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Brad Avy, State Geologist

OPEN-FILE REPORT O-20-01

EARTHQUAKE REGIONAL IMPACT ANALYSIS FOR COLUMBIA COUNTY, OREGON AND CLARK COUNTY, WASHINGTON

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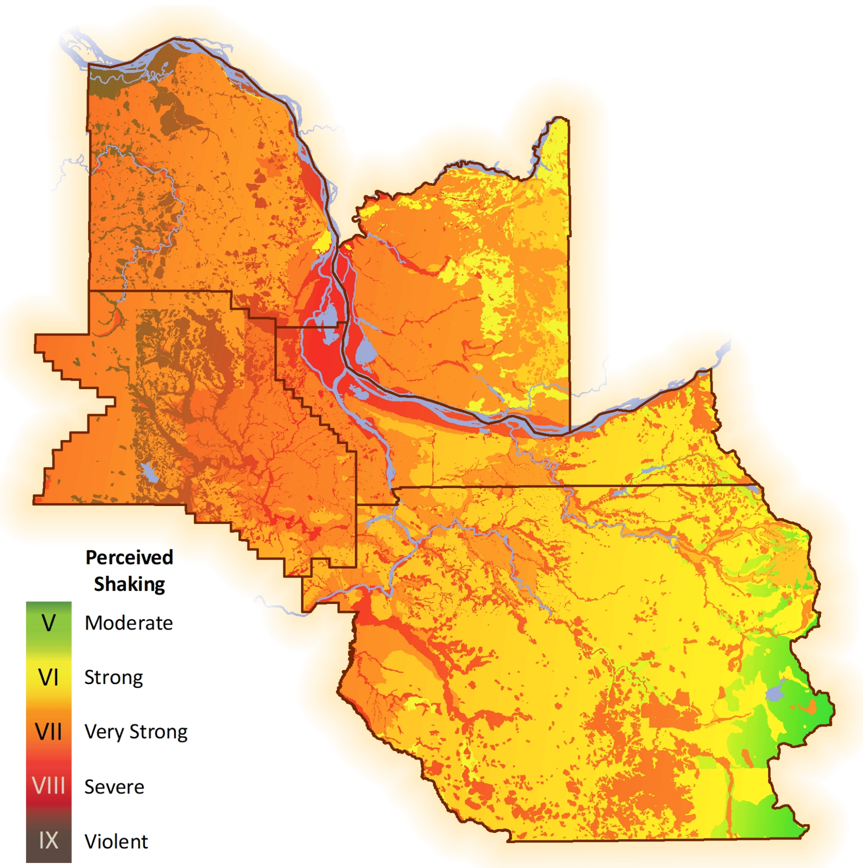
Robert Hairston-Porter[1], and Yumei Wang[1]



WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY

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Cover Image: Perceived shaking for a simulated magnitude 9.0 Cascadia Subduction Zone earthquake in the five-county study area (Clackamas, Columbia, Multnomah, and Washington Counties, Oregon, and Clark County, Washington), using updated National Earthquake Hazard Reduction Program site classifications and bedrock ground motion data developed for the 2013 Oregon Resilience Plan. See Appendix D, Plate 5 for further information.

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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_Phase2.gdb:

Feature dataset: *Phase2*

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_ClarkCo.gdb:

Rasters:

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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
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PHF_M6p8_Prob_liquefaction_wet

RDPO_GroundMotion_GroundFailure_ColumbiaCo.gdb:

Rasters:

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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
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PHF_M6p8_sa03_site
PHF_M6p8_sa10_site
PHF_M6p8_PGD_landslide_dry
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PHF_M6p8_PGD_liquefaction_wet
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PHF_M6p8_Prob_liquefaction_wet

EXECUTIVE SUMMARY

This is the second of two reports that document the estimated impacts of a major earthquake on the Portland, Oregon metropolitan region. Both reports were prepared for the Regional Disaster Preparedness Organization (RDPO), with funding provided by the Urban Areas Security Initiative Program. The reports provide damage estimates to buildings and key infrastructure sectors resulting from a major earthquake in the Portland metropolitan region, along with casualty estimates, by using updated local geologic information and recent advances in earthquake 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). The Phase 1 report was published in 2018. This second report documents Phase 2 of the project, where we applied the methods developed in Phase 1 to evaluate earthquake impacts in **Columbia County, Oregon** and **Clark County, Washington**. For the Phase 2 study, DOGAMI partnered with the Washington Geological Survey (WGS), which developed building inventory and geologic hazard mapping updates for Clark County and was actively engaged in all aspects of the Phase 2 study. This report's format is based largely on the 2018 Phase 1 report. For a regional context, tables in this report often include summaries of the three counties studied in Phase 1, along with five-county totals.

The Portland metropolitan region is vulnerable to regional and local earthquakes. We modeled damage for two earthquake scenarios: a regional 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 with a reduced 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 regional building footprint database, a building database containing detailed descriptions of each building, and an electric power transmission structure database
- **Geotechnical mapping updates:** completion of high-resolution earthquake-induced landslide susceptibility, liquefaction susceptibility, and soil classification 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 potential harm to the people who occupy them, to the region's designated emergency transportation routes, and to the electrical grid

A CSZ magnitude 9.0 earthquake will have a major impact on Columbia and Clark Counties, with building repair costs estimated at between 3.7 and 6.7 billion dollars (6% and 11% of the total building replacement cost; see 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 high hundreds or several thousands. The earthquake will generate several million tons of debris from damaged buildings.

Damage and casualty estimates resulting from a magnitude 6.8 Portland Hills fault earthquake are about the same overall in the two counties compared to a CSZ magnitude 9.0 earthquake. The spatial patterns of the damage between the two earthquake scenarios differ significantly in Columbia and Clark Counties, with damage from a CSZ being more dispersed compared to the more localized impacts from a Portland Hills fault earthquake.

Overall, in the five-county region, a CSZ magnitude 9.0 earthquake could result in building repair costs estimated at between 27 and 43 billion dollars (9% and 14% of the total building replacement cost), and casualties between 5,300 and 33,000 individuals. Between 24,000 and 116,000 individuals, or about 1% to 5% of the total population, may need temporary shelter.

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 high-resolution updated soil classification and liquefaction susceptibility data.

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. The GIS database can be merged with the GIS database published with the Phase 1 report to create a five-county perspective. A separately published DOGAMI report (Appleby and others, 2019) described the geotechnical mapping updates for the four counties in Oregon, consisting of National Earthquake Hazards Reduction Program (NEHRP) soil types, and earthquake-induced landslide and liquefaction susceptibility. The Washington Geological Survey will separately publish at a later date the landslide mapping in Clark County that was used in this report.

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.

Table ES-1. Loss estimate summary for two earthquake scenarios in the Portland metropolitan region. Lower value: dry soil conditions. Upper value: saturated soil conditions. Table includes results from the Phase 1 study covering Clackamas, Multnomah, and Washington Counties. OR is Oregon. WA is Washington.

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)	Nighttime Scenario (Thousands)
Cascadia Subduction Zone magnitude 9.0 earthquake									
Clackamas, OR	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
Clark, WA	425,363	146,460	51.7	2.8–5.2	5%–10%	1.1–1.8	3.8–24.7	2.6–4.7	0.6–2.3
Columbia, OR	49,351	32,862	8.1	0.9–1.5	12%–18%	0.5–0.7	3.0–5.9	0.7–0.9	0.3–0.6
Multnomah, OR	735,334	255,577	114	13.3–20.5	12%–18%	7.7–10.4	9.7–37.5	11.4–16.7	2.8–5.6
Washington, OR	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	2,115,750	795,174	319.0	27.2–43.4	9%–14%	14.4–19.8	23.7–116	21.6–32.8	5.3–13.3
Portland Hills fault magnitude 6.8 earthquake									
Clackamas, OR	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
Clark, WA	425,363	146,460	51.7	2.6–5.7	5%–11%	0.9–1.8	2.8–29.0	1.9–4.5	0.6–2.7
Columbia, OR	49,351	32,862	8.1	0.7–1.2	8%–15%	0.3–0.5	1.7–5.0	0.4–0.7	0.2–0.4
Multnomah, OR	735,334	255,577	114	32.3–42.7	28%–37%	15.7–19.3	50.8–120	28.9–36.3	9.3–15.3
Washington, OR	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	2,115,750	795,174	319.0	63.8–90.3	20%–28%	27.8–36.2	100–291	50.2–68.2	16.7–32.2

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

1.0 INTRODUCTION

1.1 Project 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 4,416-square mile area spans Clackamas, Columbia, Multnomah, and Washington Counties in Oregon and Clark County in Washington (**Figure 1-1**).

Figure 1-1. Regional Disaster Preparedness Organization study area, spanning Oregon and Washington. Phase 1 study area (Washington, Multnomah and Clackamas Counties, Oregon) in tan with heavy black outline, Phase 2 study area (Columbia County, Oregon and Clark County, Washngiton) in lavender with heavy gray outline. County seats shown as dots. Columbia River shown as blue line.

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. Previous earthquake loss estimates in the Portland metropolitan region were derived from several studies, each using different datasets (Wang, 1998; Hofmeister and others, 2003; FEMA, 2004; Tetra Tech, 2016, 2017). Technologies and data available for earthquake impact analysis have improved since these studies were published. 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 study area.

We divided the project into two phases. Phase 1 focused on methodology development and application of those methods to evaluate impact of a major earthquake in Clackamas, Multnomah, and Washington Counties (Oregon) (Bauer and others, 2018). For the Phase 2 portion of the study (this report), DOGAMI partnered with the Washington Geological Survey, which developed all required datasets for Clark County, Washington, and was actively involved in planning, map updates, and review of impact estimates in Clark County, and in report development. DOGAMI developed all required datasets for Columbia County, Oregon.

Columbia and Clark Counties continue to experience significant growth. The population in Columbia County increased from 43,648 in 2000 to 51,900 people in 2018 (Portland State University Population Research Center, 2018, https://www.pdx.edu/prc/population-reports-estimates). In Clark County, resident population increased from 345,238 in 2000 to 481,857 in 2018 (U.S. Census Bureau Annual Estimates of the Resident Population, July 1, 2018). Both counties have large areas of dispersed rural development outside of city boundaries.

1.2 Geologic Overview

Geology in the 1,344-square-mile study area varies widely and is influenced by local and regional processes (Evarts and others, 2009). Rock units and deposits include Columbia River basalt flows, alluvial deposits, 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 (Palmer and others, 2004; 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.

In Columbia County the predominant surficial geologic sequence throughout the western mountainous portions and extending almost to the Columbia River is an exposed surficial layer of various volcanic basalt units underlain by thick deposits of various marine sedimentary rock sequences. This type of stratigraphy results in a high probability for landslide and debris flow activity. Most of the landslide activity originates from the marine sedimentary rock units in areas of high relief, resulting in large, dynamic landslide complexes that can be reactivated by both natural and anthropomorphic factors. The surficial geology in the eastern part of Columbia County is dominated by a transition from high relief volcanic bedrock overlain by thick loess deposits to a low-relief area along the Columbia River consisting of alluvium and Missoula Flood deposits. Additionally in Columbia County are several scattered low-lying areas of volcanic bedrock that were exposed and had overlying alluvial sediments scoured away by the Missoula Floods (Burns and Coe, 2012). Potentially liquefiable soils occur throughout the county, including former riverine floodplains and valley bottomlands.

The Washington portion of the Portland metropolitan area is the second most seismically active area in Washington, after the Puget Sound area. Most of Clark County buildings lie between the Lacamas Lake Fault in the eastern part of the county and the Portland Hills fault in Oregon. Geologists have mapped faults directly underneath the cities of Portland and Vancouver. Recent studies suggest that the epicenter for the magnitude 5.5 earthquake on November 5, 1962, was located underneath the City of Vancouver (Clark Regional Emergency Services Agency, 2011). Like Columbia County, potentially liquefiable soils occur throughout the Clark County, including former riverine floodplains and valley bottomlands.

1.3 Earthquake Scenarios and Earthquake Loss Estimation

An earthquake scenario tells the story of a hypothetical description of an earthquake and its potential impacts on a community, presenting narratives and data that can help planners and community members to better understand the earthquake hazard and risk and plan for the future (Earthquake Engineering Research Institute [EERI], 2006). Scenarios use the best available geologic information on fault location and earthquake rupture frequency and 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 who 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 with a more complete picture of the range of potential impacts from a large earthquake, we modeled two distinct earthquakes originating from the Cascadia Subduction Zone (CSZ) and the 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.”

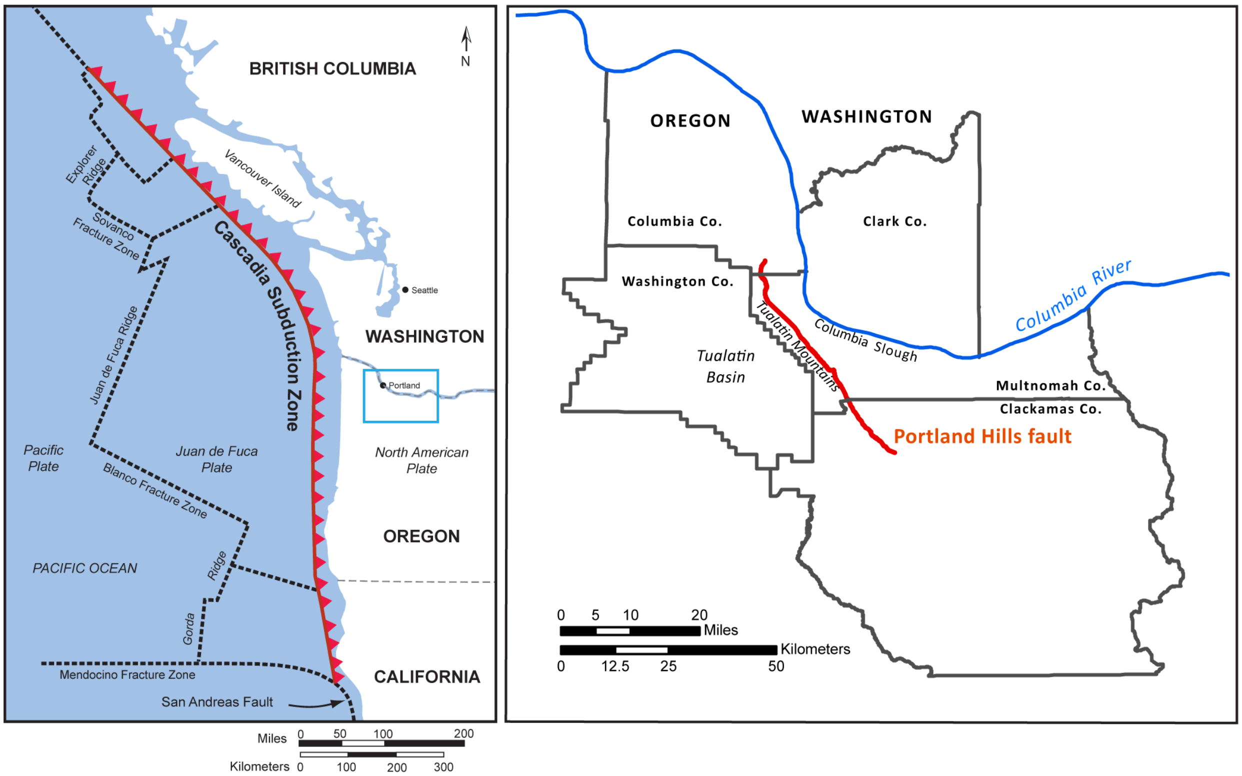
In western Oregon and Washington, soil moisture conditions vary widely throughout the calendar year. Soil moisture conditions influence the likelihood of an earthquake-triggered landslide or liquefaction. An earthquake occurring during “wet” (saturated) soil conditions is much more likely to induce landslides 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, the earthquake could cause more casualties.

Past earthquakes along the 600-mile Cascadia Subduction Zone fault (**Figure 1-2**, left) 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**, right) might be seismogenic (i.e., capable of generating earthquakes), 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, the population centers of Clackamas County and City of Scappoose in Columbia County, and its proximity to high-value industrial and commercial assets in Vancouver, Washington.

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



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. Subsequently, only one Hazus-based study has been done in the Phase 2 study area, focusing on Clark County (Tetra Tech, 2017). No earthquake impact studies have been conducted in Columbia 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 six 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 **2.0**, 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.

1.3.1 Critical Infrastructure Sectors

As discussed by Bauer and others (2018, Section 1.2.1), we focused two critical infrastructure sectors using updated ground motion and ground failure data.

1.3.1.1 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); 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 (Wang and others, 2013). 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 magnitude 7.6 earthquake (Turkey). Photographic credit: University of California, Irvine, Consortium of Universities for Research in Earthquake Engineering archives.

1.3.1.2 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[1]. Understanding which routes may be impacted by 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 magnitude 6.8 earthquake. Photographic credit: DOGAMI archives.

[1]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)

1.4 Study Limitations

Hazus-based risk analyses often include damage estimates for 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; these datasets generally capture only a portion of the nonbuilding 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 who 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 **7.0**), 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) or another engineering screening, such as American Society of Civil Engineers checklists, rather than a Hazus-based method using generic building models.

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, invalidating the basic assumptions used in the current Hazus model.

Our study focused on loss to buildings, which includes damage from earthquake-induced landslides and liquefaction (discussed further in Section **3.3**). 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 and floating structures (houseboats) from our building database. Many nonbuilding structures are retained within the building footprint database and are clearly attributed as such. The electrical transmission network is limited to the towers and poles that supply power to the distribution substations (Appendix D, **Plate 12**). The surface transportation network is limited to a subset of highways, arterials, and roads identified as Emergency Transportation Routes (Appendix D, **Plate 9**).

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.

For Columbia County we used the building footprint to define the building record, as was done in Phase 1 of this study. As such, our first task was to complete a building footprint database for the study area. Building footprints developed in 2009 were obtained from the Columbia County Assessor's Office (R. Gallo, written communication, 2018). This dataset covered much, but not all, of Columbia County. In addition, significant development has occurred since 2009. We systematically reviewed all existing footprints and added footprints where new buildings have been constructed, following the methods described by Mickelson and Burns (2012, Section 3.2.3). Where lidar data were not present or of an older vintage (discussed by Appleby and others, 2019), 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). Digitization included removing obsolete building footprints (teardowns) and modifying existing building footprints where additions had been made or other digitization errors were noted.

DOGAMI recently developed a semi-autonomous method to extract building footprints from a lidar point cloud (Hairston-Porter, 2018), and we used this technique to extract building footprints in areas not covered by the 2009 building footprint dataset, focusing on areas with more recent lidar flights. DOGAMI receives delivery of point clouds with a basic classification of unclassified and ground. DOGAMI reclassified the point clouds using algorithms within TerraSolid software to include a third classification for building rooftop points. Conversion from points to vector results in a vector polygon dataset where the polygons are analogous with the outlines of the rooftops. In two dimensions this can be considered synonymous to the building footprint. The newly generated building footprint polygons were then checked for spatial accuracy by comparing their shape to the outline of the building with either a digital surface model or aerial imagery. Polygonal inconsistencies were reshaped using the basic ArcGIS editing toolbox to ensure the polygon correctly outlines the building.

We typically did not digitize structures less than 400 square feet in area. These features are assumed to be nonbuilding 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. We note that this square footage cutoff may not capture micro-housing.

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 who 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 although they are subject to damage from tsunamis or seiches following an earthquake. 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.

In the building footprint database obtained from Columbia County, contiguous buildings were often 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 partitioning. Building footprints digitized as part of this project factored into the method for determining 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.

The Clark County GIS Department actively maintains a building footprint database for the entire county, and we determined there was no need to amend that existing building dataset.

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 of the tax lots in the study area. We obtained detailed tabular data and tax lot polygons from the two county assessor offices (Appendix A, **Table 10-1**). We used the tax lot spatial data to associate the 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 three-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 buildings occupying that particular tax lot.

For Clark County, we used as a starting point the building database assembled by Tetra Tech in support of the Clark Regional Natural Hazard Mitigation Plan (Tetra Tech, 2017). Tetra Tech associated assessor information with the tax lot centroid, using a 2015 copy of the Clark County Assessor database and tax lot spatial data. Parcel unique identifiers link the tax lot centroid points to original parcel information, such as occupancy class, year built, building type (also referred to as building class), building seismic design level (seismic design code), square footage, and number of stories. Building replacement costs for Clark County were calculated in a similar manner as Columbia County (Section **2.1.5**). We identified new developments in Clark County and registered more building footprints by using 2017 orthoimagery provided by Washington Department of Natural Resources GIS database and using Google Earth™. When agricultural buildings and residential buildings are located in the same lot, only the residential building was accounted for in the building point entry.

Neither of the two 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 locations of educational, fire, and police buildings. Appendix A, **Table 10-1** provides a complete list of other datasets used to populate the building database.

2.1.4 Building Type

The Hazus building type is a nested descriptor first specifying the basic structural system of a building, such as steel or wood frame, then providing more specific information on the building type and, where warranted, building height. For example, a steel frame building can be categorized as a steel light frame or a steel moment frame, either low-rise (1 to 3 stories), mid-rise (4 to 7 stories), or high–rise (8 or more stories). 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 the large number of buildings.

We could not find any information in any of the 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.

WGS and DOGAMI used orthophoto images, Google Earth, and visual inspection of some of the exterior walls of the structures for further refinement of the assigned building types for both counties.

Vancouver, Washington has a rich brickmaking history (Hidden, 1930). Many of these bricks were used in building construction throughout Clark County. We visually identified unreinforced masonry (URM) buildings using street level imagery and updated the building type where needed, focusing on older sections of Clark County cities. The process should not be considered definitive, however, and we do not assert that the inventory is complete or that these suspected URMs are indeed URMs as some may appear so from street view but may be a façade or have bracing.

For buildings that had no information on their primary construction material, and where we did not manually assign a building type, 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 the Hazus 4.0 database[2], which incorporated the 2014 RSMeans valuation to compute the replacement cost. We made no inflation or regional adjustments to the tabular data. The Hazus 4.0 tables were based on 2014 RSMeans national values. The Consumer Price Index difference between 2014 and 2019 was minimal. The RSMeans location factor adjusts for regional differences in labor and material costs, but 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 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 earthquake model allows a user to specify, for the given building type, its seismic performance level. The established "benchmark years" of code enforcement were then mapped into the Hazus "design level" for individual buildings. Hazus seismic design levels are a categorization of a building's strength and ductility, as described by FEMA (2011, Table 5.19). The Hazus

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[2] FEMA Hazus SQL tables [dbo].[hzRes1ReplCost] for single-family residential; [dbo].[hzReplacementCost] for all other occupancy types.

design level categories (e.g., pre-code, low-code, moderate-code, and high-code) were then used in the Hazus earthquake model to determine what damage functions are applied to a given building. The individual building's year of construction, and where available, the year of the most recent seismic retrofit, determined its design level. We used the benchmark years listed in **Table 10-2** for Columbia County and **Table 10-3** for Clark County 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 or the Washington State Building Code Council.

In the past 20 years many property owners, including private, public, and institutional, have implemented building seismic retrofits—modifications that improve a 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 county permitting or assessor offices. An analysis by the City Club of Portland (2017), for example, 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.

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 to 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.

Given the rapid growth since 2010 in suburban areas of Columbia and Clark Counties, we used the 2013–2017 American Community Survey (ACS) Census Block Group population estimates (Table DP05, Demographic and Housing Estimates) to assign permanent resident population quantities to residential buildings. We pro-rated the ACS total permanent population estimate for a given U.S. Census Bureau-defined census block group across all residential buildings, except the RES4 (hotel/motel) type, on a square footage basis. 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 three 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 database[3] 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).

2.1.8 Population and Building Density

We developed a 20-acre hexagonal grid, and 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 commonly occur in commercial/industrial corridors or predominantly agricultural areas (Appendix D, **Plate 1** and **Plate 2**). 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.

2.2 Electric Power Transmission

We constructed a transmission pole and tower point GIS dataset from spatial data obtained from local electric utility districts and, where large gaps occurred, from our own digitization. The compiled datasets were inspected for gaps and redundancies. Gaps in the transmission network were highlighted using the transmission line corridors and substations dataset downloaded from the Homeland Infrastructure Foundation-Level Data collection (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 5,469 poles and tower locations. The transmission network is incomplete, however, as we did not digitize poles in the Timber Road corridor of southwest Columbia County. Electric power transmission distribution along the corridor is typically conveyed on single poles, which are difficult to distinguish using lidar-derived imagery or orthoimagery.

[3] FEMA Hazus SQL Table [dbo].[hzDemographicsT]

2.3 Emergency Transportation Routes

We constructed an Emergency Transportation Route (ETR) polyline GIS dataset by querying authoritative GIS data from local and state departments of transportation (DOTs) using the named routes specified in the 2005 Memorandum of Understanding[4]:

> (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 networks obtained from the local and state DOTs consist of GIS polylines placed at the road centerline and include 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 feet, then 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–SR-14 intersection in Clark County, were treated as a single segment instead of a node. We identified 46 road segments and gave each a unique key for analysis purposes.

We were aware of an ongoing effort funded by the Regional Disaster Preparedness Organization to update the region's Emergency Transportation Network. However, the final products of that study were not available in time for this project. For Washington, a statewide transportation resilience assessment for a CSZ event was published in March of 2019 by the U.S. Department of Homeland Security but was not ready in time for use by this study[5].

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.

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[4] Emergency Transportation Route Post-Earthquake Damage Assessment and Coordination Portland, Oregon/Vancouver, Washington Regional Area; State of Oregon Misc. Contracts & Agreements No. 21,273, p. 2.

[5] Now available at https://mil.wa.gov/asset/5d8ba2a03a1b7

For the Cascadia Subduction Zone magnitude 9.0 earthquake scenario used in the 2013 Oregon Resilience Plan, Madin and Burns (2013) obtained synthetic bedrock ground motions from A. 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 A. Frankel (written communication, 2016) at 0.01 degree intervals and were included in the geodatabase of Bauer and others (2018).

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 for Columbia County (Appleby and others, 2019). In Clark County we used an updated NEHRP soil classification that included some additional seismic tests to determine Vs30 (shear wave velocity at 30 m) as well as newer 1:24,000–scale geologic mapping that was not used in previous site class studies (Palmer and others, 2004, Sheet 12). In Clark County we assigned a NEHRP rating of “D” to landslide deposits, following Palmer and others (2004). In Columbia County, we assigned a NEHRP rating of “F” to landslide deposits and debris flows (Appleby and others, 2019, Table 6). Sites in both counties 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 by Bauer and others (2018, Appendix B).

The site ground motion from the synthetic earthquakes in our two scenarios differs dramatically across the study area, with the Portland Hills fault exhibiting significantly higher ground motion proximal to the fault (Appendix D, **Plate 4**). The technical descriptions of earthquake ground motion such as depicted on **Plate 3** and **Plate 4** (Appendix D) can be challenging to interpret, so we developed damage potential maps using the Modified Mercalli Intensity (MMI) scale (Appendix D, **Plate 5** and **Plate 6**). 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, the relationships used by USGS ShakeMap products (Wald and others, 2006, Figure 2.5), and the MMI color scheme used by Madin and Burns (2013).

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 3-5 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. In Hazus, the Cascadia Subduction Zone magnitude 9.0 earthquake was modeled as long duration, and the Portland Hills fault magnitude 6.8 earthquake was modeled as medium duration.

3.3 Liquefaction and Landslide Susceptibility

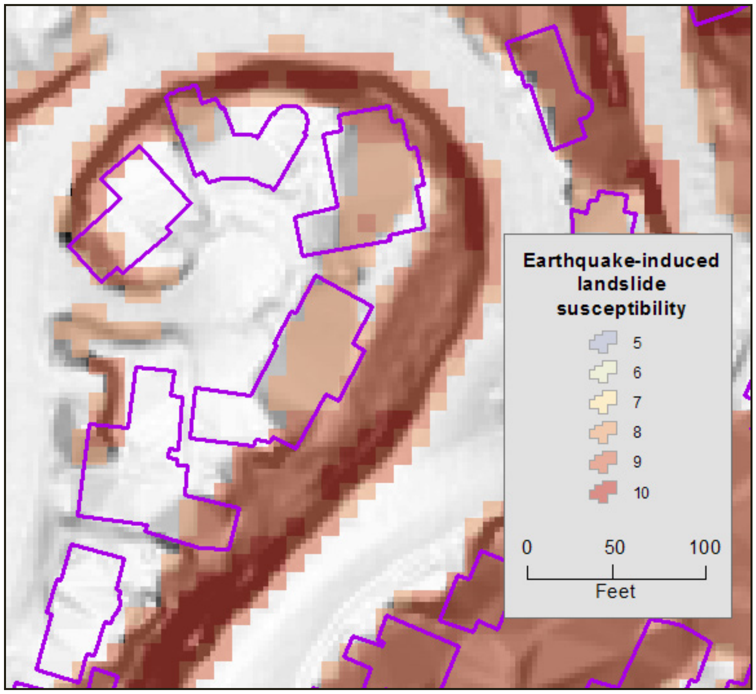
For our Hazus building damage model, we provided a liquefaction and landslide susceptibility value for each building record, thereby allowing the Hazus model to calculate the amount of ground deformation and probability of ground deformation. The Hazus building damage model first calculates building damage caused by strong ground motion; it then incorporates the calculated ground failure information into an overall building damage estimate (FEMA, 2011, Section 5.6.3).

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, 2019). For Clark County the liquefaction mapping of Palmer and others (2004, Sheet 11) was updated using the landslide mapping conducted for this study as well as updated 1:24,000–scale geologic data. 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.

Geologists experienced in landslide interpretation identified landslide landforms from lidar, which were then input into the landslide susceptibility grid. In Clark County the landslides were mapped following the landslide inventory mapping protocol of Slaughter and others (2017) and will be published by WGS at a later date. Landslides were digitized in a GIS framework and delineated by a polygon that identified the entire landslide landform (head scarp, side scarps, and body). In Columbia County, landslide landforms (deposits) were mapped as described by Appleby and others (2019).

Using high-resolution lidar-derived elevation models for Columbia and Clark Counties, we developed a 10-foot Hazus-based landslide susceptibility grid for this project (Appleby and others, 2019) 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 with 10 being the most susceptible to failure. Areas of no shading: minimal to no landslide susceptibility. Earthquake-induced landslide susceptibility data from Appleby and others (2019).



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, no region-wide groundwater mapping information currently exists. 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 chose to mimic the “wet” (saturated soil) and “dry” landslide scenarios by setting water depth to two distinct values: 5 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 landslides, along with a probability of their occurrences. We developed an in-house tool that implements the Hazus earthquake PGD models (documented in Hazus-MH 2.1 Technical Manual, Earthquake Model, Section 4.2 [FEMA, 2011]) as a continuous raster surface. The tool requires as inputs the liquefaction and landslide susceptibility, along with site peak ground acceleration data for both earthquake scenarios (Section 3.2), groundwater depth (fixed at 5 feet and 1,000 feet across the study area for our wet/dry analysis), and earthquake magnitude (a surrogate for duration, discussed in Section 3.2), and returns rasters showing estimated amount of PGD along with a probability for lateral spreading from liquefaction and from landsliding. We captured synthetic Hazus point-level data results using discretized peak ground acceleration (stepping from 0.01 g to 1.0 g in 0.01 g increments) together with the full range of liquefaction and landslide susceptibility in a lookup table for use by the tool.

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

3.5 Tsunami

An offshore CSZ-generated tsunami will propagate up the Columbia River (modeled by Allan and others, 2018, and Allan and O'Brien, 2019). In a worst-case scenario, levees in portions of Columbia County could be overtopped, with a resultant exposure of terrestrial buildings in currently designated levee-protected areas. However, such a scenario requires specific combinations of extreme flood stage, coupled with high tides, and a major CSZ tsunami scenario. Given that the probability of such a combined occurrence is extremely low (e.g., an XXL1 size CSZ scenario [~10,000 year event] coinciding with a 100-year river flood reflects a joint probability of 1:1,000,000), we did not perform any analysis of the potential impact of a tsunami. In addition, a seismic stability analysis of levees was outside this project's scope.

Floating structures such as houseboats may be damaged or dislodged due to elevated waters and high river currents resulting from a CSZ-generated tsunami. Floating structures may also be subject to damage from seiching due to the CSZ earthquake itself (Jones and others, 2008). Evaluation of damage to floating structures from such mechanisms was beyond the scope of this project.

Localized tsunamis can be triggered by landslides, including earthquake-induced landslides, and can damage structures and injure or kill people in low-lying areas next to large water bodies. On January 30, 1965, a tsunami generated by a landslide on the Oregon side of the Columbia River killed one person, destroyed houses, and damaged a levee on Puget Island in Wahkiakum County, Washington (Wahkiakum County Eagle, 1965). Modeling such events was also beyond the scope of this project.

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 version 4.0 (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 database[6]. 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 for the structural, nonstructural drift, and nonstructural acceleration components (15 total PDS values). We used the PDS values to calculate debris and displaced population and to estimate the total number of red-tagged and yellow-tagged buildings. A red-tagged building is a legal designation prohibiting access to a building or structure that has been severely damaged to the degree that it is unsafe to occupy (Applied Technology Council [ATC], 1989). A yellow-tagged building or structure has extensive damage; it is not considered unsafe to occupy but may have legal restrictions on continuous habitation or other uses.

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 user-specified number of 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."

[6] FEMA Hazus SQL table [dbo].[eqAebmProfile] contains capacity curve and fragility curve parameters for all combinations of occupancy class, building type, design level, and building height, and two sets of lognormal standard deviation values. The latter is often referred to as "betas," and describes the total variability of fragility curve damage states. One set ("relaxed betas") is intended for use in modeling earthquake scenarios; the other set intended to model a specific instrumented earthquake (Kircher, 2002). For our modeling purposes, we used the "scenario" beta set, which has the suffix "0" in the [eqAebmProfile] field.

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.

The Hazus v4.2 release modified its methods for incorporating the probability of permanent ground deformation into the final Probability of Damage State assignments for a building (FEMA, 2018b). In Hazus v4.0, the probability of permanent ground deformation was assigned in its entirety to $PDS_{Complete}$ — a conservative modeling assumption, and one that was used in the Phase 1 portion of this study, as that study used Hazus v4.0 (Bauer and others, 2018). In Hazus v4.2 Service Pack 1 (SP1), the probability is spread across $PDS_{Extensive}$ and $PDS_{Complete}$. The effect is that the number of completely damaged buildings, and thus displaced population, is lower for a given set of conditions when calculated using Hazus 4.2 versus Hazus 4.0. An overarching project goal was to obtain consistent loss estimates over all five counties; thus, we chose to use Hazus 4.0 and its conservative incorporation of liquefaction and landslide probability of damage states into the final building damage model.

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 database[7]. 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; Villemure, 2013), or damaged nonbuilding structures.

[7] FEMA Hazus SQL table [dbo].[eqDebrisAnalParms]

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 B, **Table 11-4** through **Table 11-7**). 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. Vancouver has well-defined neighborhoods for most, but not all, of its area, but other jurisdictions in Clark County do not. The Clark County neighborhood associations, maintained by the county manager, are incomplete in coverage and too large for aggregation purposes. Neither Columbia County nor its jurisdictions have formal or usable neighborhood definitions. Fire districts and zip codes were investigated, but we determined that such units 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 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 merged contiguous CBGs to create a larger unit encompassing at least 300 buildings. The merging process was limited to Clark County; we did not identify a need for such merges in Columbia County. The process resulted in reducing the two-county study area's 316 CBGs into 273 *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 or unincorporated county. The jurisdiction layer combined city limits published by Oregon Department of Transportation (2018[8]) and Washington Department of Transportation (2019[9]). The City of Woodland's jurisdictional boundary extends slightly into Clark County and encompasses 53 buildings; however, we chose not to identify it as a jurisdiction in our summary, given the relatively few buildings and concerns with sample size.

4.1.5 Seismic Design Level Improvement Modeling Exercise

Many of the buildings in the study area were constructed with minimal consideration given to seismic resilience (**Table 10-4**). 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 current-day seismic design levels within our building database (see Section **2.1.6** for definitions of moderate code and high code). For the moderate code scenario, all buildings with a Hazus-defined 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 **5.2.1**). Our analysis was limited to the Cascadia Subduction Zone earthquake scenario and was 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

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[8] https://spatialdata.oregonexplorer.info/geoportal/details;id=101b6c8f2d414d719dfeb2ed281af6c8

[9] http://geo.wa.gov/datasets/0b12f000a66f4d75a43ea3ac4ead01dc_1

greater than 2 meters. For all points with greater than 1-meter permanent ground deformation, the probability of occurrence is between 20% and 30%.

4.3 Emergency Transportation Routes

The Hazus tool provides an analysis of linear features such as roads, but we determined that 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 the 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 Portland Hills fault (also referred to in the report as PHF) "wet" (saturated) and "dry" soil condition scenarios, with the results stored in the accompanying geodatabase.

4.4 Model Limitations

Our damage estimates were primarily derived from the Hazus Advanced Engineering Building Module using generic building damage models. 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 magnitude 9 earthquake on the Cascadia Subduction Zone and a magnitude 6.8 earthquake on the Portland Hills fault. We used the upper bound for the earthquake magnitude, recognizing that an actual earthquake may rupture on only a portion of the fault that generates it. 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 been 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 of the landslide. Such flow can wreak significant damage to buildings and people (Daniell and others, 2017), but such modeling capability is not available with existing tools. The FEMA Hazus earthquake model captures only the potential damage to buildings on areas susceptible to sliding, and not on the resultant landslide deposits.

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 individual buildings in this study, we recognize that misclassifications are present, and we made statistical distribution assumptions based on building type when attribution information was not otherwise available.

We used the generic building damage models provided by the Hazus tool, which, for reasons of complexity management, does not include the 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). Although the Hazus AEBM allows a user to specify individual building-specific parameters, it is not possible to conduct a study at a 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 **Table 11-1** through **Table 11-11** we present Hazus damages and casualty estimates as a single value. Such representations can be misleading, as they suggest a high level of precision that is not warranted, in part by the uncertainties in 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.

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 an 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, 2018a) restored the Fire Following functionality but was not available for the RDPO Phase 1 report. As discussed in Section **4.1.1** we chose to use Hazus 4.0 for consistency in loss estimation across the full region.

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 Cascadia 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 B, in graphical form in Appendix D, and in electronic form in the accompanying GIS database (described in Appendix C).

5.0 RESULTS

5.1 Building Statistics

Single-family residential buildings dominate the building inventory in both counties (**Figure 5-1**). Wood frame construction dominates the residential buildings (**Table 5-1**). Appendix A, **Table 10-8** contains a complete breakdown of building type for all generalized building use categories. We caution that the number of manufactured houses listed in **Table 5-1** may be lower than actual due to the abstraction of several manufactured housing parks in Clark County as a single point (Section **2.1.2**).

Figure 5-1. Building primary usage statistics for Clark and Columbia Counties. For reference, we include data for Clackamas, Multnomah, and Washington Counties from the RDPO Phase 1 study (Bauer and others, 2018). 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. Tabular summary for Clark and Columbia Counties is in Table 5-1.

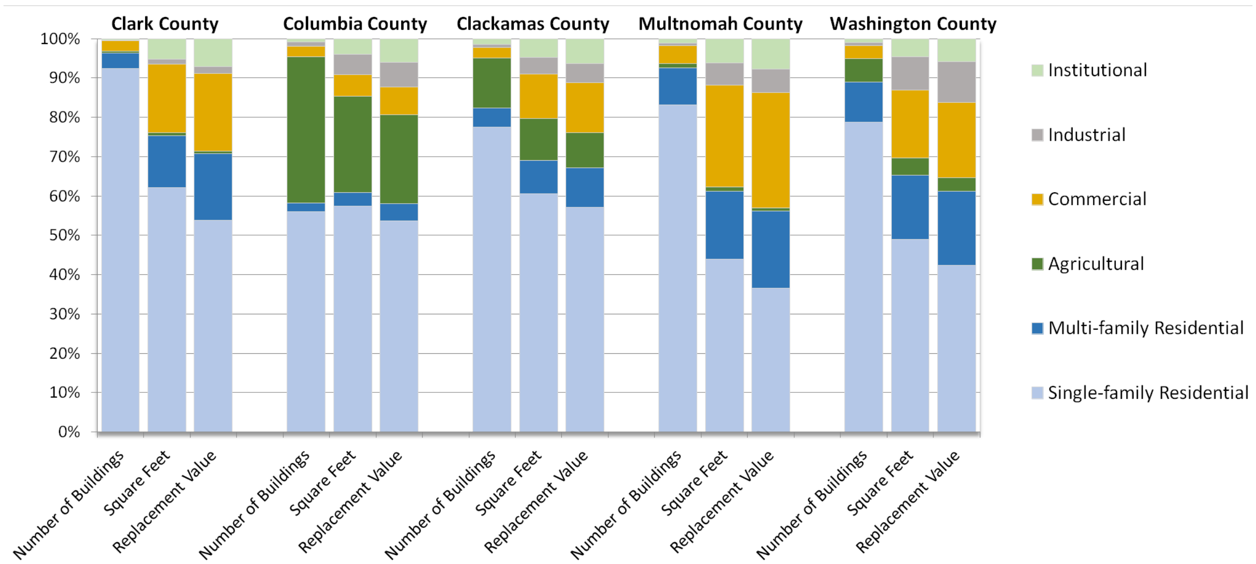


Table 5-1. Residential buildings by building type for Clark and Columbia Counties.

Occupancy Type	Building Type	Number of Buildings	Building Percent	Square Footage (thousand)	Square Footage Percent	Permanent Residents	Permanent Residents Percent
Single Family Residential	Wood	140,994	91.7%	275,057	93.7%	391,097	93.8%
	Manufactured Housing	12,519	8.1%	18,015	6.1%	25,208	6.0%
	Reinforced Masonry	120	0.1%	292	0.1%	318	0.1%
	Unreinforced Masonry	73	0.0%	101	0.0%	152	<1%
Multi-Family Residential	Wood	6,398	98.7%	53,415	95.1%	86,637	95.3%
	Reinforced Masonry	22	0.3%	138	0.2%	207	0.2%
	Unreinforced Masonry	6	0.1%	34	0.1%	63	0.1%
	Other	53	0.8%	2,581	4.6%	3,999	4.4%

Building occupancy within the different building types varies significantly between the daytime and nighttime scenarios (**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 for Clark and Columbia Counties. Building type often assigned from statistical distribution (Section 2.1.4).

Building Type	Number of Buildings	"2 PM" Daytime Occupancy	Daytime Percent	"2 AM" Nighttime Occupancy	Nighttime Percent	Permanent Residents	Permanent Residents Percent
Concrete	1,103	20,574	4%	3,719	1%	3,123	1%
Manufactured Housing	12,732	8,948	2%	25,214	5%	25,214	5%
Precast Concrete	2,097	47,787	10%	660	<1%	16	<1%
Reinforced Masonry	2,840	48,780	10%	1,123	<1%	525	<1%
Steel	3,788	47,949	10%	4,064	1%	857	<1%
Unreinforced Masonry	656	6,095	1%	290	<1%	215	<1%
Wood	156,106	294,839	62%	483,629	93%	477,731	94%
All building types	179,322	474,972		518,699		507,681	

5.2 Building Damage, Casualties, and Displaced Population

We tabulated the impacts to buildings and people at the county and jurisdictional level (Appendix B, **Table 11-8** through **Table 11-11**) 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 "wet" (saturated) soil conditions, in Appendix D, **Plate 13** and Plate 14.

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, potential building damage is generally greater in Columbia County and less in Clark County, due to Columbia County's relative proximity to the CSZ rupture zone (Appendix D, **Plate 7**) and the relatively large percentage of buildings placed on soft, liquefiable soils compared to Clark County (**Table 10-5**, **Table 10-6**). In the Portland Hills fault scenario, damage estimates correspond to proximity to the fault (e.g., the loss ratio of 22% for Scappoose compared to 2% for Clatskanie, **Table 11-10**, with ground motion differences graphically shown in Appendix D, **Plate 4**).

In the Cascadia scenario, loss ratios are significantly less in Clark County (5% in "dry" soil conditions, 10% in "wet" soil conditions) compared to Columbia County (12% in "dry" soil conditions, 18% in "wet" soil conditions; **Table 11-8** and **Table 11-9**). The damage is not equally distributed across all building uses or building types, as seen in **Table 5-3**. The average loss ratio for wood-framed single-family residential buildings ranges from 2% to 7% (for "dry" and "wet" soil conditions, respectively).

Columbia and Clark Counties have differing building code histories (**Table 10-2** and **Table 10-3**), with Clark County having more buildings at a higher seismic design level compared to Columbia County (**Table 10-4**). Combined with the higher percentage of buildings on soft soils in Columbia County (**Table 10-5**) and Columbia County's closer proximity relative to the CSZ rupture zone (Appendix D, **Plate 3** and **Plate 4**), the higher loss ratios observed in **Table 11-8** and **Table 11-9** between the two counties is not surprising.

Within each county, damage and casualty estimates vary widely, primarily due to the variations in local geology. Buildings in the City of St. Helens, for example, are mostly situated on firm basalt rock due to scour from the Missoula Floods (Burns and Coe, 2012), with few buildings exposed to potential liquefaction or landsliding (Appendix D, **Plate 7**). Yet the City of Vernonia has significantly higher building damage, because most of the buildings are sited on soft, potentially liquefiable soils.

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 11-8** through **Table 11-11**). 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 location nearer to significant assets in Clark and Columbia Counties as well as stronger shaking levels would result in much higher damage overall for those areas (Appendix C, **Table 11-10** and **Table 11-11**). Building damage estimates from a Portland Hills fault earthquake for the City of Scappoose, for example, are about double compared to a CSZ earthquake. 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 D, **Plate 3** and **Plate 4**.

Soil moisture conditions significantly influence loss estimates, with overall building loss ratios of 12% versus 18% for the Cascadia earthquake between the "dry" soil conditions and "wet" (saturated) soil conditions in Columbia County, and 5% to 10% in Clark County (Appendix C, **Table 11-8** and **Table 11-9**). As noted, many buildings are placed on soft, liquefiable soils in Columbia County (**Table 10-5** and **Table**

10-6), including high-value industrial buildings in lowlands next to the Columbia River and in the alluvial deposits of the Nehalem and Clatskanie Rivers. In Clark County, high-value commercial and industrial buildings are placed on soft, liquefiable soils in lowlands next to the Columbia River. In addition, significant suburban development in the southwest portion of Clark County is placed on moderate to highly liquefiable soils (loess and Missoula Flood deposits).

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.

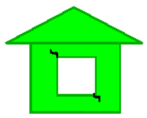
Table 5-3. Damage to buildings in Clark and Columbia Counties by building category and by earthquake scenario.

		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 ($M)**	**Building Repair Cost ($M)**	**Loss Ratio**	**Building Repair Cost ($M)**	**Loss Ratio**	**Building Repair Cost ($M)**	**Loss Ratio**	**Building Repair Cost ($M)**	**Loss Ratio**
Agricultural	2,135	337	16%	477	22%	189	9%	329	15%
Commercial	10,867	1,221	11%	1,893	17%	1,072	10%	1,889	17%
Industrial	1,333	217	16%	326	24%	107	8%	213	16%
Institutional	4,205	439	10%	597	14%	313	7%	528	13%
Multi-family residential	9,090	540	6%	1,064	12%	513	6%	1,242	14%
Single-family residential	31,420	778	2%	2,153	7%	976	3%	2,580	8%
Single-family residential: manufactured housing	757	175	23%	201	27%	88	12%	119	16%
Total	59,806	3,707	6%	6,709	11%	3,260	5%	6,901	12%

$M is millions of dollars. 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 of damages states to a light-frame wood building. We obtained the total number of buildings in a particular damage state by summarizing all buildings’ individual structural probability of damage state values, per the guidance provided by FEMA (2017a). The data in **Table 11-3** (Appendix B) 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.

5.2.1 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 conditions scenario. The Hazus building damage model assumes that 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 10-6**). 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. See Section 6.2 for usage limitations.

	"Dry" Soil Conditions			"Wet" (Saturated) Soil Conditions		
Seismic Design Level Scenario	**Unchanged**	**Moderate**	**High**	**Unchanged**	**Moderate**	**High**
Building Repair Cost ($ million)	3,707	1,559	1,240	6,709	4,827	4,552
Building Loss Ratio	6%	3%	2%	11%	8%	8%
Debris (thousands of tons)	1,639	509	371	2,542	1,545	1,430
Long-Term Displaced Population	6,799	2,727	2,585	30,625	26,972	26,850
Casualties — Daytime Scenario						
Total Casualties	3,290	676	492	5,624	3,365	3,216
Level 1 Casualties	2,422	536	391	4,106	2,475	2,355
Level 2 Casualties	626	107	78	1,113	667	643
Level 3 Casualties	82	11	8	139	77	75
Level 4 Casualties	159	21	16	266	147	142
Casualties — Nighttime Scenario						
Total Casualties	949	418	370	2,894	2,416	2,375
Level 1 Casualties	770	349	311	2,247	1,867	1,833
Level 2 Casualties	150	59	53	538	457	452
Level 3 Casualties	10	3	3	39	33	33
Level 4 Casualties	18	6	3	69	58	57

Loss estimates for unchanged (that is, the actual design level) scenario are taken from **Table 11-8** and **Table 11-9**, and provided for reference. Casualty level definitions are provided in **Table 4-1**. Total building replacement costs used for building loss ratio are taken from **Table 5-3**.

5.3 Electric Power Transmission

A Cascadia magnitude 9 earthquake is expected to have a significant impact to the electric grid in Oregon (OSSPAC, 2013), including the Portland metropolitan region. Of the 5,469 poles and towers in our database, 176 (3%) have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, and 617 (11%) have a 20% to 30% chance of experiencing more than 1 meter of ground deformation during a Cascadia magnitude 9.0 earthquake with "wet" (saturated) soil conditions (Appendix D, **Plate 12**). In the "dry" soil conditions, 18 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.

A Portland Hills fault magnitude 6.8 earthquake scenario will have a significant impact to the electrical grid in the study area. Of the 5,469 poles and towers in our database, 286 (5.2%) have a 20% to 30% chance of experiencing between 1 and 2 meters of ground deformation, and only two have a 20% to 30% chance of experiencing more than 1 meter during "wet" (saturated) soil conditions. In the "dry" soil conditions scenario, only one pole or tower has a 20% to 30% chance of experiencing between 1 or more meters of ground deformation. We note that the damage to the electrical grid from a Portland Hills fault earthquake is much higher in the Phase 1 study area (Bauer and others, 2018), and that a thorough analysis includes evaluating the full network up to the power generation facility.

5.4 Emergency Transportation Routes

In the Cascadia magnitude 9.0 earthquake, "wet" (saturated) scenario, most (34 out of 46, or 65%) route segments will have a 20% to 30% chance of experiencing significant ground deformation along some portion of the segment (Appendix D, **Plate 9**). Although regional post-earthquake road conditions significantly improve under the "dry" soil conditions scenario (Appendix D, **Plate 9**), nearly all the road segments in Columbia County may be impacted (Appendix D, **Plate 10**). 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 probabilities of failure for individual locations, such as is shown in Appendix D, **Plate 11**, 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 Appendix D, **Plate 11**, where designated emergency transportation routes commonly cross alluvial deposits that may fail due to liquefaction (inset map in showing State Route 503 crossing Salmon Creek; Appendix D, **Plate 11**). 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.

For a Portland Hills fault magnitude 6.8 earthquake, 22 out of 46 (48%) segments have a 20% to 30% chance of experiencing significant ground deformation along some portion of the segment, in the "wet" soil conditions scenario.

6.0 DISCUSSION

This study concludes our two-phase earthquake regional impact analysis for the greater Portland area. For all five counties, we have summarized earthquake impact estimates at levels useful for both regional and local planning. We present loss estimates as a range for two building occupancy scenarios and two soil moisture scenarios.

Our results will help planners get a better sense of the range of damages and casualties that may occur due to a major earthquake. This study helps answer questions such as: Which areas might experience more damage following an earthquake, given the potential for liquefaction and local site amplification? Where are people likely to be when the earthquake occurs? How many casualties might that cause?

A magnitude 9.0 Cascadia Subduction Zone earthquake will result in significant damage to buildings, with concomitant casualties, in all five counties. Transportation networks may be severely impaired, compromising emergency response. Millions of tons of debris will need to be removed 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 to the five-county area, 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. However, within Clark and Columbia Counties, the impact of a CSZ compared to a Portland Hills fault earthquake is about the same.

In this report our discussion generally focuses on earthquake impacts to Clark and Columbia Counties. Where needed, we provide a five-county perspective. Many of the observations we made in our Phase 1 report that covered Clackamas, Multnomah, and Washington Counties are applicable to Clark and Columbia Counties.

6.1 Earthquake Impacts

6.1.1 Geology Variations

Impacts within counties vary widely, both at the jurisdictional level (e.g., Appendix B, **Table 11-8**) and at the neighborhood unit level (e.g., Appendix D, **Plate 14**). Such variation should not be interpreted to suggest that some areas within the two counties will be minimally affected by a major earthquake. The City of Battle Ground, for example, has a relatively low building loss ratio, at 3% (Appendix B, **Table 11-8**), yet the Cascadia earthquake is estimated to generate $54 million in damage within the city boundaries. In addition, while damage within an area may be minimal, impacts to the regional infrastructure could be significant, limiting goods and services and employee ability to travel to and from work (e.g., Section **5.4**).

Most to nearly all of the building damage, casualties, and displaced population increases in the "wet" soil scenarios versus the "dry" soil scenarios (e.g., **Table 11-8** and **Table 11-9**) are due to the lateral spreading caused by earthquake-induced liquefaction. Although permanent ground deformation caused by increased probability of landsliding in the saturated soil conditions contributes to overall loss, its effect is relatively minor. This is due to the vast majority of the buildings in the five-county area on sites with low to moderate landslide susceptibility (**Table 10-7**). Overall, only 2% of buildings are on high to very high landslide susceptibility areas. Buildings typically are placed on flat or modestly sloping terrain, and thus have lower susceptibility to earthquake-induced landslides (FEMA, 2011, Table 4.15).

Seligson and others (2017) noted that in the "HayWired" scenario Hazus analysis of the Hayward fault, landslide-related building damage added just 1% to the regional building damage estimates produced by ground shaking. We must emphasize, however, that earthquake-induced landslide impacts to infrastructure can be severe — while the area of a landslide relative to the overall infrastructure element may be small, the entire segment must be intact for its functional operation. We emphasize the point using regional transportation as an example in **Plate 9**.

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 about 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. Some of the older non-wood frame buildings (such as unreinforced masonry; soft-story; non-ductile concrete; tilt-up) may have structural weaknesses that can lead to collapse during earthquakes.

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 present in the study area, but that our daytime casualty estimates are still useful for planning purposes. Post-earthquake emergency operations can be enhanced if personnel have an awareness of the types of population shifts between buildings throughout the day and week, and are aware of the seismic resiliency of those buildings.

6.1.3 Building Damage Inspection and Displaced Population

After a major earthquake, it is estimated that at least 48,000 buildings in Clark County and 18,000 buildings in Columbia County will need timely ATC-20-based safety inspection by qualified personnel (ATC, 1989). Our estimate includes all buildings with slight to complete damage (Appendix B, **Table 11-1**), following the quantification method outlined by EERI (2015), which also assumed a rate of four to five buildings per day per inspector. Assuming a goal of completing the task in 30 days, our Cascadia Subduction Zone magnitude 9.0 earthquake results identify a need for 320 and 120 certified inspectors ready to mobilize in Clark and Columbia Counties, respectively. 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. Though we can only speculate on such dynamics, we do provide permanent resident occupancy counts per building damage state (Appendix B, **Table 11-4** through **Table 11-7**).

6.1.4 Debris

Natural disasters are capable of generating large volumes of debris in very short time periods, often equivalent to 5 to 15 times a region's normal annual waste stream (Brown and others, 2011). Without proper planning, emergency response and recovery can be severely impacted. Our building construction debris estimates of 14 to 19 million tons for a Cascadia Subduction Zone earthquake (Appendix C, **Table 11-8** and **Table 11-9**) for all five counties may appear daunting. Assuming 25 tons per truckload, 72,000 and 29,000 truckloads of building construction debris would be generated by a Cascadia Subduction Zone earthquake ("wet" [saturated] soil scenario) in Clark and Columbia Counties, respectively. Metro's annual waste stream tonnage that incurs fees is estimated at about 1.5 million tons (Metro, 2018). This estimate is limited to the Metro service area, and is helpful as a checkpoint for our debris estimates. In the three-county area serviced by Metro, the estimate of about 13 to 17 million tons is within the aforementioned 5 to 15 times multiplier.

Debris removal will require local staging areas for storing, sorting, and eventual transfer to a permanent disposal location. 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, fuel for emergency operations, and local staging areas for light and heavy equipment that may be needed to clear roads and debris.

Of all the five counties in our combined study area, the emergency transportation routes in Columbia County are especially impacted, primarily because of the dissected terrain that is prone to landsliding (e.g., State Highway 47 between Mist and Clatskanie) and the placement of roads on riverine deposits that are prone to liquefaction (e.g., State Highway 47 north of Vernonia). While the impact to Clark County is much less in comparison to Columbia County, and segment closure in Clark County can often be accommodated by rerouting, given the gridded transportation network in much of the county, some localities such as Yacolt and Amboy that have a limited number of routes may be isolated for longer periods.

Portions of the electric distribution network may be significantly impacted due to ground failure compromising the integrity of transmission structures. For example, electrical service to the Mist-Birkenfeld and Vernonia substations may be impacted by earthquake-induced landslides and liquefaction along the transmission corridors, which for Vernonia is primarily on the Timber Road corridor (Appendix D, **Plate 12**). 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 transmission capacity or redundancy is warranted.

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 known crustal faults exist in Clark and Columbia Counties. Our intent with modeling a Portland Hills fault earthquake is to demonstrate the potential impacts of an earthquake from a crustal fault and is not intended to detract attention from other potential earthquake sources. The Portland Hills fault is on the southwestern edge of the Portland basin, a structural basin made by faulting that includes northwest trending faults on both the southwestern and the northeastern sides. The northeastern side consists of faulting near Camas and Amboy, known as the Frontal fault zone (Yelin and Patton, 1991). The 1962 Portland earthquake was centered between the Portland Hills fault and the Frontal fault zone near Vancouver. For example, the northwest-striking Lacamas Lake fault forms part of the northeastern margin of the Portland basin and spans from Clark County, east of Vancouver, Washington into Oregon. According to the USGS Quaternary Fault and Fold Database (Personius and others, 2003), the trace of the Lacamas Lake fault is marked by the very linear lower reach of Lacamas Creek. No fault scarps on Quaternary surficial deposits have been described, but the Columbia River jogs northwestward and parallels the strike of the fault, suggesting that the river may have been influenced by the fault. The Lacamas Lake fault may offset 0.6 Ma rocks of the Boring Lava, but seismic reflection studies suggest that the most recent event predates the latest Pleistocene age of Missoula flood deposits in the area (Personius and others, 2003).

Earthquakes have occurred on faults that geologists had not yet mapped at the time of the earthquake event, such as the devastating February 22, 2011, magnitude 6.3 earthquake on the Port Hills fault southeast of Christchurch, New Zealand (Campbell and others, 2012). For planning purposes at the governmental, institutional, neighborhood, and household level, the entire five-county study region should be considered earthquake-prone.

6.2 Seismic Design Level Improvements

Our seismic design level improvement modeling exercise (Section **5.2.1**) 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 damage; 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 numerous individual characteristics of the structure. We used generic building type models in our Hazus AEBM (Section **2.1.4**), which for an individual building, 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 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, including Columbia County, and reported losses by individual county. Liquefaction and landslide information were not regionally available, nor was it possible to incorporate such information into the Hazus model at that time.

More recently, Tetra Tech (2017) updated General Building Stock (GBS) inventory data for Clark County using county assessor data, and aggregated detailed building-level data to the census tract level for use in Hazus. Tetra Tech used ShakeMap ground motion data from the USGS for a CSZ magnitude 9.0 and a Portland Hills fault magnitude 6.5 earthquake. Liquefaction susceptibility and soils data were obtained from previously published, publicly available Washington Department of Natural Resources datasets. The report listed a damage potential of $2.5 billion, or 2.2% of the total replacement value, for a CSZ earthquake, and $1.4 billion, or 1.3% of total replacement value for a Portland Hills fault earthquake.

Our building loss ratio estimates for Clark County of 5% to 10% for a CSZ magnitude 9.0 earthquake, and 5% to 11% for a Portland Hills fault magnitude 6.8 earthquake are higher than the loss ratios in the Tetra Tech (2017) report. We account for this increase due to several factors. Our Hazus AEBM model used "default betas" (Kircher and others, 2006; Kircher and others, 1997; Kircher, 2002) for estimating building damage from ground shaking. The default betas, also referred to as *relaxed betas*, are used in the fragility curve analysis of the Hazus earthquake model. They were crafted by the Hazus earthquake model developers to account for the greater uncertainties in the ground motion for an earthquake scenario compared to an instrumented earthquake event. When a user supplies their own ground motion data, such what was done in the Tetra Tech study, the Hazus General Building Stock model uses fragility curves with the smaller beta values. (The Hazus general building stock earthquake model currently uses the tighter [smaller] betas; users cannot specify that it use the relaxed betas.) While fragility curves have their subtleties due to the asymmetric nature of the cumulative lognormal distribution, in general, estimated losses for a building will be larger when using a larger beta value. Thus, all other model inputs being equivalent, the use of the relaxed betas in the Hazus AEBM model will produce larger loss estimates compared to the Hazus GBS model that uses the tighter (smaller) beta values.

Other contributors to the difference are as follows. In our AEBM building database, our seismic design levels (Section **2.1.6**) were more conservative than the seismic design level distributions embedded within the GBS database, sometimes referred to as the default Hazus mapping scheme. 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 and Washington building codes (Olson, 2003; Judson, 2012; Ash and others, 2017; 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 Tetra Tech GBS-based study. A higher level of seismic design assignment to building inventory will result in reduced loss estimates (**Table 5-4**).

Another well-known problem is that for GBS analysis, the Hazus earthquake model makes a single sample of the liquefaction rating and applies that value for the entire census tract. Commonly, considerable geologic heterogeneity occurs over a census tract (Price and others, 2010), so a single rating can lead to an under-or overestimate of the liquefaction potential, especially in the industrial corridors.

A significant contributor to the major differences in the "wet" soil condition scenarios is the method by which the two Hazus tools (General Building Stock [GBS] and Advanced Engineering Building Module [AEBM]) factor in the probability of ground failure from liquefaction or from earthquake-induced landslide. 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 Hazus v4.0 AEBM model, the Hazus tool assigns the ground failure probability in its entirety to the complete damage state (discussed in Section **4.1.1**). The effect is that AEBM-derived building loss, casualty, and debris estimates from Hazus v4.0 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. The difference was addressed in Hazus v4.2 SP1 (FEMA, 2018b), but for reasons of consistency, we chose to use Hazus 4.0, as discussed in Section **4.1.1**.

Lastly, another contribution to the higher loss ratio in Clark County seen in this study is our usage of updated liquefaction susceptibility mapping data (Section **3.3**). Within large portions of the developed areas in Clark County, the updated liquefaction susceptibility mapping levels are in general higher than the levels in the older 1:100,000-scale liquefaction susceptibility maps that were used in the Tetra Tech (2017) 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 CSZ scenario modeled in our study. 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.

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 795,174 buildings in our combined 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) and the Resilient Washington State report (Washington State Emergency Management Council Seismic Safety Committee [WSEMC-SSC], 2012). 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 level of harm caused to the people who occupy them, and to two key infrastructure sectors. Our recommendations below are directly supported by the findings in this study.

Our recommendations build on the efforts made 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 2009, has funded upgrades to more than 100 schools and emergency service buildings (http://www.orinfrastructure.org/Infrastructure-Programs/Seismic-Rehab/). In Washington State, the School Seismic Safety Program is a 2017–2019 Capital Budget-funded project led by the Washington Geological Survey in cooperation with the Office of Superintendent of Public Instruction (OSPI) (https:// www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/earthquakes-and-faults/school-seismic-safety) which assesses the seismic safety of more than a hundred schools in Washington. 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 and Washington statewide building codes have, through time, increased the seismic resiliency of newer construction (Judson, 2012; Ash and others, 2017). The Great Oregon Shakeout program, managed by Oregon Office of Emergency Management, has more than 420,000 participants in Clackamas, Columbia, Multnomah, and Washington Counties (https://www.shakeout.org/oregon/). The Great Washington Shakeout program has 68,000 participants in Clark County (https://www.shakeout.org/washington/). The Shakeout program elevates public awareness of the earthquake hazard by providing actions individuals can take to minimize casualties and preparation for post-earthquake disruption of services.

Planning

We encourage regional and local planners to explore the accompanying GIS data to address their specific questions and needs. Static maps, such as in Appendix D, **Plate 13** and **Plate 14**, provide 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 compared to 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

Thousands of buildings in the study area will need safety inspections after a major earthquake. Both states can sponsor annual Applied Technology Council (ATC)-20 training to registered engineers, architects, and building inspectors, 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 states, counties, and cities 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 or change in use.

Resiliency: Infrastructure Improvements

Electric utilities can use this study's updated ground motion and ground failure data 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 transmission capacity or redundancy is needed.

Resiliency: Essential and Critical Facilities

Our project did not explicitly identify or evaluate essential facilities in the study area, such as fire stations. 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 should 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 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 Lacamas Lake fault, 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 estimate of the situation.

Database Improvements

County and city databases could be improved by recording information on seismic retrofits and upgrades to individual buildings. Currently, such information is not readily available for analysis such as was done in this report, or to potential buyers of a property. Seismic evaluations of buildings during real estate transactions can help increase awareness of seismic vulnerabilities among property owners (WSEMC-SSC, 2012, Recommendation 3b).

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 directly addressed Recommendation 3a in the Resilient Washington State report (WSEMC-SSC, 2012), by providing a compilation of detailed building inventory of actual building stock. We recommend this analytic approach be taken in other Oregon counties.

The DOGAMI enhanced earthquake impact study focused primarily on direct physical impacts from a major earthquake, including building repair and replacement costs. It did not, however, consider the broader economic consequences from the event such as business disruption and lost earnings. An ongoing project funded by the Regional Disaster Preparedness Organization (RDPO) is building upon the DOGAMI analysis by layering economic data about businesses onto estimates of infrastructure damage from an earthquake. "Using the economic analysis performed by ECONorthwest (www.econw.com) the region will have a better understanding of how businesses are likely to be affected by disruptions to the labor force, supply chain, and infrastructure that support their operations. By measuring the impact to business operations, we will gain a better understanding of how the regional economy will be impacted, both through broader measures of economic health (e.g. labor compensation and employment) and the distributive effects of an earthquake to vulnerable populations. The analysis includes testing a variety of policy levers to explore how investments in resilient infrastructure or utility services may help the economy to rebound more quickly after a major earthquake" (Laura Hanson, RDPO, written communication, January 10, 2020).

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, 2014). Schmidtlein and others (2011) compared census tract Hazus-based earthquake loss estimates with their social vulnerability indices. A similar type of analysis could be conducted in our study area at the census block group level.

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.

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10.0 APPENDIX A: BUILDING DATABASE DEVELOPMENT

For a more complete perspective of the five-county area, we typically include results for the three counties (Clackamas, Multnomah, and Washington Counties, Oregon) covered in the Phase 1 report (Bauer and others, 2018) as well as the two counties that are the focus of this report (Columbia County, Oregon and Clark County, Washington).

10.1 Building Database Data Sources

Table 10.1 lists data sources used to construct the building asset database. The table is organized as follows: the most general data source for a particular attribute is listed first, followed by the source of more specific and accurate data, where available. 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, we updated the attribute with that information. More detailed datasets are typically restricted to a small subset of the buildings.

The *Year Built* field is not directly consumed by Hazus AEBM but 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
Columbia County Assessor, St. Helens, Oregon	Columbia County Tax lots and associated tabular data	May 2018	✓	✓	✓	✓	(RES2)*		Spatial association of building footprint with assessor tabular information . The structural building type is manufactured housing, or “RES2” in the FEMA Hazus software.
Columbia County Assessor, St. Helens, Oregon	Columbia County building footprints, 2009	May 2018	✓		✓	✓			Assigned occupancy class during heads-up digitization with NAIP and oblique imagery. Limited to building footprint digitized for this project.
Columbia County Assessor, St. Helens, Oregon	Locations of manufactured home parks and special facilities: schools, government buildings, churches, parks, medical facilities	May 2018	✓				(RES2)*		Refinement of Occupancy Class. The structural building type is manufactured housing, or “RES2” in the FEMA Hazus software.
Tetra Tech, Portland, Oregon	Clark County Mitigation Project (Tetra Tech, 2017)	2015	✓	✓	✓	✓	✓		Initial UDF database for Clark County
Oregon Employment Department (OED, 2018)	North American Industry Classification System (NAICS)	September 2018	✓						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. Limited to Columbia County.
Oregon Dept. of Geology and Mineral Industries	Oregon Statewide Seismic Needs Assessment (Lewis, 2007)	2007	✓	✓	✓	✓	✓		Most detailed information; limited to 51 public schools and government agency buildings in Columbia County.
Oregon Dept. of Geology and Mineral Industries	Unified Lidar Topography Map for Columbia County	2018			✓	✓			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/. Lidar years of acquisition: 2005, 2007, 2009, 2010, 2013, 2014, 2015
Washington Dept. of Natural Resources - Washington Geological Survey	Unified Lidar Topography Map for Clark County	2018			✓	✓			Lidar data acquired in different years were mosaicked and elevation discrepancies were corrected relative to highly reliable recent Lidar coverage. Lidar years of acquisition: 2002, 2010, 2013, 2017
Oregon Dept. of Transportation	Oregon city limits	October 2018						✓	Building spatial associations with particular jurisdictions and counties, including county unincorporated areas.
Washington Dept. of Transportation	Washington city and town limits	May 2019						✓	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 design.

10.2 Seismic Design Level Assignments

We assigned a Hazus seismic design level to each building based on its construction year and usage type. Seismic design codes have evolved over time, with more stringent requirements developing as the natural hazard threat is better understood. For Columbia County we used the Oregon seismic design level benchmark years used in Phase 1 of this RDPO study (Bauer and others, 2018, Table 10.2; repeated below in **Table 10-2**). For Clark County we used the benchmark years established by Ash and others (2017). From further communication with C. Ash (written and oral communication, 2019) we used coastal zone code classification for Clark County (**Table 10-3**), using a more conservative setting where a range of seismic design levels were given. For example, a building constructed in 1993 in the Oregon Structural Specialty Code "coastal zone" is assigned "Low to Moderate Code" by Ash and others (2017); for Hazus modeling purposes we assigned such buildings a "Low Code".

Table 10-2. Oregon Hazus seismic design level assignments based on building year of construction.

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

Table 10-3. Washington Hazus seismic design level assignments based on building year of construction. Clark County is in the Coastal Zone; final Hazus assignment in the *Clark County (this study)* column. WA is Washington. UBC is Uniform Building Code.

Year Built			Seismic Zone Area					
Start Year	End Year	UBC Zone	Coastal	Puget Sound	Extended Puget Sound	Eastern	Clark County (this study)	Notes
(1850)	1975	N/A	Pre Code (where applicable, engineering override)				Pre Code	1949: WA designated Zone 2, but no state building code 1952-1958: WA designated Zone 3, but no state building code 1955: WA designated seismic requirements for newly constructed No state building code before 1975
1976	1977	2/3	Pre-Low	Low-Moderate	Pre-Low	Pre-Low	Pre Code	1973 UBC Puget sound region designated Zone 3 out of 3 1973 UBC coastal and eastern WA designated Zone 2 out of 3
1978	1984	2/3	Low	Moderate	Low	Low	Low Code	1976 UBC Puget sound region designated Zone 3 out of 4 1976 UBC coastal and eastern WA designated Zone 2 out of 4
1985	1986	2/3	Low	Moderate	Low	Low	Low Code	1982 UBC Puget sound region designated Zone 3 out of 4 1982 UBC coastal and eastern WA designated Zone 2 out of 4
1987	1989	2/3	Low	Moderate	Low	Low	Low Code	1985 UBC Puget sound region designated Zone 3 out of 4 1985 UBC coastal and eastern WA designated Zone 2 out of 4
1990	1992	2B/3	Low-Moderate	Moderate-High	Moderate-High	Low-Moderate	Low Code	1988 UBC Puget sound region gets larger from 1985 designated Zone 3 1988 UBC Eastern and Coastal regions designated Zone 2B out of 4
1993	1995	2B/3	Low-Moderate	Moderate-High	Moderate-High	Low-Moderate	Low Code	1991 UBC Puget sound region designated Zone 3 out of 4 1991 UBC Eastern and Coastal regions designated Zone 2B out of 4
1996	1998	2B/3	Moderate-High	Moderate-High	Moderate-High	Low-Moderate	Moderate Code	1994 UBC Puget sound (including extended Puget sound) region and 1994 UBC Eastern WA designated Zone 2B out of 4
1999	2004	2B/3	High	High	High	Moderate	High Code	1997 UBC requires additional detailing requirements
2005	Present	N/A	High	High	High	Low-Moderate	High Code	2002 WA State adopted the IBC. Eastern WA seismicity decreases from UBC

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 10-4**). 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 10-4. Building statistics by Hazus 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
Clark	Pre Code	47,715	33%	99,477	24%	12,457	24%
	Low Code	41,986	29%	118,874	29%	14,913	29%
	Moderate Code	12,008	8%	36,360	9%	4,675	9%
	High Code	44,751	31%	152,558	37%	19,687	38%
Columbia	Pre Code	15,414	47%	29,875	42%	3,164	39%
	Low Code	5,898	18%	12,977	18%	1,556	19%
	Moderate Code	5,968	18%	13,907	20%	1,665	21%
	High Code	5,582	17%	13,707	19%	1,690	21%
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	393,286	49%	966,767	41%	127,381	40%
	Low Code	166,250	21%	605,438	25%	83,004	26%
	Moderate Code	130,089	16%	387,528	16%	50,865	16%
	High Code	105,549	13%	417,185	18%	57,723	18%

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 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. Summary statistics in **Table 10-5** 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. The effect is also seen but to a lesser extent in Clark County, where high-value commercial and industrial parks are sited on soft, liquefiable soils adjacent to the Columbia River in the cities of Vancouver, Camas, and Washougal.

Table 10-5. Building statistics by NEHRP site classification, per county (from the results of Appleby and others, 2019).

County	NEHRP Site Classification	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clark	B	7,142	5%	17,710	4%	2,045	4%
	C	2,140	1%	4,491	1%	504	1%
	D	133,805	91%	362,972	89%	46,341	90%
	E, F	3,373	2%	22,097	5%	2,841	5%
Columbia	B	4,292	16%	10,089	14%	1,290	16%
	C	10,894	40%	21,689	31%	2,366	29%
	D	8,960	33%	18,664	26%	2,156	27%
	E, F	8,716	32%	20,025	28%	2,262	28%
Clackamas	B	367	<1%	746	<1%	84	<1%
	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	<1%	63	<1%	8	<1%
	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	11,833	1%	28,607	1%	3,428	1%
	C	262,257	33%	619,698	26%	79,355	25%
	D	481,769	61%	1,489,286	63%	202,781	64%
	E, F	39,315	5%	239,325	10%	33,412	10%

Site classifications from Buildings Seismic Safety Council (1997), as modified by FEMA.

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 (2019), with the groupings listed at the bottom of each table (**Table 10-6** and **Table 10-7**). In all five counties, relatively few buildings are in high landslide susceptibility areas. In Clark County, 78% of the building value is on soils rated with moderate or higher liquefaction susceptibility.

Table 10-6. Building statistics by Hazus-based liquefaction susceptibility rating, per county (from the results of Appleby and others, 2019).

County	Liquefaction Susceptibility	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clark	None to Low	31,472	21%	77,043	19%	8,930	17%
	Moderate	95,359	65%	264,293	65%	34,291	66%
	High	18,278	12%	61,128	15%	7,943	15%
	Very High	1,351	1%	4,805	1%	567	1%
Columbia	None to Low	15,829	48%	32,616	46%	3,717	46%
	Moderate	10,620	32%	22,378	32%	2,586	32%
	High	59	<1%	163	<1%	19	<1%
	Very High	6,354	19%	15,309	22%	1,753	22%
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	<1%	2,279	<1%	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	302,905	38%	718,569	30%	90,993	29%
	Moderate	429,137	54%	1,354,450	57%	186,230	58%
	High	38,801	5%	114,997	5%	14,772	5%
	Very High	24,331	3%	188,901	8%	26,980	8%

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

Table 10-7. Building statistics by Hazus-based earthquake-induced landslide susceptibility rating, per county (from the results of Appleby and others, 2019).

County	Landslide Susceptibility, "Wet" (Saturated soil) condition	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clark	Low	131,032	89%	358,468	88%	45,790	89%
	Moderate	11,816	8%	40,305	10%	4,989	10%
	High to Very High	3,612	2%	8,497	2%	953	2%
Columbia	Low	28,185	86%	60,141	85%	6,892	85%
	Moderate	4,051	12%	9,097	13%	1,040	13%
	High to Very High	626	2%	1,228	2%	142	2%
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	710,271	89%	2,023,092	85%	268,885	84%
	Moderate	67,451	8%	299,033	13%	42,380	13%
	High to Very High	17,452	2%	54,789	2%	7,711	2%

FEMA 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 (FEMA, 2011, Table 3-2), which is a classification of a building's dominant use (**Table 10-8**). 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 10-8. Buildings statistics by primary usage, per county. See Section 2.1.2 regarding number of buildings quantification for Clark County.

County	Building Use	Number of Buildings	Building Percent	Square Footage (Thousand)	Square Footage Percent	Building Value ($ Million)	Building Value Percent
Clark	Agricultural	715	<1%	2,901	1%	309	1%
	Commercial	3,953	3%	70,886	17%	10,297	20%
	Industrial	90	<1%	5,377	1%	830	2%
	Institutional	643	<1%	21,400	5%	3,714	7%
	Multi-family Residential	5,754	4%	53,656	13%	8,739	17%
	Single-family Residential	135,305	92%	253,050	62%	27,844	54%
Columbia	Agricultural	12,241	37%	17,160	24%	1,826	23%
	Commercial	837	3%	3,886	6%	570	7%
	Industrial	357	1%	3,659	5%	504	6%
	Institutional	301	1%	2,833	4%	491	6%
	Multi-family Residential	725	2%	2,513	4%	351	4%
	Single-family Residential	18,401	56%	40,415	57%	4,334	54%
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.

11.0 APPENDIX B: BUILDING DAMAGE ASSESSMENT AND IMPACTS TO OCCUPANTS

For a more complete perspective of the five-county area, we typically include results for the three counties (Clackamas, Multnomah, and Washington Counties, Oregon) covered in the Phase 1 report (Bauer and others, 2018).

11.1 Number of Buildings by Damage State

We summarized the number of buildings in each damage state, by county (**Table 11-1**), 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 11-1. 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 9.0 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
Clark (146,460)	Slight	32,186	22%	30,711	21%	37,132	25%	34,838	24%
	Moderate	11,883	8%	11,322	8%	15,187	10%	14,202	10%
	Extensive	3,185	2%	3,074	2%	3,114	2%	3,117	2%
	Complete	1,349	1%	7,691	5%	928	1%	8,732	6%
Columbia (32,862)	Slight	7,119	22%	6,540	20%	6,971	21%	6,352	19%
	Moderate	4,976	15%	4,534	14%	4,728	14%	4,230	13%
	Extensive	2,957	9%	2,688	8%	1,978	6%	1,767	5%
	Complete	3,126	10%	5,169	16%	1,548	5%	3,729	11%
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 (795,174)	Slight	172,783	22%	164,553	21%	219,911	28%	198,552	25%
	Moderate	78,370	10%	74,200	9%	181,679	23%	162,212	20%
	Extensive	25,313	3%	23,899	3%	71,848	9%	65,754	8%
	Complete	13,059	2%	46,192	6%	36,709	5%	104,633	13%
Total number of damaged buildings		289,525	36%	308,844	39%	510,147	64%	531,152	67%

11.2 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 11-2**). 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 11-2. Collapsed buildings by county and by earthquake and soil moisture conditions.

County	Total Number of Buildings	Cascadia Subduction Zone Magnitude 9.0 Earthquake		Portland Hills Fault Magnitude 6.8 Earthquake	
		"Dry" Soils	"Wet" (Saturated) Soils	"Dry" Soils	"Wet" (Saturated) Soils
Clark	146,460	60	262	43	292
Columbia	32,862	193	291	87	194
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	795,174	923	2,162	2,184	4,583

11.3 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 11-3**. Note the figures in the "Complete" state are the same as the long-term displaced population figures in **Table 11-4** through **Table 11-7**. 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 11-3. 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. See FEMA (2011, Section 5.3) for building damage state descriptions.

		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
Clark	Slight	103,520	98,435	119,504	111,536
	Moderate	43,073	40,760	50,321	46,685
	Extensive	9,511	9,223	8,694	8,798
	Complete	3,801	24,695	2,819	28,986
Columbia	Slight	11,724	10,842	11,706	10,650
	Moderate	6,698	6,124	6,746	6,000
	Extensive	3,083	2,812	2,181	1,957
	Complete	2,998	5,930	1,738	4,979
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	482,996	459,853	604,852	544,819
	Moderate	232,280	219,356	490,363	435,549
	Extensive	59,551	56,423	188,271	171,081
	Complete	23,651	115,836	100,133	290,901

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 11-4** through **Table 11-7** quantify the number of buildings and permanent residents by generalized occupancy, per county and per building damage state, for the four earthquake scenarios.

Table 11-4. 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: Slight Damage		Moderate Damage		Extensive Damage		Complete Damage		Number of Permanent Residents: Total	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
Clark County																							
Agricultural	715	2,901	309	25	8%	0	153	21%	68	9%	13	2%	6	1%	—	—	—	—	—	—	—	—	—
Commercial	3,953	70,886	10,297	1,108	11%	21	825	21%	721	18%	364	9%	174	4%	—	—	—	—	—	—	—	—	—
Industrial	90	5,377	830	142	17%	1	13	15%	20	22%	17	19%	11	13%	—	—	—	—	—	—	—	—	—
Institutional	643	21,400	3,714	356	10%	4	119	19%	131	20%	91	14%	33	5%	—	—	—	—	—	—	—	—	—
Multi-family residential	5,754	53,656	8,739	517	6%	1	1,416	25%	693	12%	115	2%	41	1%	87,123	22,827	26%	17,277	20%	3,771	4%	1,428	2%
Single-family residential	126,216	240,536	27,318	547	2%	10	27,786	22%	7,560	6%	787	1%	342	<1%	351,091	76,605	22%	20,040	6%	2,089	1%	973	0%
Manufactured housing	9,089	12,514	525	75	14%	22	1,873	21%	2,690	30%	1,797	20%	741	8%	19,260	4,087	21%	5,756	30%	3,651	19%	1,399	7%
Columbia County																							
Agricultural	12,241	17,160	1,826	312	17%	117	2,551	21%	2,089	17%	1,293	11%	1,354	11%	—	—	—	—	—	—	—	—	—
Commercial	837	3,886	570	113	20%	17	129	15%	132	16%	102	12%	148	18%	—	—	—	—	—	—	—	—	—
Industrial	357	3,659	504	75	15%	7	57	16%	64	18%	53	15%	74	21%	—	—	—	—	—	—	—	—	—
Institutional	301	2,833	491	83	17%	5	50	17%	64	21%	47	16%	43	14%	—	—	—	—	—	—	—	—	—
Multi-family residential	725	2,513	351	23	7%	1	160	22%	75	10%	22	3%	18	2%	3,783	799	21%	428	11%	146	4%	103	3%
Single-family residential	14,971	34,914	4,102	231	6%	9	3,930	26%	1,844	12%	385	3%	223	1%	40,476	10,487	26%	5,022	12%	1,138	3%	724	2%
Manufactured housing	3,430	5,501	231	100	43%	38	242	7%	709	21%	1,056	31%	1,265	37%	5,947	437	7%	1,247	21%	1,799	30%	2,170	36%
Study Area (All Five Counties)																							
Agricultural	49,017	107,094	11,398	1,284	11%	287	9,346	19%	7,643	16%	4,497	9%	3,423	7%	—	—	—	—	—	—	—	—	—
Commercial	26,790	443,996	68,001	11,602	17%	267	4,737	18%	5,456	20%	3,873	14%	2,464	9%	—	—	—	—	—	—	—	—	—
Industrial	5,104	125,516	19,818	3,868	20%	71	753	15%	1,138	22%	998	20%	770	15%	—	—	—	—	—	—	—	—	—
Institutional	8,527	125,740	21,814	2,877	13%	71	1,505	18%	1,827	21%	1,250	15%	656	8%	—	—	—	—	—	—	—	—	—
Multi-family residential	58,110	336,018	53,481	3,828	7%	47	13,207	23%	7,035	12%	1,793	3%	663	1%	503,025	118,889	24%	95,351	19%	30,072	6%	12,592	3%
Single-family residential	618,267	1,199,597	142,828	3,473	2%	69	138,248	22%	46,609	8%	6,015	1%	1,413	<1%	1,587,656	353,938	22%	119,645	8%	16,268	1%	4,372	0%
Manufactured housing	29,359	38,955	1,636	333	20%	110	4,987	17%	8,662	30%	6,889	23%	3,670	13%	58,037	10,169	18%	17,284	30%	13,212	23%	6,689	12%
Total	795,174	2,376,916	318,975	27,265	9%	923	172,783	22%	78,370	10%	25,314	3%	13,059	2%	2,148,717	482,996	22%	232,280	11%	59,552	3%	23,652	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 11-5. 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
Clark County																							
Agricultural	715	2,901	309	40	13%	1	146	20%	64	9%	13	2%	33	5%	—	—	—	—	—	—	—	—	—
Commercial	3,953	70,886	10,297	1,739	17%	37	778	20%	676	17%	338	9%	385	10%	—	—	—	—	—	—	—	—	—
Industrial	90	5,377	830	196	24%	2	12	13%	18	20%	16	18%	18	20%	—	—	—	—	—	—	—	—	—
Institutional	643	21,400	3,714	495	13%	6	114	18%	125	20%	87	14%	56	9%	—	—	—	—	—	—	—	—	—
Multi-family residential	5,754	53,656	8,739	1,020	12%	10	1,340	23%	659	11%	116	2%	330	6%	87,123	21,391	25%	16,137	19%	3,602	4%	6,481	7%
Single-family residential	126,216	240,536	27,318	1,662	6%	173	26,524	21%	7,230	6%	821	1%	5,748	5%	351,091	73,133	21%	19,176	5%	2,197	1%	15,974	5%
Manufactured housing	9,089	12,514	525	95	18%	34	1,796	20%	2,549	28%	1,683	19%	1,122	12%	19,260	3,911	20%	5,447	28%	3,424	18%	2,240	12%
Columbia County																							
Agricultural	12,241	17,160	1,826	437	24%	170	2,328	19%	1,894	15%	1,164	10%	2,179	18%	—	—	—	—	—	—	—	—	—
Commercial	837	3,886	570	153	27%	23	115	14%	116	14%	87	10%	208	25%	—	—	—	—	—	—	—	—	—
Industrial	357	3,659	504	129	26%	10	48	14%	55	15%	46	13%	108	30%	—	—	—	—	—	—	—	—	—
Institutional	301	2,833	491	101	21%	6	46	15%	60	20%	43	14%	60	20%	—	—	—	—	—	—	—	—	—
Multi-family residential	725	2,513	351	43	12%	3	146	20%	67	9%	19	3%	61	8%	3,783	735	19%	382	10%	126	3%	311	8%
Single-family residential	14,971	34,914	4,102	491	12%	38	3,618	24%	1,653	11%	342	2%	1,193	8%	40,476	9,677	24%	4,529	11%	1,004	2%	3,288	8%
Manufactured housing	3,430	5,501	231	106	46%	41	238	7%	689	20%	988	29%	1,360	40%	5,947	429	7%	1,213	20%	1,682	28%	2,331	39%
Study Area (All Five Counties)																							
Agricultural	49,017	107,094	11,398	1,424	12%	341	9,117	19%	7,446	15%	4,367	9%	4,275	9%	—	—	—	—	—	—	—	—	—
Commercial	26,790	443,996	68,001	12,274	18%	289	4,676	17%	5,396	20%	3,833	14%	2,734	10%	—	—	—	—	—	—	—	—	—
Industrial	5,104	125,516	19,818	3,977	20%	74	743	15%	1,127	22%	990	19%	811	16%	—	—	—	—	—	—	—	—	—
Institutional	8,527	125,740	21,814	3,035	14%	74	1,497	18%	1,817	21%	1,242	15%	696	8%	—	—	—	—	—	—	—	—	—
Multi-family residential	58,110	336,018	53,481	4,352	8%	58	13,116	23%	6,993	12%	1,791	3%	994	2%	503,025	117,388	23%	94,165	19%	29,884	6%	17,852	4%
Single-family residential	618,267	1,199,597	142,828	4,848	3%	261	136,674	22%	46,088	7%	6,006	1%	7,789	1%	1,587,656	349,656	22%	118,288	7%	16,241	1%	21,936	1%
Manufactured housing	29,359	38,955	1,636	359	22%	124	4,905	17%	8,501	29%	6,706	23%	4,146	14%	58,037	9,986	17%	16,940	29%	12,868	22%	7,690	13%
Total	795,174	2,376,916	318,975	30,267	9%	1,222	170,729	21%	77,367	10%	24,934	3%	21,445	3%	2,148,717	477,030	22%	229,393	11%	58,993	3%	47,478	2%

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 11-6. 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
Clark County																							
Agricultural	715	2,901	309	17	5%	0	148	21%	59	8%	9	1%	3	<1%	—	—	—	—	—	—	—	—	—
Commercial	3,953	70,886	10,297	1,000	10%	17	937	24%	741	19%	324	8%	140	4%	—	—	—	—	—	—	—	—	—
Industrial	90	5,377	830	75	9%	1	16	18%	21	24%	11	13%	6	6%	—	—	—	—	—	—	—	—	—
Institutional	643	21,400	3,714	254	7%	2	136	21%	115	18%	58	9%	15	2%	—	—	—	—	—	—	—	—	—
Multi-family residential	5,754	53,656	8,739	487	6%	1	1,708	30%	889	15%	146	3%	47	1%	87,123	26,742	31%	16,718	19%	2,765	3%	1,088	1%
Single-family residential	126,216	240,536	27,318	740	3%	15	32,224	26%	10,971	9%	1,505	1%	489	<1%	351,091	88,577	25%	28,629	8%	3,796	1%	1,298	0%
Manufactured housing	9,089	12,514	525	37	7%	7	1,964	22%	2,390	26%	1,059	12%	228	3%	19,260	4,184	22%	4,974	26%	2,133	11%	432	2%
Columbia County																							
Agricultural	12,241	17,160	1,826	172	9%	47	2,306	19%	1,754	14%	837	7%	570	5%	—	—	—	—	—	—	—	—	—
Commercial	837	3,886	570	73	13%	8	139	17%	129	15%	76	9%	69	8%	—	—	—	—	—	—	—	—	—
Industrial	357	3,659	504	32	6%	3	53	15%	49	14%	32	9%	32	9%	—	—	—	—	—	—	—	—	—
Institutional	301	2,833	491	60	12%	2	49	16%	47	16%	27	9%	17	6%	—	—	—	—	—	—	—	—	—
Multi-family residential	725	2,513	351	27	8%	1	155	21%	76	11%	24	3%	20	3%	3,783	741	20%	393	10%	158	4%	141	4%
Single-family residential	14,971	34,914	4,102	237	6%	8	3,756	25%	1,903	13%	412	3%	213	1%	40,476	10,042	25%	5,007	12%	1,084	3%	598	1%
Manufactured housing	3,430	5,501	231	51	22%	19	513	15%	769	22%	571	17%	627	18%	5,947	923	16%	1,346	23%	938	16%	998	17%
Study Area (All Five Counties)																							
Agricultural	49,017	107,094	11,398	1,136	10%	217	9,096	19%	7,299	15%	4,036	8%	2,636	5%	—	—	—	—	—	—	—	—	—
Commercial	26,790	443,996	68,001	11,453	17%	253	4,859	18%	5,474	20%	3,807	14%	2,350	9%	—	—	—	—	—	—	—	—	—
Industrial	5,104	125,516	19,818	3,758	19%	66	753	15%	1,125	22%	971	19%	723	14%	—	—	—	—	—	—	—	—	—
Institutional	8,527	125,740	21,814	2,751	13%	66	1,520	18%	1,794	21%	1,197	14%	612	7%	—	—	—	—	—	—	—	—	—
Multi-family residential	58,110	336,018	53,481	3,801	7%	48	13,493	23%	7,233	12%	1,826	3%	671	1%	503,025	122,745	24%	94,757	19%	29,078	6%	12,289	2%
Single-family residential	618,267	1,199,597	142,828	3,671	3%	73	142,512	23%	50,079	8%	6,760	1%	1,550	<1%	1,587,656	365,465	23%	128,219	8%	17,922	1%	4,571	0%
Manufactured housing	29,359	38,955	1,636	246	15%	76	5,349	18%	8,423	29%	5,666	19%	2,519	9%	58,037	10,752	19%	16,600	29%	10,833	19%	4,550	8%
Total	795,174	2,376,916	318,975	26,818	8%	799	177,582	22%	81,426	10%	24,264	3%	11,061	1%	2,148,717	498,962	23%	239,576	11%	57,833	3%	21,410	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 11-7. Buildings and permanent residents per building damage state for Portland Hills fault magnitude 6.8 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
Clark County																							
Agricultural	715	2,901	309	30	10%	1	141	20%	56	8%	9	1%	28	4%	—	—	—	—	—	—	—	—	—
Commercial	3,953	70,886	10,297	1,769	17%	38	865	22%	676	17%	293	7%	417	11%	—	—	—	—	—	—	—	—	—
Industrial	90	5,377	830	144	17%	1	15	17%	19	21%	10	11%	13	15%	—	—	—	—	—	—	—	—	—
Institutional	643	21,400	3,714	448	12%	5	128	20%	108	17%	55	9%	46	7%	—	—	—	—	—	—	—	—	—
Multi-family residential	5,754	53,656	8,739	1,194	14%	14	1,571	27%	817	14%	144	3%	471	8%	87,123	24,322	28%	15,139	17%	2,659	3%	8,322	10%
Single-family residential	126,216	240,536	27,318	2,060	8%	214	30,255	24%	10,283	8%	1,605	1%	7,116	6%	351,091	83,249	24%	26,881	8%	4,118	1%	19,355	6%
Manufactured housing	9,089	12,514	525	59	11%	19	1,863	20%	2,244	25%	1,000	11%	641	7%	19,260	3,965	21%	4,665	24%	2,020	10%	1,308	7%
Columbia County																							
Agricultural	12,241	17,160	1,826	300	16%	103	2,105	17%	1,576	13%	753	6%	1,391	11%	—	—	—	—	—	—	—	—	—
Commercial	837	3,886	570	120	21%	15	123	15%	110	13%	63	8%	142	17%	—	—	—	—	—	—	—	—	—
Industrial	357	3,659	504	69	14%	5	47	13%	42	12%	26	7%	63	18%	—	—	—	—	—	—	—	—	—
Institutional	301	2,833	491	80	16%	4	44	15%	42	14%	23	8%	36	12%	—	—	—	—	—	—	—	—	—
Multi-family residential	725	2,513	351	48	14%	3	140	19%	66	9%	20	3%	65	9%	3,783	675	18%	332	9%	128	3%	367	10%
Single-family residential	14,971	34,914	4,102	520	13%	40	3,396	23%	1,672	11%	379	3%	1,257	8%	40,476	9,083	22%	4,402	11%	1,001	2%	3,369	8%
Manufactured housing	3,430	5,501	231	60	26%	23	496	14%	721	21%	502	15%	774	23%	5,947	892	15%	1,265	21%	827	14%	1,243	21%
Study Area (All Five Counties)																							
Agricultural	49,017	107,094	11,398	1,276	11%	274	8,888	18%	7,119	15%	3,952	8%	3,482	7%	—	—	—	—	—	—	—	—	—
Commercial	26,790	443,996	68,001	12,270	18%	282	4,771	18%	5,390	20%	3,763	14%	2,700	10%	—	—	—	—	—	—	—	—	—
Industrial	5,104	125,516	19,818	3,864	19%	70	745	15%	1,115	22%	964	19%	761	15%	—	—	—	—	—	—	—	—	—
Institutional	8,527	125,740	21,814	2,966	14%	70	1,509	18%	1,782	21%	1,190	14%	662	8%	—	—	—	—	—	—	—	—	—
Multi-family residential	58,110	336,018	53,481	4,530	8%	62	13,342	23%	7,150	12%	1,820	3%	1,140	2%	503,025	120,259	24%	93,117	19%	28,943	6%	19,749	4%
Single-family residential	618,267	1,199,597	142,828	5,275	4%	305	140,183	23%	49,160	8%	6,827	1%	9,221	1%	1,587,656	359,177	23%	125,867	8%	18,160	1%	25,398	2%
Manufactured housing	29,359	38,955	1,636	277	17%	92	5,230	18%	8,228	28%	5,539	19%	3,079	10%	58,037	10,502	18%	16,210	28%	10,609	18%	5,671	10%
Total	795,174	2,376,916	318,975	30,459	10%	1,155	174,668	22%	79,943	10%	24,056	3%	21,046	3%	2,148,717	489,938	23%	235,194	11%	57,712	3%	50,818	2%

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.

11.4 Loss Estimates by Jurisdiction

Table 11-8 through **Table 11-11** provide county-level and jurisdictional-level building inventory and building loss estimates, along with casualty estimates 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 2013–2017 U.S. Census American Community Survey estimates and Hazus population distribution models across building occupancy types (Section **2.1.7**). The estimates for jurisdictions include all buildings within their jurisdictional boundaries, as defined by Oregon Department of Transportation for Columbia County and by Washington Department of Transportation for Clark County (**Table 10-1**).

Table 11-8. Loss estimates by jurisdiction, Cascadia Subduction Zone magnitude 9.0 earthquake, "dry" soil conditions.

									Casualties: Daytime Scenario					Casualties: Nighttime Scenario				
	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	Total	Level 1	Level 2	Level 3	Level 4	Total	Level 1	Level 2	Level 3	Level 4
Study area total	474,714	179,322	477,736	59,806	3,707	6%	1,639	6,798	3,289	2,422	626	82	159	949	770	150	10	18
							Clark County											
Clark County total	425,363	146,460	407,270	51,732	2,770	5%	1,101	3,801	2,616	1,950	487	61	118	626	517	91	6	11
Battle Ground	17,571	6,044	14,576	1,822	54	3%	20	72	48	37	8	1	2	13	11	2	0	0
Camas	19,355	7,992	24,451	3,045	148	5%	69	34	261	182	53	9	17	18	14	3	0	1
La Center	2,800	1,136	2,642	313	14	5%	8	8	24	17	5	1	2	2	2	0	0	0
Ridgefield	4,763	2,844	9,176	1,122	41	4%	14	27	36	27	6	1	2	5	4	1	0	0
Vancouver	161,791	49,419	166,250	22,790	1,623	7%	667	1,829	1,641	1,225	306	38	73	309	254	46	3	6
Washougal	14,095	5,573	13,664	1,637	121	7%	53	140	143	111	26	2	4	20	17	3	0	0
Yacolt	1,566	533	943	113	6	6%	5	7	14	10	3	0	1	1	1	0	0	0
Clark County Jurisdictions total	221,941	73,541	231,702	30,842	2,008	7%	836	2,117	2,168	1,609	408	51	99	369	303	55	4	7
Clark County Unincorporated total	203,422	72,919	175,568	20,890	762	4%	265	1,685	448	341	78	10	19	257	215	37	2	3
							Columbia County											
Columbia County total	49,351	32,862	70,466	8,075	937	12%	538	2,996	673	472	139	21	41	323	253	58	4	8
Clatskanie	1,737	885	2,060	261	63	24%	36	183	98	67	21	3	7	21	16	4	0	1
Columbia City	1,946	950	2,183	264	9	3%	3	19	3	2	0	0	0	3	2	0	0	0
Prescott*	55	53	87	9	1	6%	< 1	—	—	—	—	—	—	—	—	—	—	—
Rainier	1,895	1,006	2,997	363	46	13%	23	39	54	37	11	2	3	8	6	1	0	0
Scappoose	6,592	3,131	8,011	961	108	11%	57	414	174	118	37	6	13	48	36	9	1	2
St. Helens	12,883	5,349	12,610	1,590	56	4%	28	32	74	52	15	2	5	8	7	1	0	0
Vernonia	2,151	1,277	2,153	249	47	19%	25	174	43	30	9	1	3	20	16	4	0	0
Columbia County Jurisdictions total	27,259	12,651	30,102	3,696	329	9%	173	861	445	307	94	15	30	107	83	19	2	3
Columbia County Unincorporated total	22,092	20,211	40,364	4,379	608	14%	366	2,135	228	166	45	6	11	216	170	39	3	5
Clackamas County	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
Multnomah County	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
Washington County	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
Five County Total	2,115,750	795,174	2,376,915	318,974	27,265	9%	14,433	23,650	21,575	15,764	4,145	565	1,101	5,282	4,109	889	97	187

Casualty level definitions are provided in Table 4-1.

*The total number of buildings in the City of Prescott is below minimum sample size for summarizing impact estimates. The impact estimates for Prescott are included in the overall county estimates.

Table 11-9. 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	474,714	179,322	477,736	59,806	6,709	11%	2,542	30,620	5,623	4,106	1,113	139	266	2,893	2,247	538	39	69
							Clark County											
Clark County total	425,363	146,460	407,270	51,732	5,248	10%	1,827	24,695	4,676	3,442	915	110	210	2,332	1,814	432	31	55
Battle Ground	17,571	6,044	14,576	1,822	110	6%	36	655	103	77	19	2	4	60	47	11	1	1
Camas	19,355	7,992	24,451	3,045	202	7%	84	357	316	220	65	10	20	46	36	9	1	1
La Center	2,800	1,136	2,642	313	22	7%	10	63	33	23	7	1	2	6	5	1	0	0
Ridgefield	4,763	2,844	9,176	1,122	83	7%	26	279	70	52	13	2	3	25	20	5	0	1
Vancouver	161,791	49,419	166,250	22,790	2,823	12%	1,018	9,931	2,829	2,077	555	67	130	996	772	183	15	27
Washougal	14,095	5,573	13,664	1,637	192	12%	76	756	213	163	41	3	6	71	55	13	1	2
Yacolt	1,566	533	943	113	6	6%	5	7	14	10	3	0	1	1	1	0	0	0
Clark County Jurisdictions total	221,941	73,541	231,702	30,842	3,438	11%	1,256	12,048	3,577	2,621	703	86	166	1,207	936	222	18	31
Clark County Unincorporated total	203,422	72,919	175,568	20,890	1,810	9%	571	12,647	1,099	821	212	23	44	1,125	878	210	14	23
							Columbia County											
Columbia County total	49,351	32,862	70,466	8,075	1,461	18%	715	5,924	947	664	198	29	57	561	433	106	8	14
Clatskanie	1,737	885	2,060	261	80	31%	41	268	115	79	24	4	8	30	23	6	1	1
Columbia City	1,946	950	2,183	264	23	9%	7	132	8	6	1	0	0	12	9	2	0	0
Prescott*	55	53	87	9	1	10%	< 1	—	—	—	—	—	—	—	—	—	—	—
Rainier	1,895	1,006	2,997	363	80	22%	36	107	76	53	16	2	5	14	11	3	0	0
Scappoose	6,592	3,131	8,011	961	209	22%	89	1,276	251	171	54	9	17	118	89	23	2	3
St. Helens	12,883	5,349	12,610	1,590	76	5%	35	208	88	62	18	3	5	22	18	4	0	0
Vernonia	2,151	1,277	2,153	249	74	30%	34	343	65	45	14	2	4	34	26	7	0	1
Columbia County Jurisdictions total	27,259	12,651	30,102	3,696	544	15%	243	2,333	603	416	128	20	39	230	176	44	4	6
Columbia County Unincorporated total	22,092	20,211	40,364	4,379	917	21%	472	3,591	344	247	70	9	18	331	257	62	4	8
Clackamas County	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
Multnomah County	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
Washington County	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
Five County Total	2,115,750	795,174	2,376,915	318,974	43,419	14%	19,834	115,831	32,798	23,595	6,567	897	1,739	13,293	10,085	2,517	243	448

Casualty level definitions are provided in Table 4-1.

*The total number of buildings in the City of Prescott is below minimum sample size for summarizing impact estimates. The impact estimates for Prescott are included in the overall county estimates.

Table 11-10. Loss estimates by jurisdiction, Portland Hills fault magnitude 6.8 earthquake, “dry” (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	474,714	179,322	477,736	59,806	3,260	5%	1,201	4,557	2,345	1,761	428	53	102	763	631	111	7	13
Clark County																		
Clark County total	425,363	146,460	407,270	51,732	2,609	5%	891	2,819	1,905	1,454	337	39	74	557	469	75	4	8
Battle Ground	17,571	6,044	14,576	1822	24	1%	6	7	12	10	2	0	0	5	4	0	0	0
Camas	19,355	7,992	24,451	3045	83	3%	30	22	77	58	14	2	4	11	9	1	0	0
La Center	2,800	1,136	2,642	313	6	2%	3	2	4	3	0	0	0	1	1	0	0	0
Ridgefield	4,763	2,844	9,176	1,122	33	3%	9	19	17	14	3	0	1	4	4	1	0	0
Vancouver	161,791	49,419	166,250	22,790	1,732	8%	644	1,706	1,507	1,137	275	32	62	328	273	47	3	6
Washougal	14,095	5,573	13,664	1,637	54	3%	22	42	44	36	7	0	1	9	8	1	0	0
Yacolt	1,566	533	943	113	1	1%	0	0	0	0	0	0	0	0	0	0	0	0
Clark County Jurisdictions total	221,941	73,541	231,702	30,842	1,932	6%	715	1,799	1,662	1,259	301	35	68	359	300	50	3	6
Clark County Unincorporated total	203,422	72,919	175,568	20,890	677	3%	176	1,020	243	196	37	4	7	197	169	25	1	2
Columbia County																		
Columbia County total	49,351	32,862	70,466	8,075	650	8%	310	1,738	441	307	91	14	28	206	162	36	3	5
Clatskanie	1,737	885	2,060	261	4	2%	3	6	3	3	1	0	0	1	1	0	0	0
Columbia City	1,946	950	2,183	264	6	2%	1	6	1	1	0	0	0	1	1	0	0	0
Prescott*	55	53	87	9	0	2%	< 1	—	—	—	—	—	—	—	—	—	—	—
Rainier	1,895	1,006	2,997	363	6	2%	3	2	4	3	1	0	0	1	1	0	0	0
Scappoose	6,592	3,131	8,011	961	207	22%	87	729	276	186	60	10	20	84	64	16	1	3
St. Helens	12,883	5,349	12,610	1,590	46	3%	19	23	41	30	8	1	2	7	6	1	0	0
Vernonia	2,151	1,277	2,153	249	16	6%	8	38	10	7	2	0	0	6	4	1	0	0
Columbia County Jurisdictions total	27,259	12,651	30,102	3,696	286	8%	121	805	335	229	71	12	23	101	78	18	2	3
Columbia County Unincorporated total	22,092	20,211	40,364	4,379	365	8%	189	933	106	78	20	3	5	105	84	18	1	2
Clackamas County	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
Multnomah County	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
Washington County	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	2501	547	56	106
Five County Total	2,115,750	795,174	2,376,915	318,974	63,829	20%	27,801	100,133	50,197	35,535	10,248	1,495	2,919	16,565	12,588	2,998	336	642

Casualty level definitions are provided in Table 4-1.

*The total number of buildings in the City of Prescott is below minimum sample size for summarizing impact estimates. The impact estimates for Prescott are included in the overall county estimates.

Table 11-11. 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	474,714	179,322	477,736	59,806	6,901	12%	2,300	33,961	5,262	3,858	1,039	125	240	3,171	2,458	592	44	77
Clark County																		
Clark County total	425,363	146,460	407,270	51,732	5,704	11%	1,795	28,986	4,524	3,343	883	102	195	2,703	2,097	503	37	65
Battle Ground	17,571	6,044	14,576	1,822	36	2%	9	104	22	18	4	0	1	13	11	2	0	0
Camas	19,355	7,992	24,451	3,045	147	5%	52	329	159	114	31	5	9	40	31	7	1	1
La Center	2,800	1,136	2,642	313	10	3%	4	25	8	6	1	0	0	3	2	0	0	0
Ridgefield	4,763	2,844	9,176	1,122	73	7%	21	272	48	37	9	1	2	25	20	5	0	0
Vancouver	161,791	49,419	166,250	22,790	3,445	15%	1,142	14,330	3,180	2,333	627	75	144	1,390	1,074	259	21	37
Washougal	14,095	5,573	13,664	1,637	120	7%	44	515	115	89	21	2	3	50	39	9	1	1
Yacolt	1,566	533	943	113	1	1%	0	0	0	0	0	0	0	0	0	0	0	0
Clark County Jurisdictions total	221,941	73,541	231,702	30,842	3,831	12%	1,273	15,576	3,533	2,597	693	83	159	1,521	1,177	282	22	40
Clark County Unincorporated total	203,422	72,919	175,568	20,890	1,873	9%	522	13,410	991	746	190	19	36	1,181	920	221	15	25
Columbia County																		
Columbia County total	49,351	32,862	70,466	8,075	1,197	15%	504	4,975	738	515	156	23	45	469	361	89	7	12
Clatskanie	1,737	885	2,060	261	15	6%	7	32	20	14	4	1	1	5	4	1	0	0
Columbia City	1,946	950	2,183	264	16	6%	4	81	5	4	1	0	0	7	6	1	0	0
Prescott*	55	53	87	9	1	6%	< 1	—	—	—	—	—	—	—	—	—	—	—
Rainier	1,895	1,006	2,997	363	29	8%	12	37	24	17	5	1	1	4	3	1	0	0
Scappoose	6,592	3,131	8,011	961	358	37%	136	2,086	379	259	82	13	25	193	147	38	3	5
St. Helens	12,883	5,349	12,610	1,590	71	4%	27	227	63	45	13	2	4	24	19	4	0	0
Vernonia	2,151	1,277	2,153	249	43	17%	18	195	31	22	6	1	2	19	15	4	0	0
Columbia County Jurisdictions total	27,259	12,651	30,102	3,696	534	14%	204	2,658	522	359	112	17	34	253	194	49	4	7
Columbia County Unincorporated total	22,092	20,211	40,364	4,379	662	15%	300	2,317	216	156	44	6	11	216	167	40	3	5
Clackamas County	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
Multnomah County	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
Washington County	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
Five County Total	2,115,750	795,174	2,376,915	318,974	90,312	28%	36,205	290,897	68,239	48,149	14,152	2,015	2,823	32,208	24,288	6,190	607	1,123

Casualty level definitions are provided in Table 4-1.

*The total number of buildings in the City of Prescott is below minimum sample size for summarizing impact estimates. The impact estimates for Prescott are included in the overall county estimates.

12.0 APPENDIX C: GEOGRAPHIC INFORMATION SYSTEM (GIS) DATABASE

The GIS data included with this publication are partitioned into three ArcGIS version 10.1 file geodatabases. Earthquake loss estimates and impact assessment data are contained in RDPO_Earthquake_Impact_Analysis_Phase2.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_ClarkCo.gdb and RDPO_GroundMotion_GroundFailure_ColumbiaCo.gdb. The feature class, table, and raster names and the schema are identical to the geodata distributed with the Phase 1 report of Bauer and others (2018) and can be merged to create a five-county database.

RDPO_Earthquake_Impact_Analysis_Phase2.gdb:

Feature Dataset Phase2:

Building_Footprints	Outlines of buildings and nonbuilding structures in Columbia County, Oregon
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 designated 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 (273 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** *field*

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** *field*

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_ClarkCo.gdb and **RDPO_GroundMotion_GroundFailure_ColumbiaCo.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

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

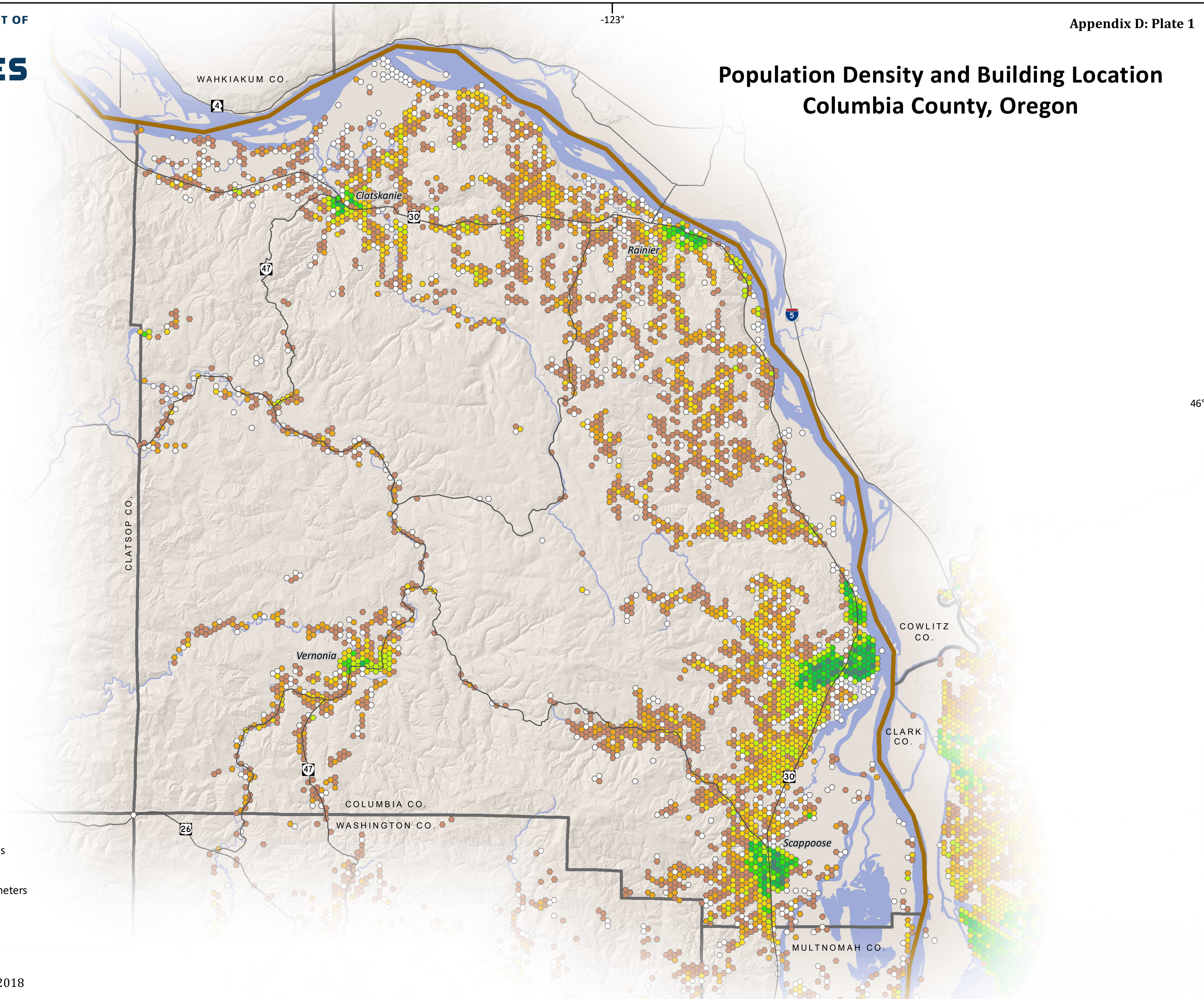
PHF_M6p8_PGD_landslide_dry	Permanent ground deformation due to earthquake-induced landslide under “wet” (or saturated) soil conditions, in centimeters.
PHF_M6p8_Prob_landslide_dry	Probability of earthquake-induced landslide under “wet” (or saturated) soil conditions. In percent.
PHF_M6p8_PGD_landslide_wet	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.

13.0 APPENDIX D: MAP PLATES

WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY

Appendix D: Plate 1

Population Density and Building Location
Columbia 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

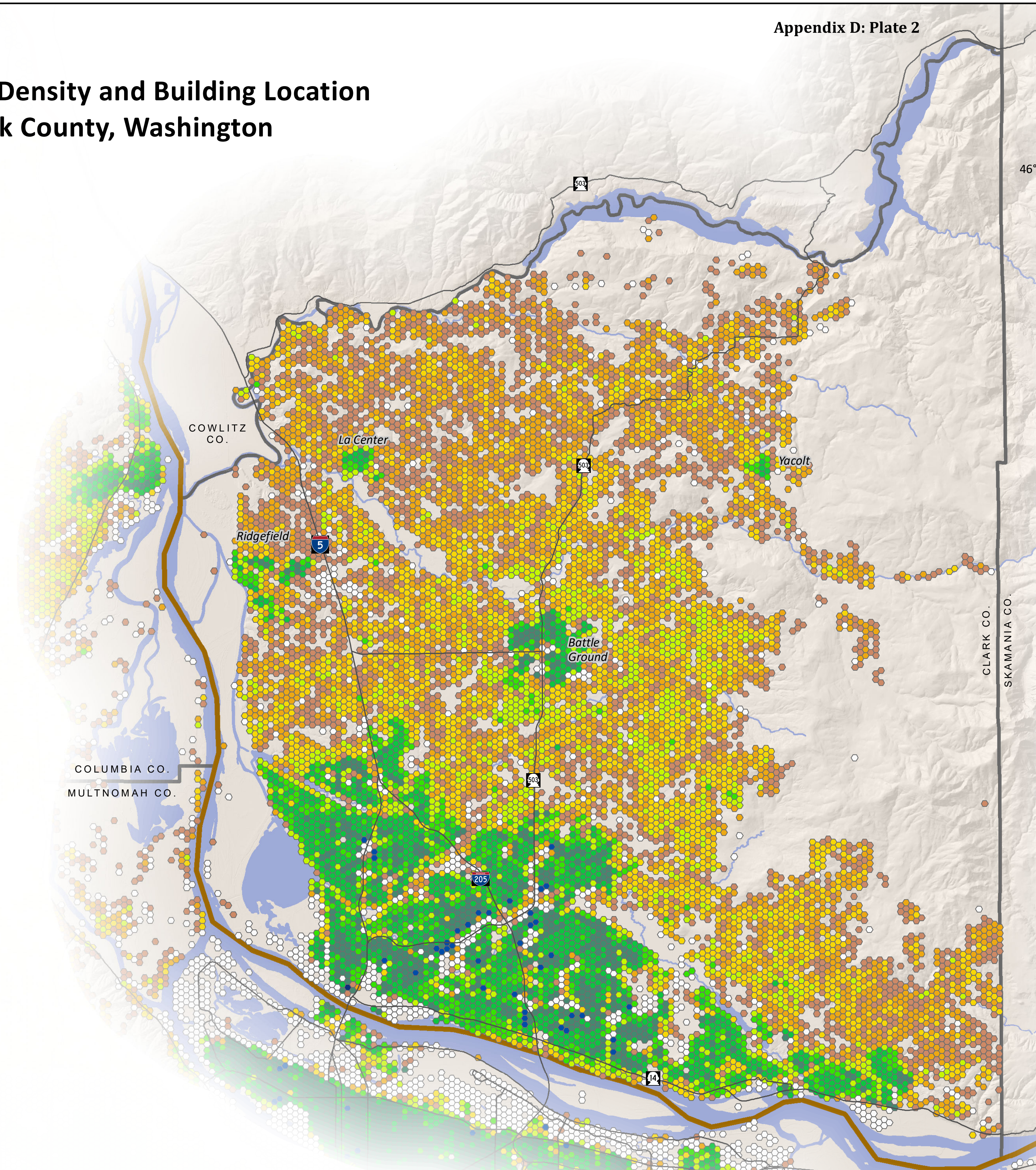
0 2.5 5 10 Miles
0 4 8 16 Kilometers

Source Data:
Hydrography: National Hydrography Dataset, 2018
Arterial network: Washington Dept. of Transportation, 2019;
Oregon Dept. of Transportation, 2018
Washington, Multnomah County population density: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY

Appendix D: Plate 2

Population Density and Building Location
Clark County, Washington



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

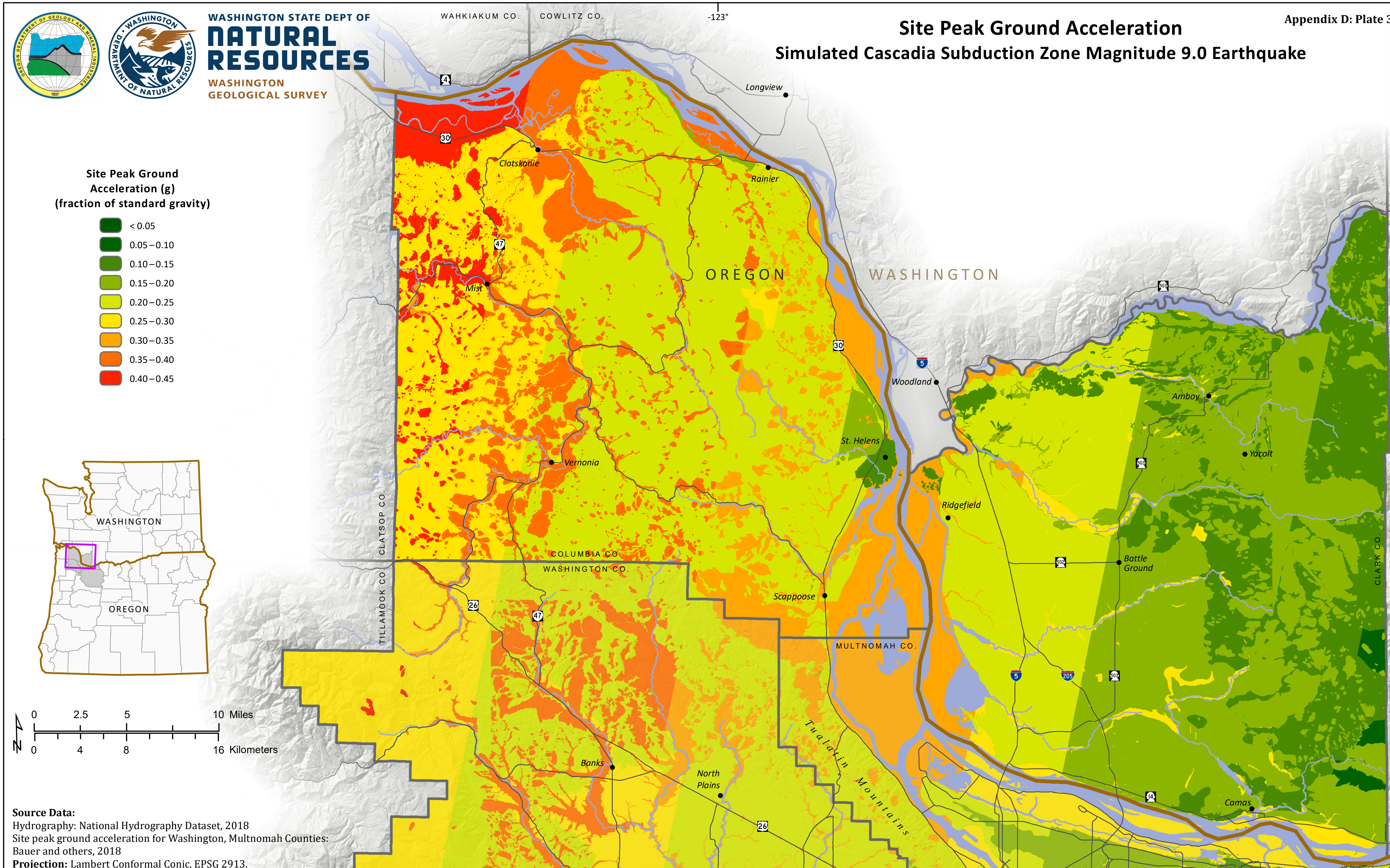
Floating structures and buildings less than 400 square feet not included in building count

0 2.5 5 10 Miles
0 4 8 16 Kilometers
N

Source Data:
Hydrography: National Hydrography Dataset, 2018
Arterial network: Washington Dept. of Transportation, 2019; Oregon Dept. of Transportation, 2018
Multnomah County population density: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

Appendix D: Plate 3

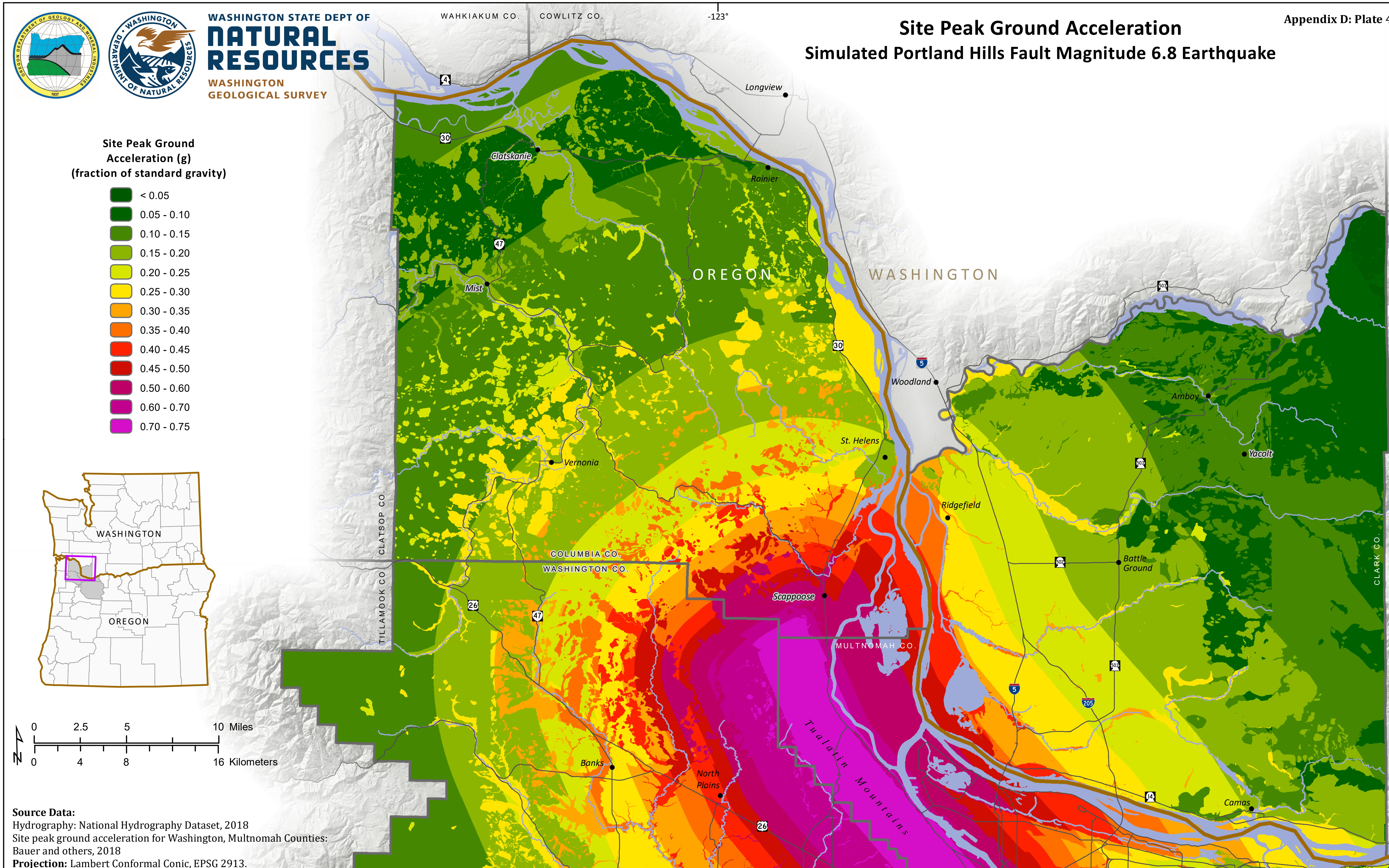
Site Peak Ground Acceleration
Simulated Cascadia Subduction Zone Magnitude 9.0 Earthquake



Source Data:
Hydrography: National Hydrography Dataset, 2018
Site peak ground acceleration for Washington, Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

Appendix D: Plate 4

Site Peak Ground Acceleration
Simulated Portland Hills Fault Magnitude 6.8 Earthquake



Source Data:
Hydrography: National Hydrography Dataset, 2018
Site peak ground acceleration for Washington, Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

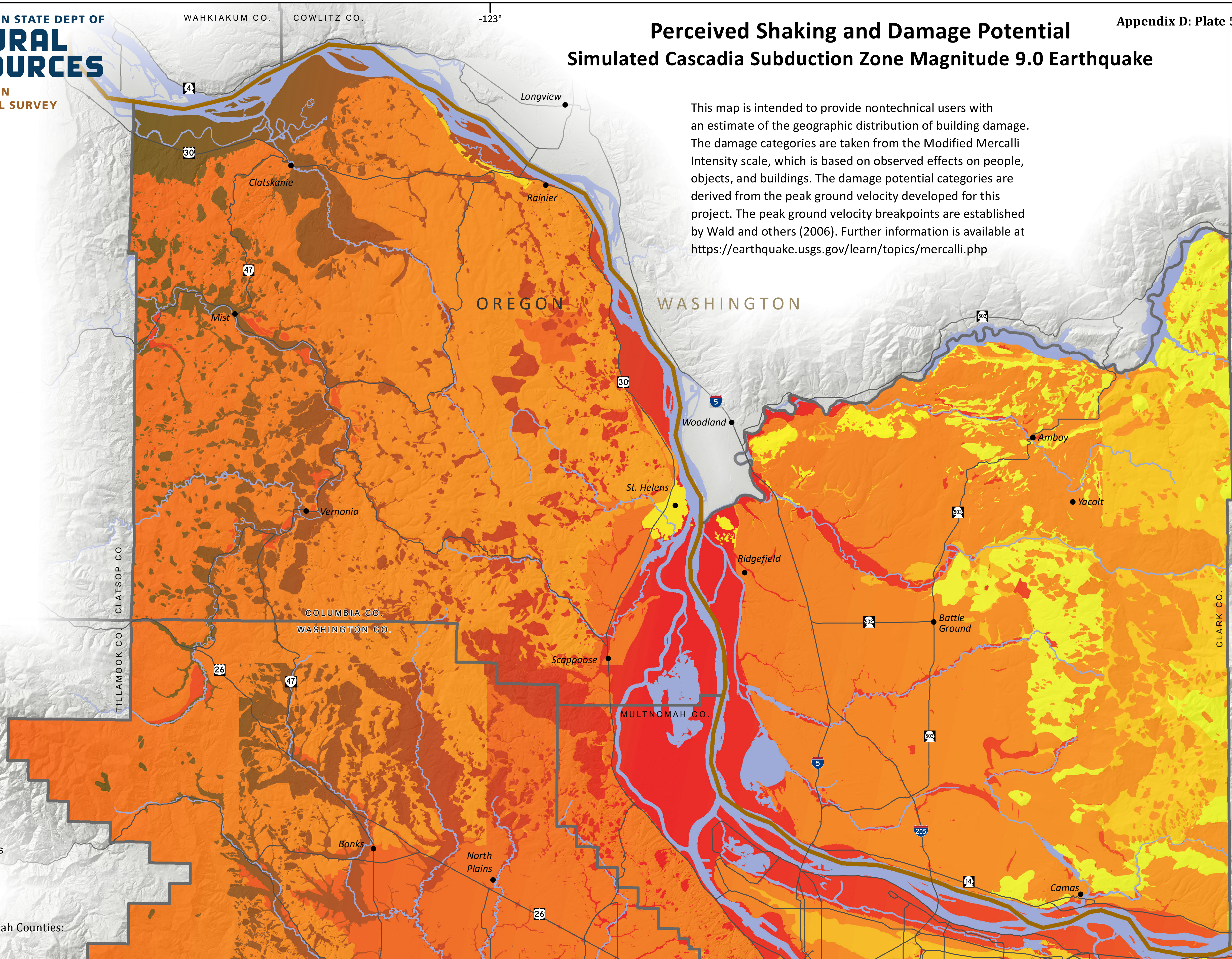
WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY

Appendix D: Plate 5

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

Modified Mercalli Intensity Scale	Perceived Shaking	Damage Potential
IV	Light	None
V	Moderate	Very light
VI	Strong	Light
VII	Very Strong	Moderate
VIII	Severe	Moderate/ Heavy
IX	Violent	Heavy



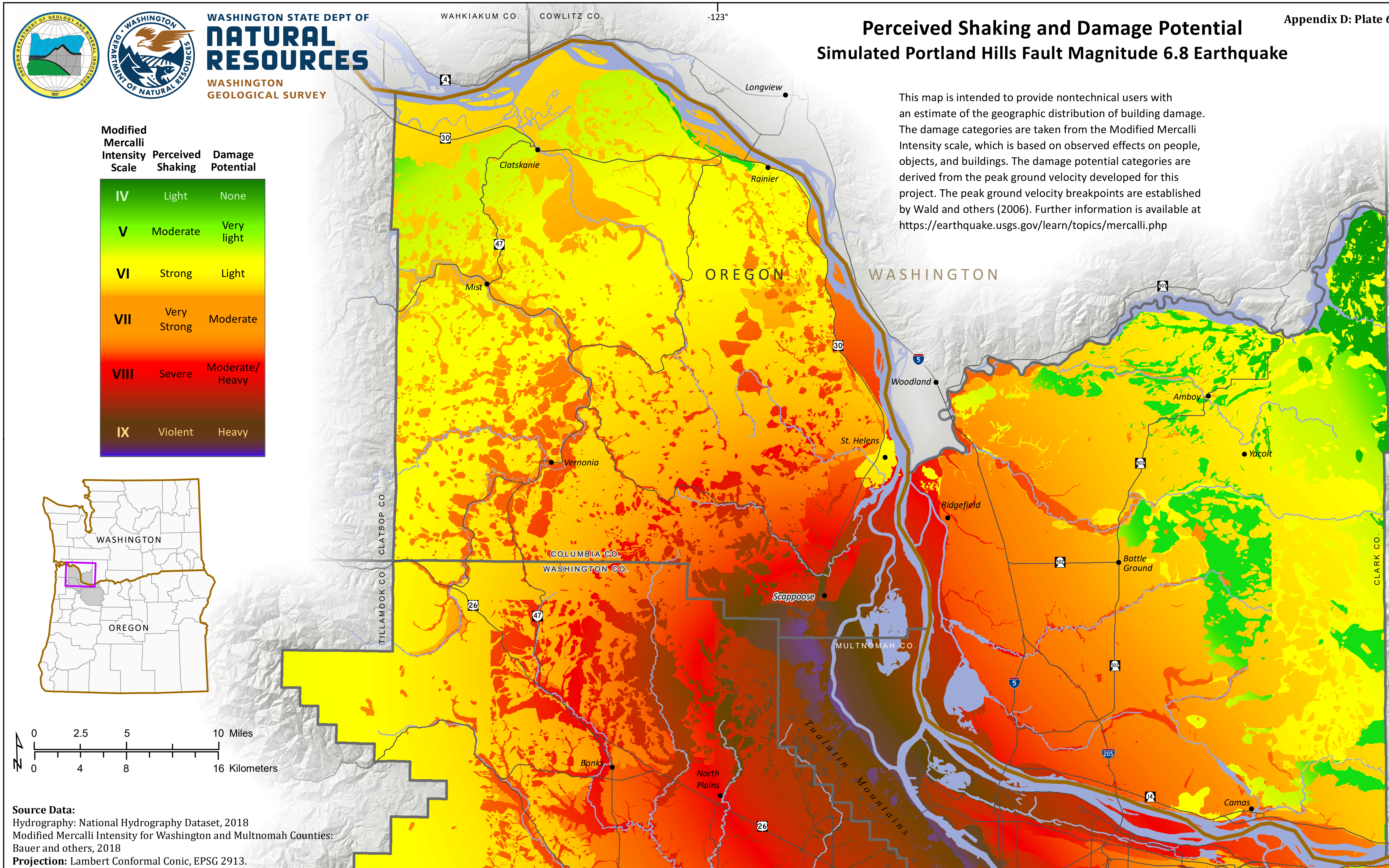
0 2.5 5 10 Miles
0 4 8 16 Kilometers

Source Data:
Hydrography: National Hydrography Dataset, 2018
Modified Mercalli Intensity for Washington and Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

Appendix D: Plate 6

Perceived Shaking and Damage Potential
Simulated Portland Hills Fault Magnitude 6.8 Earthquake

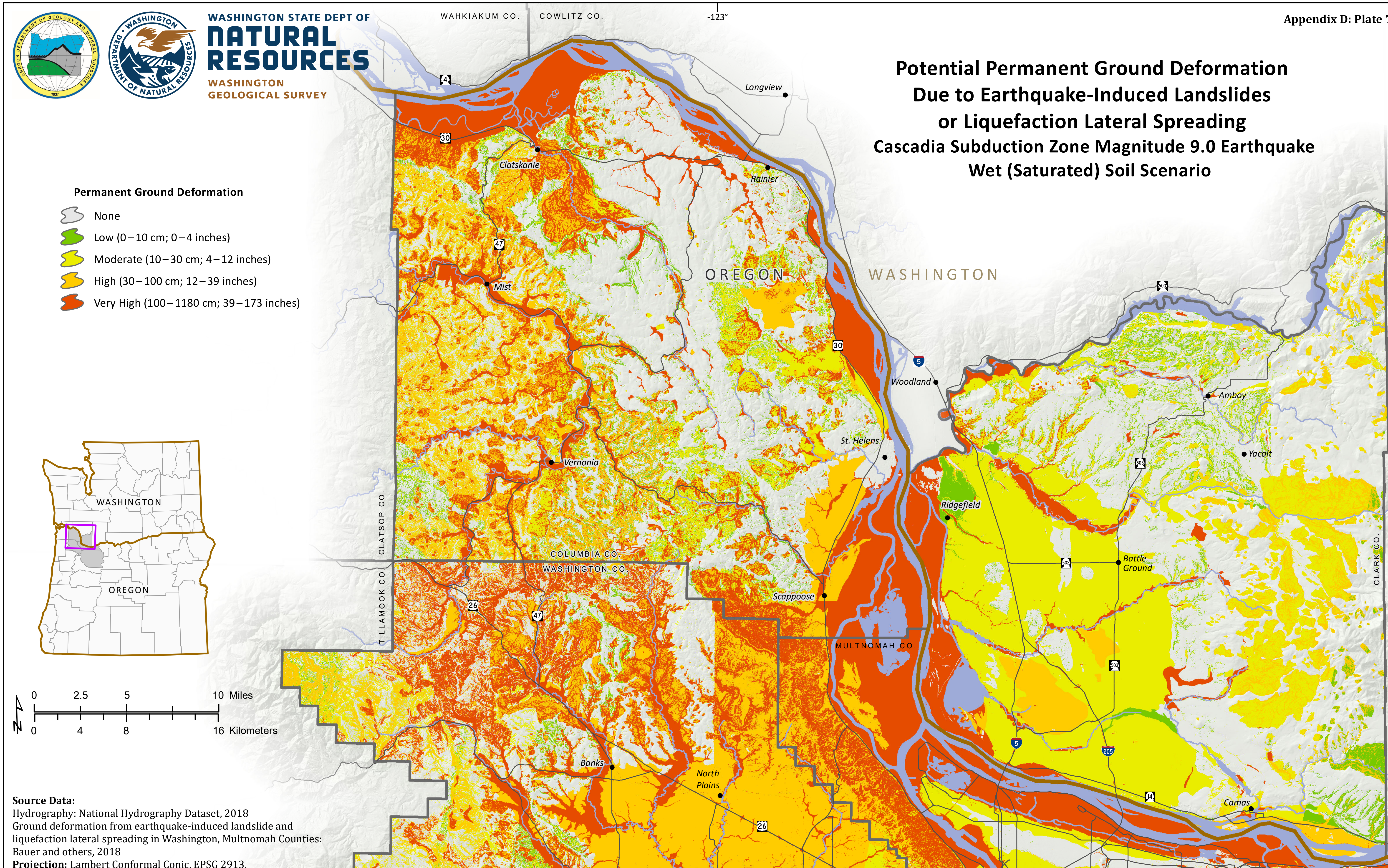
This map is intended to provide nontechnical users with an estimate of the geographic distribution of building damage. The damage categories are taken from the Modified Mercalli Intensity scale, which is based on observed effects on people, objects, and buildings. The damage potential categories are 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



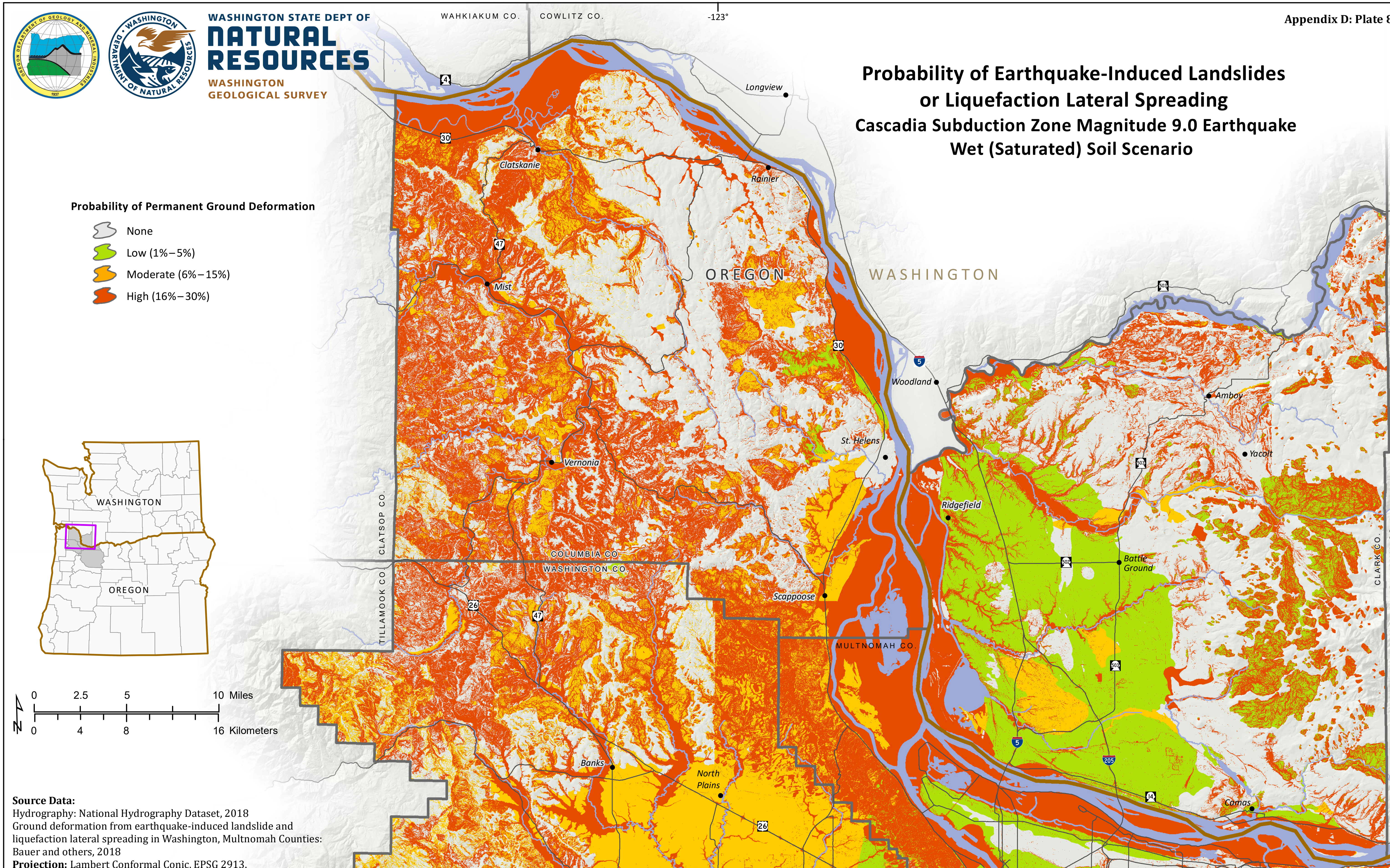
Source Data:
Hydrography: National Hydrography Dataset, 2018
Modified Mercalli Intensity for Washington and Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

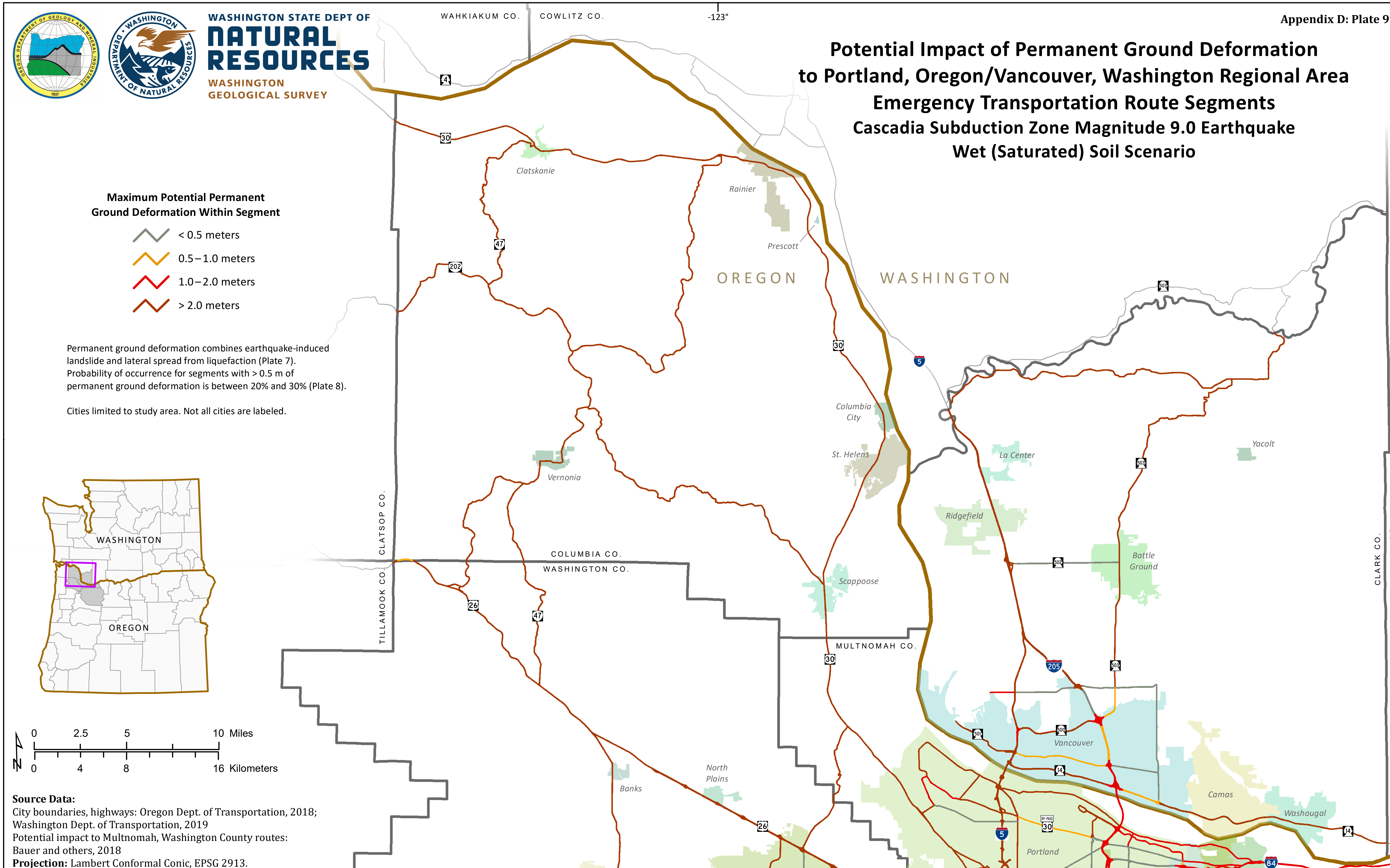
Appendix D: Plate 7

Potential Permanent Ground Deformation Due to Earthquake-Induced Landslides or Liquefaction Lateral Spreading
Cascadia Subduction Zone Magnitude 9.0 Earthquake Wet (Saturated) Soil Scenario

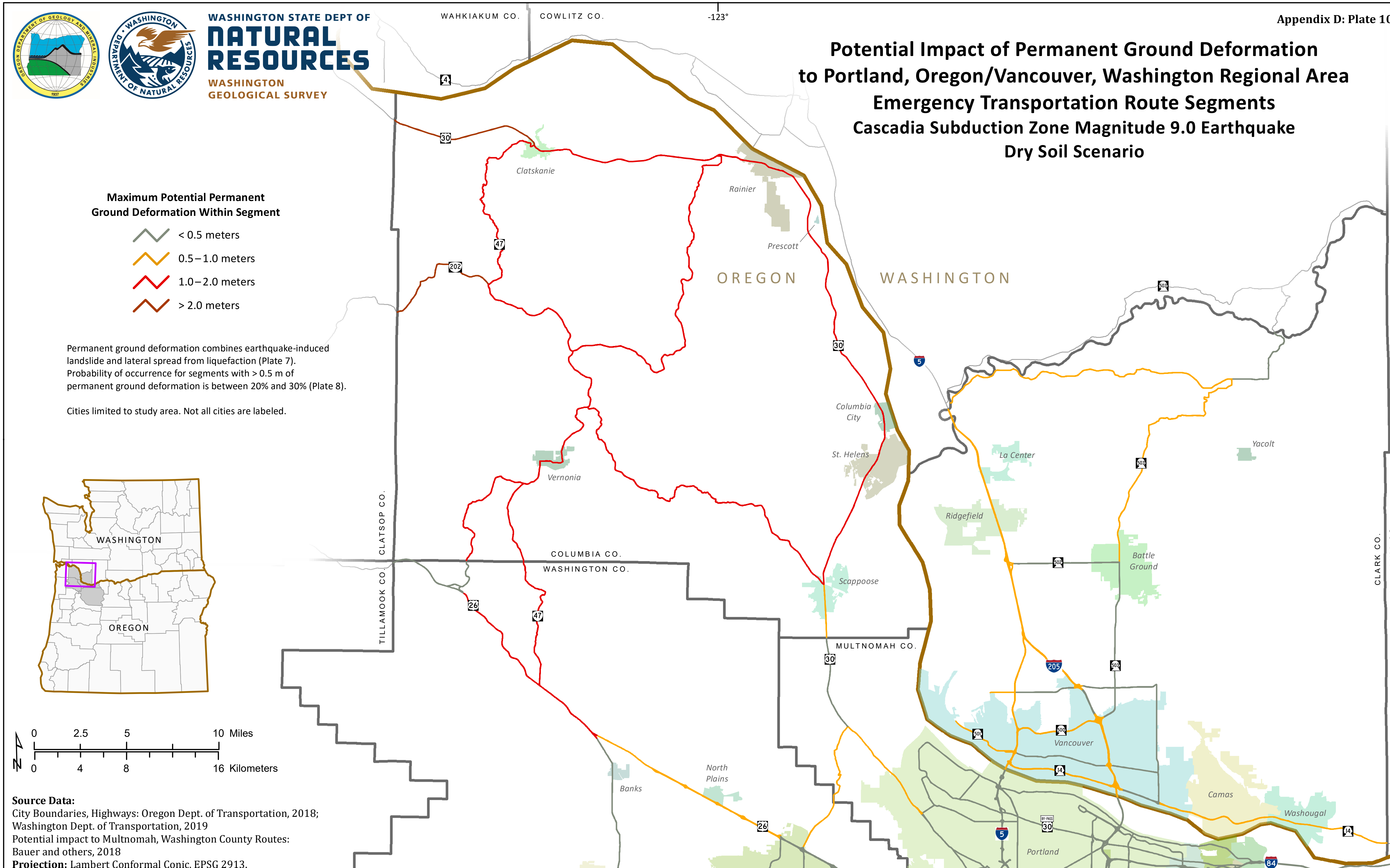


Source Data:
Hydrography: National Hydrography Dataset, 2018
Ground deformation from earthquake-induced landslide and liquefaction lateral spreading in Washington, Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.


Appendix D: Plate 8
Probability of Earthquake-Induced Landslides
or Liquefaction Lateral Spreading
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Scenario
WASHINGTON STATE DEPT OF
NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY
Probability of Permanent Ground Deformation
None
Low (1%–5%)
Moderate (6%–15%)
High (16%–30%)
WAHKIAKUM CO.
COWLITZ CO.
-123°
46°
Longview
Clatskanie
Rainier
OREGON
WASHINGTON
Mist
Woodland
Amboy
St. Helens
Yacolt
Vernonia
Ridgefield
COLUMBIA CO.
WASHINGTON CO.
Battle Ground
Scappoose
MULTNOMAH CO.
CLATSOP CO.
TILLAMOOK CO.
CLARK CO.
SKAMANIA CO.
Banks
North Plains
Camas
0
2.5
5
10 Miles
0
4
8
16 Kilometers
Source Data:
Hydrography: National Hydrography Dataset, 2018
Ground deformation from earthquake-induced landslide and liquefaction lateral spreading in Washington, Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.



Appendix D: Plate 9
Potential Impact of Permanent Ground Deformation
to Portland, Oregon/Vancouver, Washington Regional Area
Emergency Transportation Route Segments
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Wet (Saturated) Soil Scenario
WASHINGTON STATE DEPT OF
NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY
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 7). Probability of occurrence for segments with > 0.5 m of permanent ground deformation is between 20% and 30% (Plate 8).
Cities limited to study area. Not all cities are labeled.
WASHINGTON
OREGON
0 2.5 5 10 Miles
0 4 8 16 Kilometers
Source Data:
City boundaries, highways: Oregon Dept. of Transportation, 2018; Washington Dept. of Transportation, 2019
Potential impact to Multnomah, Washington County routes: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.
WAHKIAKUM CO.
COWLITZ CO.
-123°
46°
Clatskanie
Rainier
Prescott
OREGON
WASHINGTON
Columbia City
St. Helens
Vernonia
La Center
Yacolt
Ridgefield
Battle Ground
Scappoose
COLUMBIA CO.
WASHINGTON CO.
MULTNOMAH CO.
CLATSOP CO.
TILLAMOOK CO.
CLARK CO.
SKAMANIA CO.
Vancouver
Camas
Washougal
Portland
Banks
North Plains

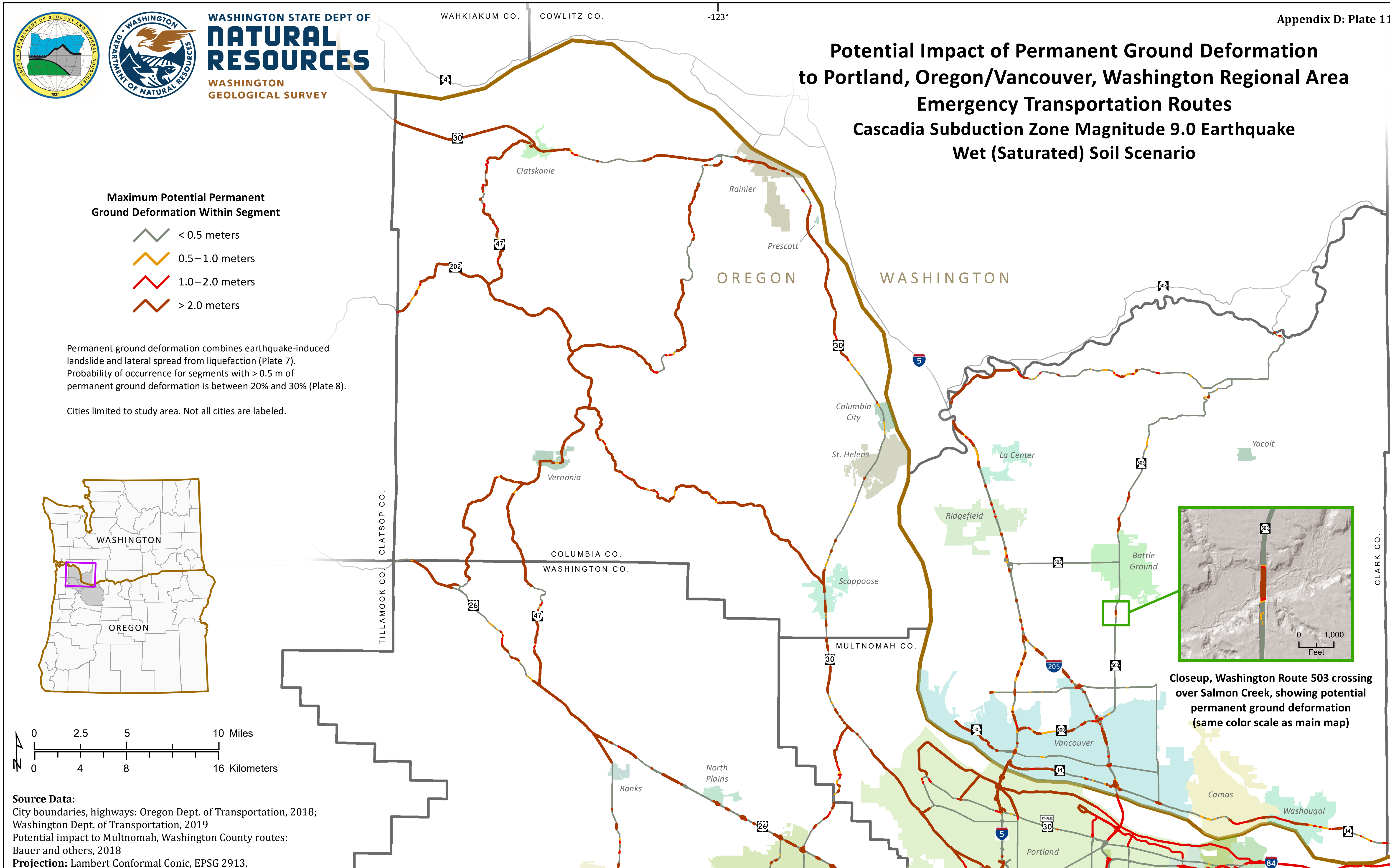


WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY
Appendix D: Plate 10
Potential Impact of Permanent Ground Deformation to Portland, Oregon/Vancouver, Washington Regional Area Emergency Transportation Route Segments
Cascadia Subduction Zone Magnitude 9.0 Earthquake
Dry Soil Scenario
Maximum Potential Permanent Ground Deformation Within Segment
< 0.5 meters
0.5 – 1.0 meters
1.0 – 2.0 meters
> 2.0 meters
Permanent ground deformation combines earthquake-induced landslide and lateral spread from liquefaction (Plate 7). Probability of occurrence for segments with > 0.5 m of permanent ground deformation is between 20% and 30% (Plate 8).
Cities limited to study area. Not all cities are labeled.
WASHINGTON
OREGON
0 2.5 5 10 Miles
0 4 8 16 Kilometers
Source Data:
City Boundaries, Highways: Oregon Dept. of Transportation, 2018; Washington Dept. of Transportation, 2019
Potential impact to Multnomah, Washington County Routes: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.
WAHKIAKUM CO.
COWLITZ CO.
-123°
46°
CLATSOP CO.
TILLAMOOK CO.
COLUMBIA CO.
WASHINGTON CO.
MULTNOMAH CO.
CLARK CO.
SKAMANIA CO.
OREGON
WASHINGTON
Clatskanie
Rainier
Prescott
Columbia City
St. Helens
Vernonia
Scappoose
Banks
North Plains
Portland
Vancouver
La Center
Ridgefield
Battle Ground
Yacolt
Camas
Washougal

Appendix D: Plate 11

Potential Impact of Permanent Ground Deformation to Portland, Oregon/Vancouver, Washington Regional Area Emergency Transportation Routes

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



Maximum Potential Permanent Ground Deformation Within Segment

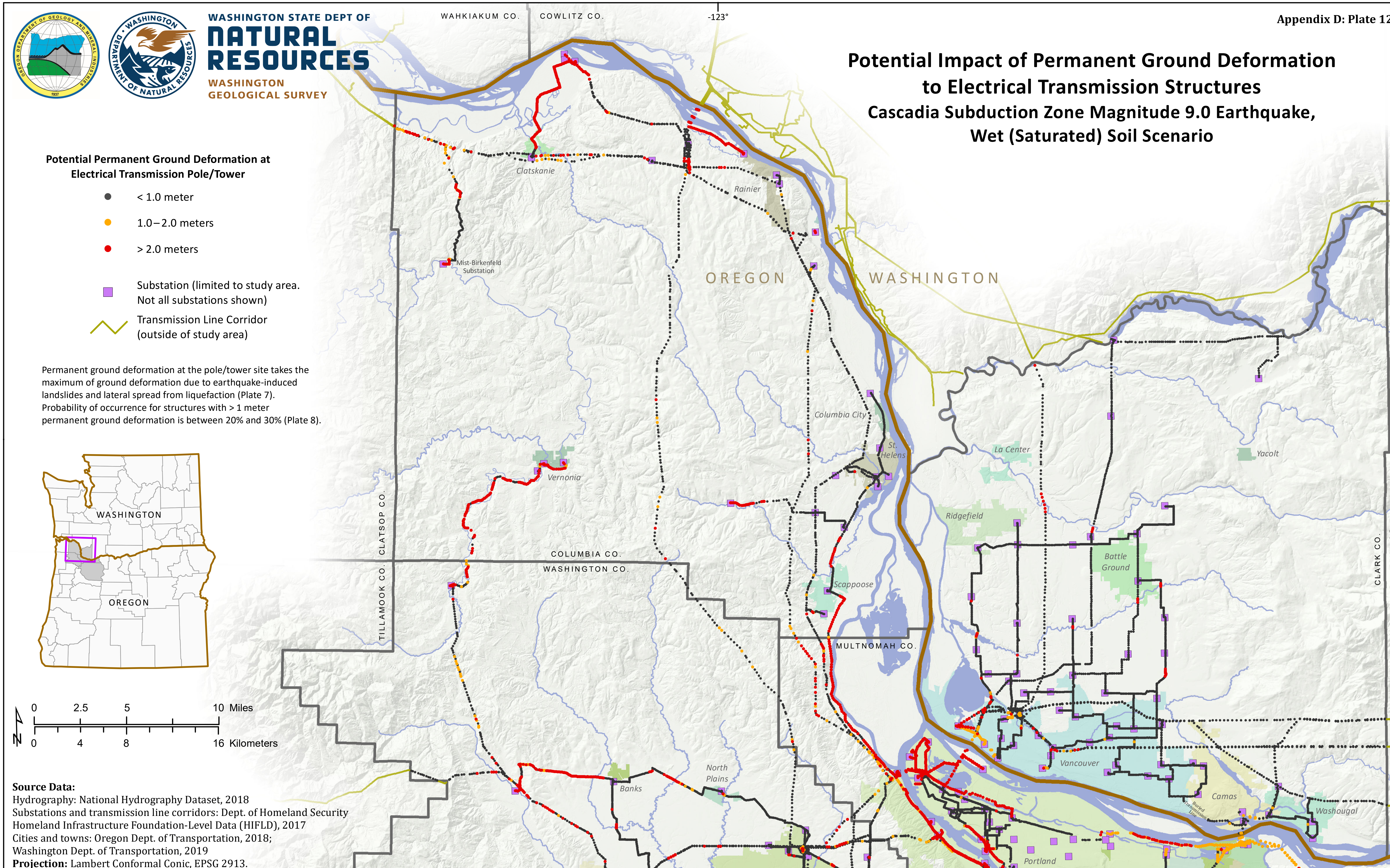
- < 0.5 meters
- 0.5 – 1.0 meters
- 1.0 – 2.0 meters
- > 2.0 meters

Permanent ground deformation combines earthquake-induced landslide and lateral spread from liquefaction (Plate 7). Probability of occurrence for segments with > 0.5 m of permanent ground deformation is between 20% and 30% (Plate 8).

Cities limited to study area. Not all cities are labeled.

Closeup, Washington Route 503 crossing over Salmon Creek, showing potential permanent ground deformation (same color scale as main map)

Source Data:
City boundaries, highways: Oregon Dept. of Transportation, 2018; Washington Dept. of Transportation, 2019
Potential impact to Multnomah, Washington County routes: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.


Appendix D: Plate 12
Potential Impact of Permanent Ground Deformation to Electrical Transmission Structures
Cascadia Subduction Zone Magnitude 9.0 Earthquake, Wet (Saturated) Soil Scenario
WASHINGTON STATE DEPT OF NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY
Potential Permanent Ground Deformation at Electrical Transmission Pole/Tower
< 1.0 meter
1.0–2.0 meters
> 2.0 meters
Substation (limited to study area. Not all substations shown)
Transmission Line Corridor (outside of study area)
Permanent ground deformation at the pole/tower site takes the maximum of ground deformation due to earthquake-induced landslides and lateral spread from liquefaction (Plate 7). Probability of occurrence for structures with > 1 meter permanent ground deformation is between 20% and 30% (Plate 8).
WASHINGTON
OREGON
0 2.5 5 10 Miles
0 4 8 16 Kilometers
Source Data:
Hydrography: National Hydrography Dataset, 2018
Substations and transmission line corridors: Dept. of Homeland Security Homeland Infrastructure Foundation-Level Data (HIFLD), 2017
Cities and towns: Oregon Dept. of Transportation, 2018; Washington Dept. of Transportation, 2019
Projection: Lambert Conformal Conic, EPSG 2913.
WAHKIAKUM CO.
COWLITZ CO.
-123°
46°
Clatskanie
Rainier
Mist-Birkenfeld Substation
OREGON
WASHINGTON
Columbia City
St. Helens
La Center
Yacolt
Vernonia
Ridgefield
Battle Ground
COLUMBIA CO.
WASHINGTON CO.
CLATSOP CO.
TILLAMOOK CO.
Scappoose
MULTNOMAH CO.
CLARK CO.
SKAMANIA CO.
Vancouver
Camas
Washougal
Banks
North Plains
Portland

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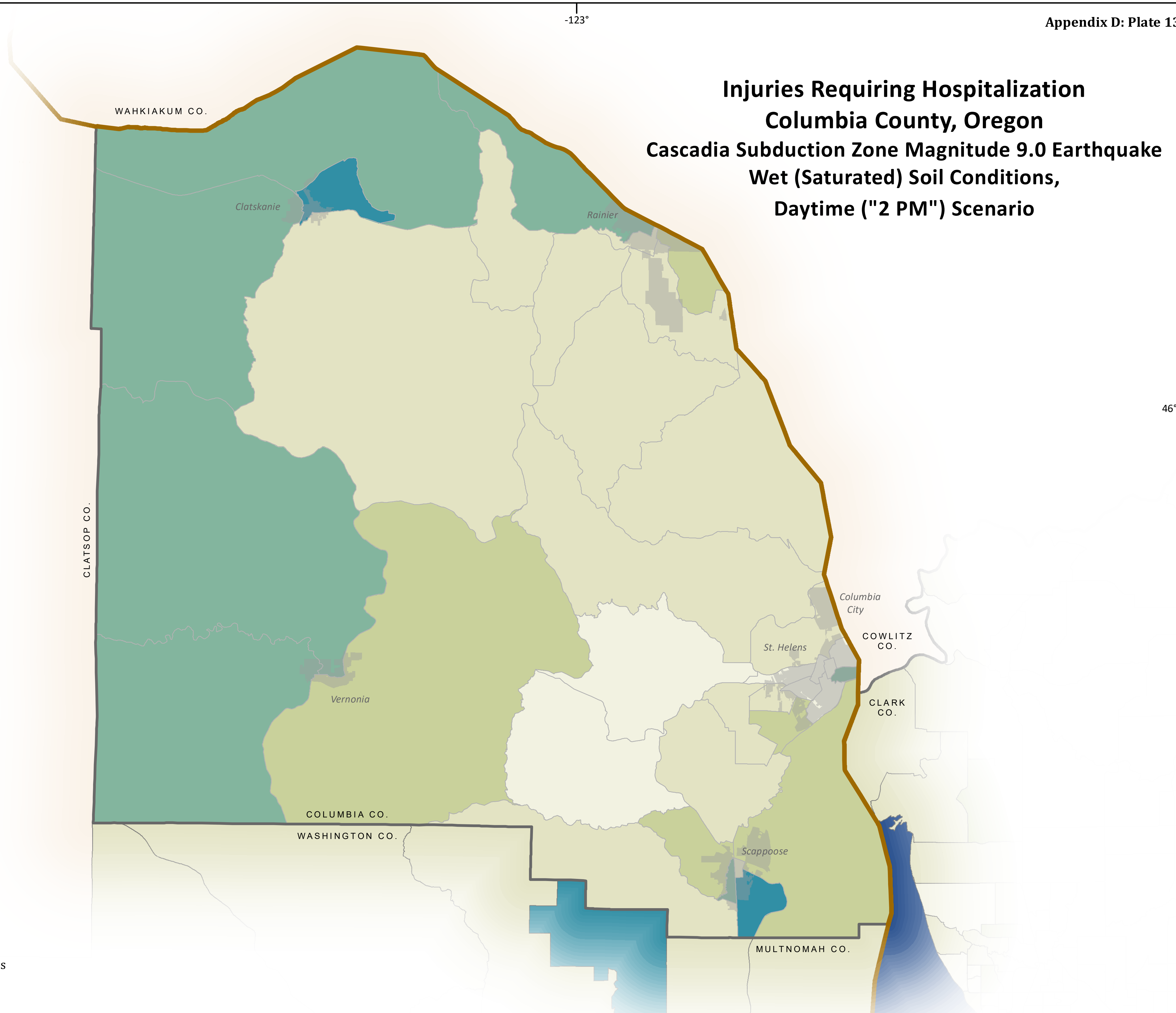
Appendix D: Plate 13

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



Injuries Requiring Hospitalization per Neighborhood Unit

- 0 – 1
- 2 – 5
- 6 – 10
- 11 – 20
- 21 – 50
- 51 – 100
- 101 – 200
- City

No hospitals exist in Columbia County.
Hospitals outside of Columbia County not shown.
"Injuries requiring hospitalization"combines Hazus casualty levels 2 and 3 (Table 4-1).

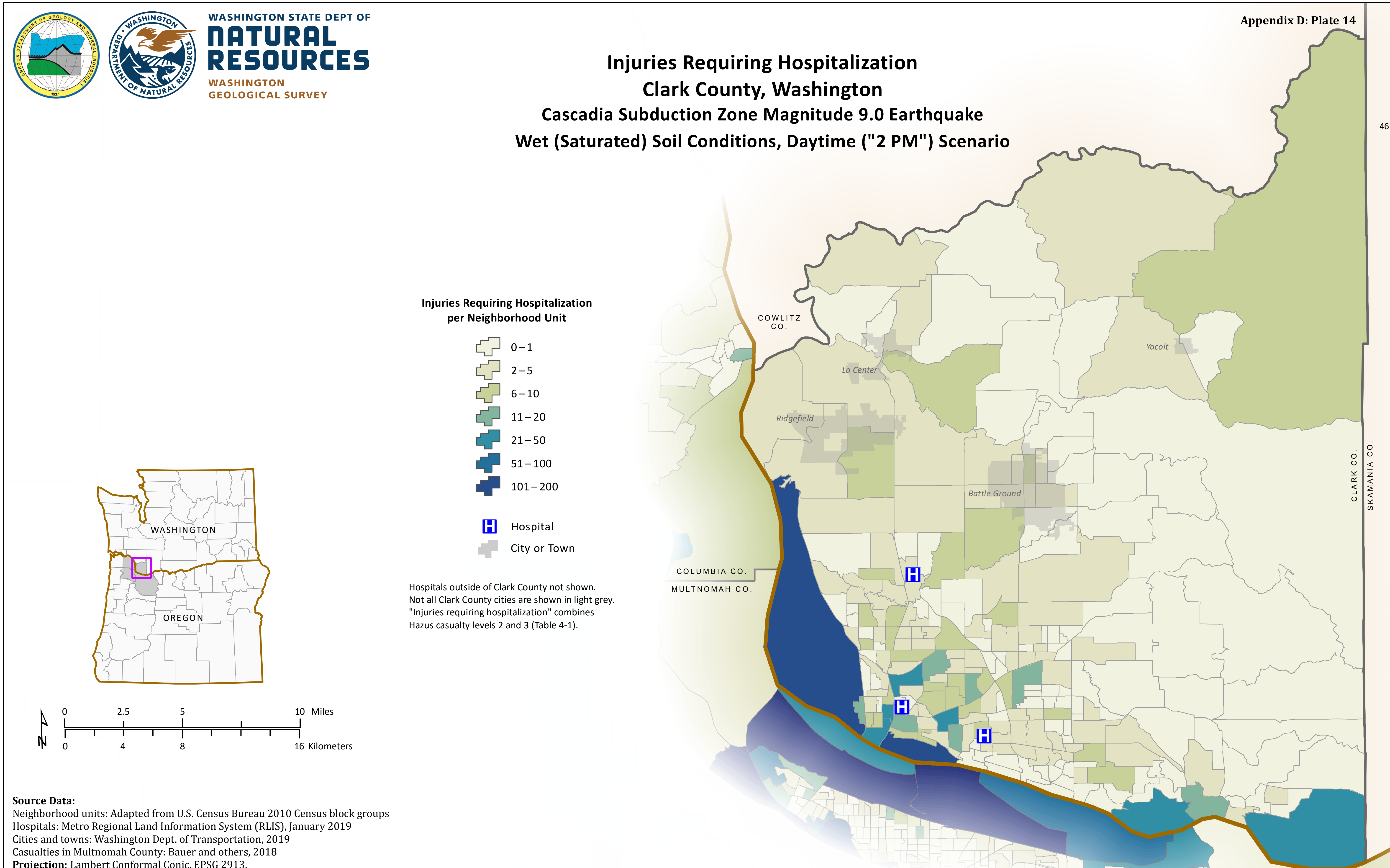
N

0 2.5 5 10 Miles
0 4 8 16 Kilometers

Source Data:
Neighborhood units: Adapted from U.S. Census Bureau 2010 census block groups
Cities and towns: Oregon Dept. of Transportation, 2018
Casualties in Washington and Multnomah Counties: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.

Appendix D: Plate 14

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



Hospitals outside of Clark County not shown.
Not all Clark County cities are shown in light grey.
"Injuries requiring hospitalization" combines Hazus casualty levels 2 and 3 (Table 4-1).

Source Data:
Neighborhood units: Adapted from U.S. Census Bureau 2010 Census block groups
Hospitals: Metro Regional Land Information System (RLIS), January 2019
Cities and towns: Washington Dept. of Transportation, 2019
Casualties in Multnomah County: Bauer and others, 2018
Projection: Lambert Conformal Conic, EPSG 2913.