irregularities, usage of cripple walls, hybrid construction techniques, and pounding from adjacent buildings (FEMA, 2015b). The Hazus AEBM allows a user to specify individual building-specific parameters, but it is not possible to conduct a study at this regional scale that incorporates such detail. The Hazus generic building damage model captures the *average* building response to an earthquake—the primary reason we present loss estimates not at the individual building level but at a minimum aggregation unit (Section **4.1.4**).

The duration of a subduction zone earthquake is significantly longer than for other types of earthquakes, including those generated from local crustal faults. Although the Hazus tool provides a method to distinguish short, medium, and long shaking duration (FEMA, 2011, Equation 5-10), the damage functions are expert- and model-driven. The most recent long-duration earthquake to impact the United States was Alaska's Good Friday earthquake in 1964, which was approximately 4.5 minutes long. Post-earthquake damage assessment protocols were not in place at the time. Hazus modelers do not have USA-construction-based empirical data for long-duration earthquakes from which to calibrate the model. The current Hazus model may be underestimating the damage to tall buildings and other large structures in response to great subduction zone earthquakes. Gomberg and others (2017) have identified this as an important research need.

In **Tables 12.8** through **Table 12.11**, we present Hazus damages and casualty estimates as single value. Such representations can be misleading, as they suggest a high level of precision that is not warranted, in part by the uncertainties of the data that were provided to the Hazus model (Remo and Pinter, 2012). One reason we chose to model both wet (saturated) and dry soil condition scenarios for a given earthquake is to better communicate our damage estimates as a range of values (**Table ES-1**).

4.4.3 Casualty Estimates

Casualty estimates are dependent on several assumptions and may underestimate the true impact from an earthquake. Daytime occupancy values use people-per-square-footage assumptions, which may be reasonable in the aggregate, but building occupancy density can vary significantly across businesses that are grouped for our modeling purposes into a fixed classification, such as “Commercial-Retail.” Running Hazus with a large number of alternate point-in-time population models may assist in better understanding the uncertainty in daytime casualties (FEMA, 2012a, Section 3.4).

In the Hazus AEBM, the casualty calculations do not include injuries to people outside of and proximal to a building. During strong ground motion, fascias can fall off buildings, masonry walls can collapse, and windows can shatter, sending shards of glass down to the pavement. Other casualties, such as from heart attacks, loss of power to medical devices such as respirators, electrocutions, collapsing bridges, exposure to released hazardous materials, and car accidents are not quantified in the Hazus model. Further, we did not model fire following earthquake, which can result in additional casualties.

4.4.4 Other Model Limitations

Fires typically follow a major earthquake and are exacerbated by compromised transportation networks and broken buried utilities. Fire following earthquake can be a major contributor to building loss and displaced population (Scawthorn and others, 2005). Early versions of the Hazus tool modeled “fire following earthquake” as an induced damage; however, due to significant bugs producing erroneous damage estimates, the option had been disabled in recent versions of the tool. The Hazus v4.2 release (FEMA, 2018) restored the Fire Following functionality, but the tool release was not available in time for this project, which used Hazus v4.0.

Several other sources may contribute to road damage, none of which we modeled in this project, and thus may lead to an underestimate of road damage. Our road damage model does not include debris generated by taller buildings that may block road access, or a road cordoned off due to a proximal building that is in danger of collapse (City Club of Portland, 2017). Our Hazus-based landslide ground deformation model does not incorporate deposits from distant earthquake-induced landslides that may block road access.

Past Hazus-based studies typically attached standardized reports generated by the Hazus tool that summarize casualties and losses in a convenient format. Such reports are currently available only with Hazus analyses using General Building Stock data, which are modeled at the census tract level. Users analyzing loss on a per-building basis, such as what we have done in this study, cannot obtain such summary reports from Hazus; thus, none are attached to this report. Instead, we present such information as tables in Appendices A and C, in graphical form in Appendix E, and in electronic form in the accompanying GIS database (Appendix D).

5.0 RESULTS

5.1 Population and Building Density

We developed a 20-acre hexagonal grid, then overlaid the grid on our building database, totaling the number of individual buildings, the number of residential buildings, and the number of permanent residents associated with the buildings within each hexagonal cell. Cells with no buildings were removed from the dataset. Cells with at least one building yet no permanent residents frequently occur in commercial/industrial corridors or predominantly agricultural areas (Appendix E, Plates 1–3). The hexagon layer provides a convenient overlay to explore population and building exposure relative to a particular natural hazard. The layer can also be useful in focusing the areas of building loss or casualties in neighborhood units with large tracts of undeveloped areas.

5.2 Building Statistics

Single-family residential buildings dominate the building inventory in all three counties (**Figure 5-1**). Wood frame construction dominates the residential buildings (**Table 5-1**). The number of masonry buildings in **Table 5-1** is due primarily to the Hazus building type statistical distribution described in Section **2.1.4**. **Table 10-8** in Appendix A contains a complete breakdown of building type for all generalized building use categories.

Figure 5-1. Building primary usage statistics by county. Tabular summary is in Table 10-7. Single-family residential combines Hazus occupancy classes RES1 and RES2 (manufactured housing). Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines Hazus occupancy classes RES3, RES5, and RES6.

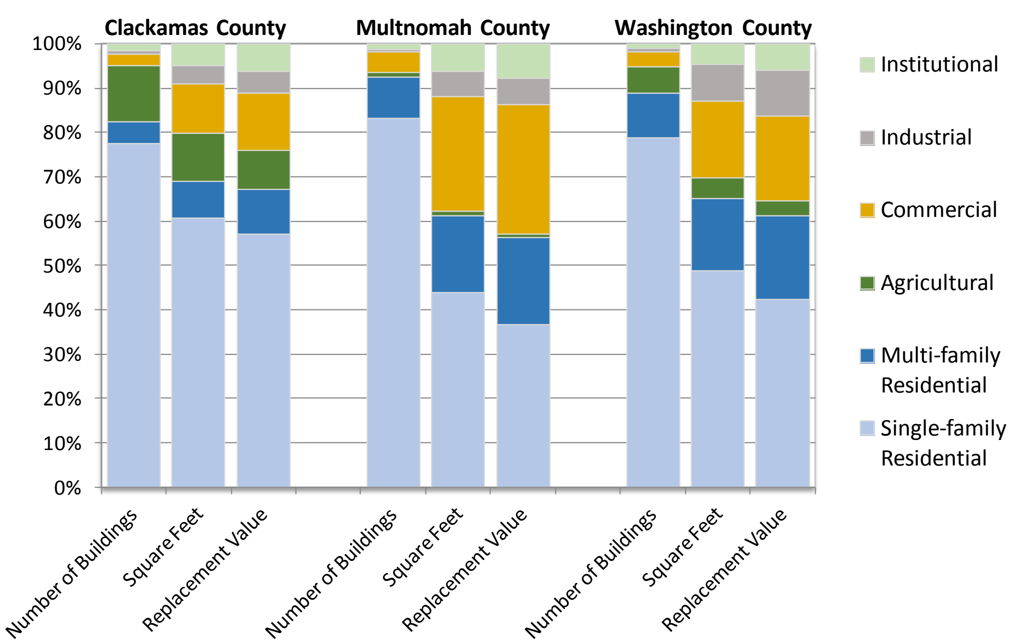


Table 5-1. Residential buildings by building type.

Occupancy Type	Building Type	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Permanent Residents	Permanent Residents Percent
Single-Family Residential	Wood	471,926	95.5%	914,096	96.7%	1,182,770	96.3%
	Manufactured Housing	16,852	3.4%	20,966	2.2%	32,969	2.7%
	Reinforced Masonry	3,549	0.7%	7,349	0.8%	9,321	0.8%
	Unreinforced Masonry	1,455	0.3%	2,298	0.2%	3,277	0.3%
	Other	138	0.0%	377	0.0%	581	0.0%
Multi-Family Residential	Wood	47,055	91.1%	204,253	73.0%	316,575	76.8%
	Reinforced Masonry	1,331	2.6%	16,026	5.7%	24,203	5.9%
	Unreinforced Masonry	403	0.8%	5,380	1.9%	8,139	2.0%
	Steel	1,636	3.2%	22,913	8.2%	24,051	5.8%
	Concrete*	1,206	2.3%	31,277	11.2%	39,150	9.5%

*Concrete includes the precast concrete building type.

Building occupancy within the different building types varies significantly between the daytime and nighttime scenario (**Table 5-2**). In the 2 AM scenario, most (87%) of the population is within wood frame construction. The daytime and nighttime occupancy models assume people from outlying counties commute into the study area; thus, daytime occupancy totals are generally higher than permanent resident population totals.

Table 5-2. Occupancy by building type.

Building Type	Number of Buildings	"2 PM" Daytime Occupancy	Daytime Percent	"2 AM" Nighttime Occupancy	Night Time Percent	Permanent Residents	Percent
Concrete	8,599	314,378	19%	60,383	4%	35,679	2%
Manufactured Housing	17,295	11,221	1%	31,387	2%	32,969	2%
Precast Concrete	6,603	195,438	12%	12,539	1%	3,811	0%
Reinforced Masonry	16,125	205,964	12%	43,218	3%	33,525	2%
Steel	16,487	213,478	13%	49,246	3%	24,291	1%
Unreinforced Masonry	5,092	52,271	3%	13,766	1%	11,416	1%
Wood	545,651	697,336	41%	1,442,287	87%	1,499,345	91%
All building types	615,852	1,690,086		1,652,825		1,641,036	

5.3 Building Damage, Casualties, and Displaced Population

We tabulated the impacts to buildings and people at the county and jurisdictional level (Appendix C, **Table 12-8** through **Table 12-11**) and at the neighborhood unit level for all earthquake scenarios. Jurisdictional and neighborhood unit level summaries are available in tabular form in the accompanying GIS database. Building damage results were also expressed as a *loss ratio*—the total repair cost estimate for all buildings in a given spatial unit divided by the total replacement cost for all buildings. Building debris tonnage was summarized at the given spatial unit. Casualties were summarized for the given spatial unit at the individual casualty level, and a total casualty level for daytime and nighttime was calculated. The tables in the GIS database enable one to express graphically the damage estimates in any number of ways, such as displaying Level 2 casualties per 10,000 people. For demonstration purposes, we present the total injuries requiring hospitalization per neighborhood unit, daytime scenario, CSZ earthquake with saturated soil conditions, in Appendix E, Plates 14–16.

Damage estimates vary widely across the study area, depending on local geology, soil moisture conditions, type of building stock, and distance from the fault. In the Cascadia Subduction Zone scenario, damage is generally greater in the western portion of the study area than in the eastern portion. Yet local geology variations can result in significant damage even well east of the Willamette River, such as the neighborhood of North Troutdale (Appendix E, **Plate 15**).

The 9% ("dry" soil conditions) to 14% ("wet") overall estimated loss from a CSZ magnitude 9.0 earthquake includes all buildings in the study area (**Table 12-8** and **Table 12-9**). The damage is not equally distributed across all building uses or building types, as seen in the referenced tables. Many high-value commercial and industrial buildings exist on areas of high to very high liquefaction hazard. The average loss ratio for wood-framed single-family residential buildings ranges from 2% to 7% (for "dry" and "wet" soil conditions, respectively; **Table 5-3**).

Although the timing of an earthquake has no impact on building damage or displaced population, more people will experience casualties during a workday earthquake scenario than if the earthquake occurred at night (Appendix C, **Table 12-8** through **Table 12-11**). During the daytime scenario, most people are occupying non-wood structures (**Table 5-2**), which typically fare worse in an earthquake than wood-frame construction.

Even though a Portland Hills fault earthquake is of shorter duration than a CSZ earthquake, its placement relative to significant assets in the region would result in much higher damage overall (Appendix C, **Table 12-10** and **Table 12-11**). At distances beyond 15 miles from the Portland Hills fault zone, damages from a Cascadia Subduction Zone scenario generally exceed a Portland Hills fault scenario, which can be visualized by comparing the ground motion data in Appendix E, Plates 4 and 5.

Soil moisture conditions significantly influence loss estimates, with overall building loss ratios of 9% versus 14% for the Cascadia earthquake between the "dry" soil conditions and "wet" (saturated) soil conditions (Appendix C, **Table 12-8** and **Table 12-9**). The large percentage of buildings in moderately liquefiable zones, such as the Tualatin Basin in Washington County, combined with the high-value buildings in very high liquefiable zones in the Columbia Slough, downtown Portland near the Willamette River, and the northwest industrial area of Portland account for much of the increase in the wet scenario loss.

Several smaller jurisdictions exhibit higher or lower loss ratios compared to other jurisdictions, due to unique situations. Johnson City in Clackamas County is almost exclusively composed of manufactured housing—a building type that experiences significantly more damage for a given ground motion than does a wood frame house (Kircher and others, 1997). The city of Barlow in Clackamas County is situated entirely on soft soils (Section **3.2**) that amplify the ground motion, on potentially liquefiable soils, and much of its building value is contained in four storage facilities constructed of a more fragile building type compared to wood-frame construction. Although the City of Sandy's boundaries span multiple soil types and liquefaction susceptibility categories, nearly all of its assets are on firm, non-liquefiable soils, and thus its loss ratio is comparatively low (1%, **Table 12-8**).

Building damage is higher in non–single-family residential structures (**Table 5-3**). Single-family residential is dominated by light-frame wood construction (**Table 5-1**), the most resilient of the 36 generic building types available in the Hazus AEBM. Multi-family residential is a mixture of wood frame construction and less resilient building types. "Single-family residential: manufactured housing" was broken out to highlight its relative seismic vulnerability.

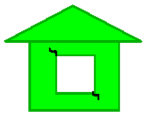
Table 5-3. Damage to buildings by building category and by earthquake scenario.

		Cascadia Subduction Zone Magnitude 9.0 Earthquake				Portland Hills Fault Magnitude 6.8 Earthquake			
		"Dry" Conditions		"Wet" (Saturated) Conditions		"Dry" Conditions		"Wet" (Saturated) Conditions	
Building Category	**Building Value ($ Million)**	**Building Repair Cost ($ Million)**	**Loss Ratio**	**Building Repair Cost ($ Million)**	**Loss Ratio**	**Building Repair Cost ($ Million)**	**Loss Ratio**	**Building Repair Cost ($ Million)**	**Loss Ratio**
Agricultural	9,263	947	10%	1,347	15%	1,271	14%	1,796	19%
Commercial	57,134	10,381	18%	14,133	25%	22,240	39%	27,326	48%
Industrial	18,485	3,651	20%	4,888	26%	6,578	36%	8,216	44%
Institutional	17,609	2,438	14%	3,114	18%	5,871	33%	7,089	40%
Multi-family residential	44,391	3,288	7%	5,621	13%	10,118	23%	14,423	32%
Single-family residential	111,408	2,695	2%	7,421	7%	14,234	13%	24,254	22%
Single-family residential: manufactured housing	879	158	18%	186	21%	257	29%	307	35%
Total	259,169	23,558	9%	36,710	14%	60,569	23%	83,411	32%

Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines Hazus occupancy classes RES3, RES5, and RES6.

The Hazus AEBM model estimates each building's probability of being in one of five damage states: *None*, *Slight*, *Moderate*, *Extensive*, and *Complete*. The five individual probabilities sum to 1.0. General descriptions for the structural damage states of 16 common building types are provided by FEMA (2011, Section 5.3); **Figure 5-2** shows an example. We obtained the total number of buildings in a particular spatial unit by summarizing all buildings' individual structural probability of damage state values, per the guidance provided by FEMA (2017a). The data in Appendix C, **Table 12-3** can be used to estimate the number of red-tagged and yellow-tagged buildings, and the number of buildings needing structural inspection after an earthquake. In addition, we summarized all permanent residents per building damage state, by generalized building types: single family residential (excluding manufactured housing); single family residential in manufactured housing, and multi-family residential.

Figure 5-2. Example damage state descriptions for a light-frame wood building (FEMA, 2010). The "None" damage state is not provided.

Damage State		Description
	**Slight**	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	**Moderate**	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	**Extensive**	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	**Complete**	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.

5.3.1 Seismic Design Level Improvement Exercise

Modeling adjustments to the building inventory seismic design level results in much lower amounts across all categories of loss (**Table 5-4**), although the effect is muted in the "wet" (saturated) soil condition scenario. The Hazus building damage model assumes damage due to ground shaking is independent of damage due to ground failure (FEMA, 2011, Section 5.6.3). In the Hazus model, improved seismic design levels will reduce damage estimates from ground shaking but not from ground failure. In our study area, more than half of the building inventory is situated on sites with a moderate or higher liquefaction susceptibility rating (**Table 10-5**). Thus, the reduction in loss in the "wet" (saturated) soil conditions is muted, due primarily to liquefaction probability being incorporated into the damage estimate. The reduction in loss estimates is more dramatic in the "dry" soil conditions scenario, where liquefaction and earthquake-induced landslide impacts are minimal.

Table 5-4. Seismic design level improvement exercise, Cascadia Subduction Zone magnitude 9.0 earthquake. See Section 4.1.5 for scenario definitions.

	"Dry" Soil Conditions			"Wet" (Saturated) Soil Conditions		
Seismic Design Level Scenario	**Unchanged**	**Moderate**	**High**	**Unchanged**	**Moderate**	**High**
Building Repair Cost ($ million)	23,558	6,466	4,230	36,710	20,988	18,979
Building Loss Ratio	9%	2%	2%	14%	8%	7%
Debris (thousands of tons)	12,794	2,512	1,304	17,292	8,148	7,121
Long-term Displaced Population	16,852	2,438	1,664	85,211	72,329	71,617
Casualties — Daytime Scenario						
Total Casualties	18,286	2,032	987	27,175	12,606	11,711
Level 1 Casualties	13,342	1,681	839	19,489	9,005	8,281
Level 2 Casualties	3,518	278	118	5,454	2,567	2,431
Level 3 Casualties	484	25	10	758	352	340
Level 4 Casualties	942	48	20	1,473	682	659
Casualties — Nighttime Scenario						
Total Casualties	4,334	902	596	10,400	7,259	6,989
Level 1 Casualties	3,338	775	525	7,838	5,484	5,262
Level 2 Casualties	739	106	60	1,979	1,404	1,364
Level 3 Casualties	87	7	4	203	131	129
Level 4 Casualties	169	14	7	380	240	235

Loss estimates for unchanged scenario are taken from **Table 12-8** and **Table 12-9**, and provided for reference. Casualty Level definitions are provided in **Table 4-1**. Total building replacement costs used for building loss ratio taken from **Table 5-3**.

5.4 Electric Power Transmission

Of the 18,098 poles and towers in our database, 921 (5%) have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, and 2,203 (12%) have a 20% to 30% chance of experiencing more than 1 meter during a Cascadia magnitude 9.0 earthquake with "wet" (saturated) soil conditions (Appendix E, **Plate 13**). In the "dry" soil conditions, only 6 poles and towers have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, with none experiencing more than 2 meters of deformation. In the "dry" soil conditions scenario, permanent ground deformation is due exclusively to earthquake-induced landslides. In the "wet" (saturated) soil conditions scenario, liquefaction is a significant contributor to permanent ground deformation proximal to the power pole or tower.

Similar potential impact is observed for the Portland Hills fault magnitude 6.8 earthquake scenario. Of the 18,098 poles and towers in our database, 2,367 (13%) have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, and 3,687 (20%) have a 20% to 30% chance of experiencing more than 1 meter during "wet" (saturated) soil conditions. In the "dry" soil conditions scenario, 100 (0.5%) poles and towers have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, and 8 poles and towers have a 20% to 30% chance of experiencing more than 2 meters.

5.5 Emergency Transportation Routes

In the Cascadia magnitude 9.0 earthquake, "wet" (saturated) scenario, most (177 out of 238, or 74%) route segments will have a 20% to 30% chance of experiencing significant ground deformation along some portion of the segment (Appendix E, **Plate 10**). Although the regional post-earthquake road conditions significantly improve under the "dry" soil conditions scenario, (Appendix E, **Plate 11**), several road segments (6 out of 238, or 3%) may still be impacted. In the "dry" soil conditions scenario, the road segments that have a chance of failure are due to their placement on 1) existing landslides, 2) areas of elevated landslide susceptibility based on slope and geology, or 3) fill material that includes a significant slope proximal to the road segment. The 20% to 30% probability of failure on a per segment basis may sound modest when taken in isolation, but when individual location probabilities of failure are combined in a binomial distribution statistical method (probability of failure = $(1 - p)^n$), the overall failure estimate for the segment can increase significantly.

For mapping and planning purposes, we categorized road segments into distinct bins, even though only a fraction of a given road segment may experience significant ground deformation. An example of this effect can be observed in Washington County, where emergency transportation routes commonly cross alluvial deposits that may fail due to liquefaction (inset map in Appendix E, **Plate 12**). Although only a portion of the road may be impacted by ground failure, the road segment is considered impassable in its entirety until repairs are made. **Plate 12** (Appendix E) shows the portions of the segments that may experience significant ground failure in a Cascadia magnitude 9.0 earthquake.

For a Portland Hills fault magnitude 6.8 earthquake, 66 out of 238 (28%), and 205 of 238 (95%) of segments have a 20% to 30% chance of experiencing significant ground deformation along some portion of the segment, in the "dry" and "wet" soil condition scenarios, respectively. The increase in percentage compared to the CSZ can be explained by the significant difference in ground motion between the two earthquake scenarios (Plates 4 and 5).

6.0 DISCUSSION

This study is the first conducted in the three-county area that provides damage estimates at levels useful for both regional and local planning. It presents loss estimates as a range for two building occupancy scenarios and two soil moisture scenarios. By doing so, planners can get a better sense of the range of damages and casualties that may occur with a major earthquake: Which areas may have experienced more damage, given the potential for liquefaction and local site amplification? Where were people when the earthquake occurred? How many casualties might that produce?

A magnitude 9.0 Cascadia Subduction Zone earthquake will result in significant damage to buildings, with concomitant casualties, throughout the three-county area. Transportation networks may be severely impaired, compromising emergency response. Millions of tons of debris will need removal to staging areas for sorting and eventual permanent disposal. Hundreds of thousands of buildings will need timely safety inspections, and thousands to tens of thousands of people will need to find other permanent housing arrangements. In comparison, a magnitude 6.8 Portland Hills fault earthquake will be devastating, primarily due to its position relative to the study area's major assets and population centers, with losses more than double those from a magnitude 9.0 Cascadia Subduction Zone earthquake.

6.1 Earthquake Impacts

6.1.1 Geographic Variations

Damage and casualty estimates vary widely throughout the three-county area. Primary reasons for the variation include the seismology, local geology, and building development history. In a Cascadia Subduction Zone earthquake, ground motion will be less in eastern part of the study area compared to the western part. Local geological characteristics can produce significant variations in ground motion (Appendix E, Plates 4 and 5). Such variation should not be interpreted to suggest that some areas within the three counties are unaffected. The City of Sandy, for example, has a relatively low building loss ratio, at 1% (Appendix C, **Table 12-9**), yet the Cascadia earthquake is estimated to generate $12 million in damage within the city boundaries.

6.1.2 Casualties

For both the Cascadia Subduction Zone earthquake and the Portland Hills fault earthquake, and in both "dry" and "wet" (saturated) soil condition scenarios, casualty estimates for a daytime earthquake are at least double in quantity compared to a nighttime earthquake. During nighttime most, but not all, of the population are in more resilient wood-frame construction (**Table 5-1**, **Table 5-2**), while during the daytime, much of the population is dispersed among non-wood frame construction buildings, such as offices, schools, and factories. This temporal pattern has been observed in past earthquakes, most recently in Christchurch, New Zealand, where two earthquakes struck, one at 4:35 AM on September 4, 2010, and one at 12:51 PM on February 22, 2011 (EERI, 2011). No deaths occurred from the early morning earthquake, whereas the afternoon earthquake resulted in the deaths of 185 people.

We emphasize that our daytime building occupancy model used as a basis for generating daytime casualty numbers is a simplification of the dynamic and complex human environment, but it is still useful for planning purposes. Post-earthquake emergency operations can be enhanced by having an awareness of the types of population shifts between buildings throughout the day and week, and the seismic resiliency of those buildings.

6.1.3 Building Damage Inspection and Displaced Population

After a major earthquake, at least 200,000 buildings in the Portland Metropolitan Region will need timely ATC-20-based safety inspection by qualified personnel (ATC, 1989). Our estimate includes all buildings with slight to complete damage (Appendix C, **Table 12-3**), following the quantification method outlined by EERI (2015), which assumed a rate of four to five buildings per day per inspector. Assuming a goal of completing the task in 30 days, our results identify a need for 1,600 to 2,000 certified inspectors for a Cascadia Subduction Zone magnitude 9.0 earthquake. A Portland Hills fault earthquake would require twice the number of inspectors. Many out-of-area inspectors can be brought into an affected area after an earthquake, as discussed in the Oregon Resilience Plan (OSSPAC, 2013, Section 2). Inspection may displace some portion of building occupants who assumed buildings were structurally sound. In other cases, inspection may restore confidence in the building's structural integrity. We can only speculate on such dynamics, but we can provide permanent resident occupancy counts per building damage state (Appendix C, **Table 12-4** through **Table 12-7**).

6.1.4 Debris

Debris removal will require local staging areas for storing, sorting, and eventual transfer to a permanent disposal location. Assuming 25 tons per truckload, 400,000 to 680,000 truckloads of building debris would be generated by a Cascadia Subduction Zone earthquake ("wet" [saturated] soil scenario). We did not estimate other types of debris, such as buckled roads, collapsed overpasses, and landslide flows. Identifying staging areas is partly a GIS exercise that uses the debris-per-neighborhood estimates supplied with this report, along with information on potential long-term compromises to the local transportation network such as bridge collapse. In addition, debris staging site selection should be informed by other emergency or recovery planning efforts that may identify the same areas for other operational needs.

6.1.5 Infrastructure

Our emergency transportation route analysis graphically shows the likelihood of a fragmented emergency transportation route network, one where distribution of goods and services may be significantly affected. It is intended to inform the planning process, emphasizing the need for adaptability and consideration of alternative routes. Our analysis did not consider other potential route blockages, such as collapsed buildings and failed bridges and overpasses. Engineering judgment from transportation sectors can be applied to determine which segments may be quickly restored and which segments may be out for longer periods. Together, such information and perspectives can be used as a basis for establishing, prior to an earthquake, local points of distribution, including food, water, and fuel for emergency operations.

Portions of the electric distribution network may be significantly impacted due to ground failure compromising the integrity of transmission structures. As with the emergency transportation route analysis, our work is intended to inform the planning process. Engineering judgment from electrical utilities sectors can be applied to determine if some areas will be impacted for longer durations, and if additional capacity or redundancy is warranted. During the Christchurch, New Zealand, earthquake sequences of 2010-2011, electric poles and towers generally fared well in the presence of liquefaction (Kwasinksi and others, 2014).

6.1.6 Alternative Earthquake Scenarios

For planning purposes, we chose to model an earthquake at the upper end of its estimated potential energy release. The Cascadia Subduction Zone magnitude 9.0 earthquake scenario assumes a full margin rupture. Partial ruptures along the CSZ have been inferred from the geologic record, with the most frequent occurrences along the southern portion of the CSZ (summarized by Priest and others, 2014). The Oregon State University Hazard Explorer for Lifelines Program maintains a web-GIS tool that displays a full CSZ rupture and three partial rupture CSZ scenarios (http://ohelp.oregonstate.edu/). We obtained the same synthetic bedrock ground motion data used in the OHELP tool from A. Frankel (written communication, 2016) of the USGS. In the Portland Metropolitan Region, the synthetic CSZ magnitude 8.7 bedrock ground motion data averages about 85% of CSZ 9.0 bedrock ground motion data, and the synthetic CSZ magnitude 8.4 bedrock ground motion, with its northern rupture extent west of Waldport, Oregon, is about 40% of the full rupture CSZ magnitude 9.0 earthquake.

Damage estimates do not scale linearly with bedrock ground motion, and one should not assume damage from a CSZ magnitude 8.4 earthquake would be 40% of the CSZ magnitude 9.0 earthquake damage estimate. Yet significant damage could still occur in the study area, primarily due to the seismic site effect where the bedrock ground motion is strongly amplified by soft soils (Section **3.2**). The most dramatic consequence of the seismic site effect observed to date is from the 1985 Mexico City earthquake, where a relatively distant rupture produced devastating building damage within the historic lakebed (Singh and others, 1988). Future studies could quantify the influence of the site effect on damage estimates across lower magnitude CSZ earthquake scenarios.

The Portland Hills fault was modeled at the upper end of its estimated magnitude range (M 6.8); it could rupture at lower magnitude. Buildings above the rupture zone will likely experience the same damage as estimated in this report. Buildings more distant from the rupture zone but situated on softer soils would experience more damage than nearby buildings situated on stiffer soils. The Portland Hills fault is part of a fault zone that includes the Oatfield fault and the East Bank fault (Wong and others, 2001). Other seismogenic faults exist in the study area (Personius and others, 2003; USGS Quaternary Fault and Fold Database: https://earthquake.usgs.gov/hazards/qfaults/). Again, buildings above the fault will experience the most damage, but buildings distant from the fault situated on soft soils may be significantly damaged.

6.2 Seismic Design Level Improvements

Our seismic design level improvement modeling exercise (Section 5.3.1) provides strong support to the suggestion that seismic upgrades to buildings, or replacement of older buildings, can significantly reduce loss and casualties. Levi and others (2015) provided a case for a wide-scale retrofitting program to poor quality buildings throughout Israel, by using Hazus-generated loss estimates based on existing building inventory and a hypothetically retrofitted building inventory. The study assumed an average estimate of US$100/per square meter (US$9.30 per square foot) to upgrade older buildings to limit extensive or complete damage. Yet any proposed improvement should take site-specific conditions into account. In the “wet” (saturated) soil scenario, ground failure due to liquefaction reduces the benefits of retrofitting, as seismic upgrades do little to prevent foundation rupture, but mitigation techniques such as compaction grouting can minimize the ground failure impact, albeit at additional cost.

We urge caution in interpreting the results of **Table 5-4**. Although it offers a hypothetical upper bound of what could be achieved from seismic retrofitting, it should not be used to support the proposed retrofitting or replacement of a particular building. A building-specific analysis incorporates individual characteristics of the structure, specifying parameters such as its yield point (FEMA, 2010). We used generic building type models in our Hazus AEBM (Section **2.1.4**), which in the particular case, may over- or underestimate the loss (Lu and others, 2017). Further, the exercise did not incorporate building foundation depth or other local site conditions that may mitigate the effects of ground failure from liquefaction. In the Moderate scenario, our modeling exercise assumed a retrofit brings buildings up to moderate or high seismic design standards. In practice, the decision to retrofit or replace an older structure is complex (Williams and others, 2009; City Club of Portland, 2017; Paxton and others, 2017), and one that we cannot address directly in this report.

6.3 Comparison with Previous Studies

Wang (1998), using an early version of Hazus, quantified the impact of a magnitude 8.5 Cascadia Subduction Zone earthquake scenario across the state of Oregon, reporting losses by individual county. Liquefaction and landslide information were not regionally available, nor was it possible to incorporate such information in the Hazus model at that time. Hofmeister and others (2003) used Hazus to estimate impact of a magnitude 6.8 Portland Hills fault and a magnitude 9.0 Cascadia Subduction Zone earthquake scenario to buildings and bridges in Clackamas County, Oregon. The study incorporated building data from the Metro (1998) inventory, and updated soil classification and liquefaction and landslide susceptibility. Local building data were aggregated into the Hazus-MH model's General Building Stock (GBS) inventory, a census track-based unit, with loss estimates derived at the GBS level. Excluding building content, the building repair cost, expressed as a percentage of the building replacement cost, was 13.3% for the Portland Hills fault and 3.4% for the Cascadia Subduction zone earthquake. More recently, Tetra Tech (2016a) updated General Building Stock inventory data for the City of Portland, using ground motion and ground failure data from Madin and Burns (2013), and estimated loss ratios of 4.3% for a Cascadia Subduction Zone scenario and 14.3% for a Portland Hills fault magnitude 6.5 scenario, using USGS ShakeMap data.

Our building loss ratio estimates of 9% to 14% for a Cascadia Subduction Zone magnitude 9.0 earthquake, and 23% to 32% for a Portland Hills fault magnitude 6.8 earthquake are higher than the loss ratios published in the aforementioned studies. We account for this increase due to several factors. The largest contributor to the difference is the method by which the two Hazus tools (General Building Stock [GBS] and Advanced Engineering Building Module [AEBM]) factor the probability of ground failure from liquefaction or from earthquake-induced landslide into the building damage model. In the GBS model, the Hazus tool distributes the ground failure probability across the Moderate, Extensive, and Complete damage states (FEMA, 2011, Equation 5-16), with most of the ground failure probability assigned to the Moderate and Extensive states and a small (<10%) portion assigned to the Complete state. In the AEBM model, the Hazus tool assigns the ground failure probability in its entirety to the Complete damage state. The effect is that AEBM-derived building loss, casualty, and debris estimates will be larger than GBS-derived estimates when all other model inputs are equal, local geological conditions are set to moderate or higher liquefaction and/or landslide susceptibility levels, and sufficient ground motion is present to induce landslides or liquefaction.

Other contributors to the difference are as follows. In our AEBM building database, our seismic design levels (Section **10.1**) were more conservative than the seismic design level distributions embedded within the GBS database, sometimes referred to as the default Hazus mapping schem*e*. Our review of that scheme suggested it was primarily based on California benchmark years and thus overly optimistic, as California building codes through the twentieth century were more stringent than Oregon building codes (Olson, 2003; Judson, 2012, FEMA, 2017c, Table 3.5). Although it is possible to alter the Hazus mapping scheme in the General Building Stock (e.g., Seligson, 2008), to our knowledge, such manipulations were not done in the aforementioned GBS-based studies. A higher level of seismic design assignment to building inventory will result in reduced loss estimates (**Table 5-4**).

Within large portions of the developed areas in the study area, our updated liquefaction susceptibility ratings were higher than the liquefaction susceptibility ratings used in the aforementioned studies (primarily Mabey and others, 1997). Appleby and others (in preparation), using the guidelines provided by FEMA (2011, Table 4.10), classified large areas containing high-value building assets with a Very High and High rating compared to the rating of High and Moderate assigned by Mabey and others (1997), particularly in the Columbia Slough, northwest industrial Portland, and eastern downtown Portland. A large portion of the developed area in Washington County was assigned a Moderate liquefaction rating by Appleby and others, which also contributed to the increased loss estimates observed in our study.

We could not directly compare our loss estimates to the losses published by FEMA (2017b), due to their usage of a probabilistic model that did not include a 500-year earthquake, which most closely resembles the Cascadia Subduction Zone scenario modeled in our study. Their debris estimate for the state of Oregon (2.1 to 21.6 million tons) is smaller than our estimate of 12 to 17 million tons, after adjusting for our study's area. (We assume our study includes about 44% of the building assets in the state, based on the area's population ratio compared to the state of Oregon.) The FEMA report used the GBS model and a simplified NEHRP "D" assignment. To our knowledge, the study did not incorporate any liquefaction susceptibility data. Further, default Hazus building inventories, such as were used in the FEMA study, commonly underestimate the square footage for nonresidential buildings, which are generally more sensitive to ground motion. Although that study provided a good nationwide comparative perspective on earthquake hazards, it is too generalized to use for county loss estimation purposes.

We examined the geological updates and the updated ground motions within the Critical Energy Infrastructure (CEI) Hub, and we compared them to the datasets used by Tetra Tech (2016b). Although some increases were observed in the updated ground motion data, we determined that the changes were not large enough to significantly alter the overall damage estimates and recommendations made in the Tetra Tech study. We note that the Hazus GBS tool was not used to generate the damage estimates in that study; damage estimates to the infrastructure were obtained from a Hazus tool that incorporates the ground failure in a manner equivalent to the Hazus AEBM.

Our Portland Hills fault results are similar to what was estimated for a magnitude 7.0 Wasatch fault earthquake in the Salt Lake City area (EERI, 2015, p. 26). The Salt Lake City area has approximately 775,000 buildings, compared to 616,000 buildings in our study area. The two faults have significant assets constructed on top of, and near to, the fault. Both areas have major assets on moderate to high liquefaction potential soils. The key difference between the two faults is the frequency of occurrence—at least 22 large earthquakes have ruptured along the central segments of the Wasatch Fault in the past 6,000 years, whereas evidence suggests the Portland Hills fault has had two ruptures in the past 15,000 years (Liberty and others, 2003).

7.0 RECOMMENDATIONS

This study provides detailed, actionable earthquake loss estimation data for the Portland metropolitan region at a range of scales. Communities, counties, businesses, non-governmental organizations, and regional agencies can use the accompanying data to better plan for, respond to, and recover from a major earthquake. Many of these recommendations build upon those listed in the Oregon Resilience Plan (OSSPAC, 2013). Planning for, responding to, and recovering from a major earthquake is a multi-faceted, multi-disciplinary effort. The scope of this project was limited to estimating damage to buildings and the people that occupy them, and to two key infrastructure sectors. Our recommendations below are directly supported by the findings in this study, and they should not be considered comprehensive.

Our recommendations build on the efforts done to date by agencies, institutions, businesses, and private homeowners to improve the region's seismic resilience. The Oregon Seismic Rehabilitation Grant Program, in place since 2007, has funded upgrades to more than 50 schools and emergency service buildings (http://www.oregongeology.org/sub/projects/rvs/). Bonneville Power Administration has identified seismic vulnerability of its transmission system and has taken several actions to improve its resiliency (Scruggs, 2014). Modifications to the Oregon statewide building code have, through time, increased the seismic resiliency of newer construction (Judson, 2012). The City of Portland's current building code requires owners of unreinforced masonry buildings to seismically retrofit their buildings on the basis of certain triggers (PBEM, 2017). The Great Oregon Shakeout program, managed by Oregon Office of Emergency Management, has more than 580,000 participants, elevating public awareness of the earthquake hazard; the program suggests actions individuals can take to minimize casualties and preparation for post-earthquake disruption of services.

Planning

We encourage regional and local planners, each who have their own questions and needs, to explore the accompanying GIS data. Static maps, such as in Appendix E, Plates 14–16, are just one representation of the loss estimates. We suggest that a primary value of the database is the spatial component: in addition to asking how many or how much, we can ask *where*—where might we expect casualties to be higher, given the time of day of the earthquake? Where can we plan staging areas for debris? At the same time, we caution against over-interpreting the loss estimates, as the data and methods used in this project contain large uncertainties.

Casualty estimates supplied in this report can be used to compare with the region's existing medical facility capacity, including trained, available personnel. The spatial nature of the data supplied with this report can be used to better understand the potential demands on specific facilities, and to quantify emergency care coordination needs at a regional level.

Counties and jurisdictions updating their natural hazard mitigation plans (NHMPs) can use the earthquake damage estimates provided in this report.

Recovery

Hundreds of thousands of buildings in the study area will need safety inspections after a major earthquake. The state can sponsor annual Applied Technology Council (ATC)-20 training to qualified engineers, and negotiate mutual aid agreements with other neighboring states. Timely inspection of damaged buildings will reduce pressure on temporary shelters.

Resiliency: Buildings

The majority of buildings in the study area do not meet current seismic building code standards, although the buildings did meet code standards in place at time of construction. The state and counties can consider incentives and other options that encourage building owners to seismically upgrade their buildings. Such upgrades will reduce casualties and building repair costs and will minimize potential loss of businesses and workforce housing. Jurisdictions can consider triggers that require seismic upgrades, such as a major building renovation.

Resiliency: Infrastructure Improvements

We cannot overstate the need for a secure, regional liquid fuel supply that supports emergency response and recovery. The emergency transportation route analysis provided in this study suggests the need to identify strategically placed local fuel points of distribution. We encourage counties to work with the Oregon Department of Energy in implementing the Oregon Fuel Action Plan (ODOE, 2017), specifically, identifying priority lifeline routes and fuel points of distribution.

Electric utilities can use this study's updated ground motions and ground failure to evaluate the potential threat to their infrastructure, such as substations. Electric system resiliency analysis can incorporate the transmission structure information provided in our geodatabase to determine if additional capacity or redundancy is needed.

Resiliency: Essential and Critical Facilities

Our project did not explicitly identify or evaluate essential facilities, such as fire stations, in the study area. We encourage all communities and planners to clearly define such facilities and evaluate their seismic resilience by using the updated ground motion and ground failure data accompanying this report along with updated Rapid Visual Screening surveys (FEMA, 2015a; Lewis, 2007). Such facilities include emergency shelters and community points of distribution.

Enhanced Emergency Management Tools

Building footprints developed for this project can be incorporated into regional and statewide databases. Location and number of buildings, especially on larger rural lots, are essential information during emergency operations such as wildfire fighting.

A rapid earthquake loss assessment tool could be developed for Oregon by building on methods established in this study and other research such as that of Erdik and others (2011). Each earthquake presents scientists with new information. The synthetic earthquake ground motion data used for this project is the best estimate available from a full rupture subduction zone and a local crustal fault earthquake. In practice, the magnitude and location of an earthquake and the ground motions and ground deformation will likely vary from what was anticipated. In addition to the Portland Hills fault, several other active local crustal faults, such as the Gales Creek fault zone, exist in the study area (Personius and others, 2003). The USGS ShakeMap program (https://earthquake.usgs.gov/data/shakemap/) provides near-real-time maps of ground motion data following significant earthquakes. Having a building database and tools in place to estimate response to a particular earthquake with its own unique ground motions can provide emergency planners with a rapid post-earthquake assessment of the situation.

Database Improvements

County and city databases could be improved with information on seismic retrofits and upgrades to individual buildings. Currently, such information is not readily available for analysis or to potential buyers of a property. At present, only one jurisdiction in the study area maintains the basics of such a database (City of Portland [2017], Unreinforced Masonry buildings).

Public Awareness

The technical information contained in this report can be used to develop practical tools and materials aimed at increasing public awareness of regional earthquake risks and encouraging preparedness actions. Examples of such tools include the Seattle and King County Ready disaster preparedness website, https://hazardready.org/seattle/ (which incorporates other natural hazards), and the report developed by the Utah Chapter of the Earthquake Engineering Research Institute describing the Wasatch Fault in Salt Lake City (EERI, 2015). Public awareness efforts should strive to reach underserved communities and communities whose primary language is other than English, as well as community members with disabilities and access or functional needs.

Future Studies

Our study was primarily focused on direct physical impacts from a major earthquake, including building repair or replacement costs. It did not consider other direct and indirect economic losses, such as lost wages. We recommend incorporating the detailed loss information from this report into a more sophisticated economic analysis, one that factors in other items such as availability of investment capital and a trained labor force, and willingness of businesses to return to the area after a damaging earthquake.

We aggregated loss data at census block groups, which is often the same aggregation unit used when social vulnerability indices are constructed (e.g., Toké and others, 2015). Schmidtlein and others (2011) compared census tract Hazus-based earthquake loss estimates with their social vulnerability indices. A similar type of an analysis could be conducted in our study area at the census block group level.

The methods developed for this project could facilitate similar earthquake impact analyses for other urbanized areas of Oregon that have known earthquake hazards, such as Klamath Falls/Altamont, Salem/Keizer, Albany/Corvallis, and Eugene/Springfield.

Although our analysis focused on impacts from an earthquake, the underlying building database can be used to quantify potential loss due to other natural hazards, such as floods, landslides, or wildfires.

8.0 ACKNOWLEDGMENTS

The Regional Disaster Preparedness Organization (RDPO), Portland, Oregon, provided funding for this project through an Urban Areas Security Initiative grant (UASI) 15-170 from U.S. Department of Homeland Security (Funding Opportunity [NOFO] #DHS-15-GPD-067-000-01; Federal Award Identification Number [FAIN] EMW-2015-SS-0004-S01). Oregon Office of Emergency Management administered the grant on behalf of RDPO. Many people contributed to this report at various levels, ranging from data creation, literature research, methods, information technology, tool development, and technical review. From the Oregon Department of Geology and Mineral Industries: Ken Aaro, Christina Appleby, Lowell Anthony, Quinn Butler, Robert Hairston-Porter, Robert Houston, Lina Ma, Gustavo Monteverde, Jesse Schaefer, Deb Schueller, Yumei Wang, Rudie Watzig, and Matthew Williams. From the

Regional Disaster Preparedness Organization: Emma Stocker, Laura Bruno, and Denise Barrett. From FEMA: Doug Bausch and the Hazus Support Team. From USGS: Art Frankel, who provided custom ground motion simulations for the Portland Hills fault. County and city emergency leads reviewed a draft copy of this document and provided helpful comments: Lisa Corbly, Carmen Merlo, Chris Voss, John Wheeler, and Jay Wilson.

9.0 REFERENCES

Applied Technology Council (ATC), 1989, Procedures for postearthquake safety evaluation of buildings: Redwood City, Calif., ATC-20 field manual, 114 p.

Bauer, J., 2016, Adapting Hazus-MH methods for large-scale risk assessments in Oregon, paper presented at the 9th Annual Hazus User Group Conference, Charleston, S.C., November 7–9, 2016, http://www.hazusconference.com/agenda/papers/Tuesday-1615.pdf

Burns, W. J., Hughes, K. L. B., Olson, K. V., McClaughry, J. D., Mickelson, K. A., Coe, D. E., English, J. T., Roberts, J. T., Smith, R. R. L., and Madin, I. P., 2011, Multi-hazard and risk study for the Mount Hood region, Multnomah, Clackamas, and Hood River counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-11-16, 179 p., 7 pl. http://www.oregongeology.org/pubs/ofr/p-O-11-16.htm

Burns, W. J., Mickelson, K. A., Jones, C. B., Pickner, S. G., Hughes, K. L. B., and Sleeter, R., 2013, Landslide hazard and risk study of northwestern Clackamas County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-08, 38 p., 74 pl., GIS data. http://www.oregongeology.org/pubs/ofr/p-O-13-08.htm

Business Oregon, 2015, Oregon benefit-cost analysis tool for evaluation of seismic rehabilitation grant program applications—User's guide appendices: Salem, Oreg., Business Oregon Infrastructure Finance Authority Division, 31 p. http://www.orinfrastructure.org/assets/apps/IFA/2015Oregon-SRGP/BCAusersGuideAppend.pdf

Charest, A. C. (ed.), 2017, Square foot costs with RSMeans data (38th annual edition): Rockland, Md., Gordian Group, Inc., 563 p. https://www.rsmeans.com/products/books/2017-cost-data-books/2017-square-foot-costs-book.aspx

Cities of Eugene and Springfield, Oregon, 2014, Eugene-Springfield multi-jurisdictional natural hazards mitigation plan, prepared for City of Eugene, Oregon, and City of Springfield, Oregon, 256 p. https://www.eugene-or.gov/DocumentCenter/View/31563

City Club of Portland, 2017, Big steps before the Big One: how the Portland area can bounce back after a major earthquake: City Club of Portland Bulletin, v. 99, no. 2, 86 p. Access PDF report from http://members.pdxcityclub.com/library/reportarchive/viewreportresolution?DocumentKey=883dee38-91ae-4d58-9bda-49ae7afcc021.

City of Portland, 2012, Development Capacity Analysis GIS model, Appendix A of Buildable Lands Inventory—summary of future development capacity: Portland, Oreg., City of Portland Bureau of Planning and Sustainability, October 3, 2012. https://www.portlandoregon.gov/bps/article/408232

City of Portland, Oregon, 2017, Development Services, Unreinforced masonry (URM) Building database as of January 6, 2017. Downloaded March 3, 2017. https://www.portlandoregon.gov/bds/70766

Clackamas County, 2017, Clackamas County GIS data portal, Hamlets dataset and Villages dataset, downloaded April 29, 2017. http://www.clackamas.us/gis/dataportal.html

Daniell, J. E., Schaefer, A. M., and Wenzel, F., 2017, Losses associated with secondary effects in earthquakes: Frontiers in Built Environment, v. 3, no. 30. https://doi.org/10.3389/fbuil.2017.00030

Earthquake Engineering Research Institute (EERI), 2005. Scenario for a magnitude 6.7 earthquake on the Seattle Fault: Oakland, Calif., report prepared in cooperation with the Washington Military Department, Emergency Management Division, Camp Murray, Wash.. 162 p., 2 app. https://www.eeri.org/wp-content/uploads/2011/05/seattscen_full_book.pdf

Earthquake Engineering Research Institute (EERI), 2006, Guidelines for developing an earthquake scenario: Oakland, Calif., EERI Publication No. EF2006-01, 20 p. https://mitigation.eeri.org/files/Developing.a.Scenario.pdf

Earthquake Engineering Research Institute (EERI), 2011, Learnings from earthquakes: The M 6.3 Christchurch, New Zealand, earthquake of February 22, 2011: Oakland, Calif., EERI Special Earthquake Report, May 2011, 16 p. https://www.eeri.org/site/images/eeri_newsletter/2011_pdf/EERI_NewZealand_EQRpt_web.pdf

Earthquake Engineering Research Institute (EERI), 2015, Scenario for a magnitude 7.0 earthquake on the Wasatch Fault—Salt Lake City segment: Hazards and loss estimates: Salt Lake City, Utah, EERI Utah chapter, 53 p. https://dem.utah.gov/wp-content/uploads/sites/18/2015/03/RS1058_EERI_SLC_EQ_Scenario.pdf

Erdik, M., Şeşetyan, K., Demircioğlu, M. B., Hancılar, U., and Zülfikar, C., 2011, Rapid earthquake loss assessment after damaging earthquakes: Soil Dynamics and Earthquake Engineering, v. 31, no. 2, p. 247–266, https:// doi.org/10.1016/j.soildyn.2010.03.009

Evarts, R. C., O'Connor, J. E., Wells, R. E., and Madin, I. P., 2009, The Portland Basin: a (big) river runs through it: GSA Today, v. 19, no. 9, p. 4–10. http://www.geosociety.org/gsatoday/archive/19/9/pdf/i1052-5173-19-9-4.pdf

Federal Emergency Management Agency (FEMA), 2004, HAZUS®-MH and DMA 2000 Pilot Project—City of Portland, Oregon: HAZUS®-MH Risk Assessment and User Group Series, FEMA Publication 436, 64 p. https://www.hsdl.org/?view&did=785063

Federal Emergency Management Agency (FEMA), 2010, Hazus-MH MR5 Advanced Engineering Building Module (AEBM) technical and user's manual: Washington, D.C., 119 p. https://www.hsdl.org/?abstract&did=12756

Federal Emergency Management Agency (FEMA), 2011, Hazus®-MH 2.1 Technical manual, Earthquake Model: Washington, D.C., 718 p. https://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf

Federal Emergency Management Agency (FEMA), 2012a, Seismic performance assessment of buildings, Vol. 1—Methodology: Redwood City, Calif., Applied Technology Council, FEMA P-58-1, 150 p. 11 app. https://www.fema.gov/media-library/assets/documents/90380

Federal Emergency Management Agency (FEMA), 2012b, Nonbuilding structure design, chap. 13 *in* 2009 NEHRP recommended seismic provisions: design examples: Washington, D.C., National Institute of Building Sciences, Building Seismic Safety Council, FEMA P-751, 916 p. https://www.fema.gov/media-library-data/1393877415270-d563663961c9f40e88ce3ad673377362/FEMA_P-751.pdf

Federal Emergency Management Agency (FEMA), 2015a, Rapid visual screening of buildings for potential seismic hazards: supporting documentation, 3rd ed.: Redwood City, Calif., Applied Technology Council, FEMA P-155, 206 p. https://www.fema.gov/media-library-data/1426210695613-d9a280e72b32872161efab26a602283b/FEMAP-155_508.pdf

Federal Emergency Management Agency (FEMA), 2015b, 2015 NEHRP recommended seismic provisions for new buildings and other structures, Vol. I: Part 1 Provisions, Part 2 Commentary: Washington, D.C., Building Seismic Safety Council of the National Institute of Building Sciences, FEMA P-1050-1, 555 p. https://www.fema.gov/media-library-data/1440422982611-3b5aa529affd883a41fbdc89c5ddb7d3/fema_p-1050-1.pdf

Federal Emergency Management Agency (FEMA), 2017a, Risk MAP CDS Hazus 4.0 user release notes, Ver. 1.0, 12 p. https://www.fema.gov/media-library-data/1493315287435-68e5171cc8856bf36651f1ce9ba2e6fe/Hazus.4.0.User.Release.Notes.pdf

Federal Emergency Management Agency (FEMA), 2017b, Hazus® estimated annualized earthquake losses for the United States: Washington, D.C., FEMA P-366, 75 p. https://www.fema.gov/media-library/assets/documents/132305

Federal Emergency Management Agency (FEMA), 2017c, Hazus tsunami model: technical guidance [for Hazus version 4.0], 1st ed.: Herndon, Va., NiyamIT, Inc., contract no. HSFE60-17-P-0004. https://www.fema.gov/media-library-data/1511284000276-4f18206fb0c7bab3c5ecbbbdf504b9fd/Hazus_40_Tsunami_Tech_Manual.pdf

Federal Emergency Management Agency (FEMA), 2018, Risk MAP CDS Hazus® 4.2 user release notes, ver. 1.0, January 29, 2018, 16 p. Available as part of Hazus 4.2 software package.

Fujisaki, E., Takhirov, S., Xie, Q., and Mosalam, K. M., 2014, Seismic vulnerability of power supply: lessons learned from recent earthquakes and future horizons of research, *in* Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014, Porto, Portugal, 30 June–2 July 2014 p. 345–350. https://paginas.fe.up.pt/~eurodyn2014/CD/papers/046_MS01_ABS_2043.pdf

Goldfinger, C., Nelson, C. H., Morey, A. E., Johnson, J. E., Patton, J. R., Karabanov, E., Gutiérrez-Pastor, J., Eriksson, A. T., Gràcia, E., Dunhill, G., Enkin, R. J., Dallimore, A., and Vallier, T., 2012, Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U.S. Geological Survey Professional Paper 1661–F, 170 p. https://pubs.usgs.gov/pp/pp1661f/

Goldfinger, C., Galer, S., Beeson, J., Hamilton, T., Black, B., Romos, C., Patton, J., Elson, H. C., Hausmann, R., and Morey, A., 2017, The importance of site selection, sediment supply, and hydrodynamics: a case study of submarine paeloseismology on the northern Cascadia margin, Washington, USA: Marine Geology, v. 384, p. 4–16, 17, 24–46. https://doi.org/10.1016/j.margeo.2016.06.008

Gomberg, J. S., and others, 2017, Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan: U.S. Geological Survey Circular 1428, 45 p., https://doi.org/10.3133/cir1428.

Good, B., Toth, J. C., and Gilpin-Jackson, A., 2009, Transmission tower seismic risk mitigation for British Columbia, *in* TCLEE 2009: lifeline earthquake engineering in a multihazard environment, Proceedings of the 2009 ASCE Technical Council on Lifeline Earthquake Engineering Conference, June 28–July 1, 2009, Oakland, Calif. p. 335–346.

Hofmeister, R. J., Hasenberg, C. S., Madin, I. P., and Wang, Y., 2003, Earthquake and landslide hazard maps and future earthquake damage estimates for Clackamas County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-03-10, 95 p., 1 pl. http://www.oregongeology.org/pubs/ofr/O-03-10.zip

U.S. Department of Homeland Security, 2017, Homeland Infrastructure Foundation-Level Data (HIFLD), electric power transmission lines. Downloaded March 17, 2017. https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines

Jones, L. M., and others, The ShakeOut Scenario: U.S. Geological Survey Open-File Report 2008-1150 and California Geological Survey Preliminary Report 25. http://pubs.usgs.gov/of/2008/1150/

Judson, S., 2012, Earthquake design history: A summary of requirements in the State of Oregon: Slaem, Oreg., State of Oregon, Building Codes Division, Feb. 7, 2012, 7 p. http://www.oregon.gov/bcd/codes-stand/Documents/inform-2012-oregon-sesmic-codes-history.pdf

Kircher, C. A., Reitherman, R. K., Whitman, R., V., and Arnold, C., 1997, Estimation of earthquake losses to buildings: Earthquake Spectra, v. 13, no. 4, p. 703–720. https://doi.org/10.1193/1.1585976

Kongar, I., Rossetto, T., and Siovinazzi, S., 2014, The effectiveness of existing methodologies for predicting electrical substation damage due to earthquakes in New Zealand, *in* Proceedings of the Second International Conference on Vulnerability and Risk Analysis and Management (ICVRAM) and the Sixth International Symposium on Uncertainty, Modeling, and Analysis (ISUMA), July 13–16, 2014, Liverpool, UK, American Society of Civil Engineers, p. 752–761. https://doi.org/10.1061/9780784413609.077

Kwasinski, A., Eidinger, J., Tang, A., and Tudo-Bornarel, C., 2014, Performance of electric power systems in the 2010-2011 Christchurch, New Zealand, earthquake sequence: Earthquake Spectra, v. 30, no. 1, p.205–230. https://doi.org/10.1193/022813EQS056M

Levi, T., Bausch, D., Katz, O., Rozelle, J., and Salamon, A., 2015, Insights from Hazus loss estimation in Israel for Dead Sea Transform earthquakes: Natural Hazards, v. 75, no. 1, p. 365–388. https://doi.org/10.1007/s11069-014-1325-y

Lewis, D., 2007, Statewide seismic needs assessment: Implementation of Oregon 2005 Senate Bill 2 relating to public safety, earthquakes, and seismic rehabilitation of public buildings: Oregon Department of Geology and Mineral Industries Open-File Report O-07-02, 140 p. Available from http://www.oregongeology.org/sub/projects/rvs/

Liberty, L. M., Hemphill-Haley, M. A., and Madin, I. P., 2003, The Portland Hills Fault: uncovering a hidden fault in Portland, Oregon using high-resolution geophysical methods: Tectonophysics, v. 368, no. 1–4, 89–103. https://doi.org/10.1016/S0040-1951(03)00152-5

Lu, X., Tian Y., Guan H., and Xiong C., 2017, Parametric sensitivity study on regional seismic damage prediction of reinforced masonry buildings based on time-history analysis: Bulletin of Earthquake Engineering, v. 15, no. 11, p. 4791–4820. https://doi.org/10.1007/s10518-017-0168-9

Ma, L., Madin, I. P., Suplantis, S., and Williams, K. J., 2012, Lidar-based surficial geologic map and database of the greater Portland, Oregon, area, Clackamas, Columbia, Marion, Multnomah, Washington, and Yamhill Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Open-File Report O-12-02, 30 p., 1 pl., http://www.oregongeology.org/pubs/ofr/p-O-12-02.htm

Mabey, M., Black, G. L., Madin, I. P., Meier, D. B., Youd, T. L., Jones, C. F., and Rice, J. B., 1997, Relative earthquake hazard map of the Portland Metro Region, Clackamas, Multnomah, and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Interpretive Map 1, 1 pl., GIS data. http://www.oregongeology.org/pubs/ims/IMS-001.zip

Madin, I. P., and Burns, W. J., 2013, Ground motion, ground deformation, tsunami inundation, coseismic subsidence, and damage potential maps for the 2012 Oregon Resilience Plan for Cascadia subduction zone earthquakes: Oregon Department of Geology and Mineral Industries Open-File Report O-13-06, 36 p., 38 pl., GIS data. Available from http://www.oregongeology.org/pubs/ofr/p-O-13-06.htm

Mahalingam, R., Olsen, M. J., Sharifi-Mood, M., and Gillins, D. T., 2015, Landslide susceptibility analysis of lifeline routes in the Oregon Coast Range: Oregon Department of Geology and Mineral Industries Open-File Report O-15-01, 1 pl., GIS data, model. Available from http://www.oregongeology.org/pubs/ofr/p-O-15-01.htm

Metro, 1998, Evaluation of non-residential and multi-family residential buildings for seismic risk: Portland, Oreg., Report prepared by Metro with assistance from Portland State University, Civil Engineering Department, FEMA Contract No. EMS-96-CA-0055, 32 p. with accompanying GIS data.

Metro, 2016, Metro Regional Land Information System (RLIS) City limits as of February 6, 2016. Accessed March 7, 2016. http://rlisdiscovery.oregonmetro.gov

Mickelson, K. A., and Burns, W. J., 2012, Landslide hazard and risk study of the U.S. Highway 30 (Oregon State Highway 92) corridor, Clatsop and Columbia Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-12-06, 105 p. 4 pl., GIS data. http://www.oregongeology.org/pubs/ofr/p-O-12-06.htm

MMI Engineering, 2012, Hazus (HAZards United States) analysis for the City and County of San Francisco's high priority city-owned buildings: Report prepared for the City and County of San Francisco's Capital Planning Program: Huntington Beach, Calif., MMI Engineering Document MMHB043-003, February 14, 2012, 41 p., 3 app. http://onesanfrancisco.org/sites/default/files/inline-files/CCSF-HAZUS-Project-Report-FINAL-2-14-20122.pdf

Olsen, A. H., and Porter, K. A., 2011, What we know about demand surge: brief summary: Natural Hazards Review, v. 12, no. 2, p. 62–71. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000028

Olson, R. A., 2003, Legislative politics and seismic safety: California's earth years and the "Field Act," 1925–1933: Earthquake Spectra, v. 19, no. 1, p. 111–131. https://doi.org/10.1193/1.1542890

Oregon Building Codes Division, 2002, Oregon manufactured dwelling and park specialty code, 2002 ed.: Salem, Oreg., Oregon Manufactured Housing Association and Oregon Building Codes Division, Department of Consumer and Business Services, 176 p. http://www.oregon.gov/bcd/codes-stand/Documents/md-2002-mdparks-code.pdf

Oregon Building Codes Division, 2010, 2010 Oregon manufactured dwelling installation specialty code: Salem, Oreg., Oregon Department of Consumer and Business Services, Building Codes Division, 67 p. http://www.oregon.gov/bcd/codes-stand/Documents/md-2010omdisc-codebook.pdf

Oregon Department of Energy (ODOE), 2017, Oregon fuel action plan: Plan, repair, respond, and recover from sever fuel shortages: Salem, Oreg., October 2017, rev. 1, 92 p. http://www.oregon.gov/energy/facilities-safety/safety/Documents/Oregon-Fuel-Action-Plan.pdf

Oregon Employment Department (OED), 2016, Quarterly census of employment and wages. Obtained October 16, 2016.

Oregon Seismic Safety Policy Advisory Commission (OSSPAC), 2013, The Oregon Resilience Plan: Reducing risk and improving recovery for the next Cascadia earthquake and tsunami. Report to the 77th Legislative Assembly, Salem, Oregon, 242 p. with 4 app. http://www.oregon.gov/oem/Documents/Oregon_Resilience_Plan_Final.pdf

Paxton, B., Elwood, K. J., and Ingham, J. M., 2017, Empirical damage relationships and benefit-cost analysis for seismic retrofit of URM buildings: Earthquake Spectra, v. 33, no. 3, p. 1053–1074. https://doi.org/10.1193/091816EQS153M

Perkins, J. B., and Chuaqui, B., 1998, Impact of the earthquake on habitability of housing units, *in* Çelebi,, M., ed., The Loma Prieta, California, earthquake of October 17, 1989—Chapter C, Building Structures: U.S. Geological Survey Professional Paper 1552-C, p. C169-C186, https://pubs.usgs.gov/pp/pp1552/pp1552c/pp1552c.pdf

Personius, S. F., Dart, R. L., Bradley, L.-A. , and Haller, K. M., 2003, Map and data for Quaternary faults and folds in Oregon: U.S. Geological Survey Open-File Report 03-095, 550 p. https://pubs.usgs.gov/of/2003/ofr-03-095/

Petersen, M. D., Cramer, C. H., and Frankel, A. D., 2002, Simulations of seismic hazard for the Pacific Northwest of the United States from earthquakes associated with the Cascadia subduction zone: Pure and Applied Geophysics, v. 159, no. 9, 2147–2168. https://doi.org/10.1007/s00024-002-8728-5

Pinter, N., Huthoff, F., Dierauer, J., Remo, J. W. F., and Damptz, A., 2016, Modeling residual flood risk behind levees, Upper Mississippi River, USA, Environmental Science & Policy, v. 58, p. 131–140. https://doi.org/10.1016/j.envsci.2016.01.003

Portland Bureau of Emergency Management (PBEM), 2017, Unreinforced masonry (URM) building policy committee report (draft), November 2017, 37 p. Final, December 2017, report available at https://www.portlandoregon.gov/pbem/article/661773

Price, J. G., Hastings, J. T., Goar, L. D., Armeno, H., Johnson, G., Depolo, C. M., Hess, R. H., and Ballard, C. M., 2010, Sensitivity analysis of loss estimation modeling using uncertainties in earthquake parameters: Environmental & Engineering Geoscience, v. 16, no. 4, p. 357–367. https://doi.org/10.2113/gseegeosci.16.4.357

Priest, G. R., Zhang, Y., Witter, R. C., Wang, K., Goldfinger, C., and Stimely, L., 2014, Tsunami impact to Washington and northern Oregon from segment ruptures on the southern Cascadia subduction zone: Natural Hazards, v. 72, no. 2, p. 849–870. https://doi.org/10.1007/s11069-014-1041-7

Remo, J. W. F., and Pinter, N., 2012, Hazus-MH earthquake modeling in the central USA: Natural Hazards, v. 63, no. 2, p. 1055–1081. https://doi.org/10.1007/s11069-012-0206-5

Scawthorn, C., Eidinger, J. M., and Schiff, A. J., eds., 2005, Fire following earthquake: Reston, Va., American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 26, 352 p.

Schmidtlein, M. C., Shafer, J. M., Berry, M., and Cutter, S. L., 2011, Modeled earthquake losses and social vulnerability in Charleston, South Carolina: Applied Geography, v. 31, no. 1, p. 269–281. https://doi.org/10.1016/j.apgeog.2010.06.001

Schneider, P. J., and Schauer, B. A., 2006, HAZUS—its development and its future: Natural Hazards Review, v. 7, no. 2, p. 40–44. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(40)

Scruggs, J., 2014, BPA preps the power grid for the "big one": Northwest Public Power Association Bulletin, v. 68, no. 1, p. 27–29. https://www.nwppa.org/wp-content/uploads/January-2014-Bulletin.pdf

Seligson, H. A., 2008, HAZUS® enhancements and implementation for the ShakeOut Scenario earthquake: supplemental study for the ShakeOut Scenario: Huntington Beach, Calif., MMI Engineering, Inc., report prepared for the U.S. Geological Survey and the California Geological Survey, to accompany U.S. Geological Survey Open File Report 2008-1150 (California Geological Survey Preliminary Report 25, ver. 1.0), 40 p.

Seligson, H., Bausch, D., and Wein, A., 2015, Hazus analysis of aftershocks for the HayWired scenario, paper presented at the 8th Annual Hazus User Group Conference, Atlanta, Ga., December 9–11, 2015. http://www.hazusconference.com/agenda/pdfs-2015/Seligson2015HazusConference.pdf

Singh, S. K., Mena, E., and Castro, R., 1988, Some aspects of source characteristics of the 19 September 1985 Michoacán earthquake and ground motion amplification in and near Mexico City from strong motion data: Bulletin of the Seismological Society of America, v. 78, no. 2, p. 451–477. https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/78/2/451/119036/

Snyder, D. T., 2008, Estimated depth to ground water and configuration of the water table in the Portland, Oregon area: U.S. Geological Survey Scientific Investigations Report 2008-5059, 39 p., https: //pubs.usgs.gov/sir/2008/5059/pdf/sir20085059.pdf

Tetra Tech, 2016a, The Mitigation Action Plan: The City of Portland's Path to Resilience, agency review draft: Portland, Oreg., report to City of Portland Bureau of Emergency Management, September 2016, 868 p. ftp://ftp02.portlandoregon.gov/pbem/MitigationActionPlan-FullText/2016_Portland MAP_AgencyReviewDraft_2016-09-29.pdf

Tetra Tech, 2016b, 2016 Critical Energy Infrastructure Hub study, draft: Portland, Oreg., prepared for City of Portland Bureau of Emergency Management, 68 p.

Toké, N. A., Boone, C.G., and Arrowsmith, J. R., 2014, Fault zone regulation, seismic hazard, and social vulnerability in Los Angeles, California: Hazard or urban amenity?: Earth's Future, v. 2, p. 440–457, doi:10.1002/2014EF000241, http://onlinelibrary.wiley.com/doi/10.1002/2014EF000241/pdf

U.S. Census Bureau, 2010, Master Address File/Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) database: Oregon census block: United States Census Bureau. https://www.census.gov/geo/maps-data/data/tiger.html

Villemure, M., Wilson, T. M., Bristow, D., Gallagher, M., Giovinazzi, S., and Brown, C., 2012, Liquefaction ejecta clean-up in Christchurch during the 2010-2011 earthquake sequence: New Zealand Society for Earthquake Engineering Annual Technical Conference, Christchurch, New Zealand, April 13-15, 2012, Paper 131. http://www.nzsee.org.nz/db/2012/Paper131.pdf

Wald, D. J., Worden, B. C., Quitoriano, V., and Pankow, K. L., 2006, ShakeMap® manual: technical manual, user's guide, and software guide: U.S. Geological Survey, Techniques and Methods TM12-A1, 156 p. Web: http://pubs.er.usgs.gov/publication/tm12A1

Wang, Y., 1998, Earthquake damage and loss estimate for Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-98-3, 10 p., 2 app. http://www.oregongeology.org/pubs/ofr/O-98-03.pdf

Wang, Y., 2017, Oregon hospital and water system earthquake risk evaluation pilot study: Oregon Department of Geology and Mineral Industries Open-File Report O-17-01, 69 p., 7 app. http://www.oregongeology.org/pubs/ofr/p-O-17-01.htm

Wang, Y., Bartlett, S. F., and Miles, S. B., 2013, Earthquake risk study for Oregon's Critical Energy Infrastructure Hub: Oregon Department of Geology and Mineral Industries Open-File Report O-13-09, 157 p. http://www.oregongeology.org/pubs/ofr/p-O-13-09.htm

Wein, A., Rose, A., Sue Wing, I., and Wei, D., 2013, Economic impacts of the SAFRR tsunami scenario in California, chap. H *of* Ross, S. L., and Jones, L. M., eds., The SAFRR (Science Application for Risk Reduction) Tsunami Scenario: U.S. Geological Survey Open-File Report 2013–1170, 50 p. https://pubs.usgs.gov/of/2013/1170/h/

Wein, A. M., Felzer, K. R., Jones, J., and Porter, K. A., 2017, chap. G *of* Detweiler, S. T., and Wein, A. M., eds., HayWired scenario aftershock sequence: U.S. Geological Survey Scientific Investigations Report 2017-5013-A–H, p. 91–112. https://pubs.er.usgs.gov/publication/sir20175013

Williams, R. J., Gardoni, P., and Bracci, J. M., 2009, Decision analysis for seismic retrofit of structures: Structural Safety, v. 31, no. 2, p. 188–196. https://doi.org/10.1016/j.strusafe.2008.06.017

Wong, I. G., Hemphill-Haley, M. A., Liberty, L. M., and Madin, I. P., 2001, The Portland Hills fault: An earthquake generator or just another old fault?: Oregon Geology, v. 63, no. 2, p. 39–50. http://www.oregongeology.org/pubs/OG/OGv63n02.pdf

10.0 APPENDIX A: BUILDING DATABASE DEVELOPMENT

10.1 Building Database Data Sources

Table 10.1 lists the several data sources used for constructing the building asset database. The table is organized as follows: the most general data source for a particular attribute is listed first, then, where available, the source of more specific and accurate data. For example, the Regional Land Information System tax lot database had an Oregon Department of Revenue-based Property Class designation assigned to each tax lot. A lookup table provided a Hazus-based occupancy class mapping for most Property Class values. All buildings on the tax lot are given that occupancy class assignment. If better information on occupancy class was available, such as the Metro Fire/Police/School/Hospital spatial dataset, we updated the attribute with that information. More detailed datasets are typically restricted to a small subset of the buildings.

The Year Built attribute is not directly consumed by Hazus AEBM, but this attribute is used to establish the seismic design level (Section **10.2**).

Table 10-1. Data sources used in construction of the building database. Table uses Hazus occupancy class names (FEMA, 2011, Table 3.2).

Dataset Owner/Distributor	Dataset	Date of Publication or Acquisition	Occupancy Class	Year Built	Square Footage	Number of Stories	Building Type	Summarization Unit	Notes
Metro, Portland, Oregon	Regional Land Information System: Tax Lots	February 2016	✓						Spatial association of building footprint with assessor tabular information.
Clackamas County Assessor, Oregon City, Oregon	Clackamas County Assessor Database (tabular)	June 2016	✓	✓	✓	✓	(RES2)[+]		Detailed information on individual structures. Square footage available only for residential properties.
Multnomah County Assessor, Portland, Oregon	Multnomah County Assessor Database (tabular)	March 2016	✓	✓	✓	✓	(RES2)[+]		Detailed information on individual structures.
Washington County Assessor, Hillsboro, Oregon	Washington County Assessor Database (tabular)	March 2016	✓	✓	✓	✓	(RES2)[+]		Detailed information on individual structures. Square footage not available for governmental or institutional buildings. Year Built information variable.
Oregon Dept. of Geology and Mineral Industries	Building footprint digitization	December 2016	✓						Assigned occupancy class during heads-up digitization with NAIP and oblique imagery. Limited to building footprint digitized for this project.
Metro, Portland, Oregon	Metro Area Disaster GIS (MADGIS) Database	1999					✓		Building construction type based on field visits and identification for ~40,000 non-single family residential buildings.
Metro, Portland, Oregon	Multi-family housing inventory	February 2017	✓				✓		Refined the distinction between single-family and multi-family residential buildings.
City of Portland	Unreinforced Masonry Building Database	January 2017		✓			✓		Includes information on seismic retrofits to URMs. Limited to City of Portland. https://www.portlandoregon.gov/bds/70767
Oregon Employment Department	North American Industry Classification System (NAICS)	September 2016	✓						Refinement of occupancy class designation for commercial and industrial buildings, building on methods described by Wein and others (2013). Data obtained under terms of a confidentiality agreement; information from dataset can be shared only in aggregate, non-individually identifiable, form.
Metro, Portland, Oregon	Regional Land Information System: Fire, Police, School, Hospital Buildings	February 2016	✓						Refinement of occupancy class designation for educational and certain governmental buildings.
Oregon Dept. of Geology and Mineral Industries	Oregon Statewide Seismic Needs Assessment (Lewis, 2007)	2007	✓	✓	✓	✓	✓		Most detailed information; limited to 777 public schools and government agency buildings.
Metro, Portland, Oregon	Regional Land Information System: Building footprints	February 2016			✓				Combined with other building footprint databases; see Section 2.1.1.
Oregon Dept. of Geology and Mineral Industries	Building footprints (Burns and others, 2011, 2013)	2011, 2013			✓				Previously digitized building footprints for portions of Multnomah and Clackamas counties.
City of Portland	Development Capacity Analysis GIS Model (City of Portland, 2012)	October 2012				✓			Established number of stories attribute for buildings in City of Portland. Used to establish building height to number of stories relationship for buildings where number of stories data were not available.
Oregon Dept. of Geology and Mineral Industries	Lidar compilation: bare earth and highest hit models	2009–2014			✓	✓			Used for building footprint (BF) development in areas where no BFs existed, and to refine existing BF database. Building height derived from lidar elevation models (highest_hit minus the bare_earth) and converted to Number of Stories using relationships established by analysis of data from City of Portland Development Capacity Analysis GIS Model. Lidar acquisition dates vary, depending on area. https://gis.dogami.oregon.gov/lidarviewer/
Metro, Portland, Oregon	Regional Land Information System: County and City Boundaries	February 2016						✓	Building spatial associations with particular jurisdictions and counties, including county unincorporated areas.
Tetra Tech, Portland, Oregon	City of Portland Risk Reporting Areas (Tetra Tech, 2016a)	September 2016						✓	Building spatial associations with one of nine Risk Reporting Areas within the City of Portland.
U.S. Census Bureau	2010 Census Block Groups	April 2010						✓	U.S. Census Block Group (CBG) 2010 boundaries, with contiguous CBGs combined by DOGAMI where needed, to establish neighborhood units. Buildings spatially associated with neighborhood units. Population numbers used to assign residential building population. https://www.census.gov/geo/reference/gtc/gtc_bg.html

[+]RES2 (Single-Family Manufactured Housing) available from Assessor records and, by definition, a Manufactured House building type.

10.2 Seismic Design Level Assignments

We assigned a Hazus seismic design level based on the building's construction year and type. Seismic design codes have evolved with time, with more stringent requirements developing as the natural hazard threat is better understood. We interpreted the relevant state building code histories as described by Judson (2012), Oregon Building Code Division (2002, 2010), and Business Oregon (2015) and developed a seismic design level categorization table (**Table 10-2**). The design level assignment is one of the parameters used by the Hazus tool to derive a damage estimate. Once the seismic design level was assigned to each building, we summarized the number of buildings, square footage, and replacement cost per seismic design level (**Table 10-3**). We did not have sufficient information to further classify buildings into the Hazus-supported Low-Special, Moderate-Special, and High-Special seismic design levels.

Table 10-2. Oregon seismic design level benchmark years.

Building Type	Year Built	Design Level	Basis
Single Family Dwelling (includes Duplexes)	prior to 1976 1976–1991 1992–2003 2004–present	Pre Code Low Code Moderate Code High Code	Interpretation of Judson (2012)
Manufactured Housing	prior to 2003 2003–2010	Pre Code Low Code	Interpretation of Oregon Manufactured Dwelling Special Codes (Oregon Building Codes Division, 2002)
	2011–present	Moderate Code	Interpretation of Oregon Manufactured Dwelling Special Codes Update (Oregon Building Codes Division, 2010)
All other buildings	prior to 1976 1976–1990 1991–present	Pre Code Low Code Moderate Code	Interpretation of Oregon Benefit-Cost Analysis Tool (Business Oregon, 2015, p. 24)

Table 10-3. Building statistics by seismic design level, per county.

County	Seismic Design Level	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Cost Percent
Clackamas	Pre Code	89,647	50%	202,323	42%	24,922	40%
	Low Code	43,530	24%	146,754	30%	19,523	31%
	Moderate Code	30,638	17%	88,682	18%	11,550	19%
	High Code	15,349	9%	48,363	10%	6,394	10%
Multnomah	Pre Code	184,704	72%	489,280	60%	67,497	59%
	Low Code	28,280	11%	111,783	14%	15,884	14%
	Moderate Code	26,383	10%	101,405	13%	14,248	12%
	High Code	16,210	6%	107,620	13%	16,418	14%
Washington	Pre Code	55,806	31%	145,812	24%	19,341	23%
	Low Code	46,556	26%	215,049	36%	31,128	38%
	Moderate Code	55,092	30%	147,174	24%	18,728	23%
	High Code	23,657	13%	94,936	16%	13,534	16%
Total Study Area	Pre Code	330,157	54%	837,415	44%	111,760	43%
	Low Code	118,366	19%	473,586	25%	66,535	26%
	Moderate Code	112,113	18%	337,261	18%	44,526	17%
	High Code	55,216	9%	250,918	13%	36,347	14%

10.3 Buildings by Geological Classification

To better understand the potential influence of local geology on the damage estimates, we summarized building information by National Earthquake Hazards Reduction Program (NEHRP) site classification and landslide and liquefaction susceptibility.

The NEHRP site classification bins a soil column's average shear wave velocity (V_{s30}), measured between 0 (surface) and 30 meters depth, into one of six categories. The site classification can be used to estimate the amplification of bedrock ground motion that may be experienced at the surface during an earthquake. Lower ratings, such as "B" and "C," minimally amplify the bedrock ground motion. Softer soil columns with lower V_{s30} values experience more surface ground motion due to the soil column's amplifying the bedrock ground motion. NEHRP site class "F" is assigned to soil columns primarily composed of fill material or certain types of clays or peat. For building seismic design purposes, such soils generally require site-specific investigations. For Hazus modeling purposes, we take a conservative approach by reclassifying NEHRP site class "F" into NEHRP site class "E"—the classification with the highest site amplification (Section **11.1**). Summary statistics in **Table 10-4** show that while a relatively small percentage of buildings are placed on NEHRP Site Classification "E" and "F" soils, their proportional building value in Multnomah County is large.

Table 10-4. Building statistics by NEHRP site classification, per county.

County	NEHRP Site Classification	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clackamas	B	367	0%	746	0%	84	0%
	C	109,012	61%	278,528	57%	35,172	56%
	D	58,301	33%	178,653	37%	23,616	38%
	E, F	11,484	6%	28,195	6%	3,518	6%
Multnomah	B	32	0%	63	0%	8	0%
	C	118,487	46%	251,404	31%	32,828	29%
	D	126,550	50%	403,956	50%	58,160	51%
	E, F	10,508	4%	154,665	19%	23,050	20%
Washington	C	21,724	12%	63,586	11%	8,484	10%
	D	154,153	85%	525,041	87%	72,507	88%
	E, F	5,234	3%	14,343	2%	1,741	2%
Total Study Area	B	399	0%	808	0%	92	0%
	C	249,223	40%	593,519	31%	76,483	30%
	D	339,004	55%	1,107,651	58%	154,284	60%
	E, F	27,226	4%	197,202	10%	28,310	11%

The liquefaction and earthquake-induced landslide susceptibility rating is a description of a site's characteristics; it is *not* descriptive of an earthquake-induced landslide or liquefaction occurrence for a particular earthquake scenario. The susceptibility ratings are a generalization of the Hazus-based classifications, obtained from Appleby and others (in preparation), with the groupings listed at the bottom of each table (**Table 10-5** and **Table 10-6**). In all three counties, relatively few buildings are in high landslide susceptibility areas. In Washington County, at least 80% of the building value is on moderate liquefaction susceptibility soils.

Table 10-5. Building statistics by Hazus-based liquefaction susceptibility rating, per county.

County	Liquefaction Susceptibility	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clackamas	None to Low	113,010	63%	288,505	59%	36,392	58%
	Moderate	58,905	33%	179,466	37%	23,738	38%
	High	746	0%	2,279	0%	276	0%
	Very High	6,503	4%	15,873	3%	1,984	3%
Multnomah	None to Low	118,909	47%	252,600	31%	32,990	29%
	Moderate	115,200	45%	377,721	47%	54,990	48%
	High	13,713	5%	34,224	4%	4,295	4%
	Very High	7,755	3%	145,543	18%	21,772	19%
Washington	None to Low	23,685	13%	67,804	11%	8,964	11%
	Moderate	149,053	82%	510,591	85%	70,625	85%
	High	6,005	3%	17,204	3%	2,239	3%
	Very High	2,368	1%	7,371	1%	903	1%
Total Study Area	None to Low	255,604	42%	608,909	32%	78,346	30%
	Moderate	323,158	52%	1,067,777	56%	149,354	58%
	High	20,464	3%	53,707	3%	6,810	3%
	Very High	16,626	3%	168,787	9%	24,659	10%

Hazus-based liquefaction scale mapping: 0–2: none to low; 3: moderate; 4: high; 5: very high.

Table 10-6. Building statistics by Hazus-based earthquake-induced landslide susceptibility rating, per county.

County	Landslide Susceptibility	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clackamas	Low	161,505	90%	440,935	91%	56,485	91%
	Moderate	14,582	8%	37,445	8%	4,890	8%
	High to Very High	3,077	2%	7,742	2%	1,015	2%
Multnomah	Low	224,754	88%	614,891	76%	84,347	74%
	Moderate	23,638	9%	167,945	21%	25,449	22%
	High to Very High	7,185	3%	27,251	3%	4,250	4%
Washington	Low	164,795	91%	548,657	91%	75,370	91%
	Moderate	13,364	7%	44,242	7%	6,012	7%
	High to Very High	2,952	2%	10,071	2%	1,351	2%
Total Study Area	Low	551,054	89%	1,604,483	84%	216,202	83%
	Moderate	51,584	8%	249,632	13%	36,351	14%
	High to Very High	13,214	2%	45,064	2%	6,616	3%

Hazus-based landslide scale mapping: 0–5: none to low; 6–7: moderate; 8–10: high to very high.

10.4 Buildings by Primary Usage

We summarized the number of buildings on a generalized Hazus occupancy class basis, which is a classification of a building's dominant use (**Table 10-7**). In the case of mixed-use buildings, such as retail stores on the first floor and residential quarters on the upper floors, we assigned the occupancy class based on the largest square foot usage.

Table 10-7. Buildings statistics by primary usage, per county.

County	Building Use	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clackamas	Agricultural	22,768	13%	52,063	11%	5,541	9%
	Commercial	4,593	3%	54,616	11%	7,929	13%
	Industrial	1,573	1%	20,621	4%	3,063	5%
	Institutional	2,558	1%	23,264	5%	3,940	6%
	Multi-family Residential	8,959	5%	40,880	8%	6,293	10%
	Single-family Residential	138,713	77%	294,677	61%	35,624	57%
Multnomah	Agricultural	2,540	1%	8,146	1%	867	1%
	Commercial	11,544	5%	210,231	26%	33,390	29%
	Industrial	1,685	1%	45,292	6%	6,874	6%
	Institutional	3,094	1%	50,145	6%	8,812	8%
	Multi-family Residential	24,197	9%	140,585	17%	22,428	20%
	Single-family Residential	212,517	83%	355,689	44%	41,675	37%
Washington	Agricultural	10,753	6%	26,823	4%	2,855	3%
	Commercial	5,863	3%	104,377	17%	15,815	19%
	Industrial	1,399	1%	50,567	8%	8,548	10%
	Institutional	1,931	1%	28,098	5%	4,856	6%
	Multi-family Residential	18,475	10%	98,385	16%	15,671	19%
	Single-family Residential	142,690	79%	294,721	49%	34,987	42%

Commercial includes the Hazus RES4 class. Institutional combines the Hazus GOV1, GOV2, EDU1, EDU2, and REL1 classes. Single-family residential combine the Hazus RES1 and RES2 classes.

10.5 Building Type by Primary Usage

We summarized the number of buildings by their generalized basic structural system (in Hazus, referred to as the building type), by generalized occupancy class (**Table 10-8**). Although several ancillary datasets informed our assignments (Section **2.1.4**), most (563,583 out of 615,852, or 92%) were based on the statistical distributions listed in the Hazus Earthquake Technical Manual (FEMA, 2011, Tables 3.A1–3.A.10).

Table 10-8. Building type by generalized building use.

Building Use	Building Type	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Cost ($ Million)	Cost Percent
Agricultural	Concrete	1,650	5%	4,032	5%	429	5%
	Precast Concrete	2,921	8%	7,130	8%	759	8%
	Reinforced Masonry	4,327	12%	10,973	13%	1,168	13%
	Steel	8,772	24%	20,635	24%	2,196	24%
	Trailers	365	1%	588	1%	63	1%
	Unreinforced Masonry	1,097	3%	2,896	3%	308	3%
	Wood	16,929	47%	40,778	47%	4,340	47%
Commercial	Concrete	3,530	16%	78,946	21%	13,635	24%
	Precast Concrete	2,304	10%	82,355	22%	10,624	19%
	Reinforced Masonry	4,660	21%	58,567	16%	8,729	15%
	Steel	3,143	14%	74,659	20%	12,263	21%
	Trailers	7	0%	36	0%	7	0%
	Unreinforced Masonry	1,654	8%	14,842	4%	2,271	4%
	Wood	6,702	30%	59,819	16%	9,606	17%
Industrial	Concrete	579	12%	17,557	15%	2,840	15%
	Precast Concrete	904	19%	40,200	35%	6,557	35%
	Reinforced Masonry	569	12%	13,527	12%	2,332	13%
	Steel	1,649	35%	33,406	29%	5,206	28%
	Trailers	51	1%	179	0%	21	0%
	Unreinforced Masonry	155	3%	1,939	2%	259	1%
	Wood	750	16%	9,672	8%	1,270	7%
Institutional	Concrete	1,685	22%	29,392	29%	5,130	29%
	Precast Concrete	347	5%	7,989	8%	1,337	8%
	Reinforced Masonry	1,689	22%	21,678	21%	3,751	21%
	Steel	1,225	16%	14,277	14%	2,483	14%
	Trailers	9	0%	30	0%	5	0%
	Unreinforced Masonry	328	4%	4,861	5%	853	5%
	Wood	2,300	30%	23,279	23%	4,050	23%
Multi-Family Residential	Concrete	1,091	2%	28,476	10%	5,114	12%
	Precast Concrete	115	0%	2,801	1%	509	1%
	Reinforced Masonry	1,331	3%	16,026	6%	2,876	6%
	Steel	1,636	3%	22,913	8%	4,011	9%
	Unreinforced Masonry	403	1%	5,380	2%	947	2%
	Wood	47,055	91%	204,253	73%	30,934	70%
Single-Family Residential	Other	138	0%	377	0%	44	0%
	Reinforced Masonry	3,549	1%	7,349	1%	893	1%
	Unreinforced Masonry	1,455	0%	2,298	0%	268	0%
	Wood	471,926	99%	914,096	99%	110,199	99%
Single-Family Res. – Manuf. Housing		16,852	100%	20,966	100%	882	100%

Commercial combines all Hazus COM occupancy classes and RES4. Institutional combines Hazus occupancy classes REL1, GOV1, EDU1, and EDU2. Multi-family residential is limited to RES3, RES5, and RES6 types. Single-Family Residential – Manuf. Housing is the Hazus occupancy class RES2, and is broken out separately, given the building type's heightened sensitivity to ground shaking.

11.0 APPENDIX B: SITE GROUND MOTION AND GROUND DEFORMATION MAP DEVELOPMENT

11.1 Site Ground Motion Maps

We converted the bedrock ground motion data referenced in Section 3.1 to a 30-foot grid limited in extent to the three-county study area. For the Portland Hills fault magnitude 6.8 earthquake, we used the Nearest Neighbor tool in the Esri Spatial Analyst. For the Cascadia Subduction Zone magnitude 9.0 earthquake, we used the bedrock data published by Madin and Burns (2013). The NEHRP site classification polygons from Appleby and others (in preparation) were converted to a 30-foot grid. Sites classified as NEHRP “F” were re-assigned to NEHRP “E,” a conservative and commonly implemented assumption for loss estimation purposes.

We used the revised F_a, F_v, and F_{PGA} site coefficients as published by FEMA (2015b, Tables 11.4-1, 11.4-2, 11.8-1) to derive site ground motion. For completeness, we include the NEHRP “A” class (V_{S30} > 1,500 m/s), even though such stiff material is not present in the study area. We note the coefficients are identical to what is used by the Hazus 4.0 model for probabilistic and arbitrary earthquake events available in the Hazus SQL database tables as:

[dbo].[eqPGASoilAmpFact],
[dbo].[eqPGVSoilAmpFact] ,
[dbo].[eqSa03SoilAmpFact] , and
[dbo].[eqSa10SoilAmpFact].

The coefficients applied directly will result in a non-monotonic site amplification function. To overcome the problem, we implemented the straight-line interpolation guidance given by FEMA (2015b) for intermediate values, and we added a y-intercept to the amplification function and adjusted the slope factor, so that the end point of the interval matches the specified amplification. We note the Hazus tool implements a similar piecewise linear function for probabilistic and arbitrary earthquakes. The functions listed in **Table 11-1** through **Table 11-4** were then implemented using the Esri Spatial Analyst raster calculator as a series of conditional statements.

For Hazus purposes, the raster data were converted to the requisite polygon data format by first discretizing the continuous site ground motion data into integer *percent g* bins, then converting the integer raster data to polygon format. The pgv was rounded to the nearest integer inches/second category, and then converted to polygon format.

Table 11-1. Site amplification coefficients for peak ground acceleration (pga, in g).

	Site Multiplication Coefficients NEHRP Site Classification					Piecewise Linear Representation NEHRP Site Classification				
pga_bedrock	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
0.0–0.1	0.8	0.9	1.3	1.6	2.4	0.8*x + 0	0.9*x + 0	1.3*x + 0	1.6*x + 0	2.4*x + 0
0.1–0.2	0.8	0.9	1.2	1.4	1.9	0.8*x + 0	0.9*x + 0	1.1*x + 0.02	1.2*x + 0.04	1.4*x + 0.1
0.2–0.3	0.8	0.9	1.2	1.3	1.6	0.8*x + 0	0.9*x + 0	1.2*x + 0	1.1*x + 0..06	1.0*x + 0.18
0.3–0.4	0.8	0.9	1.2	1.2	1.4	0.8*x + 0	0.9*x + 0	1.2*x + 0	0.9*x + 0.12	0.8*x + 0.24
0.4–0.5	0.8	0.9	1.2	1.1	1.2	0.8*x + 0	0.9*x + 0	1.2*x + 0	0.7*x + 0.2	0.4*x + 0.4
> 0.5	0.8	0.9	1.2	1.1	1.2	0.8*x + 0	0.9*x + 0	1.2*x + 0	1.1*x + 0	1.1*x + 0.05

Table 11-2. Site amplification coefficients for peak ground velocity (pgv, in inches/second).

	Site Multiplication Coefficients NEHRP Site Classification					Piecewise Linear Representation NEHRP Site Classification				
pgv_bedrock	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
0–3.75	0.8	1.0	1.7	2.4	3.5	0.8*x + 0	1.0*x + 0	1.7*x + 0	2.4*x + 0	3.5*x + 0
3.75–7.5	0.8	1.0	1.6	2.0	3.2	0.8*x + 0	1.0*x + 0	1.5*x + 0.75	1.6*x + 3	2.9*x + 2.25
7.5–11.25	0.8	1.0	1.5	1.8	2.8	0.8*x + 0	1.0*x + 0	1.3*x + 2.25	1.4*x + 4.5	2.0*x + 9.0
11.25–15	0.8	1.0	1.4	1.6	2.4	0.8*x + 0	1.0*x + 0	1.1*x + 4.5	1.0*x + 9	1.2*x + 18
15–18.75	0.8	1.0	1.3	1.5	2.0	0.8*x + 0	1.0*x + 0	0.9*x + 7.5	1.1*x + 7.5	0.4*x + 30
> 18.75	0.8	1.0	1.3	1.5	2.0	0.8*x + 0	1.0*x + 0	1.3*x + 0	1.5*x + 0	2.0*x + 0

Table 11-3. Site amplification coefficients for spectral acceleration at 0.3 second (sa03, in g).

	Site Multiplication Coefficients NEHRP Site Classification					Piecewise Linear Representation NEHRP Site Classification				
sa03_bedrock	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
0–0.25	0.8	0.9	1.3	1.6	2.4	0.8*x + 0	0.9*x + 0	1.3*x + 0	1.6*x + 0	2.4*x + 0
0.25–0.50	0.8	0.9	1.3	1.4	1.7	0.8*x + 0	0.9*x + 0	1.3*x + 0	1.2*x + 0.1	1.0*x + 0.35
0.50–0.75	0.8	0.9	1.2	1.2	1.3	0.8*x + 0	0.9*x + 0	1.0*x + 0.15	0.8*x + 0.3	0.5*x + 0.6
0.75–1.00	0.8	0.9	1.2	1.1	1.1	0.8*x + 0	0.9*x + 0	1.2*x + 0	0.8*x + 0.3	0.5*x + 0.6
1.00–1.25	0.8	0.9	1.2	1.0	0.9	0.8*x + 0	0.9*x + 0	1.2*x + 0	0.6*x + 0.5	1.0*x + 1
> 1.25	0.8	0.9	1.2	1.0	0.9	0.8*x + 0	0.9*x + 0	1.2*x + 0	1.0*x + 0	0.9*x + 0

Table 11-4. Site amplification coefficients for spectral acceleration at 1.0 second (sa10, in g).

	Site Multiplication Coefficients NEHRP Site Classification					Piecewise Linear Representation NEHRP Site Classification				
sa10_bedrock	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
0–0.1	0.8	0.8	1.5	2.4	4.2	0.8*x + 0	0.8*x + 0	1.5*x + 0	2.4*x + 0	4.2*x + 0
0.1–0.2	0.8	0.8	1.5	2.2	3.3	0.8*x + 0	0.8*x + 0	1.5*x + 0	2.0*x + 0.04	2.4*x + 0.18
0.2–0.3	0.8	0.8	1.5	2.0	2.8	0.8*x + 0	0.8*x + 0	1.5*x + 0	1.6*x + 0.12	1.8*x + 0.3
0.3–0.4	0.8	0.8	1.5	1.9	2.4	0.8*x + 0	0.8*x + 0	1.5*x + 0	1.6*x + 0.12	1.2*x + 0.48
0.4–0.5	0.8	0.8	1.5	1.8	2.2	0.8*x + 0	0.8*x + 0	1.5*x + 0	1.4*x + 0.2	1.4*x + 0.4
> 0.5	0.8	0.8	1.4	1.7	2.0	0.8*x + 0	0.8*x + 0	1.4*x + 0.05	1.7*x + 0.05	2.0*x + 0.1

11.2 Ground Deformation Maps

We provided the liquefaction and landslide susceptibility data from Appleby and others (in preparation) and the site peak ground acceleration data for both earthquake scenarios developed in Section 3.2 as input to the tool developed by Sharifi-Mood and others (in preparation). The tool implements the methods for permanent ground deformation (PGD) estimation described by Madin and Burns (2013, Section 4), which implemented the Hazus ground failure models described in the Hazus Earthquake Technical Manual (FEMA, 2011). The tool generates raster grids describing the amount and probability of PGD resulting from liquefaction lateral spreading and earthquake-induced landslides. The tool is currently limited to modeling lateral spread from liquefaction in "wet" (saturated) soil conditions. For earthquake-induced landslide modeling, it implements the WET portion of Table 4.15 in the Hazus Earthquake Technical Manual (FEMA, 2011). For liquefaction, it assumes a water depth of 5.0 feet. The tool provides PGD and probability of occurrence estimates for liquefaction lateral spreading and for earthquake-induced landslides. The data are provided in the accompanying geodatabase for the CSZ and the Portland Hills fault simulated earthquakes.

To aid in interpretation, Appendix E, Plates 8 and 9 combine the PGD and probability occurrence from the two mechanisms (earthquake-induced landslides and lateral spread resulting from liquefaction). For a given raster cell, the plates represent the maximum PGD and maximum probability from the two mechanisms.

Our "dry" soil conditions scenario assumes non-saturated soils, thus ground failure due to liquefaction does not occur. However, earthquake-induced landslides may still occur, depending on the ground shaking intensity and local geologic conditions (FEMA, 2011, Table 4.15(A)). To overcome the current limitation of the tool, we developed a "dry" soil conditions scenario ground failure model due to earthquake-induced landslides as follows. As part of a statewide multi-hazard risk assessment effort for Oregon, we developed a lookup table method for rapid loss estimation from a Cascadia Subduction Zone earthquake (Bauer, 2016). All combinations of ground motion, at discrete intervals, and all combinations of liquefaction and landslide susceptibility values, were run through the Hazus model. Building loss ratios, along with ground failure probabilities and lateral spread amount, were captured in a lookup table. Of the four site ground motion parameters (Section **11.1**), the Hazus ground failure model uses only the site peak ground acceleration. A Hazus-based ground failure layer can then be created by associating the local landslide susceptibility rating and the site peak ground acceleration with the lookup table. We repeated the lookup table process for the Portland Hills fault "dry" soil conditions scenario.

The "dry" soil conditions scenario ground failure and probability values are included in the accompanying geodatabase. The lookup table method used the discretized peak ground acceleration (pga) intervals described in Section **11.1** and while it is not as continuous as what is available via the tool developed by Sharifi-Mood and others (in preparation), we determined it is a reasonable representation of the Hazus ground failure model for earthquake-induced landslides in the "dry" soil conditions scenario.

12.0 APPENDIX C: BUILDING DAMAGE ASSESSMENT AND IMPACTS TO OCCUPANTS

12.1 Number of Buildings by Damage State

We summarized the number of buildings in each damage state, by county (**Table 12-1**), using the structural damage states (StrPDS) obtained from the Hazus AEBM output. The quantification of buildings in each damage state follows the methods discussed by FEMA (2017a). The information can inform the planning process for post-earthquake building inspection needs.

Table 12-1. Number of buildings per damage state, by county and by earthquake and soil moisture scenario. Numbers for buildings in the None damage state are not included.

		Cascadia Subduction Zone Magnitude 9.0 Earthquake				Portland Hills Fault Magnitude 6.8 Earthquake			
County (Number of Buildings)	Building Damage State	"Dry" Soil	Building Percent	"Wet" Saturated Soil	Building Percent	"Dry" Soil	Building Percent	"Wet" Saturated Soil	Building Percent
Clackamas (179,164)	Slight	34,145	19%	33,133	18%	46,152	26%	42,988	24%
	Moderate	15,936	9%	15,386	9%	47,122	26%	43,417	24%
	Extensive	5,390	3%	5,228	3%	22,526	13%	20,761	12%
	Complete	2,265	1%	6,267	3%	12,898	7%	24,008	13%
Multnomah (255,577)	Slight	54,660	21%	52,362	20%	72,471	28%	64,772	25%
	Moderate	25,194	10%	23,946	9%	69,876	27%	61,556	24%
	Extensive	7,478	3%	7,017	3%	28,338	11%	25,590	10%
	Complete	3,536	1%	13,039	5%	14,843	6%	39,970	16%
Washington (181,111)	Slight	44,673	25%	41,807	23%	57,184	32%	49,602	27%
	Moderate	20,381	11%	19,012	11%	44,766	25%	38,807	21%
	Extensive	6,303	3%	5,892	3%	15,892	9%	14,519	8%
	Complete	2,784	2%	14,026	8%	6,492	4%	28,194	16%
Study Area Total (615,852)	Slight	133,478	22%	127,301	21%	175,807	29%	157,363	26%
	Moderate	61,512	10%	58,344	9%	161,765	26%	143,781	23%
	Extensive	19,171	3%	18,137	3%	66,756	11%	60,870	10%
	Complete	8,585	1%	33,331	5%	34,233	6%	92,171	15%
Total number of damaged buildings		232,811	38%	237,113	39%	438,560	71%	454,185	74%

12.2 Number of Collapsed Buildings

We used the collapse percentage rates listed in the Hazus Earthquake Technical Manual (FEMA, 2011, Table 13.8), together with probability of Complete structural damage state from the Hazus AEBM output, to estimate the number of collapsed buildings by county and earthquake scenario (**Table 12-2**). The casualty calculations built into Hazus AEBM factor in an assumption that a percentage of completely damaged buildings will collapse, which varies based on building type. For example, the Hazus methods estimate 15% of completely damaged unreinforced masonry buildings will collapse, whereas completely damaged manufactured housing and single family wood frame construction buildings have only a 3% chance of collapse.

Table 12-2. Collapsed buildings by county and by earthquake and soil moisture conditions

		Cascadia Subduction Zone Magnitude 9.0 Earthquake		Portland Hills Fault Magnitude 6.8 Earthquake	
County	**Total Number of Buildings**	**“Dry” Soils**	**“Wet” (Saturated) Soils**	**“Dry” Soil**	**“Wet” (Saturated) Soils**
Clackamas	179,164	158	313	666	1,066
Multnomah	255,577	302	677	1,001	1,876
Washington	181,111	209	619	387	1,155
Total	615,852	668	1,609	2,054	4,097

12.3 Permanent Residents by Building Damage State

We assigned permanent residents to individual residential buildings based on the building's square footage, the total square footage of residential buildings for a census block group, and the U.S. Census 2010 population amount for that census block group (Section **2.1.7**). Using the Hazus AEBM output, we multiplied the individual building's permanent residential population by each structural probability of damage state. Summary statistics by county and earthquake scenario are provided in **Table 12-3**. Note the figures in the Complete state are the same as the long-term displaced population figures in **Table 12-4** through **Table 12-7**. The Hazus Complete damage state equates to the ATC-20 red-tag designation (ATC, 1989), and the Extensive damage state equates to the ATC-20 yellow-tag designation. All other building damage states are considered green-tagged (FEMA, 2010, Table 6.1). Qualitative descriptions of the building damage states as relates to the characteristics of the building, per building type (such as Steel Moment Frame), are provided by FEMA (2011, Section 5.3).

Table 12-3. Permanent residents per building damage state, by county and by earthquake and soil moisture conditions scenario.Numbers for permanent residents occupying buildings in the None damage state are not included.

		Cascadia Subduction Zone Magnitude 9.0 Earthquake		Portland Hills Fault Magnitude 6.8 Earthquake	
County	Building Damage State	"Dry" Soil	"Wet" (Saturated) Soil	"Dry" Soil	"Wet" (Saturated) Soil
Clackamas	Slight	75,828	73,670	101,881	94,448
	Moderate	31,559	30,471	105,523	96,722
	Extensive	6,644	6,580	47,996	44,065
	Complete	1,931	10,093	25,152	50,802
Multnomah	Slight	158,506	151,736	203,333	182,865
	Moderate	84,462	79,688	190,409	167,696
	Extensive	24,258	22,643	81,131	72,394
	Complete	9,736	37,461	50,842	120,124
Washington	Slight	133,418	125,169	168,428	145,320
	Moderate	66,488	62,313	137,364	118,446
	Extensive	16,055	15,165	48,269	43,868
	Complete	5,185	37,657	19,582	86,010
Total	Slight	367,752	350,575	473,642	422,632
	Moderate	182,509	172,471	433,296	382,865
	Extensive	46,957	44,387	177,396	160,328
	Complete	16,852	85,211	95,577	256,936

We recognize that planning for short-term and long-term shelter needs throughout the response and recovery phases is a complex task requiring many assumptions, but at its base the planning requires underlying data on demographics as relates to predicted building damage. **Table 12-4** through **Table 12-7** quantify the number of buildings and permanent residents by generalized occupancy, per county and per building damage state, for the four earthquake scenarios.

Table 12-4. Buildings and permanent residents per building damage state for Cascadia Subduction Zone magnitude 9.0 earthquake, "dry" soil conditions. Dash (—): not applicable

Building Category	Total Number of Buildings	Building Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Number of Collapsed Buildings	Number of Buildings								Number of Permanent Residents								
							Slight Damage		Moderate Damage		Extensive Damage		Complete Damage			Slight Damage		Moderate Damage		Extensive Damage		Complete Damage	
							Number	Percent	Number	Percent	Number	Percent	Number	Percent	Total	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Clackamas County																							
Agricultural	22,768	52,063	5,541	465	8%	78	3,882	17%	3,276	14%	1,818	8%	992	4%	—	—	—	—	—	—	—	—	—
Commercial	4,593	54,616	7,929	927	12%	24	823	18%	894	19%	544	12%	248	5%	—	—	—	—	—	—	—	—	—
Industrial	1,573	20,621	3,063	396	13%	11	246	16%	372	24%	278	18%	145	9%	—	—	—	—	—	—	—	—	—
Institutional	2,558	23,264	3,940	391	10%	17	448	17%	530	21%	335	13%	162	6%	—	—	—	—	—	—	—	—	—
Multi-family residential	8,959	40,880	6,293	305	5%	3	1,964	22%	975	11%	190	2%	50	1%	55,042	13,571	25%	9,036	16%	1,965	4%	563	1%
Single-family residential	132,641	286,514	35,282	672	2%	9	25,687	19%	8,226	6%	1,002	1%	167	0%	309,744	60,191	19%	19,412	6%	2,477	1%	501	0%
Manufactured housing	6,072	8,163	343	51	15%	15	1,096	18%	1,662	27%	1,223	20%	502	8%	11,206	2,067	18%	3,111	28%	2,202	20%	868	8%
Multnomah County																							
Agricultural	2,540	8,146	867	114	13%	16	455	18%	403	16%	252	10%	188	7%	—	—	—	—	—	—	—	—	—
Commercial	11,544	210,231	33,390	7,144	21%	158	1,878	16%	2,387	21%	1,915	17%	1,433	12%	—	—	—	—	—	—	—	—	—
Industrial	1,685	45,292	6,874	1,905	28%	39	204	12%	341	20%	374	22%	398	24%	—	—	—	—	—	—	—	—	—
Institutional	3,094	50,145	8,812	1,257	14%	25	555	18%	664	21%	438	14%	229	7%	—	—	—	—	—	—	—	—	—
Multi-family residential	24,197	140,585	22,428	1,829	8%	22	5,078	21%	2,539	10%	655	3%	248	1%	215,232	46,355	22%	39,385	18%	15,311	7%	7,328	3%
Single-family residential	206,322	348,436	41,371	1,034	2%	23	45,563	22%	16,840	8%	2,203	1%	373	0%	507,022	110,112	22%	40,851	8%	5,648	1%	1,126	0%
Manufactured housing	6,195	7,253	304	57	19%	20	927	15%	2,020	33%	1,641	26%	667	11%	13,080	2,039	16%	4,226	32%	3,299	25%	1,282	10%
Washington County																							
Agricultural	10,753	26,823	2,855	368	13%	76	2,305	21%	1,808	17%	1,120	10%	884	8%	—	—	—	—	—	—	—	—	—
Commercial	5,863	104,377	15,815	2,310	15%	47	1,083	18%	1,321	23%	948	16%	460	8%	—	—	—	—	—	—	—	—	—
Industrial	1,399	50,567	8,548	1,350	16%	13	234	17%	341	24%	276	20%	143	10%	—	—	—	—	—	—	—	—	—
Institutional	1,931	28,098	4,856	790	16%	21	333	17%	438	23%	338	18%	189	10%	—	—	—	—	—	—	—	—	—
Multi-family residential	18,475	98,385	15,671	1,155	7%	20	4,588	25%	2,754	15%	811	4%	305	2%	141,844	35,337	25%	29,225	21%	8,879	6%	3,169	2%
Single-family residential	138,117	289,198	34,755	990	3%	18	35,281	26%	12,139	9%	1,637	1%	308	0%	379,323	96,542	25%	34,321	9%	4,916	1%	1,047	0%
Manufactured housing	4,573	5,523	232	49	21%	15	850	19%	1,582	35%	1,173	26%	495	11%	8,543	1,539	18%	2,943	34%	2,260	26%	969	11%
Study Area (All Three Counties)																							
Agricultural	36,061	87,033	9,263	947	10%	170	6,642	18%	5,487	15%	3,190	9%	2,063	6%	—	—	—	—	—	—	—	—	—
Commercial	22,000	369,224	57,134	10,381	18%	229	3,783	17%	4,603	21%	3,407	15%	2,141	10%	—	—	—	—	—	—	—	—	—
Industrial	4,657	116,480	18,485	3,651	20%	63	683	15%	1,054	23%	928	20%	685	15%	—	—	—	—	—	—	—	—	—
Institutional	7,583	101,507	17,609	2,438	14%	62	1,336	18%	1,632	22%	1,112	15%	580	8%	—	—	—	—	—	—	—	—	—
Multi-family residential	51,631	279,849	44,391	3,288	7%	45	11,630	23%	6,267	12%	1,656	3%	604	1%	412,118	95,262	23%	77,646	19%	26,155	6%	11,060	3%
Single-family residential	477,080	924,147	111,408	2,695	2%	50	106,532	22%	37,205	8%	4,843	1%	848	0%	1,196,089	266,845	22%	94,583	8%	13,041	1%	2,674	0%
Manufactured housing	16,840	20,940	879	158	18%	50	2,872	17%	5,263	31%	4,036	24%	1,664	10%	32,829	5,645	17%	10,280	31%	7,762	24%	3,119	10%
Total	615,852	1,899,180	259,169	23,558	9%	668	133,478	22%	61,512	10%	19,171	3%	8,585	1%	1,641,036	367,752	22%	182,509	11%	46,957	3%	16,852	1%

Number of buildings estimates are derived using the Hazus Advanced Engineering Building Module (AEBM) structural probability of damage states (FEMA, 2010).

Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines the Hazus occupancy classes RES3, RES5, and RES6 categories.

Permanent resident values are based on U.S. Census 2010 population data. Permanent residents are assigned only to buildings designated as Hazus occupancy class RES1, RES2, RES3, RES5, and RES6.

Manufactured housing building category is limited to Hazus occupancy class RES2, and does not include modular construction that may be present in other Hazus occupancy classes.

Table 12-5. Buildings and permanent residents per building damage state for Cascadia Subduction Zone magnitude 9.0 earthquake, "wet" (saturated) soil conditions. Dash (—): not applicable

Building Category	Total Number of Buildings	Building Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Number of Collapsed Buildings	Number of Buildings: Slight Damage Number	Slight Damage Percent	Moderate Damage Number	Moderate Damage Percent	Extensive Damage Number	Extensive Damage Percent	Complete Damage Number	Complete Damage Percent	Number of Permanent Residents: Total	Slight Damage Number	Slight Damage Percent	Moderate Damage Number	Moderate Damage Percent	Extensive Damage Number	Extensive Damage Percent	Complete Damage Number	Complete Damage Percent
Clackamas County																							
Agricultural	22,768	52,063	5,541	598	11%	114	3,747	16%	3,159	14%	1,733	8%	1,570	7%	—	—	—	—	—	—	—	—	—
Commercial	4,593	54,616	7,929	1,124	14%	34	801	17%	864	19%	516	11%	367	8%	—	—	—	—	—	—	—	—	—
Industrial	1,573	20,621	3,063	476	16%	15	240	15%	360	23%	263	17%	188	12%	—	—	—	—	—	—	—	—	—
Institutional	2,558	23,264	3,940	461	12%	23	437	17%	511	20%	314	12%	229	9%	—	—	—	—	—	—	—	—	—
Multi-family residential	8,959	40,880	6,293	426	7%	9	1,919	21%	946	11%	186	2%	223	2%	55,042	13,269	24%	8,746	16%	1,906	3%	1,663	3%
Single-family residential	132,641	286,514	35,282	1,431	4%	99	24,909	19%	7,924	6%	1,038	1%	3,075	2%	309,744	58,361	19%	18,680	6%	2,548	1%	7,377	2%
Manufactured housing	6,072	8,163	343	57	17%	18	1,080	18%	1,622	27%	1,177	19%	614	10%	11,206	2,040	18%	3,045	27%	2,126	19%	1,053	9%
Multnomah County																							
Agricultural	2,540	8,146	867	191	22%	30	408	16%	358	14%	219	9%	408	16%	—	—	—	—	—	—	—	—	—
Commercial	11,544	210,231	33,390	9,977	30%	226	1,747	15%	2,196	19%	1,713	15%	2,150	19%	—	—	—	—	—	—	—	—	—
Industrial	1,685	45,292	6,874	2,613	38%	53	183	11%	300	18%	317	19%	542	32%	—	—	—	—	—	—	—	—	—
Institutional	3,094	50,145	8,812	1,614	18%	37	530	17%	628	20%	406	13%	364	12%	—	—	—	—	—	—	—	—	—
Multi-family residential	24,197	140,585	22,428	3,180	14%	56	4,868	20%	2,408	10%	621	3%	1,109	5%	215,232	44,050	20%	36,542	17%	13,911	6%	17,065	8%
Single-family residential	206,322	348,436	41,371	2,846	7%	247	43,729	21%	16,126	8%	2,217	1%	7,543	4%	507,022	105,712	21%	39,101	8%	5,664	1%	18,591	4%
Manufactured housing	6,195	7,253	304	68	22%	28	896	14%	1,930	31%	1,523	25%	924	15%	13,080	1,974	15%	4,044	31%	3,068	23%	1,806	14%
Washington County																							
Agricultural	10,753	26,823	2,855	558	20%	123	2,126	20%	1,657	15%	1,016	9%	1,601	15%	—	—	—	—	—	—	—	—	—
Commercial	5,863	104,377	15,815	3,031	19%	76	1,016	17%	1,242	21%	891	15%	784	13%	—	—	—	—	—	—	—	—	—
Industrial	1,399	50,567	8,548	1,799	21%	21	218	16%	318	23%	257	18%	225	16%	—	—	—	—	—	—	—	—	—
Institutional	1,931	28,098	4,856	1,039	21%	31	312	16%	410	21%	315	16%	298	15%	—	—	—	—	—	—	—	—	—
Multi-family residential	18,475	98,385	15,671	2,016	13%	59	4,319	23%	2,592	14%	766	4%	1,367	7%	141,844	33,289	23%	27,529	19%	8,377	6%	11,319	8%
Single-family residential	138,117	289,198	34,755	3,144	9%	287	33,018	24%	11,313	8%	1,556	1%	8,993	7%	379,323	90,437	24%	32,039	8%	4,695	1%	24,858	7%
Manufactured housing	4,573	5,523	232	61	26%	23	798	17%	1,480	32%	1,089	24%	758	17%	8,543	1,442	17%	2,745	32%	2,092	24%	1,480	17%
Study Area (All Three Counties)																							
Agricultural	36,061	87,033	9,263	1,347	15%	268	6,281	17%	5,174	14%	2,969	8%	3,579	10%	—	—	—	—	—	—	—	—	—
Commercial	22,000	369,224	57,134	14,133	25%	337	3,564	16%	4,302	20%	3,121	14%	3,301	15%	—	—	—	—	—	—	—	—	—
Industrial	4,657	116,480	18,485	4,888	26%	89	641	14%	979	21%	837	18%	955	21%	—	—	—	—	—	—	—	—	—
Institutional	7,583	101,507	17,609	3,114	18%	91	1,278	17%	1,549	20%	1,036	14%	891	12%	—	—	—	—	—	—	—	—	—
Multi-family residential	51,631	279,849	44,391	5,621	13%	124	11,106	22%	5,946	12%	1,573	3%	2,698	5%	412,118	90,608	22%	72,818	18%	24,195	6%	30,047	7%
Single-family residential	477,080	924,147	111,408	7,421	7%	632	101,656	21%	35,363	7%	4,812	1%	19,611	4%	1,196,089	254,510	21%	89,820	8%	12,906	1%	50,826	4%
Manufactured housing	16,840	20,940	879	186	21%	69	2,774	16%	5,031	30%	3,789	22%	2,296	14%	32,829	5,457	17%	9,833	30%	7,286	22%	4,338	13%
Total	615,852	1,899,180	259,169	36,710	14%	1,609	127,301	21%	58,344	9%	18,137	3%	33,331	5%	1,641,036	350,575	21%	172,471	11%	44,387	3%	85,211	5%

Number of buildings estimates are derived using the Hazus Advanced Engineering Building Module (AEBM) structural probability of damage states (FEMA, 2010).

Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines the Hazus occupancy classes RES3, RES5, and RES6 categories.

Permanent resident values are based on U.S. Census 2010 population data. Permanent residents are assigned only to buildings designated as Hazus occupancy class RES1, RES2, RES3, RES5, and RES6.

Manufactured housing building category is limited to Hazus occupancy class RES2, and does not include modular construction that may be present in other Hazus occupancy classes.

Table 12-6. Buildings and permanent residents per building damage state for Portland Hills fault magnitude 6.8 earthquake, "dry" soil conditions. Dash (—): not applicable

							Number of Buildings								Number of Permanent Residents								
							Slight Damage		Moderate Damage		Extensive Damage		Complete Damage			Slight Damage		Moderate Damage		Extensive Damage		Complete Damage	
Building Category	Total Number of Buildings	Building Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Number of Collapsed Buildings	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Total	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Clackamas County																							
Agricultural	22,768	52,063	5,541	787	14%	145	4,935	22%	4,949	22%	2,794	12%	1,718	8%	—	—	—	—	—	—	—	—	—
Commercial	4,593	54,616	7,929	3,054	39%	111	641	14%	1,042	23%	933	20%	1,096	24%	—	—	—	—	—	—	—	—	—
Industrial	1,573	20,621	3,063	1,141	37%	37	191	12%	342	22%	342	22%	438	28%	—	—	—	—	—	—	—	—	—
Institutional	2,558	23,264	3,940	1,339	34%	58	360	14%	579	23%	514	20%	573	22%	—	—	—	—	—	—	—	—	—
Multi-family residential	8,959	40,880	6,293	1,483	24%	33	2,269	25%	2,742	31%	1,360	15%	723	8%	55,042	12,101	22%	17,230	31%	9,877	18%	6,365	12%
Single-family residential	132,641	286,514	35,282	4,975	14%	219	37,211	28%	36,264	27%	14,899	11%	6,267	5%	309,744	88,733	29%	85,978	28%	34,980	11%	15,010	5%
Manufactured housing	6,072	8,163	343	142	41%	63	545	9%	1,205	20%	1,683	28%	2,083	34%	11,206	1,047	9%	2,315	21%	3,139	28%	3,778	34%
Multnomah County																							
Agricultural	2,540	8,146	867	175	20%	27	476	19%	463	18%	272	11%	313	12%	—	—	—	—	—	—	—	—	—
Commercial	11,544	210,231	33,390	14,269	43%	400	1,614	14%	2,374	21%	2,237	19%	3,470	30%	—	—	—	—	—	—	—	—	—
Industrial	1,685	45,292	6,874	3,025	44%	76	156	9%	272	16%	337	20%	724	43%	—	—	—	—	—	—	—	—	—
Institutional	3,094	50,145	8,812	3,274	37%	75	496	16%	687	22%	565	18%	683	22%	—	—	—	—	—	—	—	—	—
Multi-family residential	24,197	140,585	22,428	5,805	26%	102	6,897	29%	5,714	24%	2,338	10%	1,501	6%	215,232	48,640	23%	48,949	23%	29,097	14%	31,396	15%
Single-family residential	206,322	348,436	41,371	5,677	14%	298	61,845	30%	58,400	28%	21,082	10%	7,363	4%	507,022	152,533	30%	137,314	27%	48,933	10%	17,893	4%
Manufactured housing	6,195	7,253	304	63	21%	24	987	16%	1,966	32%	1,508	24%	789	13%	13,080	2,160	17%	4,145	32%	3,101	24%	1,553	12%
Washington County																							
Agricultural	10,753	26,823	2,855	309	11%	51	2,526	23%	2,057	19%	1,011	9%	593	6%	—	—	—	—	—	—	—	—	—
Commercial	5,863	104,377	15,815	4,917	31%	100	1,062	18%	1,537	26%	1,245	21%	937	16%	—	—	—	—	—	—	—	—	—
Industrial	1,399	50,567	8,548	2,412	28%	22	225	16%	357	26%	317	23%	216	15%	—	—	—	—	—	—	—	—	—
Institutional	1,931	28,098	4,856	1,258	26%	34	342	18%	490	25%	396	21%	316	16%	—	—	—	—	—	—	—	—	—
Multi-family residential	18,475	98,385	15,671	2,831	18%	55	5,664	31%	5,085	28%	2,085	11%	1,016	6%	141,844	38,908	27%	41,465	29%	19,438	14%	10,404	7%
Single-family residential	138,117	289,198	34,755	3,582	10%	109	46,643	34%	33,685	24%	9,504	7%	2,888	2%	379,323	128,109	34%	92,956	25%	26,404	7%	8,275	2%
Manufactured housing	4,573	5,523	232	52	23%	16	722	16%	1,556	34%	1,335	29%	527	12%	8,543	1,411	17%	2,943	34%	2,427	28%	903	11%
Study Area (All Three Counties)																							
Agricultural	36,061	87,033	9,263	1,271	14%	222	7,937	22%	7,469	21%	4,076	11%	2,624	7%	—	—	—	—	—	—	—	—	—
Commercial	22,000	369,224	57,134	22,240	39%	611	3,317	15%	4,953	23%	4,415	20%	5,503	25%	—	—	—	—	—	—	—	—	—
Industrial	4,657	116,480	18,485	6,578	36%	135	571	12%	971	21%	996	21%	1,377	30%	—	—	—	—	—	—	—	—	—
Institutional	7,583	101,507	17,609	5,871	33%	167	1,198	16%	1,756	23%	1,475	19%	1,572	21%	—	—	—	—	—	—	—	—	—
Multi-family residential	51,631	279,849	44,391	10,118	23%	190	14,831	29%	13,541	26%	5,784	11%	3,241	6%	412,118	99,648	24%	107,645	26%	58,413	14%	48,165	12%
Single-family residential	477,080	924,147	111,408	14,234	13%	626	145,699	31%	128,349	27%	45,485	10%	16,518	3%	1,196,089	369,376	31%	316,249	26%	110,317	9%	41,177	3%
Manufactured housing	16,840	20,940	879	257	29%	102	2,254	13%	4,726	28%	4,526	27%	3,399	20%	32,829	4,618	14%	9,403	29%	8,666	26%	6,234	19%
Total	615,852	1,899,180	259,169	60,569	23%	2,054	175,807	29%	161,765	26%	66,756	11%	34,233	6%	1,641,036	473,642	29%	433,296	26%	177,396	11%	95,577	6%

Number of buildings estimates are derived using the Hazus Advanced Engineering Building Module (AEBM) structural probability of damage states (FEMA, 2010).

Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines the Hazus occupancy classes RES3, RES5, and RES6 categories.

Permanent resident values are based on U.S. Census 2010 population data. Permanent residents are assigned only to buildings designated as Hazus occupancy class RES1, RES2, RES3, RES5, and RES6.

Manufactured housing building category is limited to Hazus occupancy class RES2, and does not include modular construction that may be present in other Hazus occupancy classes.

Table 12-7. Buildings and permanent residents per building damage state for Portland Hills fault magnitude 6.8 earthquake, "wet" (saturated) soil conditions. Dash (—): not applicable.

							Number of Buildings								Number of Permanent Residents								
							Slight Damage		Moderate Damage		Extensive Damage		Complete Damage			Slight Damage		Moderate Damage		Extensive Damage		Complete Damage	
Building Category	Total Number of Buildings	Building Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Number of Collapsed Buildings	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Total	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Clackamas County																							
Agricultural	22,768	52,063	5,541	1,009	18%	204	4,691	21%	4,671	21%	2,624	12%	2,678	12%	—	—	—	—	—	—	—	—	—
Commercial	4,593	54,616	7,929	3,578	45%	134	589	13%	936	20%	826	18%	1,401	30%	—	—	—	—	—	—	—	—	—
Industrial	1,573	20,621	3,063	1,332	44%	46	176	11%	308	20%	301	19%	541	34%	—	—	—	—	—	—	—	—	—
Institutional	2,558	23,264	3,940	1,520	39%	71	336	13%	529	21%	464	18%	719	28%	—	—	—	—	—	—	—	—	—
Multi-family residential	8,959	40,880	6,293	1,879	30%	57	2,083	23%	2,482	28%	1,229	14%	1,425	16%	55,042	11,141	20%	15,542	28%	8,861	16%	10,644	19%
Single-family residential	132,641	286,514	35,282	6,890	20%	482	34,598	26%	33,393	25%	13,819	10%	14,830	11%	309,744	82,316	27%	79,066	26%	32,402	10%	35,761	12%
Manufactured housing	6,072	8,163	343	158	46%	72	516	9%	1,099	18%	1,498	25%	2,414	40%	11,206	991	9%	2,114	19%	2,803	25%	4,397	39%
Multnomah County																							
Agricultural	2,540	8,146	867	262	30%	44	413	16%	388	15%	221	9%	577	23%	—	—	—	—	—	—	—	—	—
Commercial	11,544	210,231	33,390	17,324	52%	489	1,427	12%	2,064	18%	1,927	17%	4,464	39%	—	—	—	—	—	—	—	—	—
Industrial	1,685	45,292	6,874	3,614	53%	89	135	8%	231	14%	279	17%	863	51%	—	—	—	—	—	—	—	—	—
Institutional	3,094	50,145	8,812	3,862	44%	95	450	15%	610	20%	497	16%	922	30%	—	—	—	—	—	—	—	—	—
Multi-family residential	24,197	140,585	22,428	7,857	35%	183	6,207	26%	5,009	21%	2,075	9%	3,764	16%	215,232	44,235	21%	42,709	20%	24,932	12%	50,070	23%
Single-family residential	206,322	348,436	41,371	9,750	24%	941	55,202	27%	51,428	25%	19,246	9%	28,205	14%	507,022	136,577	27%	121,130	24%	44,695	9%	67,697	13%
Manufactured housing	6,195	7,253	304	79	26%	35	937	15%	1,827	29%	1,344	22%	1,174	19%	13,080	2,053	16%	3,857	29%	2,767	21%	2,357	18%
Washington County																							
Agricultural	10,753	26,823	2,855	525	18%	104	2,309	21%	1,858	17%	914	8%	1,386	13%	—	—	—	—	—	—	—	—	—
Commercial	5,863	104,377	15,815	6,424	41%	157	922	16%	1,328	23%	1,085	19%	1,580	27%	—	—	—	—	—	—	—	—	—
Industrial	1,399	50,567	8,548	3,270	38%	36	198	14%	312	22%	278	20%	355	25%	—	—	—	—	—	—	—	—	—
Institutional	1,931	28,098	4,856	1,707	35%	52	300	16%	426	22%	346	18%	514	27%	—	—	—	—	—	—	—	—	—
Multi-family residential	18,475	98,385	15,671	4,687	30%	142	4,846	26%	4,372	24%	1,876	10%	3,418	19%	141,844	33,220	23%	35,496	25%	17,208	12%	28,812	20%
Single-family residential	138,117	289,198	34,755	7,614	22%	637	40,371	29%	29,117	21%	8,833	6%	20,009	14%	379,323	110,815	29%	80,303	21%	24,493	6%	55,551	15%
Manufactured housing	4,573	5,523	232	70	30%	28	656	14%	1,394	30%	1,188	26%	932	20%	8,543	1,285	15%	2,647	31%	2,168	25%	1,647	19%
Study Area (All Three Counties)																							
Agricultural	36,061	87,033	9,263	1,796	19%	352	7,413	21%	6,916	19%	3,758	10%	4,641	13%	—	—	—	—	—	—	—	—	—
Commercial	22,000	369,224	57,134	27,326	48%	780	2,938	13%	4,328	20%	3,838	17%	7,445	34%	—	—	—	—	—	—	—	—	—
Industrial	4,657	116,480	18,485	8,216	44%	171	510	11%	850	18%	858	18%	1,759	38%	—	—	—	—	—	—	—	—	—
Institutional	7,583	101,507	17,609	7,089	40%	217	1,086	14%	1,566	21%	1,307	17%	2,155	28%	—	—	—	—	—	—	—	—	—
Multi-family residential	51,631	279,849	44,391	14,423	32%	383	13,136	25%	11,863	23%	5,180	10%	8,607	17%	412,118	88,596	21%	93,747	23%	51,000	12%	89,526	22%
Single-family residential	477,080	924,147	111,408	24,254	22%	2,059	130,171	27%	113,938	24%	41,899	9%	63,043	13%	1,196,089	329,708	28%	280,500	23%	101,590	8%	159,009	13%
Manufactured housing	16,840	20,940	879	307	35%	136	2,109	13%	4,320	26%	4,030	24%	4,520	27%	32,829	4,329	13%	8,618	26%	7,737	24%	8,401	26%
Total	615,852	1,899,180	259,169	83,411	32%	4,097	157,363	26%	143,781	23%	60,870	10%	92,171	15%	1,641,036	422,632	26%	382,865	23%	160,328	10%	256,936	16%

Number of buildings estimates are derived using the Hazus Advanced Engineering Building Module (AEBM) structural probability of damage states (FEMA, 2010).

Institutional combines Hazus occupancy classes REL1, GOV1, GOV2, EDU1, and EDU2. Commercial combines all Hazus COM occupancy classes and RES4. Multi-family residential combines the Hazus occupancy classes RES3, RES5, and RES6 categories.

Permanent resident values are based on U.S. Census 2010 population data. Permanent residents are assigned only to buildings designated as Hazus occupancy class RES1, RES2, RES3, RES5, and RES6.

Manufactured housing building category is limited to Hazus occupancy class RES2, and does not include modular construction that may be present in other Hazus occupancy classes.

12.4 Loss Estimates by Jurisdiction

Table 12-8 through **Table 12-11** provide county-level and jurisdictional level building inventory and building loss estimates, along with casualty estimate for the daytime and nighttime earthquake scenarios. The jurisdictional data are available electronically in the accompanying geodatabase. Casualty and displaced population estimates are based on 2010 U.S. Census data and Hazus population distribution models across business types (Section **2.1.7**). The estimates for jurisdictions include all buildings within their 2016 jurisdictional boundaries, as defined by the Metro (2016) Regional Land Information System city boundary layer, dated February 2016.

Table 12-8. Loss estimates by jurisdiction, Cascadia Subduction Zone magnitude 9.0 earthquake, "dry" soil conditions.

	U.S. Census Population 2010	Number of Buildings	Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Debris (Thousands of Tons)	Long-Term Displaced Population	Casualties: Daytime Scenario					Casualties: Nighttime Scenario				
									Total	Level 1	Level 2	Level 3	Level 4	Total	Level 1	Level 2	Level 3	Level 4
Study area total	1,641,036	615,852	1,899,180	259,169	23,558	9%	12,794	16,852	18,286	13,342	3,518	484	942	4,334	3,338	739	87	169
							Clackamas County											
Clackamas County total	375,992	179,164	486,122	62,390	3,207	5%	1,671	1,931	2,034	1,530	368	46	90	461	373	70	7	12
Barlow	135	60	124	15	4	29%	2	1	3	2	1	0	0	1	0	0	0	0
Canby	15,829	5,559	14,978	1,890	58	3%	34	78	38	31	6	1	1	14	12	2	0	0
Estacada	2,695	1,309	3,361	448	23	5%	17	12	29	22	5	1	2	3	3	0	0	0
Gladstone	11,497	4,022	8,749	1,129	51	5%	27	63	48	35	9	1	3	13	10	2	0	0
Happy Valley	13,903	5,856	19,882	2,692	59	2%	28	8	41	31	7	1	2	5	4	1	0	0
Johnson City	566	275	249	11	3	33%	5	88	2	2	0	0	0	9	7	2	0	0
Lake Oswego	36,619	13,770	47,252	6,805	337	5%	134	220	174	132	31	4	8	50	39	8	1	2
Milwaukie	20,291	7,891	21,596	2,890	295	10%	162	93	294	218	56	7	14	34	27	5	1	1
Molalla	8,108	3,176	6,827	854	21	2%	11	8	12	9	2	0	0	3	3	0	0	0
Molalla Prairie Hamlet	—	4,165	10,102	1,137	62	5%	38	8	19	15	3	0	1	3	2	0	0	0
Mulino Hamlet	—	2,021	4,178	491	41	8%	22	10	20	14	4	1	1	3	2	0	0	0
Oregon City	31,859	12,641	31,984	4,190	277	7%	148	102	258	187	50	7	14	38	30	6	1	1
Rivergrove	289	196	539	70	2	3%	0	1	0	0	0	0	0	0	0	0	0	0
Sandy	9,570	3,734	8,551	1,077	11	1%	5	4	5	4	1	0	0	2	2	0	0	0
Stafford Hamlet	—	1,206	3,543	477	23	5%	10	6	21	15	4	1	1	1	1	0	0	0
The Villages at Mt Hood	—	3,795	7,268	886	18	2%	7	7	5	4	1	0	0	3	2	0	0	0
West Linn	25,109	9,170	28,162	3,817	117	3%	39	96	68	51	13	2	4	19	16	3	0	0
Wilsonville	19,509	5,492	31,168	4,410	291	7%	155	147	199	155	34	4	7	38	30	6	1	1
Clackamas County Jurisdictions total[+]	195,979	84,338	248,512	33,289	1,695	5%	844	952	1,238	926	225	29	57	238	191	36	4	7
Clackamas County Unincorporated total	—	94,481	240,494	29,470	1,539	5%	854	1,006	778	594	137	16	31	216	176	32	3	5
							Multnomah County											
Multnomah County total	735,334	255,577	810,087	114,046	13,340	12%	7,724	9,736	11,418	8,231	2,248	318	621	2,762	2,085	493	62	122
Fairview	8,920	2,611	7,976	1,061	24	2%	12	71	10	8	1	0	0	11	9	2	0	0
Gresham	105,594	29,043	83,478	11,160	314	3%	143	399	235	181	39	5	9	81	68	11	1	1
Maywood Park	752	339	627	74	3	4%	1	1	4	3	1	0	0	0	0	0	0	0
Portland (by Bureau of Emergency Management Risk Reporting Areas):																		
Airport	—	284	12,971	1,898	678	36%	439	6	452	308	97	16	31	64	44	13	2	4
Central City	—	2,809	108,884	18,436	3,952	21%	2,615	3,535	3,333	2,373	666	99	195	1,054	771	201	28	54
Central Northeast Neighborhoods	—	19,883	47,310	6,226	741	12%	372	434	575	432	109	12	22	121	94	21	2	4
East Portland Neighborhood Office	—	46,301	114,853	15,359	758	5%	388	658	543	416	96	11	20	182	147	28	3	5
Neighbors West/Northwest	—	7,663	50,308	7,320	1,685	23%	1,043	1,414	1,588	1,123	328	47	91	318	230	62	9	17
North Portland Neighborhood Services	—	25,468	87,894	12,076	2,331	19%	1,292	794	2,039	1,472	408	54	105	268	204	48	6	11
Northeast Coalition	—	22,178	52,444	6,994	434	6%	235	342	520	374	100	15	31	96	75	15	2	4
Southeast Uplift Neighborhood Program	—	57,291	124,011	16,652	1,134	7%	603	978	991	721	187	28	55	278	217	45	5	11
Southwest Neighborhoods	—	24,288	72,458	10,945	952	9%	418	712	966	698	186	28	55	228	175	39	5	9
Portland (total)	583,776	206,165	671,134	95,906	12,666	13%	7,405	8,872	11,008	7,917	2,177	310	604	2,610	1,958	472	61	119
Troutdale	15,962	5,161	13,481	1,730	77	4%	39	12	56	43	10	1	2	8	6	1	0	0
Wood Village	3,878	1,194	3,507	408	9	2%	6	55	5	5	1	0	0	9	7	1	0	0
Multnomah County Jurisdictions total[+]	718,882	244,513	780,203	110,339	13,092	12%	7,606	9,410	11,319	8,157	2,230	316	616	2,720	2,050	487	62	121
Multnomah County Unincorporated total	—	11,053	29,359	3,614	249	7%	117	335	95	70	18	2	5	44	36	7	1	1
							Washington County											
Washington County total	529,710	181,111	602,970	82,732	7,011	8%	3,399	5,185	4,834	3,581	903	119	231	1,110	881	176	18	35
Banks	1,777	646	1,491	194	20	10%	10	7	37	27	7	1	2	3	2	1	0	0
Beaverton	89,803	24,005	96,327	13,813	1,230	9%	548	1,227	845	635	154	19	37	223	175	36	4	8
Cornelius	11,869	3,517	7,844	963	80	8%	36	118	57	44	10	1	2	21	18	3	0	0
Durham	1,351	399	1,887	277	20	7%	6	24	5	4	1	0	0	4	3	1	0	0
Forest Grove	21,083	7,267	19,462	2,617	303	12%	159	492	381	272	76	11	22	74	58	12	1	2
Gaston*	637	312	618	79	8	10%	4	4	9	7	2	0	1	1	1	0	0	0
Hillsboro	91,611	26,846	116,113	17,603	1,810	10%	946	938	1,339	983	253	35	68	262	203	44	5	10
King City	3,111	1,610	3,702	494	33	7%	11	44	8	6	1	0	0	8	6	1	0	0
North Plains	1,947	952	2,602	328	38	12%	24	7	38	27	8	1	2	3	2	0	0	0
Sherwood	18,194	5,873	17,792	2,335	140	6%	87	27	132	97	25	3	7	12	10	2	0	0
Tigard	48,035	16,004	62,578	8,490	756	9%	405	329	448	337	82	10	19	85	68	13	1	2
Tualatin	26,054	7,535	41,411	5,751	521	9%	290	147	381	291	67	8	15	65	51	11	1	2
Washington County Jurisdictions total[+]	315,472	94,966	371,828	52,943	4,958	9%	2,526	3,361	3,680	2,728	686	90	175	760	598	123	13	26
Washington County Unincorporated total	—	86,501	228,783	29,512	2,025	7%	847	1,788	1,178	868	222	30	58	357	287	54	5	10

[+] The jurisdiction is associated with the county it occupies most by area. Figures are for the entire jurisdiction and may include building data from neighboring counties. Summaries by all jurisdictions and unincorporated area for a given county will vary slightly with the county total.

[*] Gaston census numbers are for entire jurisdiction. Gaston loss figures limited to buildings and residences in Washington County and do not include buildings, casualties, debris, and displaced population in Yamhill County.

Casualty level definitions are provided in **Table 4-1** and are based on U.S. Census 2010 population figures.

Table 12-9. Loss estimates by jurisdiction, Cascadia Subduction Zone magnitude 9.0 earthquake, “wet” (saturated) soil conditions.

	U.S. Census Population 2010	Number of Buildings	Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Debris (Thousands of Tons)	Long-Term Displaced Population	Casualties: Daytime Scenario					Casualties: Nighttime Scenario				
									Total	Level 1	Level 2	Level 3	Level 4	Total	Level 1	Level 2	Level 3	Level 4
Study area total	1,641,036	615,852	1,899,180	259,169	36,710	14%	17,292	85,211	27,175	19,489	5,454	758	1,473	10,400	7,838	1,979	203	380
							Clackamas County											
Clackamas County total	375,992	179,164	486,122	62,390	4,573	7%	2,092	10,093	2,757	2,038	523	67	129	1,115	866	202	17	30
Barlow	135	60	124	15	7	47%	3	28	5	4	1	0	0	3	2	1	0	0
Canby	15,829	5,559	14,978	1,890	61	3%	36	159	40	33	6	1	1	20	16	3	0	0
Estacada	2,695	1,309	3,361	448	27	6%	18	27	33	24	6	1	2	5	4	1	0	0
Gladstone	11,497	4,022	8,749	1,129	69	6%	32	235	61	44	12	2	3	26	21	5	0	1
Happy Valley	13,903	5,856	19,882	2,692	75	3%	32	89	50	38	9	1	2	11	9	2	0	0
Johnson City	566	275	249	11	4	35%	5	97	3	2	0	0	0	9	7	2	0	0
Lake Oswego	36,619	13,770	47,252	6,805	523	8%	184	1,207	258	191	49	6	12	130	99	24	2	4
Milwaukie	20,291	7,891	21,596	2,890	394	14%	193	830	380	278	74	10	19	92	71	17	1	3
Molalla	8,108	3,176	6,827	854	21	2%	11	8	12	9	2	0	0	3	3	0	0	0
Molalla Prairie Hamlet	—	4,165	10,102	1,137	83	7%	45	133	29	22	6	1	1	12	10	2	0	0
Mulino Hamlet	—	2,021	4,178	491	70	14%	32	151	28	20	6	1	2	14	10	3	0	0
Oregon City	31,859	12,641	31,984	4,190	342	8%	170	307	318	228	63	9	18	57	44	10	1	2
Rivergrove	289	196	539	70	8	12%	2	40	1	1	0	0	0	3	3	1	0	0
Sandy	9,570	3,734	8,551	1,077	12	1%	5	6	5	4	1	0	0	2	2	0	0	0
Stafford Hamlet	—	1,206	3,543	477	36	8%	14	68	33	23	7	1	2	6	5	1	0	0
The Villages at Mt Hood	—	3,795	7,268	886	67	8%	21	411	15	11	3	0	1	34	26	7	0	1
West Linn	25,109	9,170	28,162	3,817	209	5%	64	797	99	73	19	3	5	72	56	13	1	2
Wilsonville	19,509	5,492	31,168	4,410	423	10%	196	894	315	235	59	7	14	100	77	19	2	3
Clackamas County Jurisdictions total[+]	195,979	84,338	248,512	33,289	2,429	7%	1,063	5,488	1,686	1,239	322	43	82	601	465	109	9	17
Clackamas County Unincorporated total	—	94,481	240,494	29,470	2,180	7%	1,060	4,652	1,058	793	197	23	45	508	397	91	7	13
							Multnomah County											
Multnomah County total	735,334	255,577	810,087	114,046	20,489	18%	10,395	37,461	16,660	11,824	3,397	487	950	5,558	4,126	1,072	124	236
Fairview	8,920	2,611	7,976	1,061	58	6%	29	335	51	36	11	2	3	32	25	6	0	1
Gresham	105,594	29,043	83,478	11,160	726	7%	279	4,244	549	400	107	14	27	382	296	72	5	10
Maywood Park	752	339	627	74	3	4%	1	2	5	3	1	0	0	0	0	0	0	0
Portland (by Bureau of Emergency Management Risk Reporting Areas):																		
Airport	—	284	12,971	1,898	983	52%	565	14	694	470	151	25	48	118	82	25	4	8
Central City	—	2,809	108,884	18,436	5,672	31%	3,369	7,422	4,419	3,102	907	138	271	1,591	1,142	317	45	88
Central Northeast Neighborhoods	—	19,883	47,310	6,226	979	16%	459	1,177	758	562	148	17	31	203	154	38	4	7
East Portland Neighborhood Office	—	46,301	114,853	15,359	1,212	8%	576	1,204	964	705	188	24	47	289	223	50	5	10
Neighbors West/Northwest	—	7,663	50,308	7,320	2,419	33%	1,285	4,073	2,039	1,430	428	62	120	566	411	114	14	28
North Portland Neighborhood Services	—	25,468	87,894	12,076	3,581	30%	1,770	3,972	3,126	2,224	645	88	169	611	455	119	13	24
Northeast Coalition	—	22,178	52,444	6,994	641	9%	308	1,920	697	494	139	21	42	230	175	43	4	8
Southeast Uplift Neighborhood Program	—	57,291	124,011	16,652	1,676	10%	786	5,492	1,431	1,023	284	42	82	656	499	122	12	23
Southwest Neighborhoods	—	24,288	72,458	10,945	1,785	16%	658	5,352	1,518	1,084	304	44	86	666	500	128	13	24
Portland (total)	583,776	206,165	671,134	95,906	18,947	20%	9,776	30,627	15,645	11,095	3,194	459	896	4,930	3,641	955	115	220
Troutdale	15,962	5,161	13,481	1,730	169	10%	83	245	188	130	40	6	12	35	27	7	1	1
Wood Village	3,878	1,194	3,507	408	9	2%	6	55	5	5	1	0	0	9	7	1	0	0
Multnomah County Jurisdictions total[+]	718,882	244,513	780,203	110,339	19,911	18%	10,175	35,507	16,444	11,668	3,354	482	939	5,389	3,996	1,040	121	232
Multnomah County Unincorporated total	—	11,053	29,359	3,614	565	16%	216	1,891	204	148	41	5	10	164	127	31	2	4
							Washington County											
Washington County total	529,710	181,111	602,970	82,732	11,648	14%	4,805	37,657	7,758	5,627	1,534	204	394	3,727	2,846	705	63	113
Banks	1,777	646	1,491	194	35	18%	15	113	56	40	11	1	3	11	9	2	0	0
Beaverton	89,803	24,005	96,327	13,813	1,943	14%	751	6,267	1,313	964	254	33	63	633	481	119	12	22
Cornelius	11,869	3,517	7,844	963	159	17%	62	1,089	119	89	23	2	5	94	73	18	1	2
Durham	1,351	399	1,887	277	33	12%	9	94	10	7	2	0	0	9	7	2	0	0
Forest Grove	21,083	7,267	19,462	2,617	496	19%	223	2,238	596	418	124	19	36	216	165	41	4	6
Gaston*	637	312	618	79	9	12%	5	17	10	7	2	0	1	3	2	1	0	0
Hillsboro	91,611	26,846	116,113	17,603	2,884	16%	1,280	7,124	2,186	1,564	439	62	121	800	602	154	16	29
King City	3,111	1,610	3,702	494	56	11%	17	195	15	11	3	0	1	20	15	4	0	1
North Plains	1,947	952	2,602	328	61	19%	32	157	56	39	12	2	4	15	11	3	0	0
Sherwood	18,194	5,873	17,792	2,335	217	9%	113	534	209	149	42	6	12	54	41	10	1	2
Tigard	48,035	16,004	62,578	8,490	1,087	13%	516	2,306	672	494	130	17	32	248	191	46	4	7
Tualatin	26,054	7,535	41,411	5,751	732	13%	362	1,030	549	409	104	12	24	144	110	27	3	5
Washington County Jurisdictions total[+]	315,472	94,966	371,828	52,943	7,712	15%	3,383	21,164	5,792	4,191	1,146	155	300	2,247	1,707	425	40	74
Washington County Unincorporated total	—	86,501	228,783	29,512	3,913	13%	1,395	16,509	1,992	1,451	394	50	96	1,491	1,146	282	22	40

[+] The jurisdiction is associated with the county it occupies most by area. Figures are for the entire jurisdiction and may include building data from neighboring counties. Summaries by all jurisdictions and unincorporated area for a given county will vary slightly with the county total.

[*] Gaston census numbers are for entire jurisdiction. Gaston loss figures limited to buildings and residences in Washington County and do not include buildings, casualties, debris, and displaced population in Yamhill County.

Casualty level definitions are provided in **Table 4-1** and are based on U.S. Census 2010 population figures.

Table 12-10. Loss estimates by jurisdiction, Portland Hills fault magnitude 6.8 earthquake, "dry" soil conditions.

	U.S. Census Population 2010	Number of Buildings	Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Debris (Thousands of Tons)	Long-Term Displaced Population	Casualties: Daytime Scenario					Casualties: Nighttime Scenario				
									Total	Level 1	Level 2	Level 3	Level 4	Total	Level 1	Level 2	Level 3	Level 4
Study area total	1,641,036	615,852	1,899,180	259,169	60,569	23%	26,600	95,577	47,853	33,774	9,820	1,442	2,817	15,802	11,957	2,888	328	629
							Clackamas County											
Clackamas County total	375,992	179,164	486,122	62,390	12,922	21%	4,960	25,152	8,881	6,340	1,804	251	486	3,245	2,538	567	50	91
Barlow	135	60	124	15	4	29%	2	2	3	2	1	0	0	1	1	0	0	0
Canby	15,829	5,559	14,978	1,890	159	8%	76	202	109	83	19	2	5	41	34	6	0	1
Estacada	2,695	1,309	3,361	448	42	9%	27	25	55	40	10	2	3	6	5	1	0	0
Gladstone	11,497	4,022	8,749	1,129	437	39%	139	1,816	351	244	74	11	22	197	153	36	3	5
Happy Valley	13,903	5,856	19,882	2,692	243	9%	79	118	179	128	36	5	10	30	24	4	0	1
Johnson City	566	275	249	11	9	82%	11	319	7	5	1	0	0	25	19	5	0	0
Lake Oswego	36,619	13,770	47,252	6,805	1,877	28%	552	3,243	965	691	194	27	53	418	323	74	7	14
Milwaukie	20,291	7,891	21,596	2,890	1,341	46%	542	2,459	1,427	1,002	302	42	82	326	252	59	6	10
Molalla	8,108	3,176	6,827	854	37	4%	16	17	17	13	2	0	1	7	6	1	0	0
Molalla Prairie Hamlet	—	4,165	10,102	1,137	63	6%	33	13	15	11	2	0	1	5	4	1	0	0
Mulino Hamlet	—	2,021	4,178	491	96	19%	43	81	39	27	8	1	3	13	10	2	0	0
Oregon City	31,859	12,641	31,984	4,190	1,319	31%	496	2,983	1,286	896	269	41	80	383	297	68	6	11
Rivergrove	289	196	539	70	8	11%	1	11	1	0	0	0	0	2	1	0	0	0
Sandy	9,570	3,734	8,551	1,077	20	2%	8	4	8	7	1	0	0	3	3	0	0	0
Stafford Hamlet	—	1,206	3,543	477	118	25%	38	112	94	64	20	3	7	15	12	2	0	0
The Villages at Mt Hood	—	3,795	7,268	886	11	1%	3	2	1	1	0	0	0	2	1	0	0	0
West Linn	25,109	9,170	28,162	3,817	899	24%	251	1,679	493	343	103	16	32	216	171	37	3	6
Wilsonville	19,509	5,492	31,168	4,410	406	9%	196	181	255	199	43	5	9	50	40	8	1	1
Clackamas County Jurisdictions total+	195,979	84,338	248,512	33,289	7,088	21%	2,513	13,269	5,305	3,756	1,085	158	307	1,737	1,356	303	27	51
Clackamas County Unincorporated total	—	94,481	240,494	29,470	5,895	20%	2,491	12,036	3,582	2,590	720	93	179	1,500	1,177	262	22	39
							Multnomah County											
Multnomah County total	735,334	255,577	810,087	114,046	32,287	28%	15,658	50,842	28,915	20,159	6,032	920	1,805	9,346	6,918	1,773	223	432
Fairview	8,920	2,611	7,976	1,061	30	3%	12	39	13	11	2	0	0	9	8	1	0	0
Gresham	105,594	29,043	83,478	11,160	459	4%	165	314	216	176	32	3	6	103	89	12	1	1
Maywood Park	752	339	627	74	6	8%	2	6	4	3	1	0	0	2	1	0	0	0
Portland (by Bureau of Emergency Management Risk Reporting Areas):																		
Airport	—	284	12,971	1,898	655	35%	411	7	415	286		14	27	57	40	12	2	4
Central City	—	2,809	108,884	18,436	9,989	54%	5,895	13,914	8,942	6,159	1,897	298	588	3,069	2,175	627	90	177
Central Northeast Neighborhoods	—	19,883	47,310	6,226	1,210	19%	535	1,261	913	672	177	22	42	282	220	48	5	10
East Portland Neighborhood Office	—	46,301	114,853	15,359	1,316	9%	549	1,652	776	592	136	16	31	383	314	56	4	8
Neighbors West/Northwest	—	7,663	50,308	7,320	3,786	52%	1,939	6,932	3,392	2,339	728	110	215	1,129	795	233	34	66
North Portland Neighborhood Services	—	25,468	87,894	12,076	4,192	35%	2,023	3,739	3,864	2,727	802	114	221	725	554	131	14	27
Northeast Coalition	—	22,178	52,444	6,994	1,472	21%	639	2,520	1,737	1,200	362	59	116	459	352	80	9	17
Southeast Uplift Neighborhood Program	—	57,291	124,011	16,652	4,296	26%	1,804	10,538	4,082	2,840	848	133	262	1,586	1,211	284	31	60
Southwest Neighborhoods	—	24,288	72,458	10,945	4,129	38%	1,435	8,545	4,276	2,948	903	143	281	1,383	1,032	262	30	58
Portland (total)	583,776	206,165	671,134	95,906	31,046	32%	15,230	49,106	28,396	19,763	5,942	908	1,783	9,074	6,693	1,733	220	427
Troutdale	15,962	5,161	13,481	1,730	67	4%	29	11	35	27	6	1	1	8	7	1	0	0
Wood Village	3,878	1,194	3,507	408	10	2%	4	12	3	3	0	0	0	4	4	1	0	0
Multnomah County Jurisdictions total+	718,882	244,513	780,203	110,339	31,618	29%	15,442	49,488	28,667	19,982	5,982	912	1,790	9,200	6,803	1,748	221	428
Multnomah County Unincorporated total	—	11,053	29,359	3,614	636	18%	205	1,320	181	132	35	5	9	142	112	25	2	4
							Washington County											
Washington County total	529,710	181,111	602,970	82,732	15,360	19%	5,982	19,582	10,056	7,275	1,984	271	526	3,211	2,501	547	56	106
Banks	1,777	646	1,491	194	12	6%	5	4	16	12	3	0	1	2	1	0	0	0
Beaverton	89,803	24,005	96,327	13,813	3,510	25%	1,310	5,597	2,721	1,961	546	73	141	787	605	138	15	28
Cornelius	11,869	3,517	7,844	963	52	5%	20	37	22	18	3	0	0	13	11	1	0	0
Durham	1,351	399	1,887	277	47	17%	13	63	12	9	2	0	0	8	7	1	0	0
Forest Grove	21,083	7,267	19,462	2,617	127	5%	61	115	84	66	13	1	3	28	24	4	0	0
Gaston*	637	312	618	79	2	3%	1	1	2	1	0	0	0	0	0	0	0	0
Hillsboro	91,611	26,846	116,113	17,603	3,320	19%	1,476	2,116	2,255	1,625	444	63	122	533	406	94	11	22
King City	3,111	1,610	3,702	494	55	11%	17	78	12	9	2	0	1	14	11	2	0	0
North Plains	1,947	952	2,602	328	53	16%	28	20	44	31	9	1	3	6	4	1	0	0
Sherwood	18,194	5,873	17,792	2,335	148	6%	80	34	98	74	17	2	4	16	13	2	0	0
Tigard	48,035	16,004	62,578	8,490	1,873	22%	870	1,404	1,180	859	233	30	58	272	215	45	4	8
Tualatin	26,054	7,535	41,411	5,751	956	17%	453	432	672	504	125	15	28	134	105	22	2	4
Washington County Jurisdictions total+	315,472	94,966	371,828	52,943	10,156	19%	4,335	9,902	7,117	5,170	1,398	187	362	1,812	1,404	311	34	64
Washington County Unincorporated total	—	86,501	228,783	29,512	5,176	18%	1,614	9,563	3,000	2,144	601	86	168	1,410	1,105	239	23	43

+ The jurisdiction is associated with the county it occupies most by area. Figures are for the entire jurisdiction and may include building data from neighboring counties. Summaries by all jurisdictions and unincorporated area for a given county will vary slightly with the county total.

* Gaston census numbers are for entire jurisdiction. Gaston loss figures limited to buildings and residences in Washington County and do not include buildings, casualties, debris, and displaced population in Yamhill County.

Casualty level definitions are provided in **Table 4-1** and are based on U.S. Census 2010 population figures.

Table 12-11. Loss estimates by jurisdiction, Portland Hills fault magnitude 6.8 earthquake, "wet" (saturated) soil conditions.

	U.S. Census Population 2010	Number of Buildings	Square Footage (Thousand)	Building Value ($ Million)	Building Repair Cost ($ Million)	Building Loss Ratio	Debris (Thousands of Tons)	Long-Term Displaced Population	Casualties: Daytime Scenario					Casualties: Nighttime Scenario				
									Total	Level 1	Level 2	Level 3	Level 4	Total	Level 1	Level 2	Level 3	Level 4
Study area total	1,641,036	615,852	1,899,180	259,169	83,411	32%	33,905	256,936	62,977	44,290	13,114	1,891	3,682	29,038	21,830	5,598	563	1,046
Clackamas County																		
Clackamas County total	375,992	179,164	486,122	62,390	16,367	26%	5,990	50,802	10,912	7,768	2,244	307	593	5,232	4,032	973	81	146
Barlow	135	60	124	15	7	48%	3	31	5	3	1	0	0	3	2	1	0	0
Canby	15,829	5,559	14,978	1,890	231	12%	103	874	172	127	32	4	8	93	74	16	1	2
Estacada	2,695	1,309	3,361	448	74	17%	39	197	105	73	22	3	7	21	16	4	0	1
Gladstone	11,497	4,022	8,749	1,129	504	45%	157	2,656	394	275	83	12	24	258	199	48	4	7
Happy Valley	13,903	5,856	19,882	2,692	318	12%	100	552	217	154	44	6	13	65	51	11	1	2
Johnson City	566	275	249	11	9	85%	11	330	7	6	1	0	0	26	20	5	0	1
Lake Oswego	36,619	13,770	47,252	6,805	2,377	35%	685	6,391	1,194	853	243	33	65	659	504	123	11	21
Milwaukie	20,291	7,891	21,596	2,890	1,598	55%	615	5,456	1,595	1,122	338	46	89	546	418	104	9	16
Molalla	8,108	3,176	6,827	854	37	4%	16	17	17	13	2	0	1	7	6	1	0	0
Molalla Prairie Hamlet	—	4,165	10,102	1,137	88	8%	42	149	28	21	5	1	1	15	12	3	0	0
Mulino Hamlet	—	2,021	4,178	491	142	29%	58	319	55	38	12	2	4	30	24	6	0	1
Oregon City	31,859	12,641	31,984	4,190	1,422	34%	525	3,827	1,364	950	286	43	85	448	346	82	7	13
Rivergrove	289	196	539	70	20	29%	5	94	3	2	1	0	0	8	6	2	0	0
Sandy	9,570	3,734	8,551	1,077	21	2%	8	16	9	7	1	0	0	4	4	0	0	0
Stafford Hamlet	—	1,206	3,543	477	151	32%	47	274	123	83	27	5	9	27	21	5	0	1
The Villages at Mt Hood	—	3,795	7,268	886	42	5%	12	240	8	6	2	0	0	20	15	4	0	0
West Linn	25,109	9,170	28,162	3,817	1,093	29%	304	3,457	566	395	118	18	35	347	270	63	5	9
Wilsonville	19,509	5,492	31,168	4,410	681	15%	283	1,616	505	371	98	12	24	173	131	33	3	6
Clackamas County Jurisdictions total⁺	195,979	84,338	248,512	33,289	8,816	26%	3,013	26,497	6,368	4,500	1,315	188	364	2,750	2,118	510	44	78
Clackamas County Unincorporated total	—	94,481	240,494	29,470	7,602	26%	3,024	24,307	4,555	3,276	930	120	229	2,462	1,900	459	37	67
Multnomah County																		
Multnomah County total	735,334	255,577	810,087	114,046	42,747	37%	19,270	120,124	36,278	25,244	7,643	1,146	1,146	15,302	11,333	3,001	335	633
Fairview	8,920	2,611	7,976	1,061	65	6%	29	305	54	38	11	2	3	30	24	5	0	1
Gresham	105,594	29,043	83,478	11,160	1,114	10%	376	6,734	694	510	135	17	33	604	468	113	8	15
Maywood Park	752	339	627	74	8	10%	3	24	7	4	1	0	0	3	2	0	0	0
Portland (by Bureau of Emergency Management Risk Reporting Areas):																		
Airport	—	284	12,971	1,898	1,016	54%	569	19	700	476	152	24	48	116	81	24	4	7
Central City	—	2,809	108,884	18,436	11,593	63%	6,534	17,698	9,845	6,767	2,099	329	650	3,565	2,519	734	105	207
Central Northeast Neighborhoods	—	19,883	47,310	6,226	1,721	28%	714	4,289	1,284	935	257	32	60	552	421	103	10	18
East Portland Neighborhood Office	—	46,301	114,853	15,359	2,193	14%	881	6,597	1,563	1,136	308	41	79	855	664	153	14	25
Neighbors West/Northwest	—	7,663	50,308	7,320	4,513	62%	2,154	10,830	3,724	2,567	801	121	235	1,453	1,032	301	41	79
North Portland Neighborhood Services	—	25,468	87,894	12,076	5,587	46%	2,524	12,934	5,009	3,523	1,051	148	287	1,511	1,139	293	28	51
Northeast Coalition	—	22,178	52,444	6,994	2,200	31%	885	9,004	2,306	1,591	488	77	151	982	743	187	18	33
Southeast Uplift Neighborhood Program	—	57,291	124,011	16,652	6,046	36%	2,365	29,189	5,402	3,757	1,136	172	337	3,050	2,307	585	56	103
Southwest Neighborhoods	—	24,288	72,458	10,945	5,434	50%	1,809	18,570	5,108	3,531	1,084	166	327	2,220	1,654	435	45	85
Portland (total)	583,776	206,165	671,134	95,906	40,304	42%	18,436	109,130	34,942	24,283	7,375	1,110	2,173	14,304	10,561	2,815	320	608
Troutdale	15,962	5,161	13,481	1,730	167	10%	77	281	174	120	37	6	11	39	30	7	1	1
Wood Village	3,878	1,194	3,507	408	10	2%	4	12	3	3	0	0	0	4	4	1	0	0
Multnomah County Jurisdictions total⁺	718,882	244,513	780,203	110,339	41,667	38%	18,925	116,486	35,874	24,958	7,560	1,135	2,221	14,985	11,089	2,941	330	625
Multnomah County Unincorporated total	—	11,053	29,359	3,614	1,030	28%	329	3,505	320	230	65	9	16	306	236	58	4	8
Washington County																		
Washington County total	529,710	181,111	602,970	82,732	24,297	29%	8,645	86,010	15,787	11,279	3,226	437	844	8,503	6,465	1,624	147	267
Banks	1,777	646	1,491	194	27	14%	10	104	35	26	7	1	2	10	8	2	0	0
Beaverton	89,803	24,005	96,327	13,813	5,201	38%	1,775	19,130	3,850	2,751	790	105	203	1,861	1,404	357	35	65
Cornelius	11,869	3,517	7,844	963	125	13%	45	894	80	60	15	2	3	77	60	14	1	2
Durham	1,351	399	1,887	277	84	30%	23	277	26	19	5	1	1	24	19	5	0	1
Forest Grove	21,083	7,267	19,462	2,617	259	10%	107	1,242	236	170	47	7	13	122	94	23	2	3
Gaston*	637	312	618	79	4	5%	2	6	3	2	1	0	0	1	1	0	0	0
Hillsboro	91,611	26,846	116,113	17,603	5,269	30%	2,063	12,836	3,771	2,663	778	112	219	1,476	1,104	287	30	56
King City	3,111	1,610	3,702	494	105	21%	30	412	28	21	5	1	1	41	31	8	1	1
North Plains	1,947	952	2,602	328	92	28%	41	266	73	51	15	2	5	25	20	5	0	1
Sherwood	18,194	5,873	17,792	2,335	295	13%	130	963	250	177	51	7	15	91	70	17	1	3
Tigard	48,035	16,004	62,578	8,490	2,783	33%	1,164	7,409	1,814	1,299	371	49	95	755	578	143	12	22
Tualatin	26,054	7,535	41,411	5,751	1,469	26%	619	2,782	1,072	785	211	26	50	343	261	65	6	12
Washington County Jurisdictions total⁺	315,472	94,966	371,828	52,943	15,713	30%	6,010	46,320	11,239	8,024	2,297	313	605	4,827	3,649	925	89	164
Washington County Unincorporated total	—	86,501	228,783	29,512	8,584	29%	2,603	39,822	4,621	3,302	946	127	246	3,707	2,839	706	59	104

⁺ The jurisdiction is associated with the county it occupies most by area. Figures are for the entire jurisdiction and may include building data from neighboring counties. Summaries by all jurisdictions and unincorporated area for a given county will vary slightly with the county total.

* Gaston census numbers are for entire jurisdiction. Gaston loss figures limited to buildings and residences in Washington County and do not include buildings, casualties, debris, and displaced population in Yamhill County.

Casualty level definitions are provided in **Table 4-1** and are based on U.S. Census 2010 population figures.

13.0 APPENDIX D: GEOGRAPHIC INFORMATION SYSTEM (GIS) DATABASE

The GIS data included with this publication are partitioned into two ArcGIS version 10.1 file geodatabases. Earthquake loss estimates and impact assessment data are contained in RDPO_ Earthquake_Impact_Analysis_Phase1.gdb. Loss estimates for a particular earthquake scenario are contained in independent tables and can be joined to the appropriate polygon dataset to graphically represent impacts. Ground motion and ground deformation data are contained in RDPO_GroundMotion_GroundFailure_Phase1.gdb.

RDPO_Earthquake_Impact_Analysis_Phase1.gdb:

Feature Dataset Phase1:

Building_Footprints	Outlines of buildings and other non-building structures.
Electrical_Transmission_Structures	Pointfile containing locations of electrical transmission poles and towers, and an estimate of permanent ground deformation at the location for all four earthquake scenarios.
Emergency_Transportation_Routes	Buffered and segmented version of the Metro area Emergency Transportation Routes, and a categorization, per segment, of the impact of permanent ground deformation on the segment, for all four earthquake scenarios.
Jurisdictions	Cities, villages, hamlets, and unincorporated areas, and summary statistics for number of buildings, square footage, replacement cost, and population estimates. Contains **Jurisdiction** attribute for joining to loss estimate tables.
Neighborhood_Units	Neighborhood units (876 total), and summary statistics for number of buildings, square footage, replacement cost, and population estimates. Contains **NUID** attribute for joining to loss estimate tables.
Population_and_Building_Density	20-acre hexagonal grid with summary statistics for number of buildings, number of residential buildings, and permanent residents per hexagonal cell. All cells contain at least one building.

Tables with building loss, casualty, and displaced population estimates for a given scenario

Loss estimates by jurisdiction

Tables can be joined to the Jurisdictions *feature class using* **Jurisdiction** *attribute*

Loss_Jurisdiction_CSZ_M9p0_dry	Scenario: Cascadia Subduction Zone M 9.0, “dry” soil conditions
Loss_Jurisdiction_CSZ_M9p0_wet	Scenario: Cascadia Subduction Zone M 9.0, “wet” (saturated) soil conditions
Loss_Jurisdiction_PHF_M6p8_dry	Scenario: Portland Hills fault M 6.8, “dry” soil conditions
Loss_Jurisdiction_PHF_M6p8_wet	Scenario: Portland Hills fault M 6.8, “wet” (saturated) soil conditions

Loss estimates by neighborhood unit

Tables can be joined to the Neighborhood_Units *feature class using the* **NUID** *attribute*

Loss_Neighborhood_Unit_CSZ_M9p0_dry	Scenario: Cascadia Subduction Zone M 9.0, “dry” soil conditions
Loss_Neighborhood_Unit_CSZ_M9p0_wet	Scenario: Cascadia Subduction Zone M 9.0, “wet” (saturated) soil conditions
Loss_Neighborhood_Unit_PHF_M6p8_dry	Scenario: Portland Hills fault M 6.8, “dry” soil conditions
Loss_Neighborhood_Unit_PHF_M6p8_wet	Scenario: Portland Hills fault M 6.8, “wet” (saturated) soil conditions

RDPO_GroundMotion_GroundFailure_Phase1.gdb:

Synthetic Cascadia Subduction Zone magnitude 9.0 earthquake

Site ground motion (rasters)

CSZ_M9p0_pga_site	Site peak ground acceleration, in g (standard gravity).
CSZ_M9p0_pgv_site	Site peak ground velocity, in centimeters per second.
CSZ_M9p0_sa03_site	Site spectral acceleration at 0.3 sec, in g (standard gravity).
CSZ_M9p0_sa10_site	Site spectral acceleration at 1.0 sec, in g (standard gravity).

Permanent Ground Deformation (PGD) (rasters)

Each PGD raster is accompanied with a probability (Prob) raster

CSZ_M9p0_PGD_landslide_dry	Permanent ground deformation due to earthquake-induced landslide under wet (or saturated) soil conditions, in centimeters.
CSZ_M9p0_Prob_landslide_dry	Probability of earthquake-induced landslide under wet (or saturated) soil conditions. In percent.
CSZ_M9p0_PGD_landslide_wet	Permanent ground deformation due to earthquake-induced landslide under wet (or saturated) soil conditions, in centimeters.
CSZ_M9p0_Prob_landslide_wet	Probability of earthquake-induced landslide under wet (or saturated) soil conditions. In percent.
CSZ_M9p0_PGD_liquefaction_wet	Permanent ground deformation due to liquefaction lateral spreading. Liquefaction assumes wet (or saturated) soil conditions, in centimeters.
CSZ_M9p0_Prob_liquefaction_wet	Probability of liquefaction under wet (or saturated) soil conditions. In percent.

Synthetic Portland Hills fault magnitude 6.8 earthquake

Bedrock ground motion

PHF_M6p8_bedrock_groundmotion	Pointfile with descriptors of bedrock ground motion (pga, pgv, sa03, sa10)

Site ground motion (rasters)

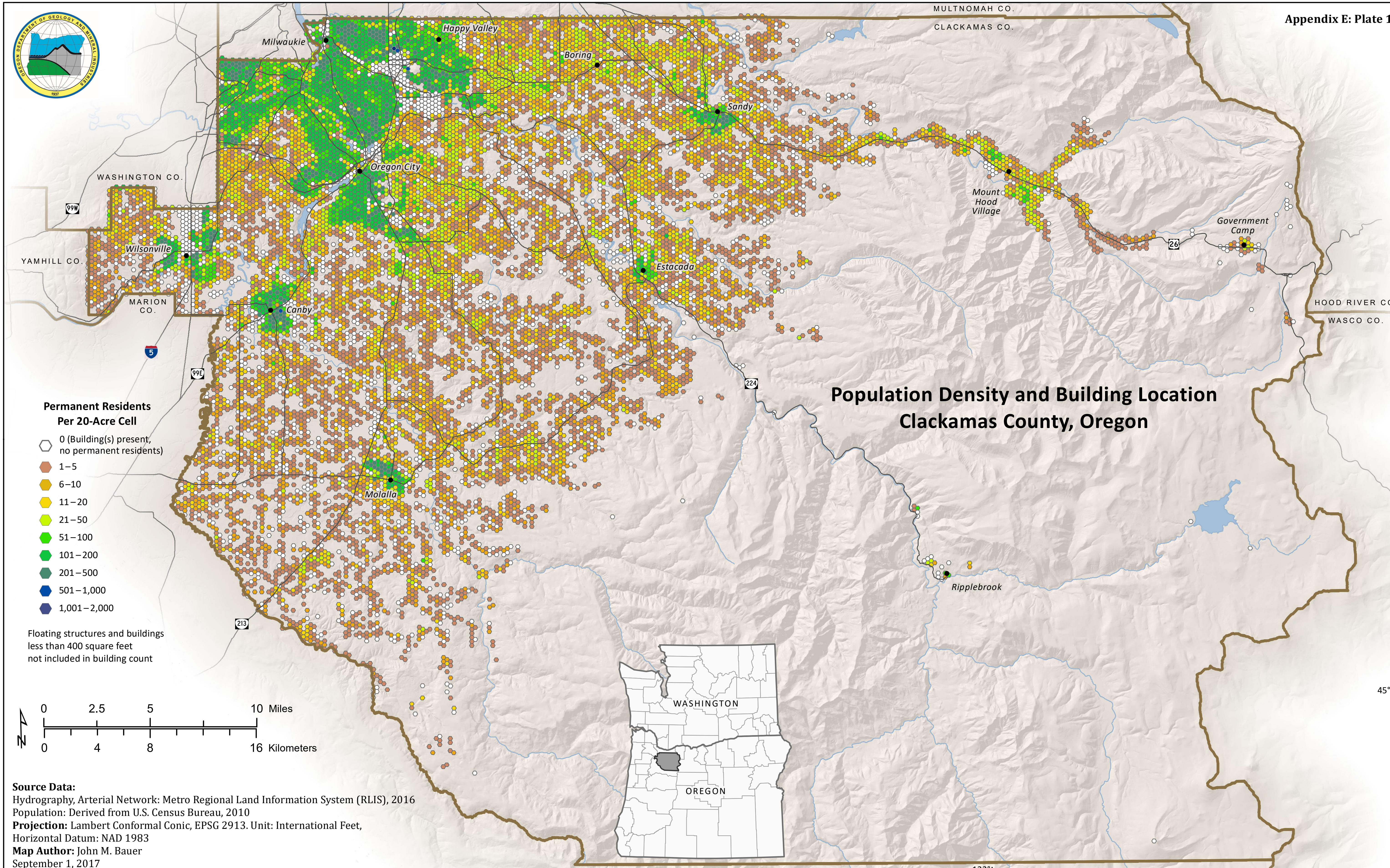
PHF_M6p8_pga_site	Site peak ground acceleration, in g (standard gravity).
PHF_M6p8_pgv_site	Site peak ground velocity, in centimeters per second.
PHF_M6p8_sa03_site	Site spectral acceleration at 0.3 sec, in g (standard gravity).
PHF_M6p8_sa10_site	Site spectral acceleration at 1.0 sec, in g (standard gravity).

Permanent Ground Deformation (PGD) (rasters)

Each PGD raster is accompanied with a probability (Prob) raster

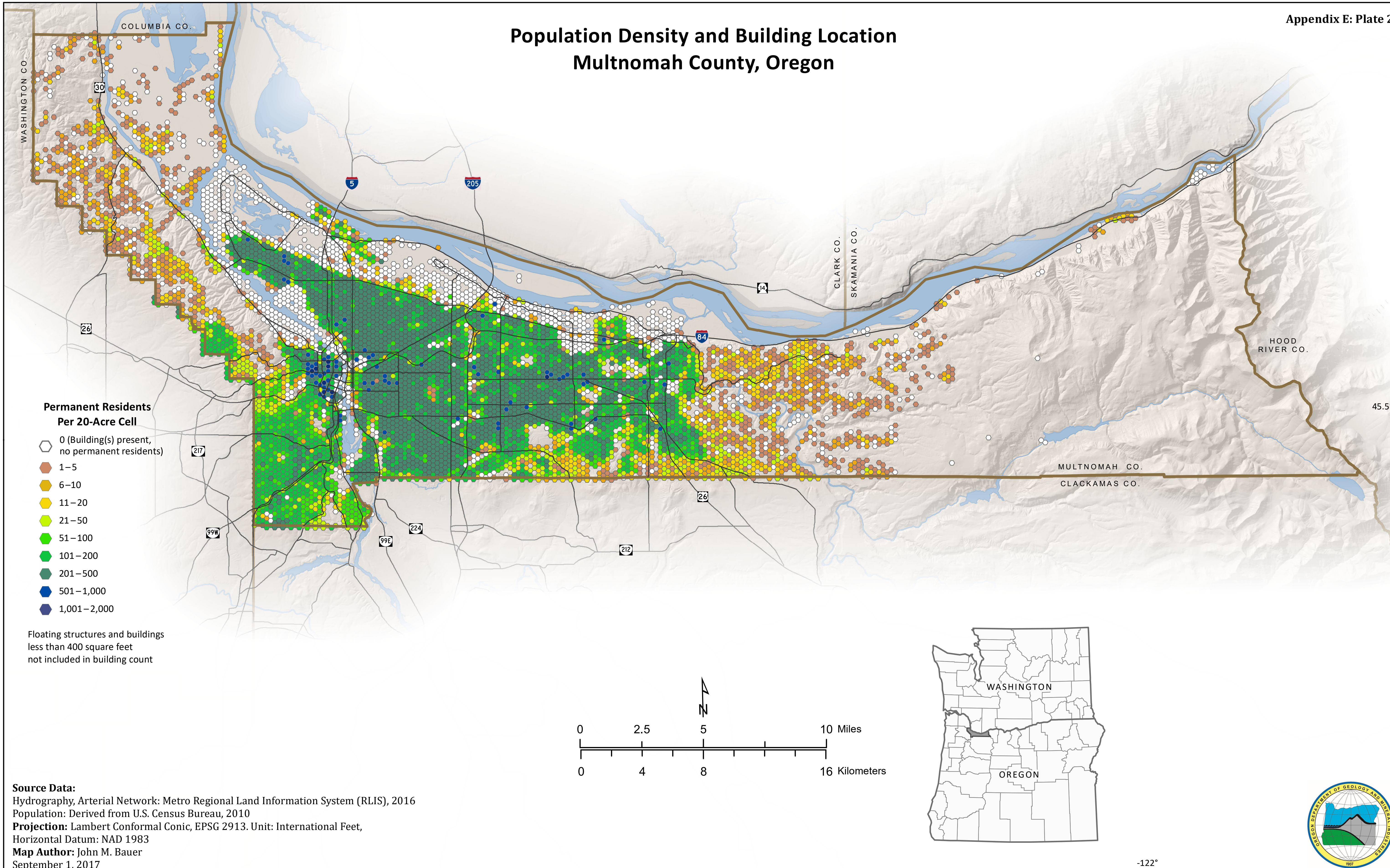
PHF_M6p8_PGD_landslide_dry	Permanent ground deformation due to earthquake-induced landslide under wet (or saturated) soil conditions, in centimeters.
PHF_M6p8_Prob_landslide_dry	Probability of earthquake-induced landslide under wet (or saturated) soil conditions. In percent.
PHF_M6p8_PGD_landslide_wet	Permanent ground deformation due to earthquake-induced landslide under wet (or saturated) soil conditions, in centimeters.
PHF_M6p8_Prob_landslide_wet	Probability of earthquake-induced landslide under wet (or saturated) soil conditions. In percent.
PHF_M6p8_PGD_liquefaction_wet	Permanent ground deformation due to liquefaction lateral spreading. Liquefaction assumes wet (or saturated) soil conditions, in centimeters.
PHF_M6p8_Prob_liquefaction_wet	Probability of liquefaction under wet (or saturated) soil conditions. In percent.

14.0 APPENDIX E: MAP PLATES


Appendix E: Plate 1
Population Density and Building Location
Clackamas County, Oregon
MULTNOMAH CO.
CLACKAMAS CO.
WASHINGTON CO.
YAMHILL CO.
MARION CO.
HOOD RIVER CO.
WASCO CO.
Milwaukie
Happy Valley
Boring
Sandy
Oregon City
Wilsonville
Estacada
Canby
Molalla
Mount Hood Village
Government Camp
Ripplebrook
99W
99E
5
224
26
213
45°
-122°
Permanent Residents
Per 20-Acre Cell
0 (Building(s) present, no permanent residents)
1–5
6–10
11–20
21–50
51–100
101–200
201–500
501–1,000
1,001–2,000
Floating structures and buildings less than 400 square feet not included in building count
0 2.5 5 10 Miles
0 4 8 16 Kilometers
N
WASHINGTON
OREGON
Source Data:
Hydrography, Arterial Network: Metro Regional Land Information System (RLIS), 2016
Population: Derived from U.S. Census Bureau, 2010
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017

Appendix E: Plate 2

Population Density and Building Location
Multnomah County, Oregon



Permanent Residents Per 20-Acre Cell

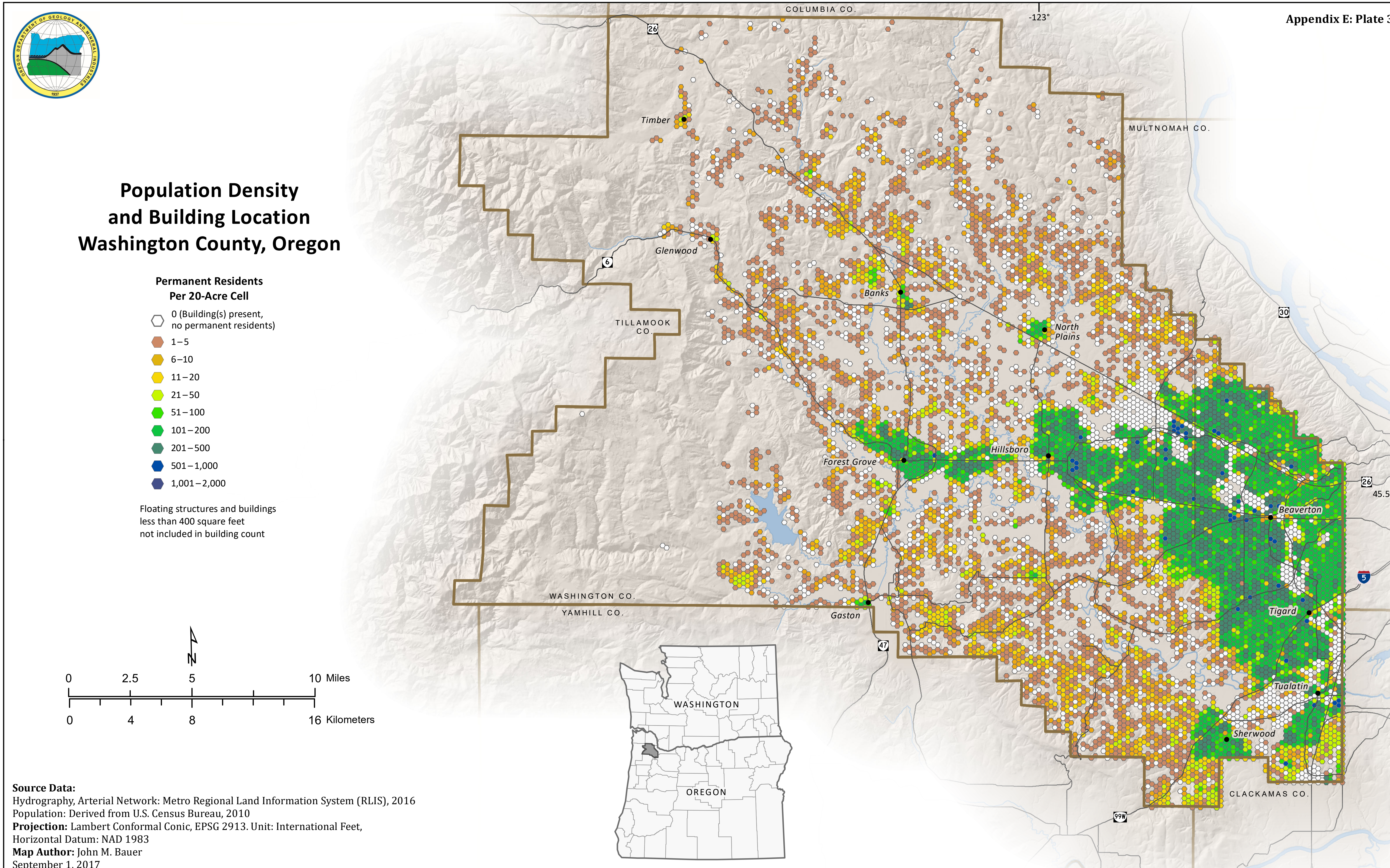
- 0 (Building(s) present, no permanent residents)
- 1–5
- 6–10
- 11–20
- 21–50
- 51–100
- 101–200
- 201–500
- 501–1,000
- 1,001–2,000

Floating structures and buildings less than 400 square feet not included in building count

Source Data:
Hydrography, Arterial Network: Metro Regional Land Information System (RLIS), 2016
Population: Derived from U.S. Census Bureau, 2010
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017

Appendix E: Plate 3

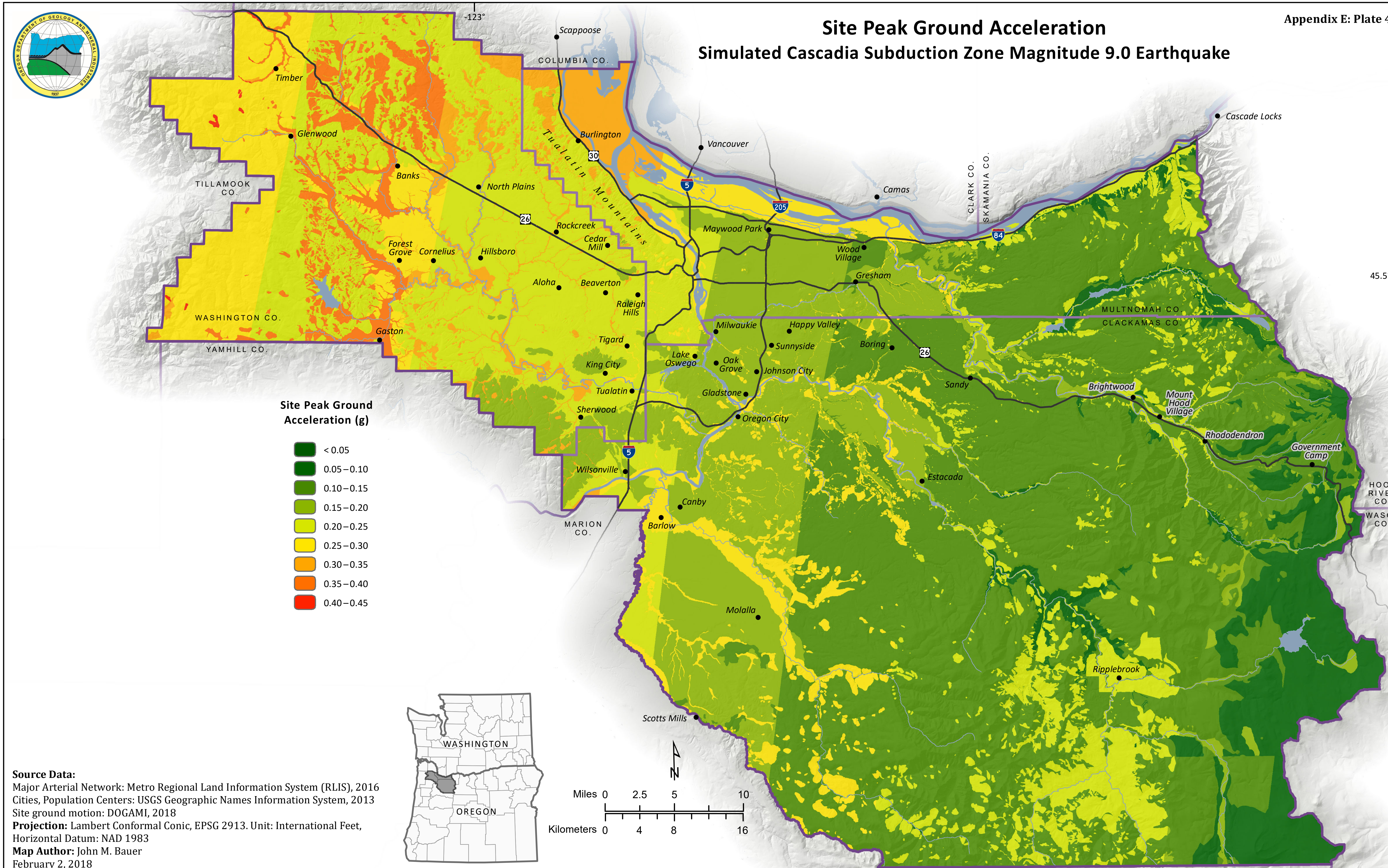
Population Density and Building Location Washington County, Oregon



Source Data:
Hydrography, Arterial Network: Metro Regional Land Information System (RLIS), 2016
Population: Derived from U.S. Census Bureau, 2010
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017

Appendix E: Plate 4

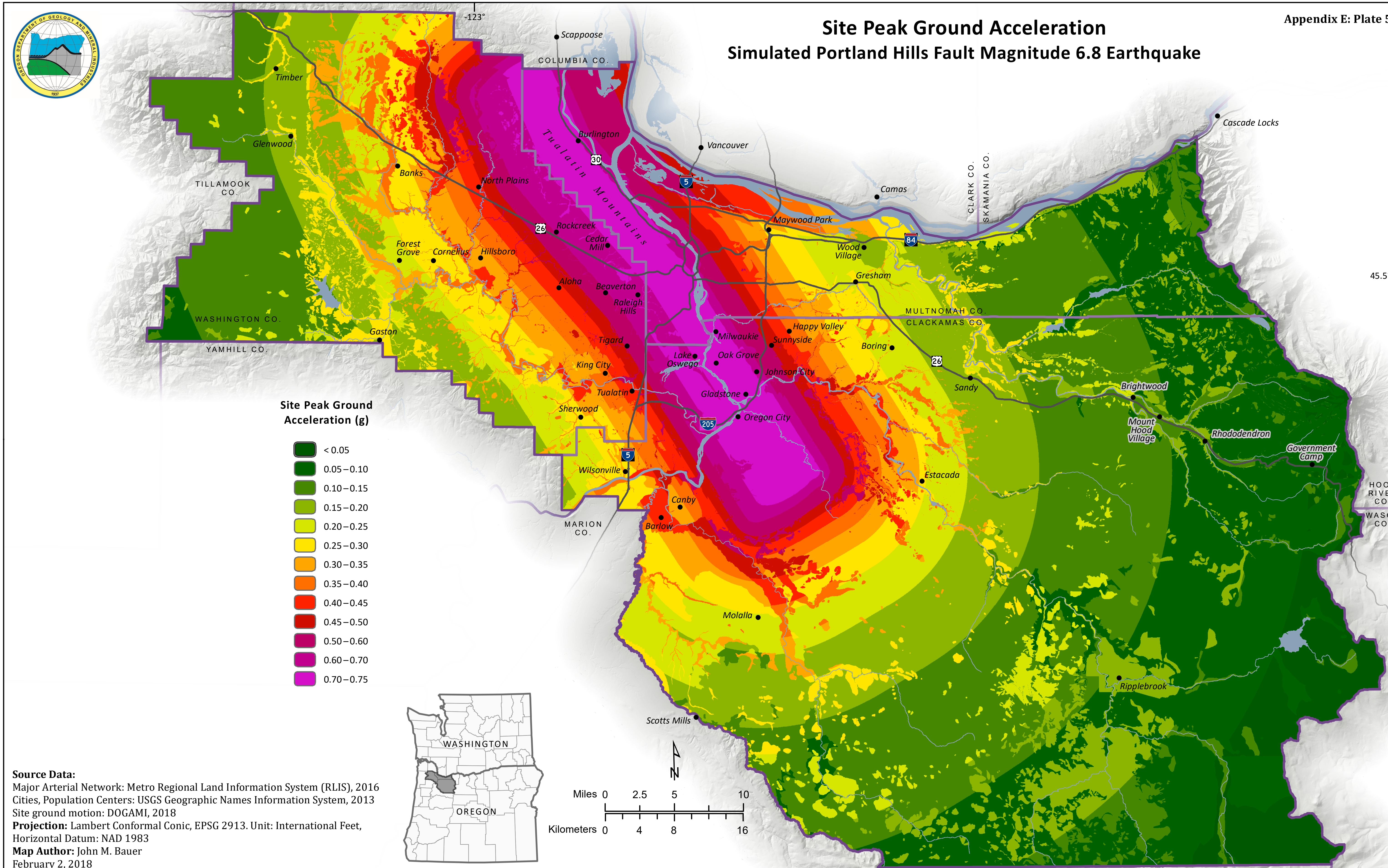
Site Peak Ground Acceleration
Simulated Cascadia Subduction Zone Magnitude 9.0 Earthquake



Source Data:
Major Arterial Network: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Site ground motion: DOGAMI, 2018
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 2, 2018

Appendix E: Plate 5

Site Peak Ground Acceleration
Simulated Portland Hills Fault Magnitude 6.8 Earthquake

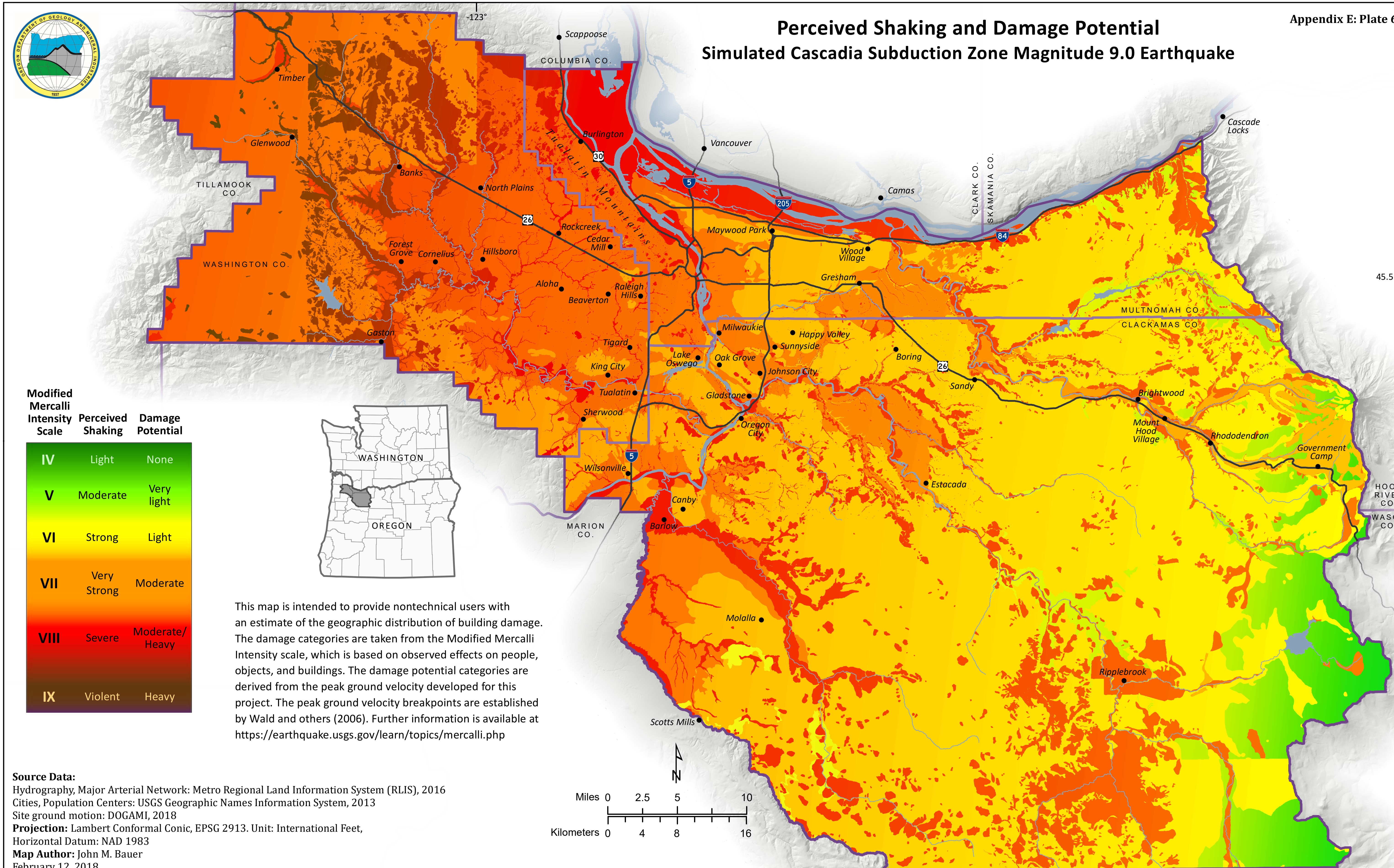


Source Data:
Major Arterial Network: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Site ground motion: DOGAMI, 2018
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 2, 2018

Appendix E: Plate 6

Perceived Shaking and Damage Potential

Simulated Cascadia Subduction Zone Magnitude 9.0 Earthquake



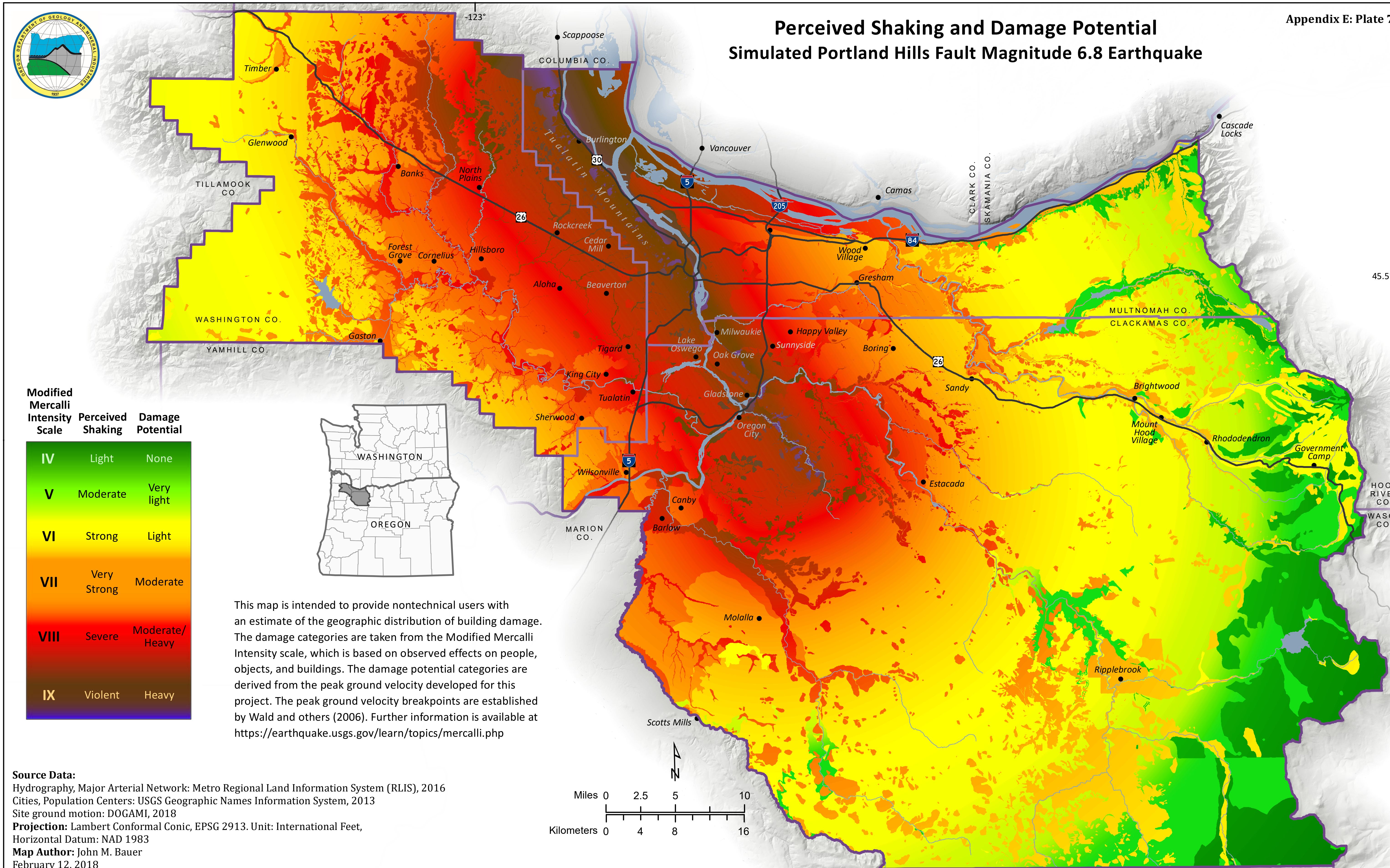
This map is intended to provide nontechnical users with an estimate of the geographic distribution of building damage. The damage categories are taken from the Modified Mercalli Intensity scale, which is based on observed effects on people, objects, and buildings. The damage potential categories are derived from the peak ground velocity developed for this project. The peak ground velocity breakpoints are established by Wald and others (2006). Further information is available at https://earthquake.usgs.gov/learn/topics/mercalli.php

Source Data:
Hydrography, Major Arterial Network: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Site ground motion: DOGAMI, 2018
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Appendix E: Plate 7

Perceived Shaking and Damage Potential

Simulated Portland Hills Fault Magnitude 6.8 Earthquake



This map is intended to provide nontechnical users with an estimate of the geographic distribution of building damage. The damage categories are taken from the Modified Mercalli Intensity scale, which is based on observed effects on people, objects, and buildings. The damage potential categories are derived from the peak ground velocity developed for this project. The peak ground velocity breakpoints are established by Wald and others (2006). Further information is available at https://earthquake.usgs.gov/learn/topics/mercalli.php

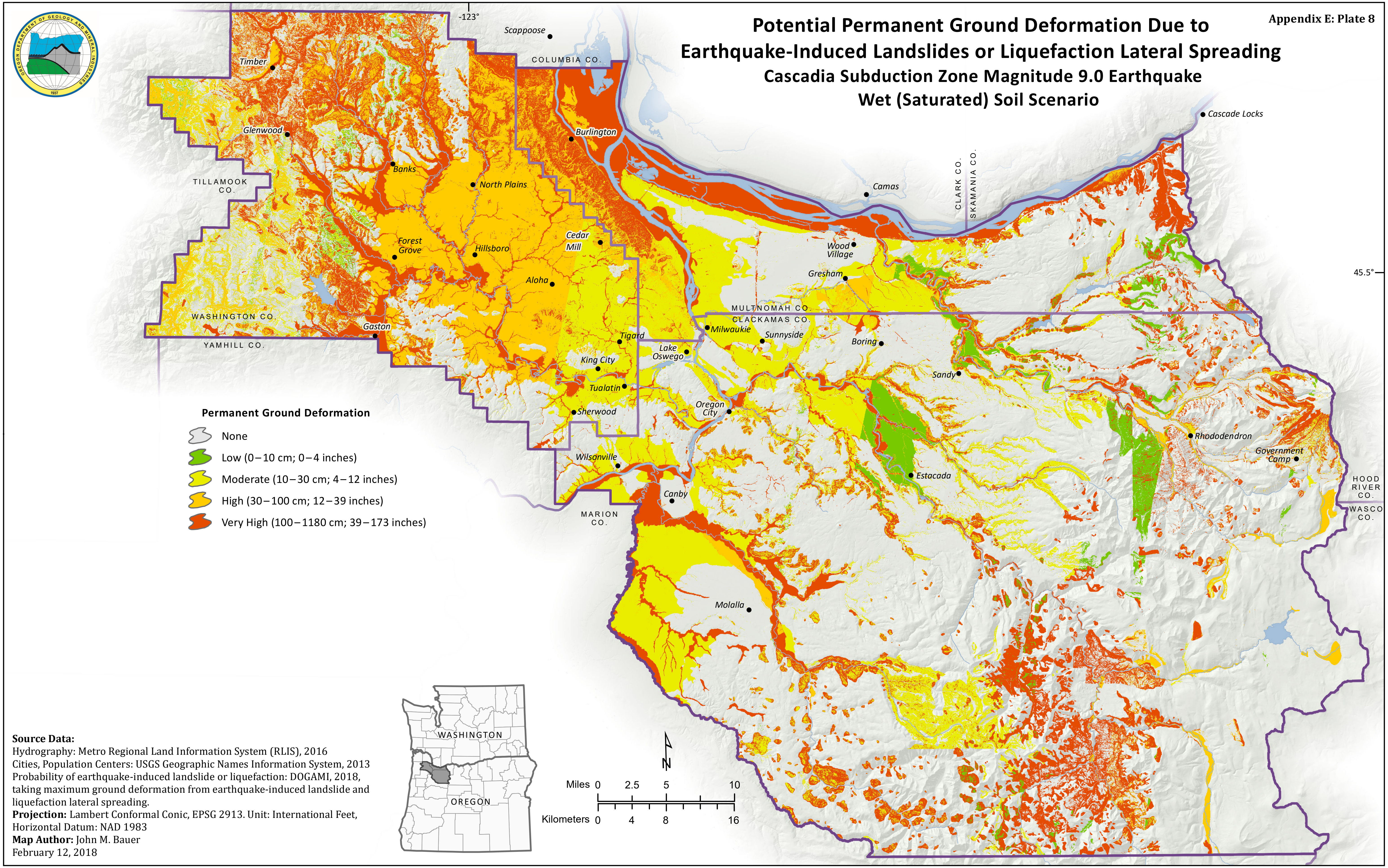
Source Data:
Hydrography, Major Arterial Network: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Site ground motion: DOGAMI, 2018
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Appendix E: Plate 8

Potential Permanent Ground Deformation Due to Earthquake-Induced Landslides or Liquefaction Lateral Spreading

Cascadia Subduction Zone Magnitude 9.0 Earthquake

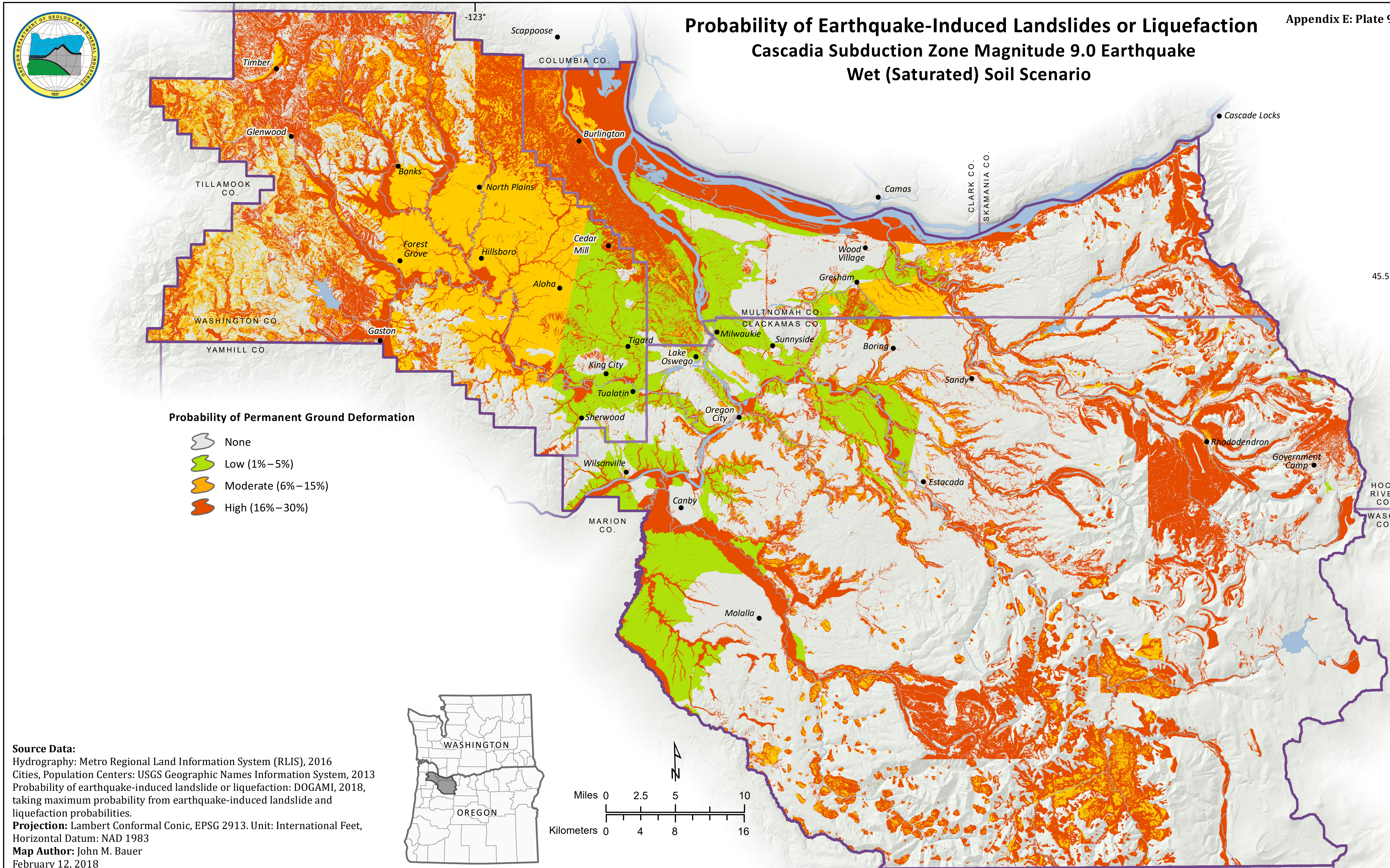
Wet (Saturated) Soil Scenario



Source Data:
Hydrography: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Probability of earthquake-induced landslide or liquefaction: DOGAMI, 2018, taking maximum ground deformation from earthquake-induced landslide and liquefaction lateral spreading.
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Appendix E: Plate 9

Probability of Earthquake-Induced Landslides or Liquefaction
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Scenario

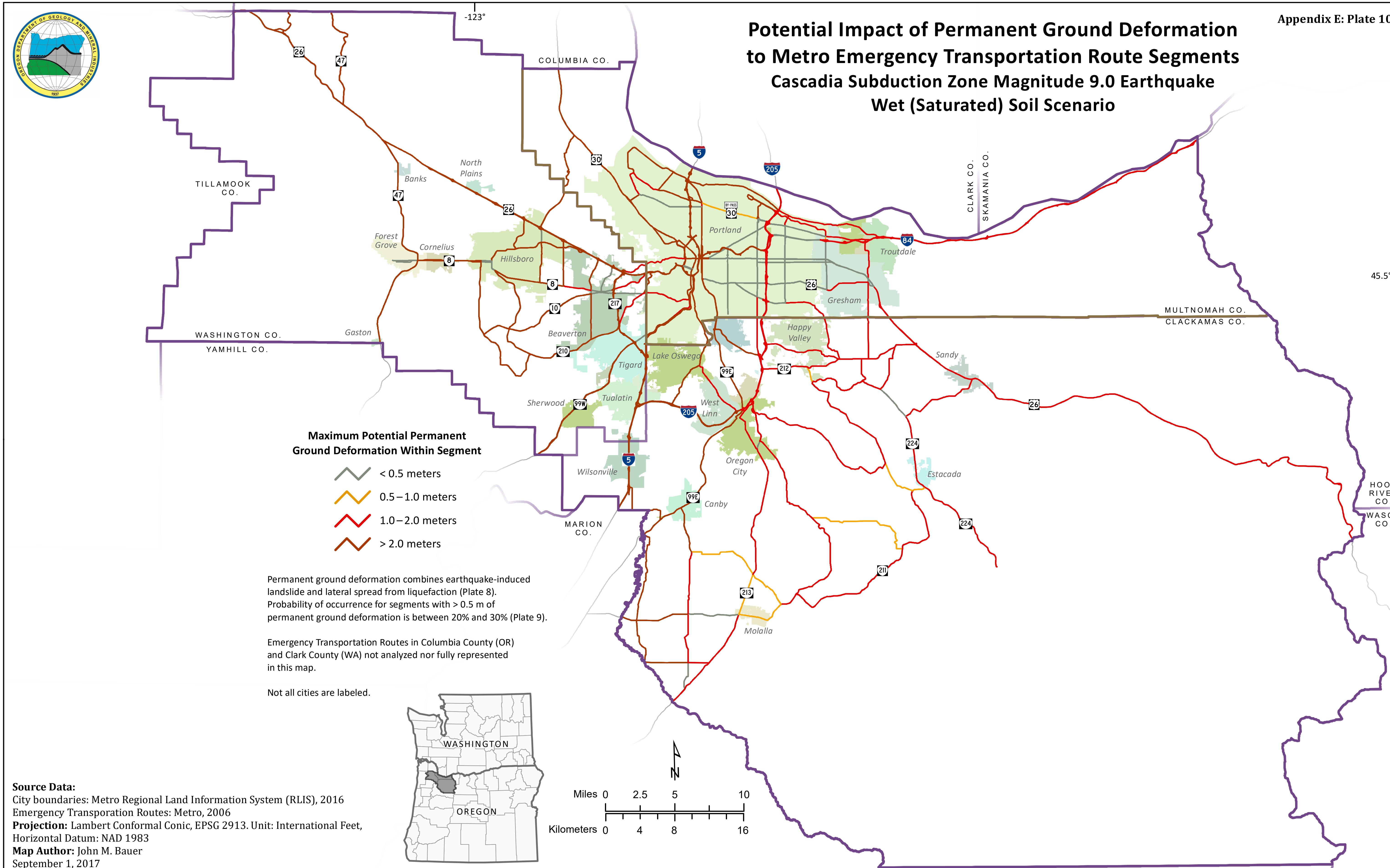


Source Data:
Hydrography: Metro Regional Land Information System (RLIS), 2016
Cities, Population Centers: USGS Geographic Names Information System, 2013
Probability of earthquake-induced landslide or liquefaction: DOGAMI, 2018, taking maximum probability from earthquake-induced landslide and liquefaction probabilities.
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Appendix E: Plate 10

Potential Impact of Permanent Ground Deformation to Metro Emergency Transportation Route Segments

Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Scenario



Maximum Potential Permanent Ground Deformation Within Segment

- < 0.5 meters
- 0.5 – 1.0 meters
- 1.0 – 2.0 meters
- > 2.0 meters

Permanent ground deformation combines earthquake-induced landslide and lateral spread from liquefaction (Plate 8). Probability of occurrence for segments with > 0.5 m of permanent ground deformation is between 20% and 30% (Plate 9).

Emergency Transportation Routes in Columbia County (OR) and Clark County (WA) not analyzed nor fully represented in this map.

Not all cities are labeled.

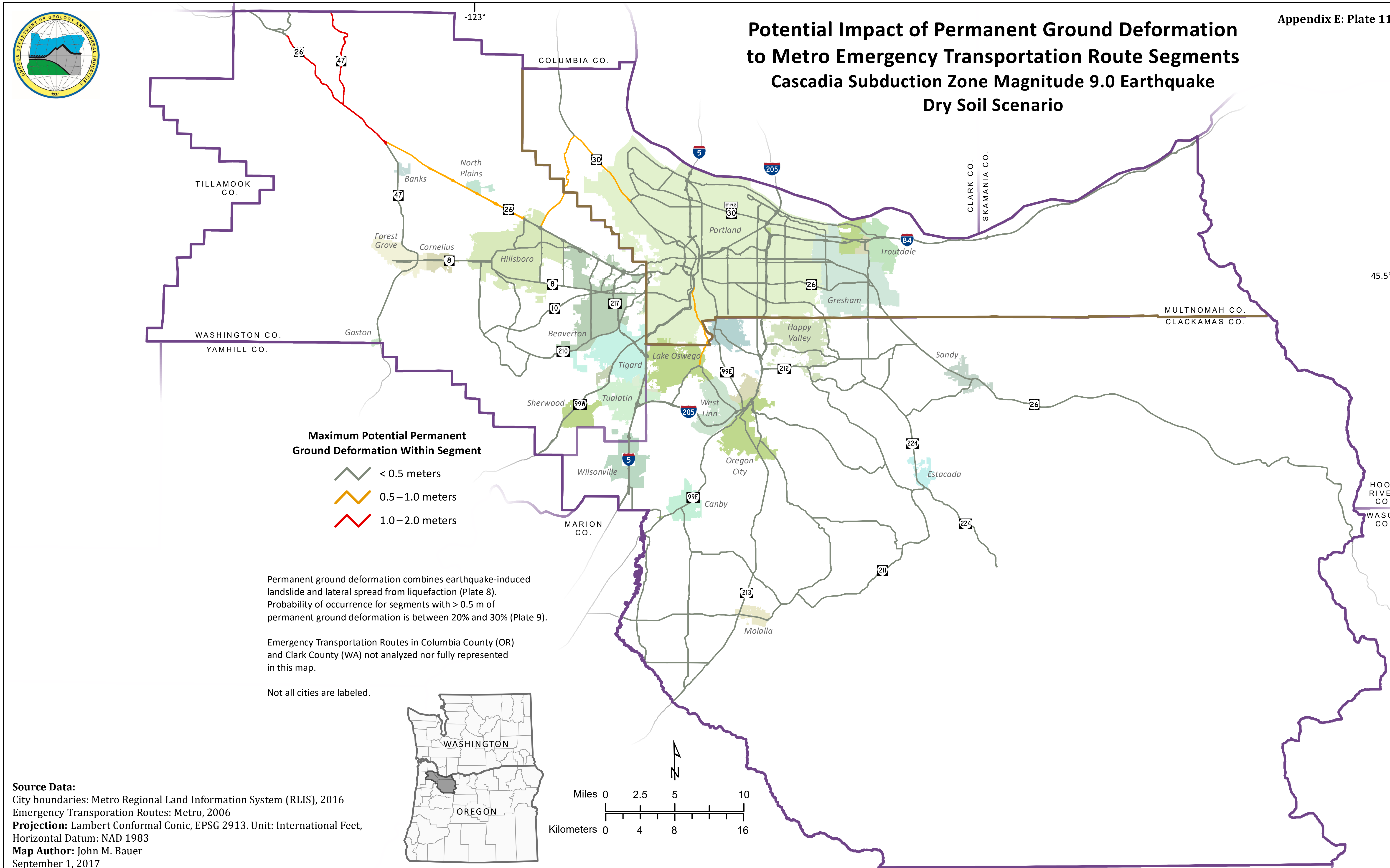
Source Data:
City boundaries: Metro Regional Land Information System (RLIS), 2016
Emergency Transporation Routes: Metro, 2006
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017

Appendix E: Plate 11

Potential Impact of Permanent Ground Deformation to Metro Emergency Transportation Route Segments

Cascadia Subduction Zone Magnitude 9.0 Earthquake

Dry Soil Scenario



Maximum Potential Permanent Ground Deformation Within Segment

- < 0.5 meters
- 0.5 – 1.0 meters
- 1.0 – 2.0 meters

Permanent ground deformation combines earthquake-induced landslide and lateral spread from liquefaction (Plate 8). Probability of occurrence for segments with > 0.5 m of permanent ground deformation is between 20% and 30% (Plate 9).

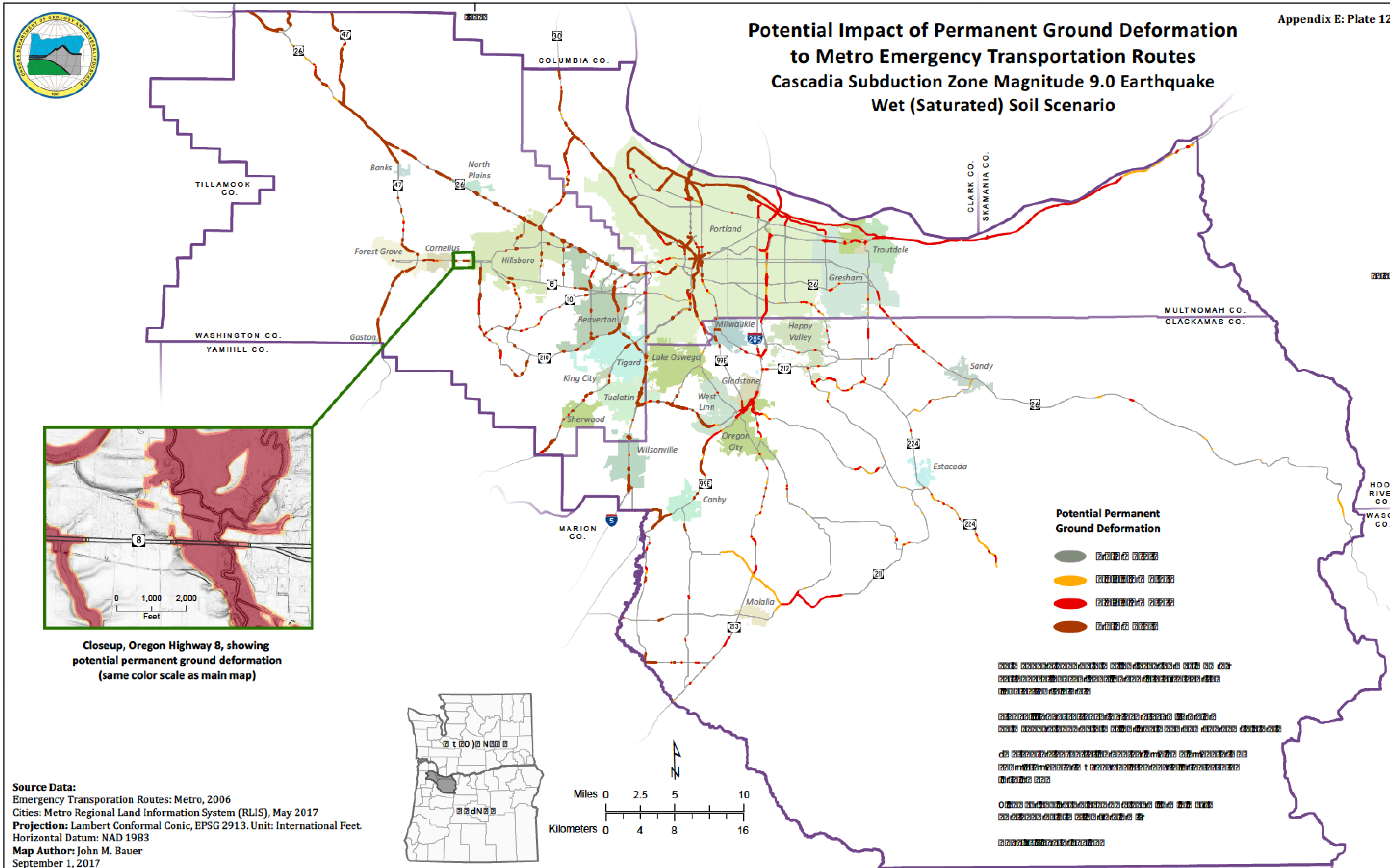
Emergency Transportation Routes in Columbia County (OR) and Clark County (WA) not analyzed nor fully represented in this map.

Not all cities are labeled.

Source Data:
City boundaries: Metro Regional Land Information System (RLIS), 2016
Emergency Transporation Routes: Metro, 2006
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet,
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017

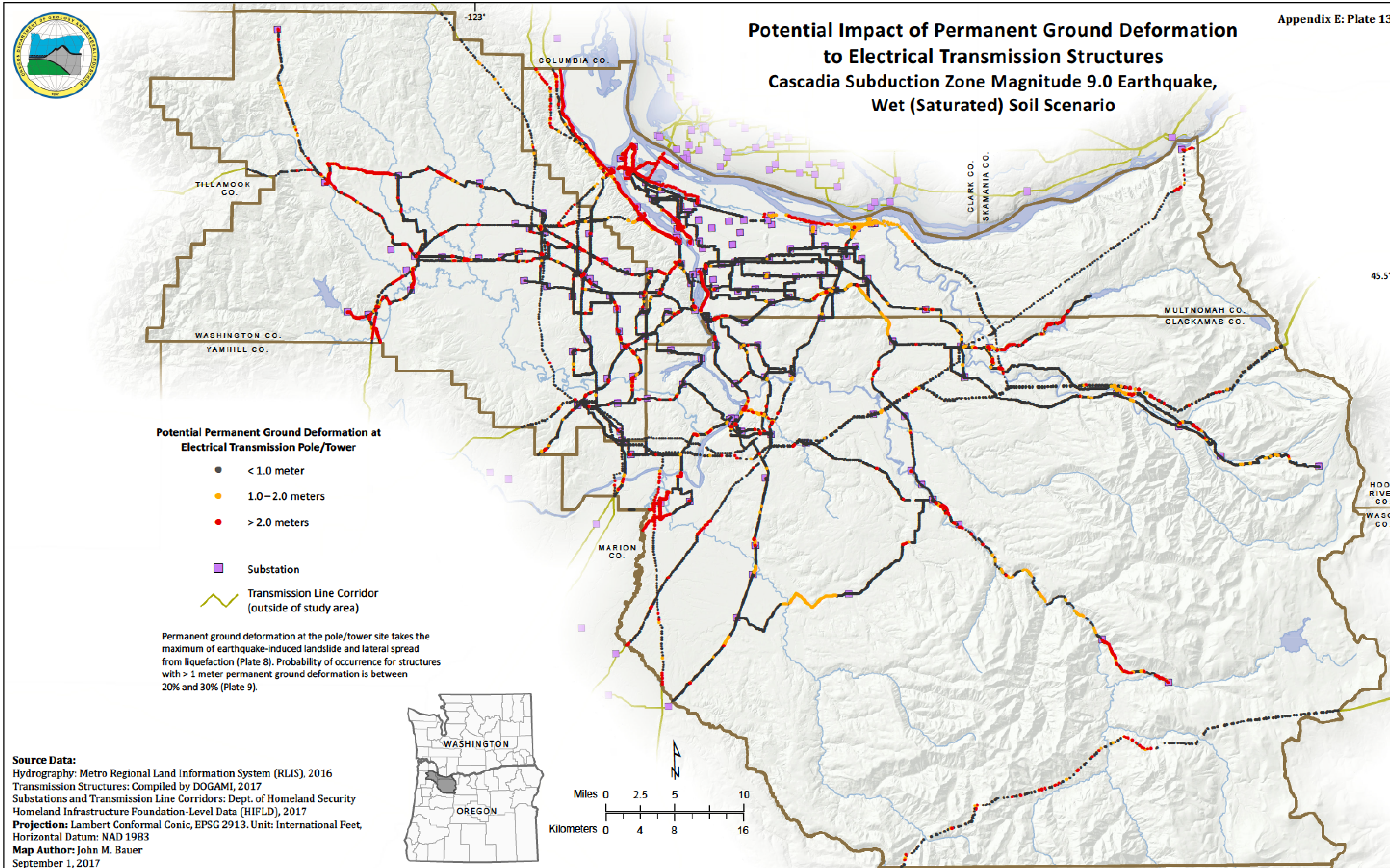
Appendix E: Plate 12

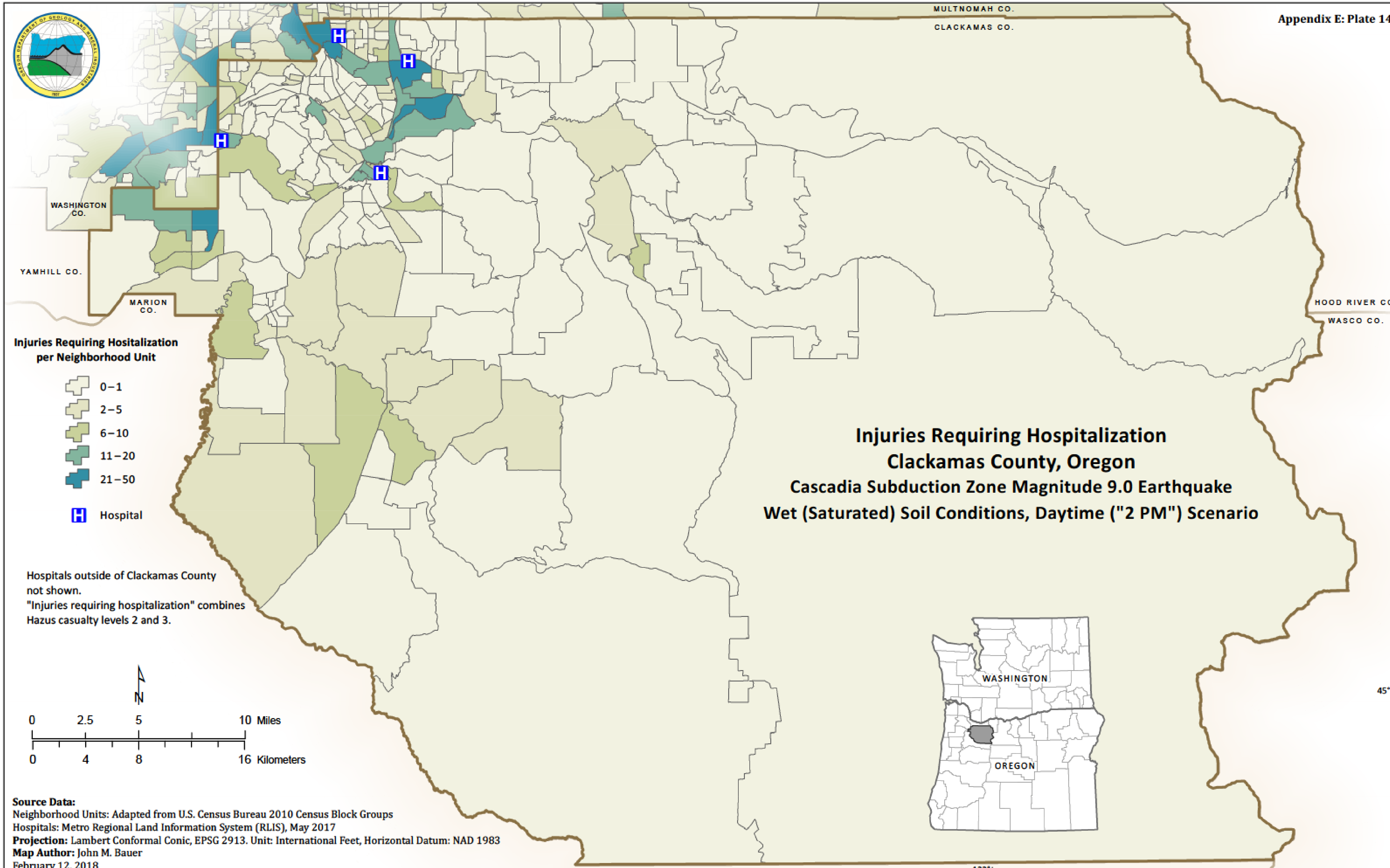
Potential Impact of Permanent Ground Deformation to Metro Emergency Transportation Routes
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Scenario



Closeup, Oregon Highway 8, showing potential permanent ground deformation (same color scale as main map)

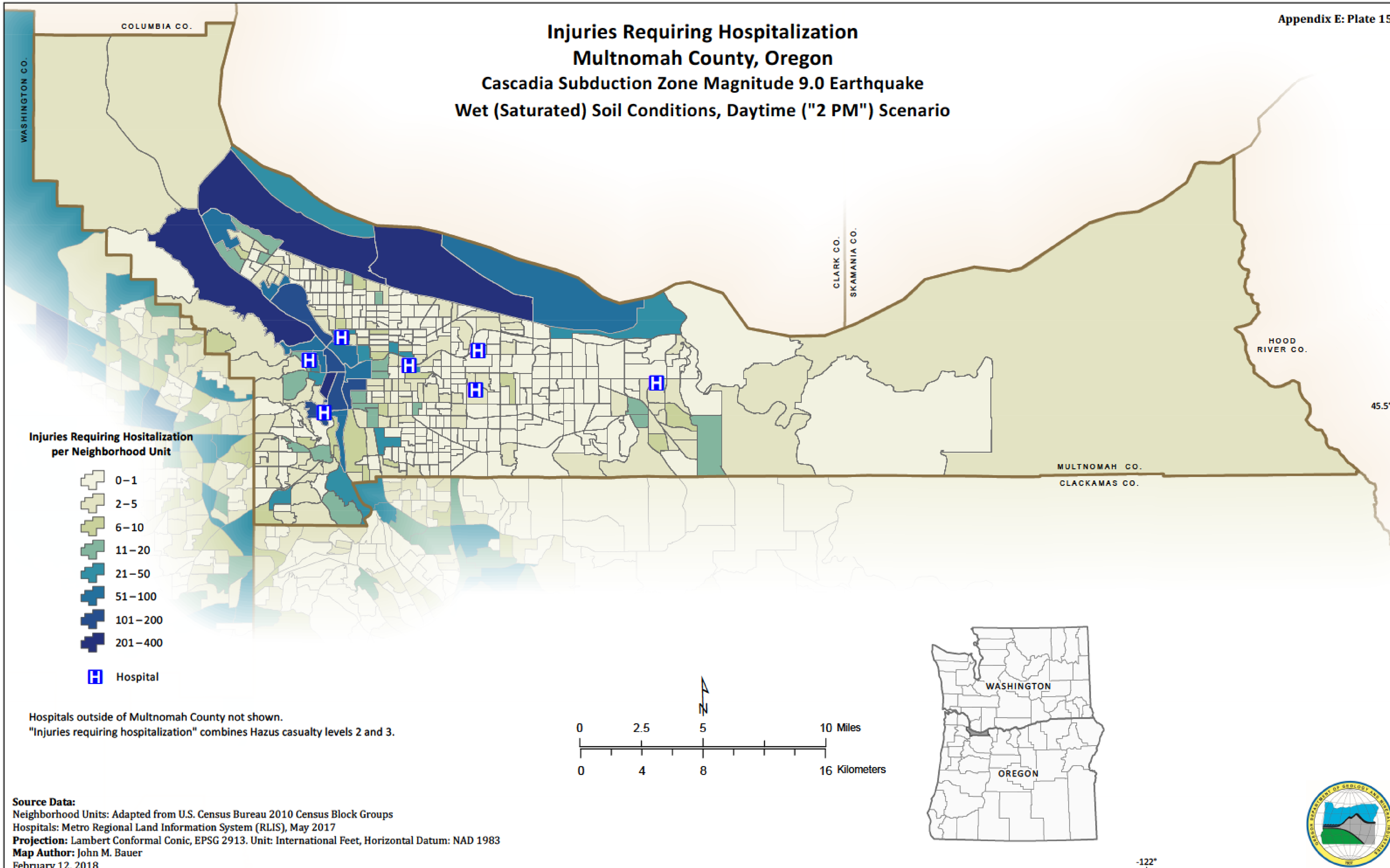
Source Data:
Emergency Transporation Routes: Metro, 2006
Cities: Metro Regional Land Information System (RLIS), May 2017
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet.
Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017


Appendix E: Plate 13
Potential Impact of Permanent Ground Deformation to Electrical Transmission Structures
Cascadia Subduction Zone Magnitude 9.0 Earthquake, Wet (Saturated) Soil Scenario
-123°
45.5°
COLUMBIA CO.
TILLAMOOK CO.
WASHINGTON CO.
YAMHILL CO.
CLARK CO.
SKAMANIA CO.
MULTNOMAH CO.
CLACKAMAS CO.
HOOD RIVER CO.
WASCO CO.
MARION CO.
Potential Permanent Ground Deformation at Electrical Transmission Pole/Tower
< 1.0 meter
1.0 – 2.0 meters
> 2.0 meters
Substation
Transmission Line Corridor (outside of study area)
Permanent ground deformation at the pole/tower site takes the maximum of earthquake-induced landslide and lateral spread from liquefaction (Plate 8). Probability of occurrence for structures with > 1 meter permanent ground deformation is between 20% and 30% (Plate 9).
WASHINGTON
OREGON
N
Miles 0 2.5 5 10
Kilometers 0 4 8 16
Source Data:
Hydrography: Metro Regional Land Information System (RLIS), 2016
Transmission Structures: Compiled by DOGAMI, 2017
Substations and Transmission Line Corridors: Dept. of Homeland Security Homeland Infrastructure Foundation-Level Data (HIFLD), 2017
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
September 1, 2017


Appendix E: Plate 14
Injuries Requiring Hospitalization
Clackamas County, Oregon
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Conditions, Daytime ("2 PM") Scenario
MULTNOMAH CO.
CLACKAMAS CO.
WASHINGTON CO.
YAMHILL CO.
MARION CO.
HOOD RIVER CO.
WASCO CO.
Injuries Requiring Hositalization per Neighborhood Unit
0–1
2–5
6–10
11–20
21–50
Hospital
Hospitals outside of Clackamas County not shown.
"Injuries requiring hospitalization" combines Hazus casualty levels 2 and 3.
N
0 2.5 5 10 Miles
0 4 8 16 Kilometers
WASHINGTON
OREGON
45°
-122°
Source Data:
Neighborhood Units: Adapted from U.S. Census Bureau 2010 Census Block Groups
Hospitals: Metro Regional Land Information System (RLIS), May 2017
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Appendix E: Plate 15

Injuries Requiring Hospitalization
Multnomah County, Oregon
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Conditions, Daytime ("2 PM") Scenario

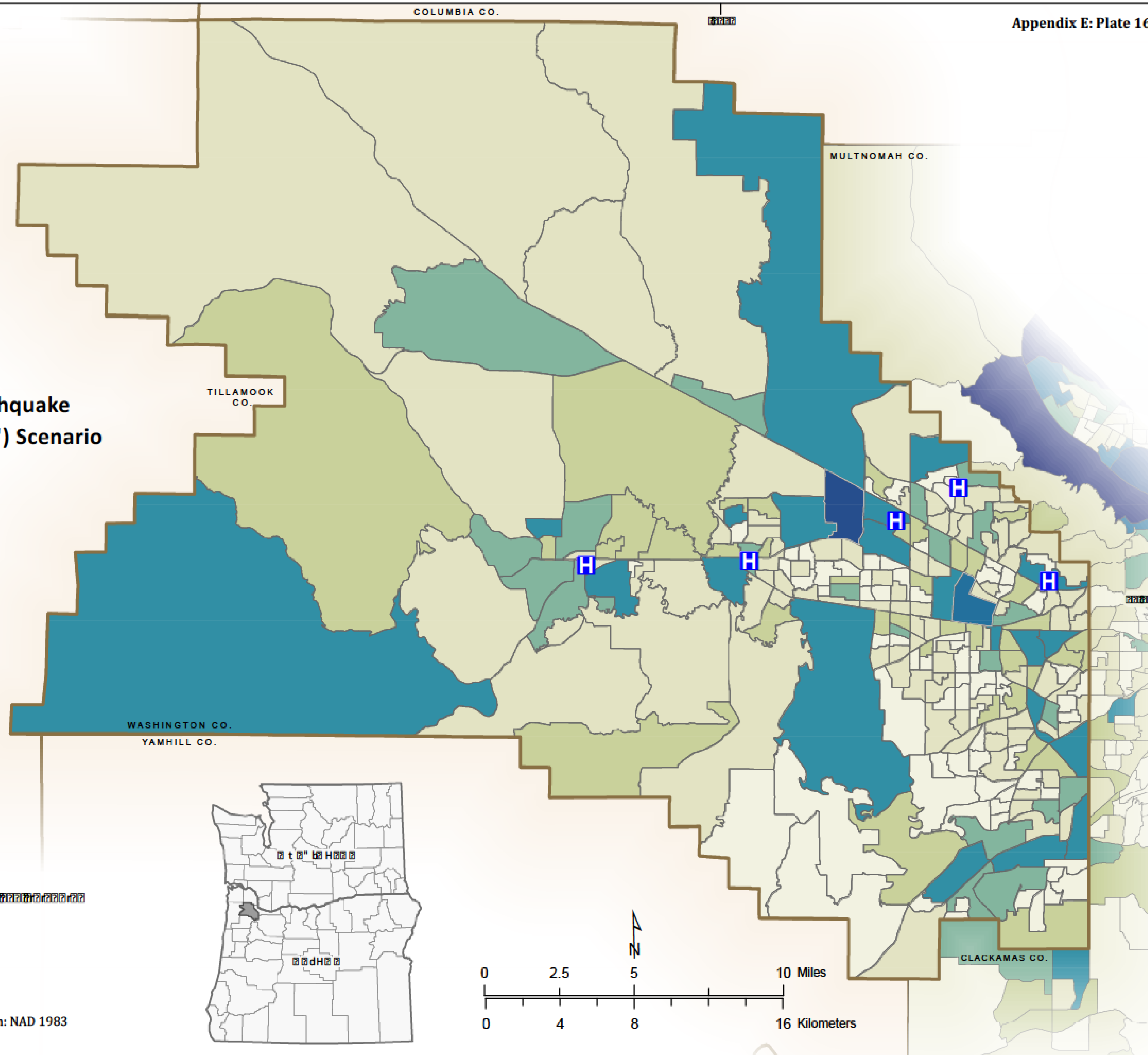


Hospitals outside of Multnomah County not shown.
"Injuries requiring hospitalization" combines Hazus casualty levels 2 and 3.

Source Data:
Neighborhood Units: Adapted from U.S. Census Bureau 2010 Census Block Groups
Hospitals: Metro Regional Land Information System (RLIS), May 2017
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018

Injuries Requiring Hospitalization
Washington County, Oregon
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Conditions, Daytime ("2 PM") Scenario

Injuries Requiring Hositalization per Neighborhood Unit



Source Data:
Neighborhood Units: Adapted from U.S. Census Bureau 2010 Census Block Groups
Hospitals: Metro Regional Land Information System (RLIS), May 2017
Projection: Lambert Conformal Conic, EPSG 2913. Unit: International Feet, Horizontal Datum: NAD 1983
Map Author: John M. Bauer
February 12, 2018