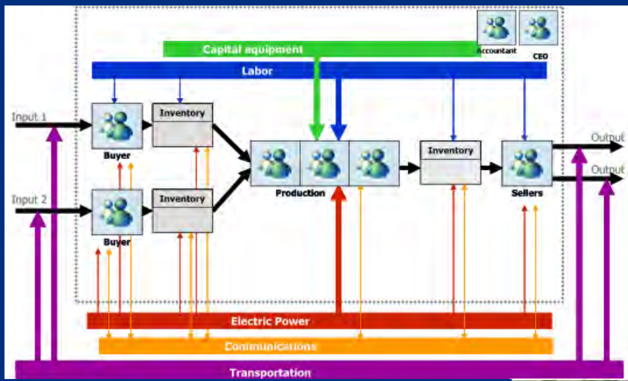

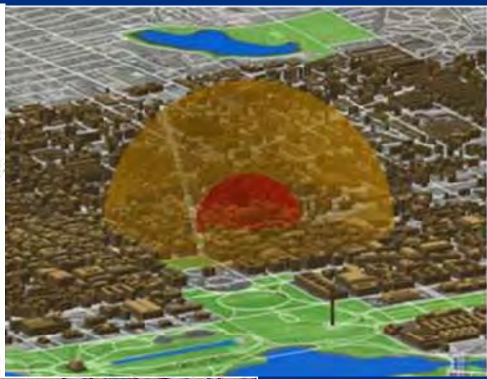
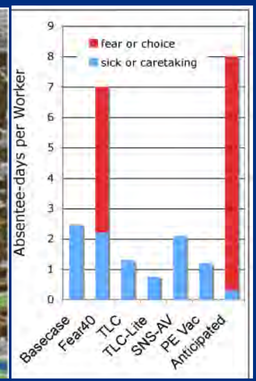

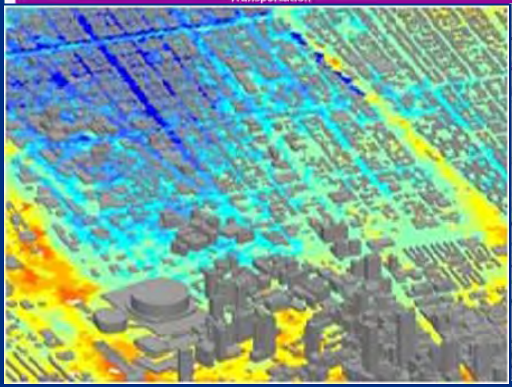

National Infrastructure Simulation and Analysis Center
Homeland Infrastructure Threat and Risk Analysis Center
Office of Infrastructure Protection
National Protection and Programs Directorate

Draft Analytical Baseline Study for the Cascadia Earthquake and Tsunami

September 12, 2011

Homeland Security

Revision Log

Revision Number	Date of Revision	Purpose of Revision	Name or Org.
1A			
1B	02/25/11		
1C	05/24/11	Added Section 2: Purpose of Analytic Effort; added Section 2,1; added Section 2. 2 Decision Making; changed graphic on cover; added revision log	jsw/RDMB-NISAC
1D	06/09/11	Replaced Section 7 "study plan" with Section 7 Conclusion, added Executive Summary placeholder, added caveats placeholder page, changed Section 5 title from Analytical Methodology to Analytical Methodology and Impacts, various formatting changes	NISAC Team/SNL, LANL
1E	06/10/11	Added analytical results	NISAC Team/SNL, LANL
1F	08/19/11	Major revision of analysis, including new Hazus runs, Tsunami calculations and corresponding analyses with new maps, charts, tables, graphics	NISAC Team/SNL, LANL
1G	09/12/11	Added cascading effects analysis, and new maps, charts, tables and graphics	NISAC Team/SNL, LANL

Caveats

This is the second of three major planned phases of the Cascadia Analytical Baseline Study prior to the production of the final version.

Phase 1: Direct Effects

Phase 2: Cascading Effects and Interdependencies

Phase 3: Economic Impacts

The first phase was previously delivered in two iterations. These drafts are being shared with stakeholders with the understanding that each is a work in progress. They are being disseminated to avoid delays in use of the early results and to elicit feedback to improve the final product.

This draft reports the analysis of direct and indirect impacts on infrastructure and population from a catastrophic earthquake and tsunami in the Cascadia Subduction Zone. The final phase will incorporate economic and supply chain impacts, including impacts on Alaska.

Finally, the analytical production team has endeavored to incorporate the input and data provided by partners in the most appropriate manner. The suggestions received to date are strongly appreciated. The goal with respect to this aspect is the same as the other aspects of this endeavor: to make the analysis as collaborative and transparent as possible while ensuring that the Cascadia planning process is effectively supported.

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Executive Summary

In 1700 the Pacific Northwest experienced an earthquake and tsunami that rivals the recent incident off the coast of Japan. A catastrophic earthquake of this magnitude along the Cascadia fault off the coast of Oregon and Washington is estimated to occur every 500 years. This report analyzes the possible direct impacts from a 9.0-magnitude earthquake and ensuing tsunami on population and infrastructure.

Key points from the analysis include:

- The 9.0-magnitude earthquake along the Cascadia fault line off the coast of northern California, Oregon, and Washington, along with a resulting tsunami, causes significant damage and loss of life along coastal regions of California, Oregon, and Washington.
- Almost two thousand lives could be lost and another 2,300 or more injured due to tsunami inundation along the Pacific coast, with the communities of Crescent City and Grays Harbor particularly hard hit.
- An additional 1,100 fatalities could be expected to result from ground shaking, primarily due to the collapse of structures, with approximately 25,000 injured.
- Extensive electric power outages would be experienced throughout the region, with medium-term outages forecast for the coastal areas. Restoration is expected to occur on a prioritized basis within one to eight days.
- Natural Gas
  - Segments of the backbone natural gas transmission pipeline serving western Washington and Oregon are at risk of being damaged.
  - Both the transmission pipeline and the networks of distribution pipelines are likely to suffer enough damage that the majority of customers in western Washington and western Oregon will lose natural gas service.
  - Combined with electrical outages, many homes may lose all sources of heating.
- Telecommunications
  - Regional communication disruptions are expected in wireline, wireless, and the Internet.
  - Major undersea transpacific cables are likely severed, disrupting communication service to East Asia. A two- to three-month restoration time is expected.
  - Undersea cables serving Alaska are likely severed, disrupting communication between Alaska and the contiguous United States.
- Transportation Fuels
  - A significant number of pump stations along the Olympic and Oregon Line refined-product pipeline system will sustain damage. As a result, the ability to move refined product by pipeline will be disrupted.
  - A substantial number of refined product terminals in the region will sustain significant damage. The inability to store and distribute fuels locally will have a major impact on regional fuel supplies.

- Transportation
  - Significant damage to roads can be expected, particularly those along the coast and connecting the coast to the I-5 corridor. U.S. 101 is expected to suffer substantial damage due to both shaking and tsunami, resulting in limited capacity for several months. Nearby coastal areas may be isolated for the short term.
  - Tsunami damage at the mouth of the Columbia River will impact navigation and the ability to export agricultural commodities.
  - Road and bridge damage will likely impact accessibility of emergency services as well as essential repair crews for other sectors.
  - Long-term rail traffic disruptions can be expected along the I-5 corridor. A complete loss of key rail bridges in the Olympia and Seattle area and downtown Portland can be expected.
- Emergency Services
  - Widespread damage to police stations, fire stations, and hospitals along the coast is expected.
  - Bridge and road outages will inhibit/limit emergency response capabilities.
  - Communications challenges will affect all coastal emergency operations.
  - Supplying transportation fuels to key emergency operations centers may become an issue until road access is restored.
- Banking and Finance
  - Loss of the Alaska telecommunications link would significantly impact the ability of Alaskan banks to process payments/ settlements. Satellite uplinks might not be an available option due to scarcity of bandwidth and contractual agreements.
  - Loss of major transpacific undersea cable capacity would affect transoceanic commerce, settlement, and transpacific financial market exchanges. With the loss of approximately half the undersea cable capacity, communications systems could face abnormally high congestion.
- Health Care
  - The potential of 15,000 to 30,000 casualties combined with the expected loss due to damage of 15-27 hospitals comprising 524-1708 regular beds and 60-228 critical bed facilities concentrated near the coast would be sufficient to saturate the excess capacity of other hospitals within a 250-mile range of the worst damage.
- Water & Wastewater
  - Disruptions to potable water supply are expected with restoration times of 3 weeks to 7 months with greatest damage and restoration times near the coastline.
  - There is some risk of release of untreated wastewater. The region may experience an increase in waterborne diseases due to contamination of drinking water.
  - Availability of water supply and wastewater systems can delay economic recovery particularly along the coastline.

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1 Introduction

Within the Department of Homeland Security (DHS), analytical baseline documents are developed to provide coordination between various organizations in their analytical efforts. Analytical baselines help assure the consistency of assumptions and data usage as well as consistency in scenario construction between groups operating in overlapping analytical domains, thereby improving the consistency of analytic results obtained by different analytic groups.

In 1700 the Pacific Northwest experienced an earthquake and tsunami that rivals the recent incident off the coast of Japan. A catastrophic earthquake of this magnitude along the Cascadia fault off the coast of Oregon and Washington is estimated to occur every 500 years.

This is the draft product of the second phase of the analytical baseline. This draft analyzes the direct effects on population and the direct and indirect infrastructure impacts of the earthquake scenario. The analytical baseline study is the first step in the analytical process that the Cascadia Subduction Zone (CSZ) Interagency Working Group is applying in preparation for a potential earthquake and tsunami in the CSZ region. The Homeland Infrastructure Threat and Risk Analysis Center (HITRAC) is serving as the coordinating organization; HITRAC's Risk Development and Modeling Branch's (RDMB's) National Infrastructure Simulation and Analysis Center (NISAC) is providing analytical integration.

Draft notes: this draft addresses the direct and indirect impacts on infrastructure and population. Economic impacts will be included in a future draft.

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2 Purpose of Analytical Effort

While it is useful to understand the potential effects of a subduction earthquake, this analysis only provides a general assessment of how the area might fare in a 9.0-magnitude earthquake. Because there are so many variables in earthquakes, the actual event will undoubtedly be different than the scenario on which the analysis is based.

Nonetheless, the analysis will provide important information that can be used to prepare effectively for a potential disaster and to allow decision-makers at all levels to make better-informed decisions at the right time about appropriate allocations of resources.

2.1 Emergency Preparedness Planning

An analysis of the direct and cascading effects that might be expected in the event of a CSZ earthquake allow for far more effective emergency preparedness planning, as well as providing a means to identify those infrastructures at higher risk that might be potential candidates for risk mitigation.

Most people who live in Cascadia know something about the earthquake risk, but they may not know how to prepare. They may not know what to do to protect themselves from a tsunami. Educating both residents and visitors will help prevent loss of life when the earthquake strikes. This analysis will provide a baseline projection of likely direct and cascading effects of a plausible scenario that will enable Federal, State, and local emergency planners to inform local populations better about the risks of, and possible protection strategies against, such a catastrophic event.

2.2 Decision-making

The ultimate purposes of this study are not only to enable decision-makers to make better-informed choices about the most appropriate course of action in the event of a true emergency, but also to identify opportunities for infrastructure improvement that may mitigate the results of such a catastrophic event. While the scenario upon which this study is based is somewhat arbitrary, it is a very reasonable scenario that will provide useful information that informs both high-level decisions to be made well in advance of a catastrophe and more immediate decisions to be made at the time of a real event.

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3 Scenario

3.1 Parameters

The development of an earthquake scenario hinges on a number of parameters. A key parameter for commencing analysis is the strength of the earthquake, often measured in terms of a magnitude. Magnitude in turn depends on the fault area that slips, how much slippage occurs during the earthquake, and the fault's proximity to the Earth's surface. Other important parameters include the specific date (so that seasonal population changes can be considered in the analysis) and time of day of the event, the expected number and severity of aftershocks, and, in the case of an earthquake fault that breaks the seafloor, the anticipated wave heights and temporal evolution of the associated tsunami. The description of the scenario constructed for this analysis can be found below.

3.2 Earthquake Scenario in the Cascadian Subduction Zone

RDMB-NISAC examined both the direct and indirect impacts of an earthquake impacting the Pacific Northwest. The scenario earthquake examined by RDMB-NISAC is not intended to generate the greatest impacts across the entire region. The scenario was designed rather to demonstrate earthquake modeling capabilities and produce both direct and indirect results that can be used for planning and exercises. The direct impacts are damage caused by the earthquake and tsunami. The indirect impacts are cascading impacts to infrastructure systems and the local population.

The CSZ is an 800-mile-long offshore earthquake fault, stretching from northern California to Vancouver Island. The scenario for analysis is a 9.0-magnitude earthquake along the length of the fault, as specified by the Cascadia Region Earthquake Workgroup (CREW).[1] A map of the CSZ is shown in Figure 3-1; the red line indicates the Juan de Fuca plate beginning its descent (in the direction of the red arrowheads) beneath the North American plate. The buried interface between these two plates, which extends from the red line to the coastline or farther inland in some places, comprises the fault zone, which is capable of breaking in one great earthquake or possibly in sections as smaller earthquakes.

[1] Cascadia Subduction Zone Earthquake: A magnitude 9.0 scenario, 2005.

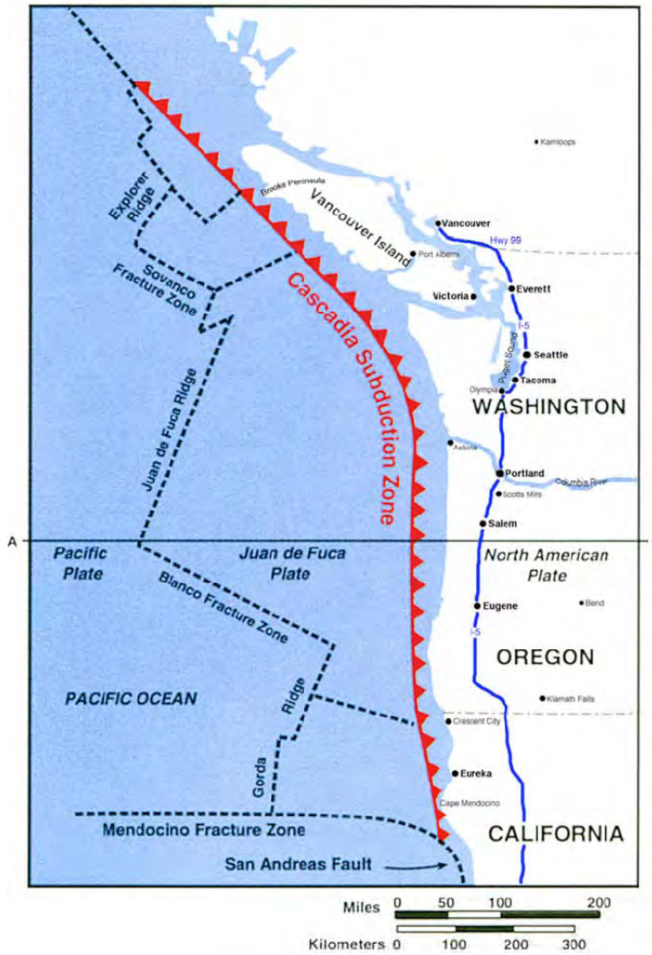

Figure 3-1. Cascadia Subduction Zone, reproduced from CREW scenario report

The 9.0-magnitude earthquake scenario examined for this study in the CSZ has an epicenter approximately 95 miles west of Eugene, OR. The earthquake generates a tsunami that impacts most of the Pacific Ocean, but this study examines tsunami impacts for specific populated areas in Washington, Oregon, and northern California. The direct damage caused by the earthquake was estimated using the Federal Emergency Management Agency's (FEMA's) Hazus®-MH 2.0 Multi-hazard Loss Estimation Methodology (Hazus) tool. The Hazus calculation factored in ground-shaking, liquefaction, and potential landslide to estimate damage to buildings, roadways, and physical infrastructure.

3.2.1 Earthquake and Liquefaction Metrics Terminology

The maps used for this study geospatially depict the intensity or degree of ground shaking and liquefaction. The following lay definitions for ground shaking and liquefaction quantities are intended to enable understanding of the modeled damage extent to various infrastructure and building types:

- Peak Ground Acceleration (PGA): The maximum acceleration that any point on the ground would experience. The units are in G-force (gravity). PGA can be thought of as the force that something on the ground experiences. For example, if a rock that weighs 100 pounds receives a 50-lb. shaking force, it is said to have a PGA of 0.5, or half of a G-force (half of its weight).

- Peak Ground Velocity (PGV): The maximum speed that a point on the ground will achieve due to ground shaking in an earthquake. Units are in centimeters per second.
- Spectral Acceleration (SA): The maximum acceleration that a point on the ground would experience at a particular frequency. In the audio world, this would be the equivalent to how much of the bass, mid-range, or treble are in a particular sound. This is of interest in relation to harmonic resonance with structures. Larger and taller structures in particular are more susceptible to damage from lower frequency motion.
- Lateral Spread: The relative distance that a point on the ground may move (measured in inches) due to spreading and ground settlement. Lateral spread is a measure of liquefaction and can represent the degree of foundation instability for structures.

The following maps use these terms to illustrate the earthquake scenario for this study.

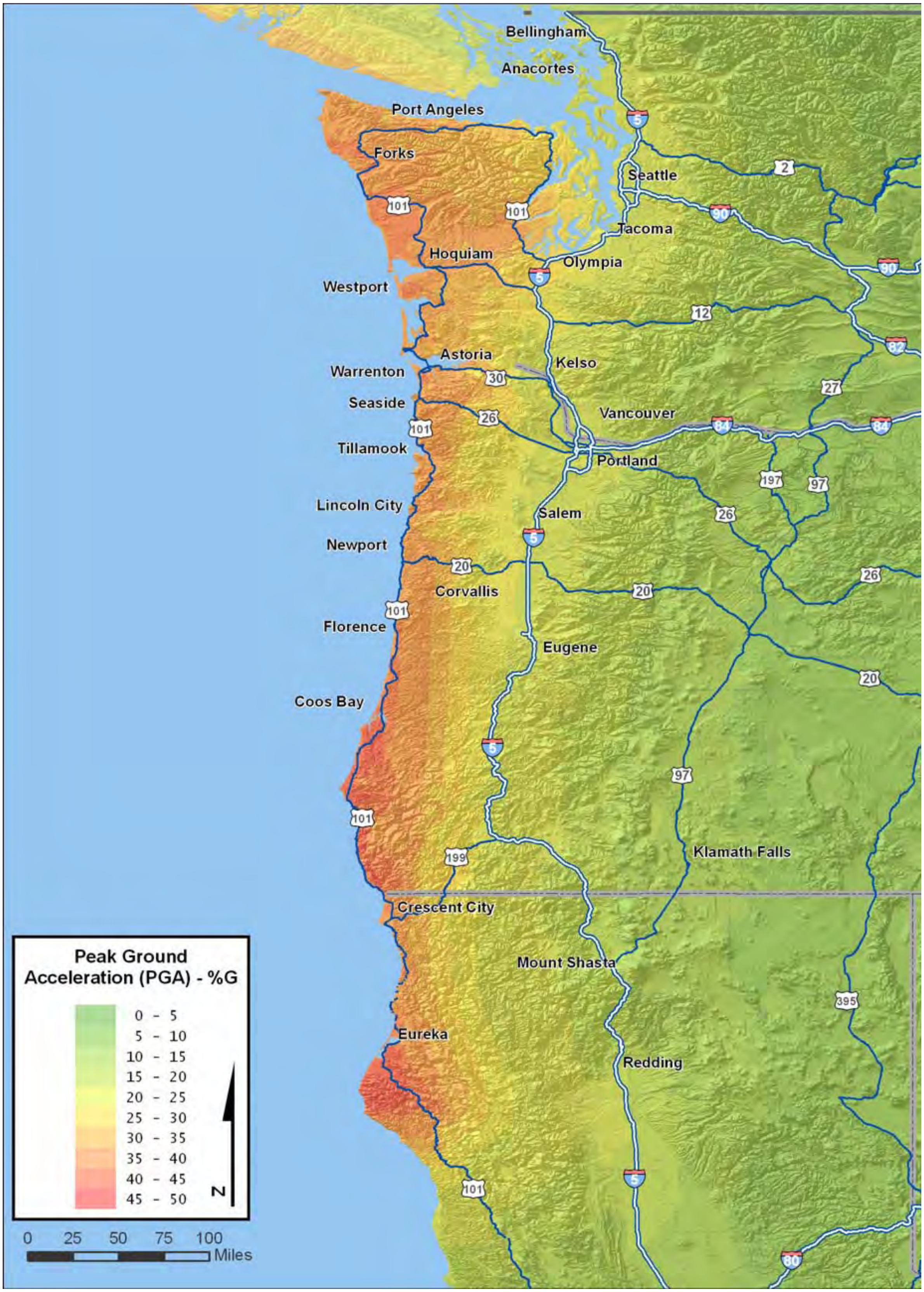

Figure 3-2. Peak ground acceleration (percent G)

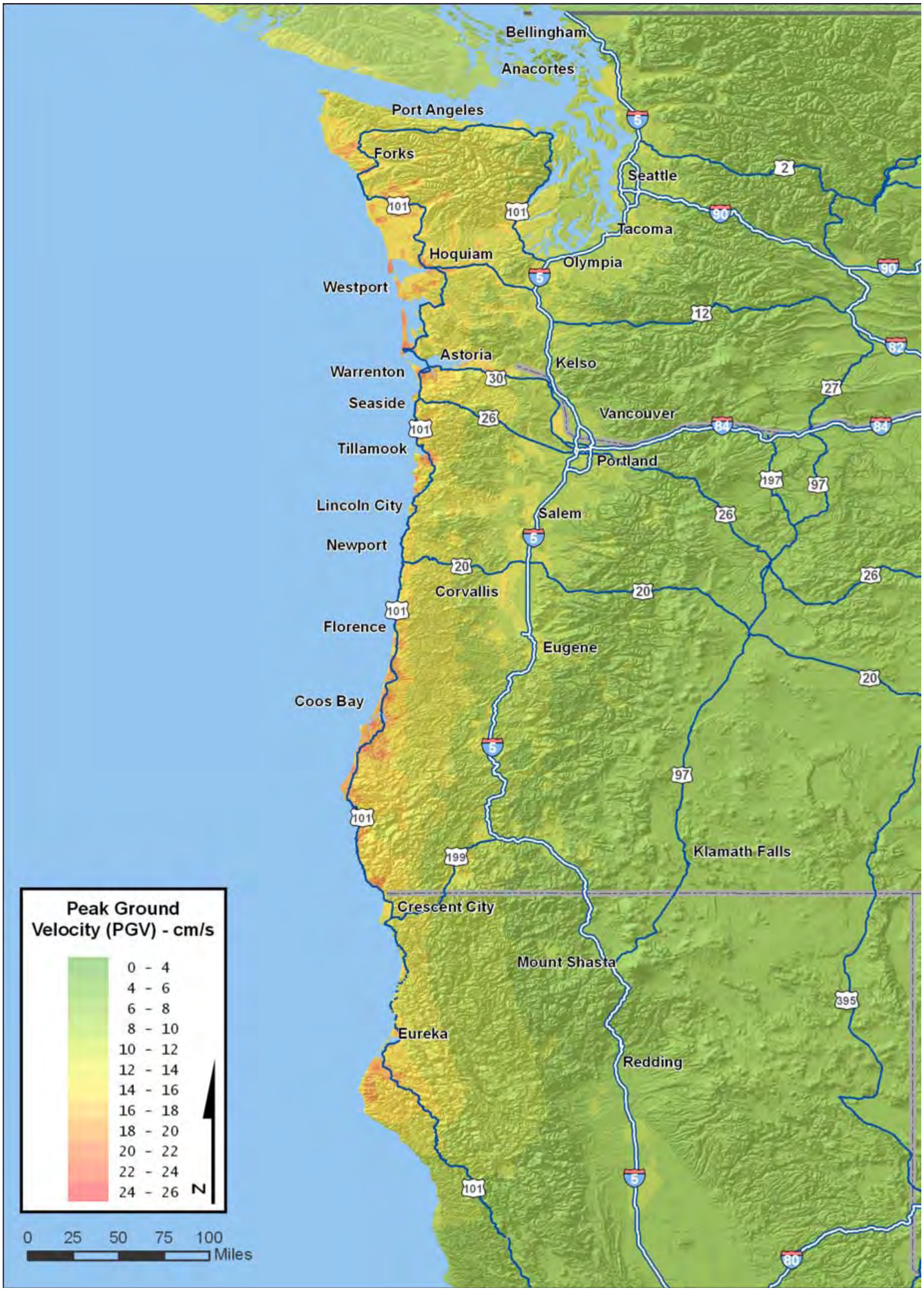

Figure 3-3. Peak ground velocity (cm/s)

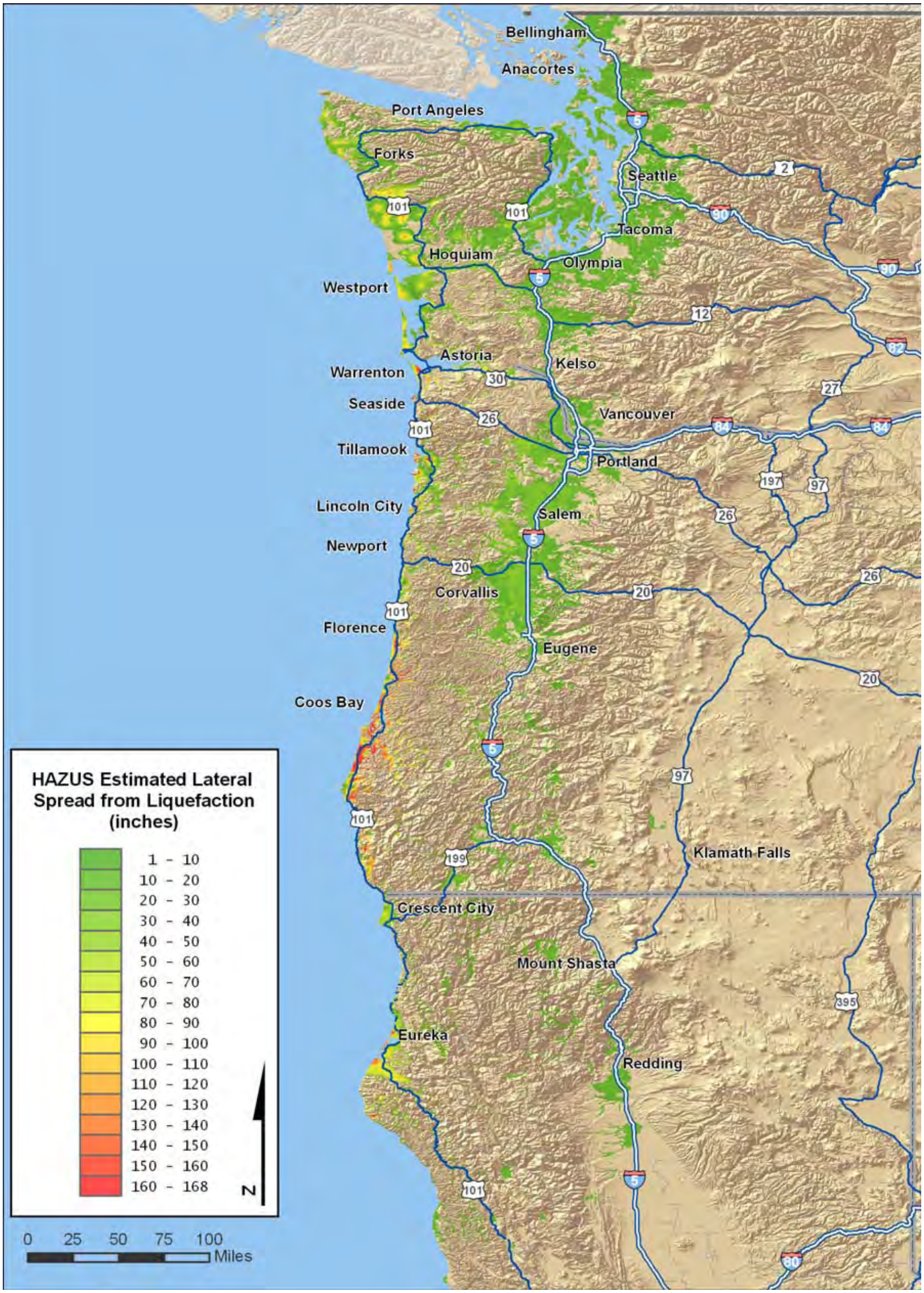

Figure 3-4. Hazus estimated lateral spread from liquefaction (inches)

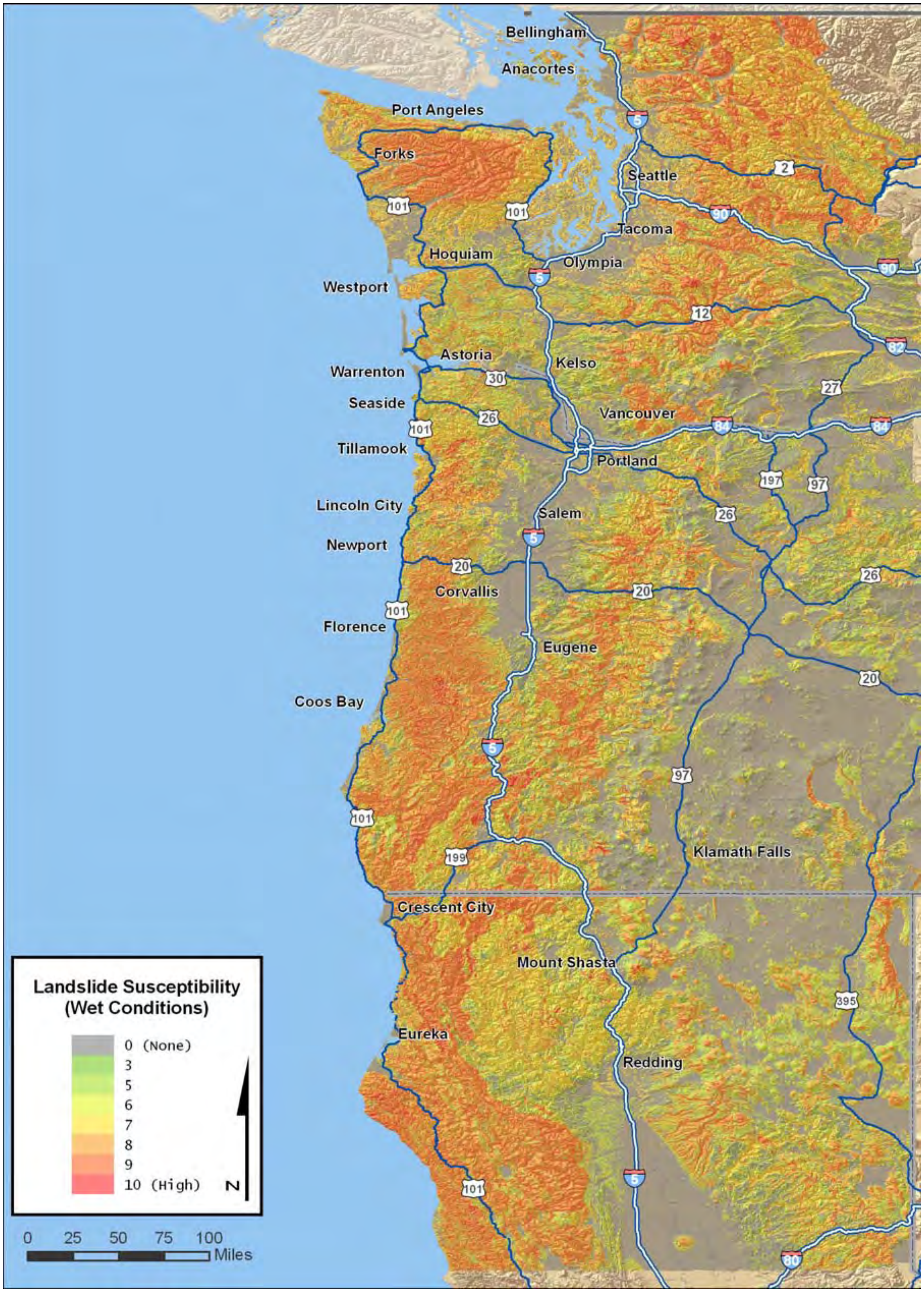

Figure 3-5. Landslide susceptibility (wet conditions)

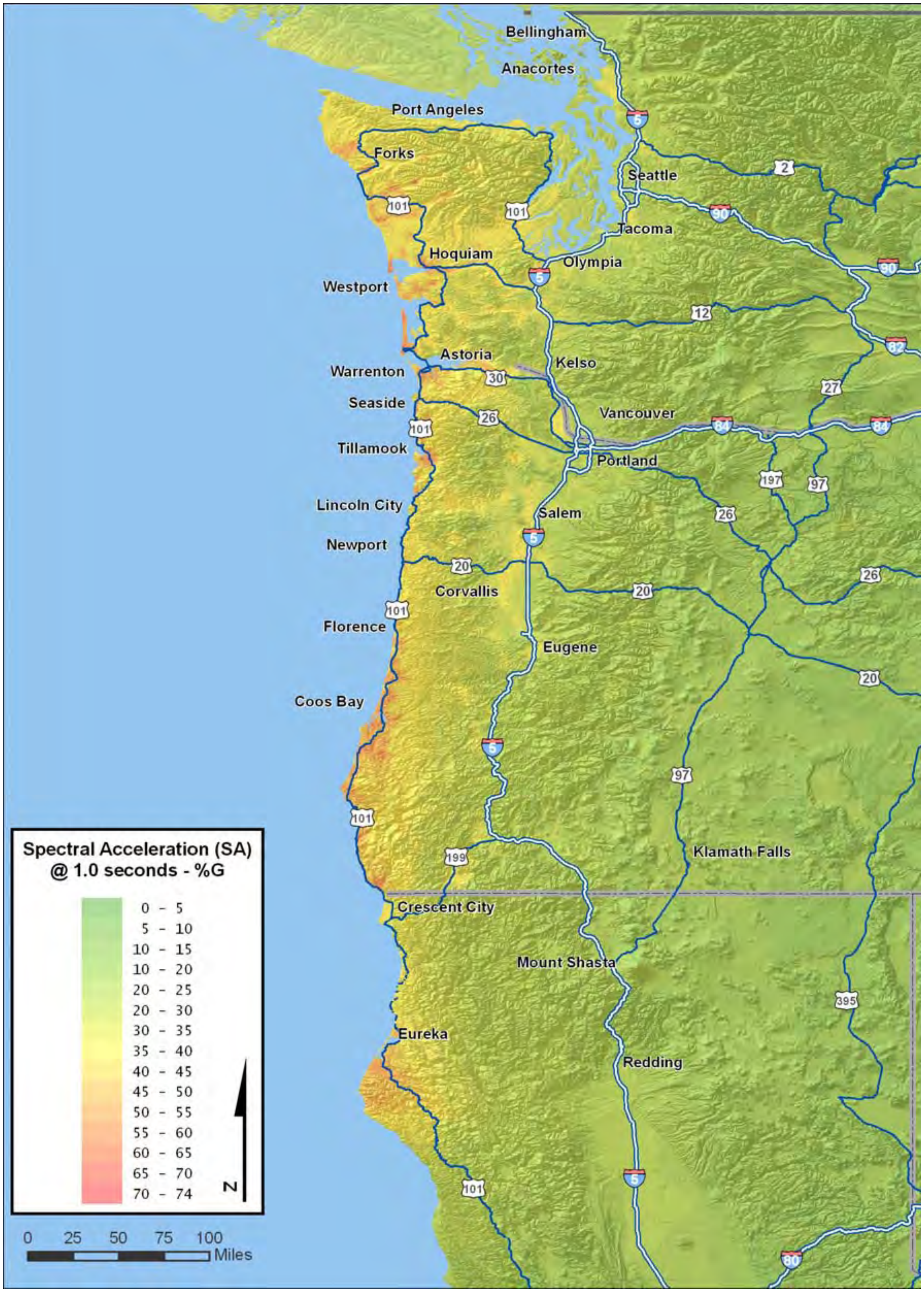

Figure 3-6. Spectral acceleration at 1. 0 seconds (percent G)

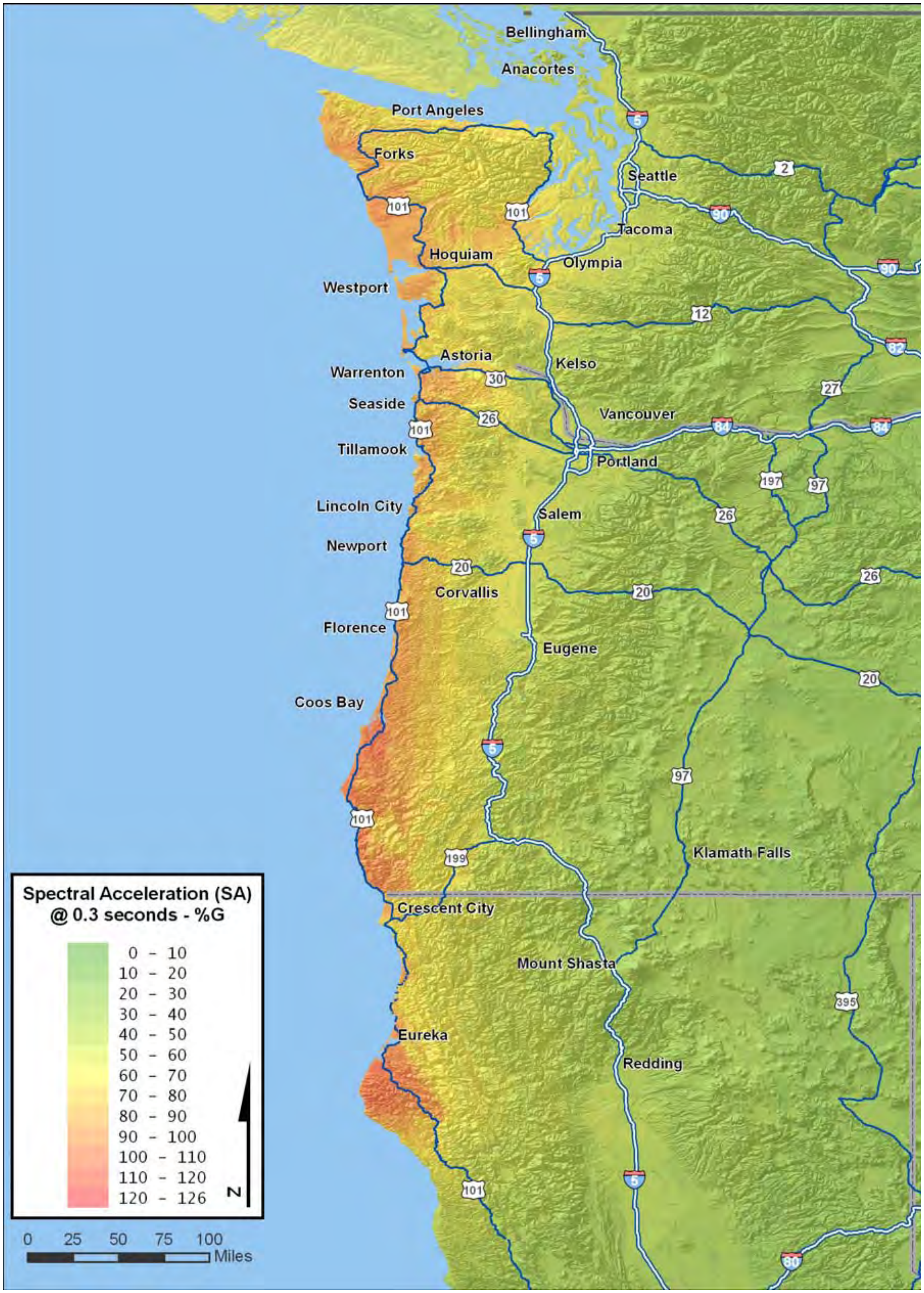

Figure 3-7. Spectral acceleration at 0. 3 seconds (percent G)

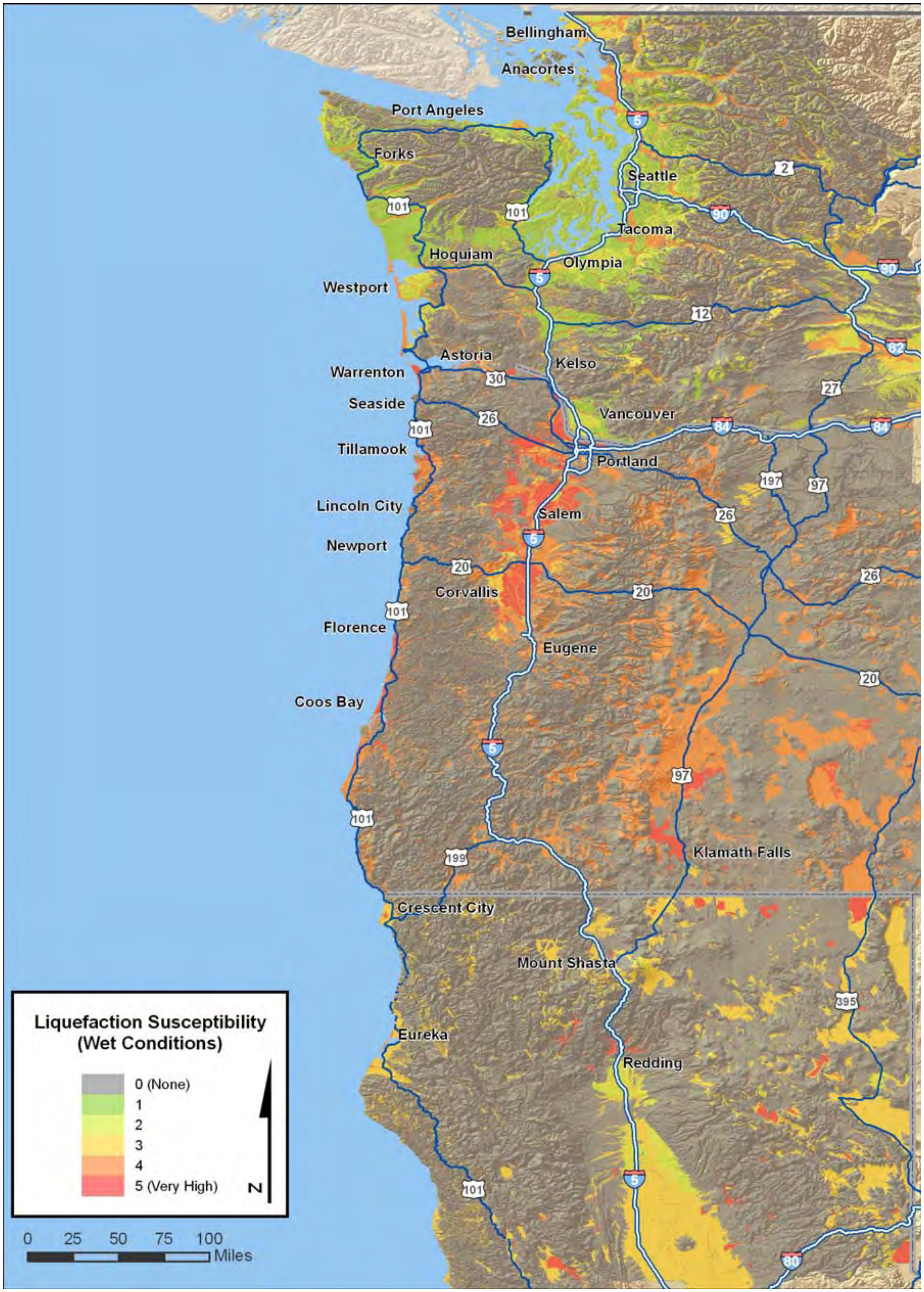

Figure 3-8. Liquefaction susceptibility (wet conditions)

3.3 The Earthquake and Resulting Tsunami

The key starting point of the scenario in this study is a ShakeMap[2] generated by the U.S. Geological Survey (USGS) specifically for a 9.0-magnitude Cascadia event.[3] This 2011 ShakeMap (see Figure 3-2) is an authoritative model of the ground shaking expected for a geologically plausible 9.0-magnitude earthquake in the CSZ. A tsunami source term (wave height, direction, and velocity) was developed from the Pacifex 11 Exercise[4] model runs combined with NISAC modeling. This source term was used in inundation modeling to obtain the direct impacts of the scenario tsunami. These steps are described below. Although the output of the ShakeMap was not used directly as input to the Pacifex results, both were constructed to be consistent with the CREW scenario.

3.4 Scenario Comparison with the 2011 Tōhoku, Japan, Earthquake

The April 6th, 2011, Tōhoku earthquake off the Pacific coast of Japan bears many similarities to the CSZ scenario. Both are megathrust faults capable of producing some of the world's strongest and longest-duration earthquakes. In the case of Tōhoku, the magnitude was 9.0 and it was 5 minutes in duration. The Tōhoku quake also resulted in a large tsunami that had severe impacts along the immediate coastline.

3.4.1 Situational Comparison

The CSZ scenario has an epicenter at 45.73°N, 125.12°W, which is about 60 miles off the Oregon coast, 170 miles west of Portland. and 270 miles southwest of Seattle. By contrast, the Tōhoku earthquake epicenter was at 38.32°N, 142.37°E, which is about 40 miles off the Pacific coast of Japan. The Tōhoku earthquake epicenter is somewhat closer to the coastline, as shown in Figure 3-9 and Figure 3-10. The scale is the same for both maps.

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[2] ShakeMap is a product of the U.S. Geological Survey Earthquake Hazards Program in conjunction with regional seismic network operators.

[3] The scenario shake map: earthquake.usgs.gov/earthquakes/shakemap/global/shake/Casc9.0_se/, accessed July 15, 2011.

[4] nthmp.tsunami.gov/documents/PACIFEX11Final.pdf, accessed June 10, 2011.

Figure 3-9. Cascadia earthquake scenario epicenter

Figure 3-10. Tōhoku, Japan, 2011 earthquake epicenter

3.4.2 Tsunami Susceptibility

In comparison with the Washington, Oregon, and northern California coastlines, the coastline of Japan near the Tōhoku quake epicenter has significantly more low-lying areas, particularly in the vicinity of Sendai, the capital city of Miyagi Prefecture. In contrast, the terrain of the Washington, Oregon, and northern California coast includes a coastal mountain range that descends rapidly to the shoreline with fewer low-lying areas.

There are several communities in low-lying areas along the Washington, Oregon, and northern California coast with populations at risk of tsunami inundation in this scenario (estimates of 50,000 or more and fatality estimates of 1,700 or more. See section on Tsunami Modeling). In comparison, Japan has far more low-lying areas that are far more densely populated. The city of Sendai alone has a population of more than 1 million people and, according to a study by Risk Management Solutions, Inc.;[5] the Pacific coastline of Japan north of Tokyo has over 1.3 million people living within two kilometers of the coast.

Table 3-1 compares the relative population density of the Tōhoku earthquake and tsunami zones to the corresponding Cascadia scenario earthquake and tsunami zones.

Table 3-1. Population 100 miles north and south of the shoreline point closest to epicenters for Tōhoku, Japan, and the Cascadia scenario

Distance from Coastline	Location	Population (LandScan World 2008[6])
5 km	Tōhoku	769,031
5 km	Cascadia	131,851
5 km (below 10 m elevation)	Tōhoku	515,605
5 km (below 10 m elevation)	Cascadia	87,224
40 km	Tōhoku	3,034,373
40 km	Cascadia	204,264
80 km	Tōhoku	5,113,973
80 km	Cascadia	547,963

LandScan World 2008[7] data shows a factor of 6 to 10 times the population density for areas in Tōhoku as compared with equivalent areas in Cascadia.

As a result of the relative lack of low-lying areas combined with a significantly less dense population distribution as compared with those areas affected by the Tōhoku tsunami, the tsunami resulting from the Cascadia earthquake scenario is not expected to have nearly the impact in terms of fatalities or damaged or destroyed infrastructure seen in the Tōhoku tsunami.

[5] www.rms.com/Publications/RMS_JapanMortalityStudy.pdf, accessed September 2011.
[6] www.ornl.gov/sci/landscan, accessed September 2011.
[7] www.ornl.gov/sci/landscan, accessed September 2011.

3.4.3 Shaking Susceptibility

3.4.3.1 Building Codes

The State of California has had stringent building codes in place for many decades. The States of Washington and Oregon have more recently implemented building codes to withstand earthquakes. These building codes, where implemented, improve the earthquake survivability of structures as well as minimize the loss of life among occupants of those structures, even for those structures that are irreparably damaged. Most buildings in California and newer buildings in Washington and Oregon should be better able to survive or at least withstand the shaking effects of the Cascadia scenario.

Japan has also had highly stringent earthquake building codes in place for a very long time. The results of these are borne out in the relatively limited damage and structural loss in the areas affected by the 9.0 Tōhoku earthquake. A stark comparison can be made between the survivability of structures in the recent (2010) quakes in Haiti and Chile. Haiti, with virtually no building codes, suffered huge fatality rates in excess of 200,000 due to widespread structure collapse from a 7.0-magnitude quake. In contrast, the 8.8-magnitude quake in Chile resulted in 500 fatalities and left many buildings standing despite being subjected to a vastly stronger quake.

3.4.3.2 Population and Infrastructure Density

Population and infrastructure density in the affected areas of the Tōhoku earthquake far exceed that of areas impacted by the Cascadia earthquake scenario. Again, referencing Table 3-1 above, the coastal areas in particular, where shaking would be greatest, are substantially less populated and contain less critical infrastructure than the corresponding coastal areas affected in Japan. Even looking as far inland as 80 km, the population numbers and assumed infrastructure density are still higher by nearly a factor of ten. For this reason, the overall loss of life and loss of infrastructure is expected to be substantially less for the Cascadia scenario than for the Tōhoku earthquake simply due to the lesser concentration of people and infrastructure, particularly along the coastline.

Figures 3-11 and 3-12 compare populations within and outside the tsunami inundation range for both Tōhoku in Japan and Washington, Oregon, and northern California in the United States. Note the scale and relative size of the prefectures in Japan compared to the corresponding counties in the United States. The prefectures are all much smaller and closer to both the coast and the earthquake epicenter. (Note these maps are not drawn to the same scale.) The Japanese prefectures in Japan are thus more likely to suffer shaking damage compared to the U.S. counties that reach much farther inland and distant from the epicenter.

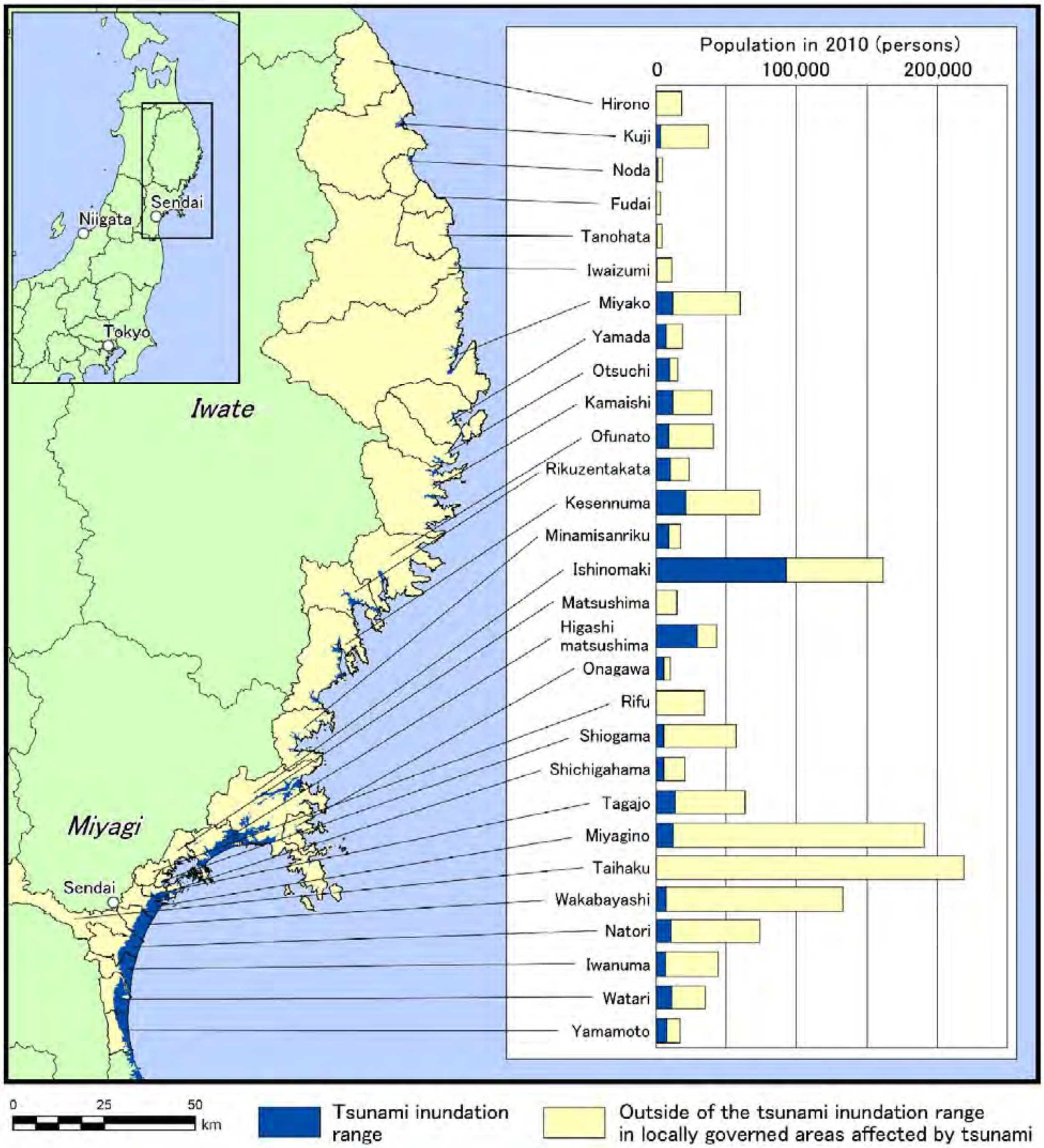

Figure 3-11. Population of prefectures within the tsunami inundation range[8]

[8] Graphic from The 2011 East Japan Earthquake Bulletin of the Tōhoku Geographical Association, 7 May 2011.

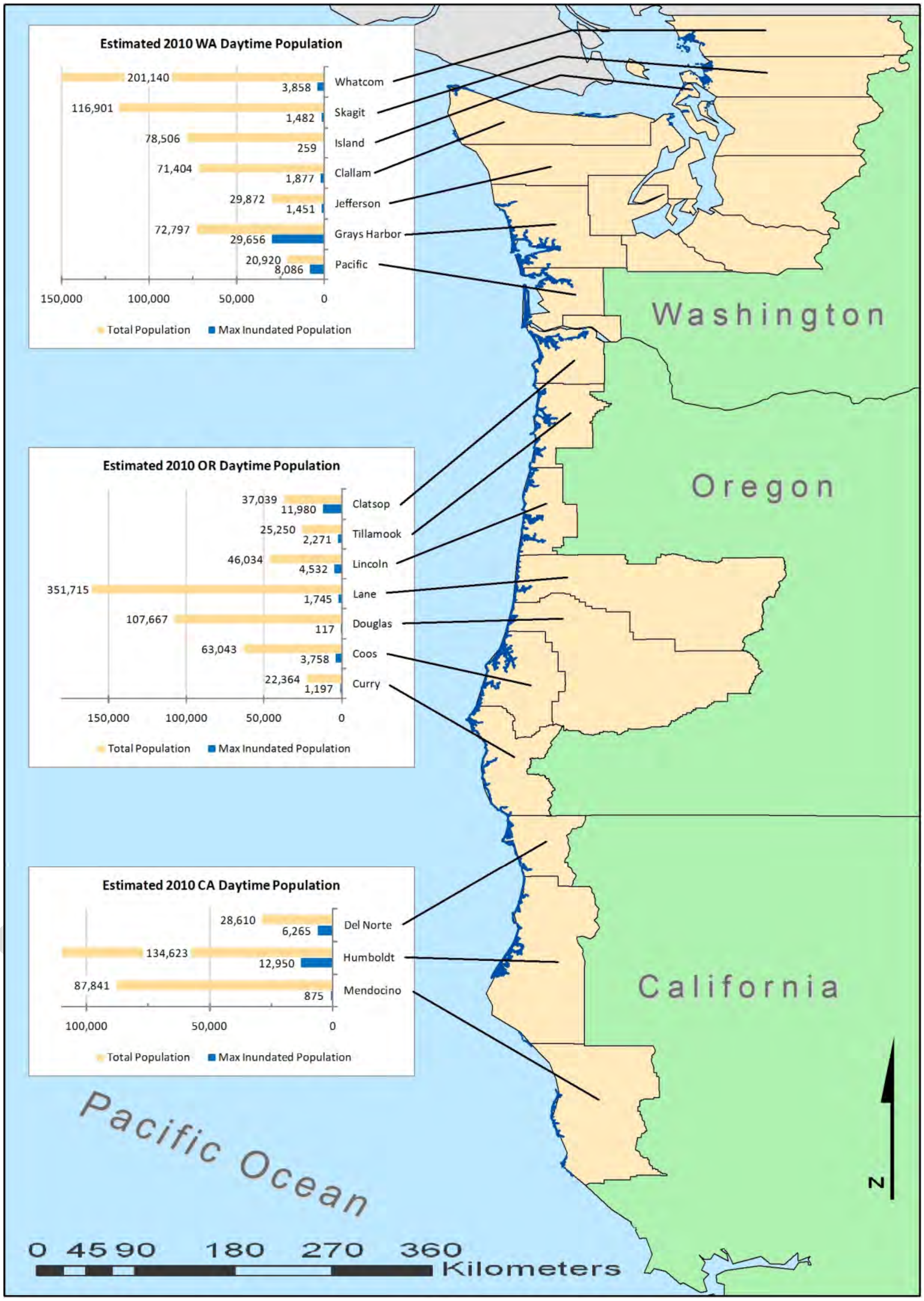

Figure 3-12. Total population and population at risk of tsunami inundation for Pacific Northwest counties

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4 Assumptions

For the CSZ effort, the constructed scenario is the basic planning assumption that underlies the analysis. In particular, the following assumptions are made with respect to the 9.0-magnitude earthquake:

1. Epicenter 95 miles west of Eugene, OR (45.73°N, 125.12°W)
2. Length: 850 km, width: 100 km, depth: 2 km
3. Strike: 345°, dip: 13°, slip 90°
4. Moment: 3. $55x10^{29}$ dyne-cm
5. Fault ruptures to the north at 2. 5 km/second
6. Event occurs February 6, 2012, at 09:41 am PST (outside of tourist season)
7. No aftershocks

Although various analytical groups perform many modifications to the datasets they use, in general they are not resourced to verify all elements of the datasets employed. Thus there is an unavoidable assumption that the data provided, such as HSIP Gold and commercial sources (discussed in Section 0), are accurate with respect to the scenario under analysis.

Simplifying assumptions about the availability of restoration workers and restart times for operable infrastructure are required. The assumptions that the normal number of workers will be available for electrical restoration and typical restart timelines for chemical facilities experiencing unplanned shut down underlie a given scenario under analysis. These assumptions do not apply to facilities directly damaged by the earthquake or tsunami, but rather those facilities forced down by loss of electrical supply or minor flooding.

All models have numerous assumptions embedded within them. Given the number of models employed in this analysis and which will be employed in future analyses, it is not feasible to list all assumptions. Using models with widespread testing, experience, and validation mitigates this issue, as the embedded assumptions are tested through such use.

One key model employed in this analysis is Hazus 2.0 from FEMA. It was assumed that ground shaking would last four to six minutes, and the possibilities of liquefaction and landslides were included in the runs. Modifications to liquefaction and landslide parameters for long-duration ground motion were included as prescribed by Hazus technical staff.

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5 Analytical Methodology and Impacts

The basic analytical method employed in this study is to use the direct physical effects (area of seismic shaking, inundation zone) to determine the direct impacts on population and infrastructure. Infrastructure modeling and analysis can then be employed to find the disruptions to services and key cascading impacts. These results will then be employed to estimate impacts to the response environment and the economy.

5.1 Earthquake and Tsunami Effects Modeling

Damage to facilities from earthquake shaking is computed by Hazus 2.0, accounting for liquefaction susceptibility and landslide susceptibility. Damage is represented as a probability distribution over five damage states: None, Slight, Moderate, Severe, and Complete. These damage states are defined differently for each infrastructure and asset type, but conceptually represent similar levels of damage. The expected damage state is reported and in many cases, the 90th-percentile damage state is given to contrast the average case to the nearly worst case. The 90th-percentile damage state is the case where 90 times out of 100, the damage is less severe. The average damage case typically overlooks instances of low-probability damage, while the 90th-percentile damage case tends to depict more severe damage.

At this time, no analytical foundation exists to combine the damage effects of ground shaking with a tsunami; hence they are reported separately. As noted above, Hazus defines damage from an earthquake as a probability distribution over five damage states. As the Crescent City, CA, example below shows, tsunami damage is described primarily in terms of flood inundation levels. The current RDMB-NISAC tools describe the flood-state condition for an asset rather than its probability of damage. Thus for Crescent City, CA, the tsunami modeling predicts that the Del Norte County Sheriff's Department will be under at least 12 feet of water, but a probability of damage is not provided. However, analysts can clearly determine that the Sheriff's Department will sustain substantial damage. On the other hand, the Crescent City Police Department will be flooded by up to one foot of water, resulting in some degree of slight damage.

5.1.1 Ground Shaking and Liquefaction

The USGS 2011 Cascadia 9. 0 event ShakeMap was used as a baseline for modeling this event scenario. The ShakeMap shows a 9. 0 earthquake off the coast of Oregon along the Cascadia fault line, which runs roughly parallel to the coast, ranging from 10 to 50 miles offshore. The earthquake in this scenario shook the seafloor and land areas. Damage to manmade structures will result both from the energy of shaking as well as possible amplified shaking and ground displacement due to liquefaction. A sizable tsunami will also result, causing damage along the coastline.

Effects of the earthquake are assessed as follows. Ground shaking data provided by the USGS ShakeMap is shown in Figure 3-2. Ground surface factors are combined to generate liquefaction susceptibility data for the regions of interest. Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Surface geology and the degree of water saturation determine the local susceptibility to liquefaction. Liquefaction conditions can exacerbate earthquake damage and are important elements to include in the assessment of earthquake effects. Different building structures and construction materials have a substantial affect on a structure's resistance to being damaged. Shaking, liquefaction, and building structure types combine to create what can appear to be a non-uniform distribution of resulting damage states. Some higher liquefaction susceptibilities, particularly in the Willamette Valley and the Puget Sound areas, tend to increase the potential for structural damage; however, the substantial distance of the epicenter from these areas help reduce the overall impacts of the earthquake for these areas that include the two major cities of Seattle and Portland. Figure 3-4 shows the potential for liquefaction across the region.

5.1.2 Tsunami Effects

Offshore tsunami models from the National Oceanic and Atmospheric Administration (NOAA) combined with RDMB-NISAC onshore inundation modeling show that a considerable tsunami wave would result and produce significant impact inundation risk to the coastal areas. Although there are no large cities immediately on the coast, there are several medium-sized to small communities that would see inundation and significant localized damage. Due to the proximity of the quake, coastal communities may have as little as 15 minutes warning before the tsunami strikes, in addition to 5 minutes of intense ground shaking, which may result in loss of life for those who are not able to evacuate to nearby higher ground. Some areas lack nearby high ground for shelter from a Tsunami.

Infrastructure assets in the tsunami inundation area may be subject to damage based on either construction type or flooding. The force of the incoming wave may in some cases be strong enough to destroy concrete structures. Because there is not a heavy concentration of people or infrastructure along the coast and because of the relatively steep rise in terrain immediately inland of much of the coastal region, little infrastructure damage would occur that would have a national or regional impact.

Tsunami models show that there would be significant attenuation of the tsunami effects as it progresses into the mouth of the Columbia River and into Puget Sound. Consequently, little tsunami effects are expected to impact the more inland reaches, and no significant tsunami impacts are forecast for the Portland and Seattle ports and waterfronts.

5.1.3 Tsunami Modeling

A tsunami is a very long wavelength wave of water generated by sudden displacement of the seafloor or disruption of any body of standing water. Tsunamis are sometimes called seismic sea waves, although they can be generated by mechanisms (such as volcanoes) other than earthquakes. Because tsunamis occur suddenly, often without warning, they are extremely dangerous to coastal communities. As a tsunami leaves the deep water of the open sea and arrives at the shallow waters near the coast, it undergoes a transformation. The velocity of the tsunami is related to the water depth; thus, as the depth of the water decreases, the velocity of the tsunami decreases. The total energy of the tsunami, however, remains constant. Furthermore, the period of the wave remains the same, and, thus, more water is forced between the wave crests, causing the height of the wave to increase. Because of this wave shoaling effect, a tsunami that was imperceptible in deep water may grow to have wave heights of several meters.

Analysis of the Cascadia scenario considers the effects of the earthquake-induced tsunami that could strike the Pacific West Coast from California to Alaska. These analyses rely on the modeling effort of NOAA's National Tsunami Hazard Mitigation Program as developed for the Pacifex 11 exercise conducted in March 2011 and based on a 9. 0-magnitude Cascadia earthquake similar to the one defined by the USGS. The tsunami modeling provided marigrams (plots of tsunami wave amplitude as a function of time) for several locations along the West Coast that enabled RDMB-NISAC modeling of inundation in terms of depth and velocity.

To assess adequately the timing, extent, depth, and velocity associated with a tsunami event, RDMB-NISAC used a two-dimensional model based on the fundamentals of free surface fluid dynamics to evaluate coastal tsunami impacts. The inputs required for the coastal tsunami model included representation of bare earth (bathymetry and topography), coastal water surface elevation at the time of the tsunami event, and a boundary condition representing the wave amplitude at near-coast locations over the entire simulation period. RDMB-NISAC used National Geophysical Data Center bathymetric and topographic data for each of the locations. The datum used for each location was mean high water, a more conservative assumption relative to flooding than mean sea level. The boundary conditions used to represent the tsunami wave were obtained from the PACIFEX 11 simulation results. RDMB-NISAC obtained marigrams[9] from the modeled tsunami at near-coast locations, which were used as boundary conditions in the higher-resolution two-dimensional inland inundation model. For some sites, no directly associated marigram was available, so the nearest marigram was used to set the boundary conditions for the tsunami simulation. This injects some degree of error into the assessment of the inundation and velocities; however, the error in assessing infrastructure damage, injuries, and deaths is small, as long as the marigram is relatively close to the site. Appendix C provides detailed discussion of the modeling approach used when no marigram is available.

Results from the tsunami model included time-series depth and velocity. Analysts used these results to evaluate infrastructure and population impacts to affected communities. Damage and casualty effects from inundation are based on the method described in Penning-Rowsell et al. [10]

> The main factors that affect death or injury to people during floods include flow velocity, flow depth, and the degree to which people are exposed to the flood. The exposure potential is related to such factors as the ''suddenness'' of flooding (and amount of flood warning), the extent of the floodplain, people's location on the floodplain, and the character of their accommodation. In addition, risks to people are affected by social factors including their vulnerability and behavior. A methodology is based on defining zones of different flood hazards and, for each zone, estimating the total number of people located there, the proportion who are likely to be exposed to a flood, and the proportion of those exposed who are likely to be injured or killed during a flood event.

Table 5-1 lists the locations that RDMB-NISAC modeled for tsunami damage. RDMB-NISAC analyzed sites that have significant tsunami vulnerability. Publications of the USGS by N. Wood[11] document vulnerability to tsunamis for municipalities along the Washington and Oregon

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[9] The authors are grateful to the Pacific Marine Environmental Laboratory for sharing Pacifex 11 data.

[10] Penning-Rowsell, E., P. Floyd, D. Ramsbottom, and S. Surendran, "Estimating Injury and Loss of Life in Floods: A Deterministic Framework," Natural Hazards 36, 43–64, 2005.

[11] USGS Web page, "Variations in City Exposure and Sensitivity to Tsunami Hazards in Oregon," pubs.usgs.gov/sir/2007/5283/, accessed June 22, 2011; USGS Web page, "Variations in Community Exposure and Sensitivity to Tsunami Hazards on the Open-Ocean and Strait of Juan de Fuca Coasts of Washington," pubs.usgs.gov/sir/2008/5004/, accessed June 22, 2011.

coast. According to Wood, in Oregon, 64 percent of the population living in potential tsunami inundation zones reside in one of the 26 incorporated municipalities. For Washington, 70 percent live in the 13 incorporated municipalities or 7 Indian reservations. For Oregon and Washington, the RDMB-NISAC analysis covers 55 percent and 66 percent, respectively, of the population living in the tsunami zones. For California, about 21,000 live in the tsunami inundation zone for Del Norte, Humboldt, and Mendocino counties; the analysis covers about 50 percent of that population.

Table 5-1. Tsunami modeling and damage estimation performed at these sites

Alaska	California	Oregon	Washington
Homer	Crescent City	Cannon Beach	Bellingham
Kodiak	Eureka/Humboldt	Coos Bay	Moclips-Westport
Nikolski		East Astoria	Neah Bay
Sand Point		Newport	Port Angeles
Seward		Port Orford	Seattle
Sitka		Gearhart/Seaside	Grays Harbor
Unalaska		Warrenton	South Bend/Raymond
Yakutat		Rockaway Beach	
		Lincoln City	
		Waldport/Yachats	

The modeling results for Crescent City, CA, are presented here as a representative of the analysis results. Figure 5-1 shows the tsunami wave amplitude as a function of time at a location just off the coast from Crescent City, CA. The wave amplitude is between 4. 5 and 5. 0 meters. As the wave moves toward shore, the wave height increases, up to a factor of three. As it crosses the shoreline it moves inland, inundating the land until the energy of the wave is depleted. Multiple pulses re-flood the inundation area roughly every hour for 3 hours.

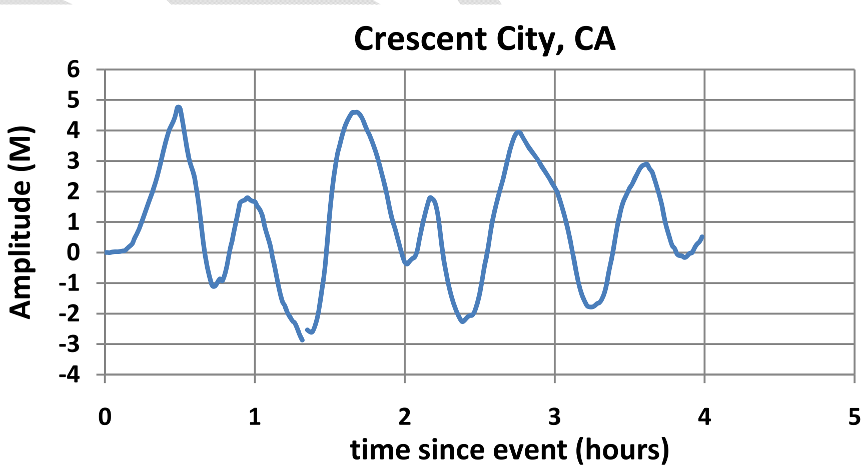

Figure 5-1. Crescent City, CA, seismic event marigram

Figure 5-2 shows damage contours, depicting areas in which certain building types would fail due to inundation. Buildings are assumed to fall into one of the following categories: large concrete, concrete, well-built masonry, well-built timber, and poorly constructed. The combination of building category, water depth, and wave velocity determine the actual damage. The damage categories are hierarchical, so that the damage zone that causes concrete buildings to fail also causes failure in well-built masonry, well-built timber, and poorly constructed buildings. RDMB-NISAC does not have the data to assess the building category of a structure, but if a well-built masonry structure is in the zone where concrete buildings fail, then the damage to the well-built masonry structure is also assumed to be complete.

Figure 5-2. Predicted areas where different building types will collapse in Crescent City, CA

Figure 5-3 shows the predicted inundation depth and impacted critical infrastructure assets for Crescent City, CA; Figure 5-4 shows impacted emergency services facilities. Table 5-2 lists the population at risk (PAR) for nighttime and daytime. Estimates of injuries and deaths are provided based on a U. S. Army Corps of Engineers (USACE) methodology. Table 5-3 lists the number of facilities impacted across various sectors.

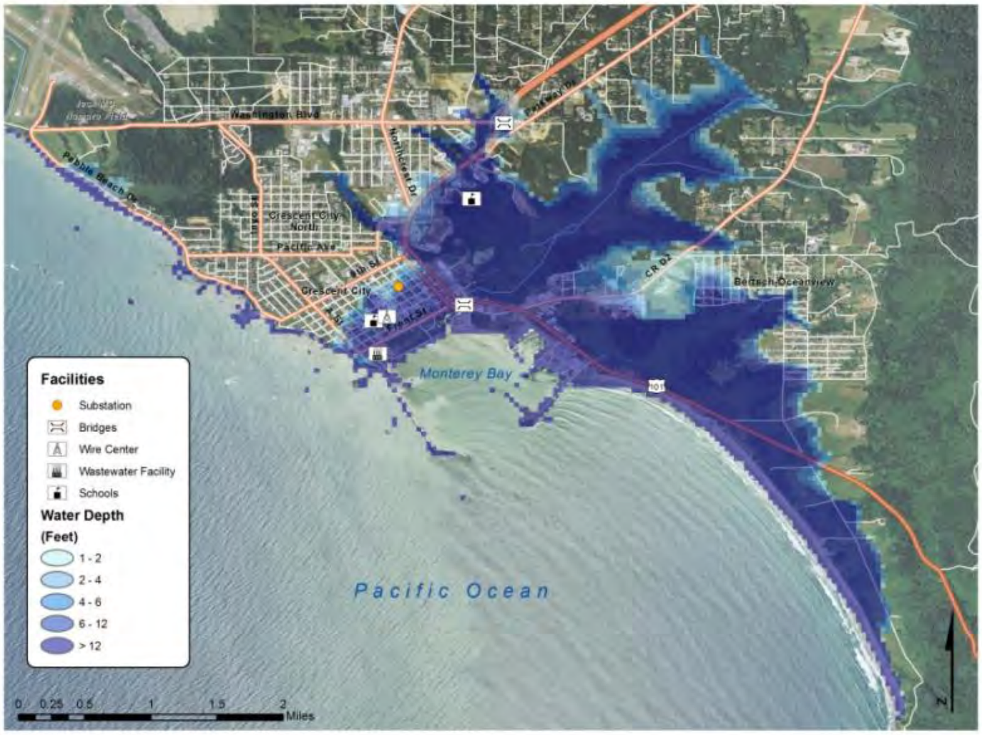

Figure 5-3. Expected tsunami inundation depths and facility impacts for Crescent City, CA

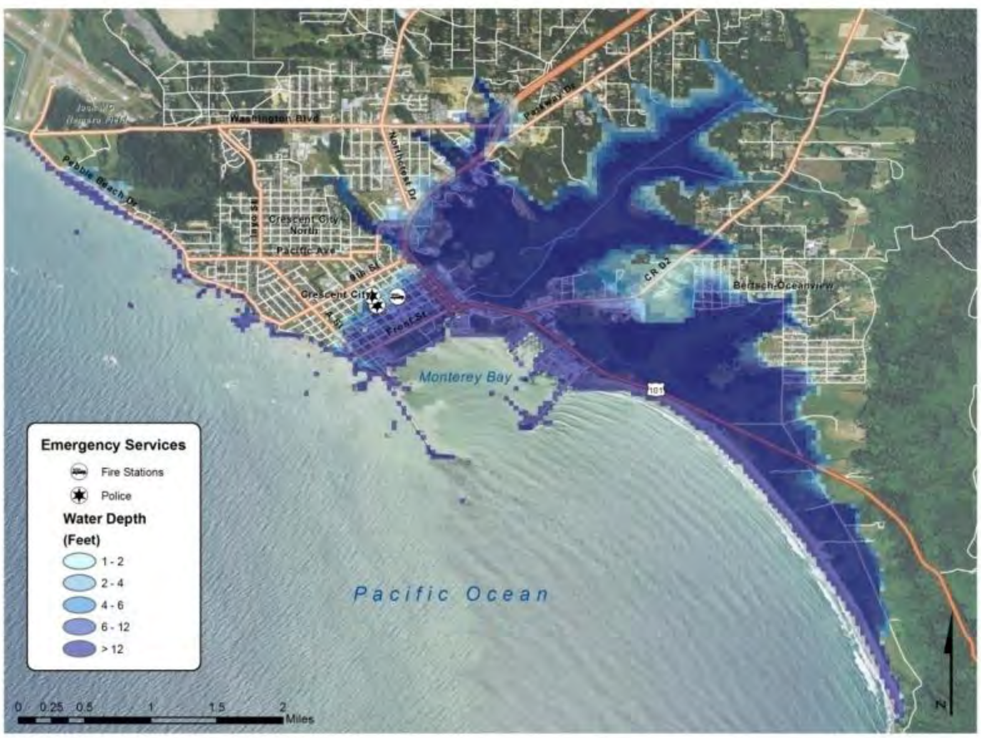

Figure 5-4. Expected tsunami inundation and emergency service impacts for Crescent City, CA

Table 5-2. Population at risk in Crescent City, CA

Population Impacts	Number of Population at Risk (PAR)
Nighttime PAR	3190
Daytime PAR	5180
Injuries	780
Deaths	910

Table 5-3. Impacted sectors in Crescent City, CA

Sector	Number of Facilities
Water/Wastewater	1
Emergency Services	4
Transportation	8
Schools	3
Energy	1
Telecommunications	1

5.2 Population Impacts

5.2.1 Ground Shaking Impacts on Population

Table 5-4 provides a summary of the total injuries and total deaths due to earthquake effects for the West Coast counties identified for this analysis. Hazus predicts a total of 24,662 injuries and 1,132 deaths as a result of the earthquake. Of the deaths, 411 are projected for Washington, 674 for Oregon, and 47 in northern California. The injuries are distributed with 9,508 in Washington, 14,109 in Oregon, and 1,045 in California.

Table 5-4. Summary of total injuries and total deaths due to earthquake effects

County	Total Injuries	Total Deaths
California		
Butte	7	0
Colusa	1	0
Del Norte	196	10
Glenn	6	0
Humboldt	744	36
Lake	1	0
Mendocino	17	1
Napa	1	0
Shasta	41	0
Siskiyou	4	0
Solano	1	0
Sonoma	1	0
Sutter	2	0
Tehama	16	0
Trinity	5	0
Yolo	1	0
Yuba	1	0

County	Total Injuries	Total Deaths
Oregon		
Benton	821	46
Clackamas	442	8
Clatsop	949	62
Columbia	159	7
Coos	1888	126
Curry	591	36
Deschutes	2	0
Douglas	407	15
Hood River	2	0
Jackson	165	2
Jefferson	1	0
Josephine	418	20
Klamath	3	0
Lane	1415	59
Lincoln	1076	68
Linn	384	16
Marion	943	39
Multnomah	1643	54
Polk	326	15
Tillamook	427	26
Wasco	2	0
Washington	1590	55
Yamhill	455	20
Washington		
Benton	1	0
Chelan	1	0
Clallam	322	15
Clark	641	15
Cowlitz	617	34
Douglas	1	0
Grays Harbor	1367	93
Island	41	1
Jefferson	32	1
King	2699	101
Kitsap	353	11
Kittitas	1	0
Lewis	410	21
Mason	193	9
Pacific	461	31
Pierce	941	32
San Juan	4	0
Skagit	133	6
Skamania	1	0
Snohomish	582	13
Thurston	643	27
Wahkiakum	25	1
Whatcom	35	0
Yakima	4	0
Total	24662	1132

Most of the injuries and deaths in Washington are in the Seattle area (King County), followed by Grays Harbor County on the Pacific Coast. For California, Humboldt County is by far the most affected. Oregon is the state with the most widespread affects, with most injuries occurring in Coos, Lane, and Lincoln counties (on the Pacific Coast) and in the Portland metropolitan area (Multnomah and Washington counties). Most injuries and deaths take place in the Portland and Seattle metropolitan areas.

5.2.2 Tsunami Impacts on Population

Table 5-4 provides a summary of the initial modeling results for population at risk, injuries, and deaths in the calculated inundation areas. Appendix D provides results by individual location. Overall deaths and injuries in Alaska is estimated to be zero, as the state has more than four hours warning and marigram levels are less than a meter in most cases. Some sites in Alaska have inundation levels of 0. 5 meters or less.

Table 5-4. Summary table of tsunami model results for casualties and deaths

Location	Nighttime Population at Risk (PAR)	Daytime PAR	Injuries	Deaths
Alaska				
Homer	5010	5010	0	0
Kodiak	6130	6130	0	0
Nikolski	20	20	0	0
Sand Point	980	980	0	0
Seward	2700	2700	0	0
Sitka	8890	8890	0	0
Unalaska	4380	4380	0	0
Yakutat	670	670	0	0
California				
Crescent City	3190	5180	780	910
Eureka-Humboldt	180	180	10	10
Oregon				
Cannon Beach	370	990	110	240
Coos Bay	210	150	30	30
East Astoria	820	960	20	10
Newport	250	420	50	20
Port Orford	40	40	10	10
Gearhart/Seaside	720	730	50	10
Warrenton	2720	3840	550	280
Rockaway Beach	75	70	4	1
Lincoln City	370	420	70	40
Waldport/Yachats	80	90	3	2
Washington				
Bellingham	60	290	10	0
Grays Harbor	650	780	12	1
Moclips/Westport	5500	4920	430	140

Location	Nighttime Population at Risk (PAR)	Daytime PAR	Injuries	Deaths
Neah Bay	20	10	0	0
Port Angeles	40	50	10	0
Seattle	2110	7100	190	50
South Bend/Raymond	750	2500	7	4
Totals	46,935	57,500	2,346	1,758

California sustains over 900 deaths due to short warning time and a large wave height striking the coastal cities. Oregon has approximately 650 deaths, mostly due to the vulnerabilities of Cannon Beach and Warrenton. Washington sustains approximately 200 deaths due mostly to the vulnerability of the Moclips-Westport area. While 50 deaths are estimated for Seattle, this may be an overestimation because the inundation level is expected to be less than 0.5 meters.

5.3 Infrastructure Impacts

The Hazus model estimated damage to each infrastructure asset within a given sector/subsector. The results from the Hazus model are broken into five damage state categories, given in a percentage, for each asset. The five damage states are None, Slight, Moderate, Severe, and Complete. RDMB-NISAC then applied a methodology to estimate a likely damage state for each infrastructure asset based upon the Hazus calculations. For these calculations, the assumed date of February 6 indicates wet soils, which was reflected in the Hazus input as an increase in the susceptibility category over dry conditions, and the use of wet landslide susceptibility categories.

5.3.1 Electrical Disruption and Restoration

Generating plants, including thermal plants, gas turbines, hydroelectric plants, and nuclear power plants, are the main supply components of electric power infrastructure systems. Power is transmitted from these supply components through power transmission lines to substations and switching stations to allocate power to the served community.

5.3.1.1 Ground Shaking Effects

Ground shaking can affect the structural integrity of electric power assets through various modes of permanent ground deformation: liquefaction, lateral spreading, or vertical displacement. The RDMB-NISAC model only examines generation, switching, and substation assets; no transmission line assets are assessed. When an electric power asset is damaged, it may either continue to operate at a reduced capacity or lose functionality. For example, if a substation reaches a moderate or more severe damage state, power utility companies have indicated that this facility will most likely lose complete functionality. RDMB-NISAC calculates damage probability distributions using its Fragility Analysis Tool in accordance with the damage curves defined in Hazus. Rather than assess the expected damage state, a number of cases are examined (in this instance, 20 cases) for which a damage state is assigned to each asset according to the damage probability distribution. In each case, power system analysis tools are used to estimate the lost generation and unserved demand over the entire network.

Based on the configuration of the electric power network and damages to certain network assets, some areas may experience power outages because they are isolated from the grid, even though assets within these isolated regions are undamaged. In such cases, the affected assets are termed outaged, because they provide no electric power until they are reconnected to the working electric grid. Outaged assets include both substations and generating units. Based on a measure of the electric power disruption, the cases are assessed to determine the median damage case and the maximum damage case. The median damage case roughly corresponds to the expected damage case and the maximum damage case roughly corresponds to the 90^{th}-percentile damage case.

Table 5-5 lists the number of electric power assets in each damage category for the median case. The number of outaged assets is shown under the None/Slight damage state category. Damaged assets under the Moderate, Extensive, or Complete damage state categories are also noted in the table. Of these assets, 58 generation units are undamaged but out of service, resulting in a generation loss of 3.4 gigawatts (GW), while 396 essentially undamaged substations are expected to be out of service, resulting in 4.6 GW of unserved load. A total of 122 generators are removed from service by the earthquake, resulting in a loss of 7.2 GW of generation to the electrical system. A total of 1,004 substations are removed from service by the earthquake, resulting in 10.7 GW of unserved customer demand.

Table 5-5. Asset counts, lost generation, and unserved load for each damage state using the median damage case

Damage State	Electric Generators			Substations		
	Outaged	Damaged	Generation Lost (GW)	Outaged	Damaged	Unserved Load (GW)
None/Slight	58	n/a	3. 4	396	n/a	4. 6
Moderate	n/a	45	3. 2	n/a	365	3. 8
Extensive	n/a	5	0. 03	n/a	93	0. 6
Complete	n/a	14	0. 5	n/a	150	1. 7

Figure 5-5 and Figure 5-6 show the geographical locations of the damaged and outaged assets of the electric power substations and generators, respectively, for the median damage case.

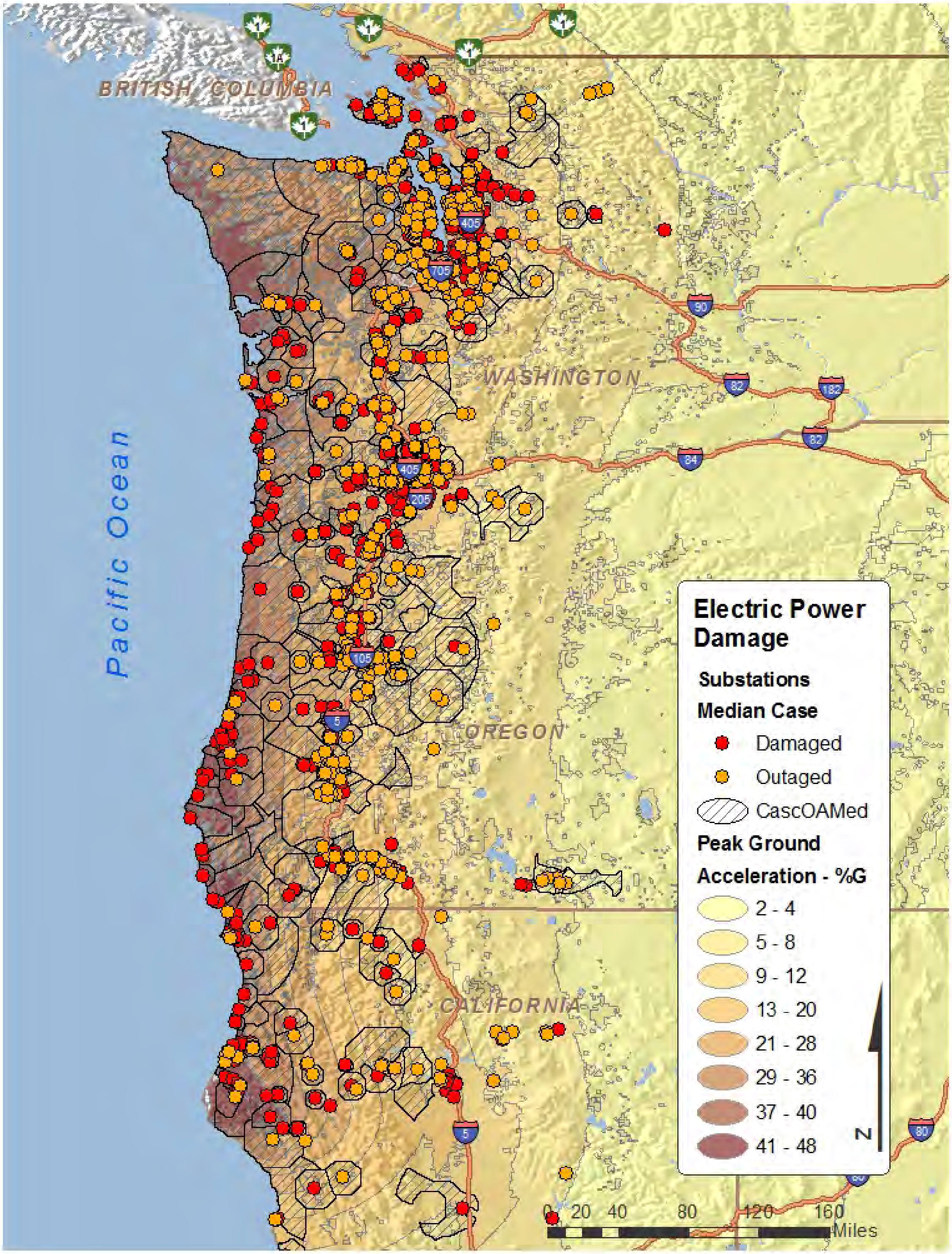

Figure 5-5. Predicted outage areas and earthquake-induced damage (including outaged assets) to electric power substations for the median damage case

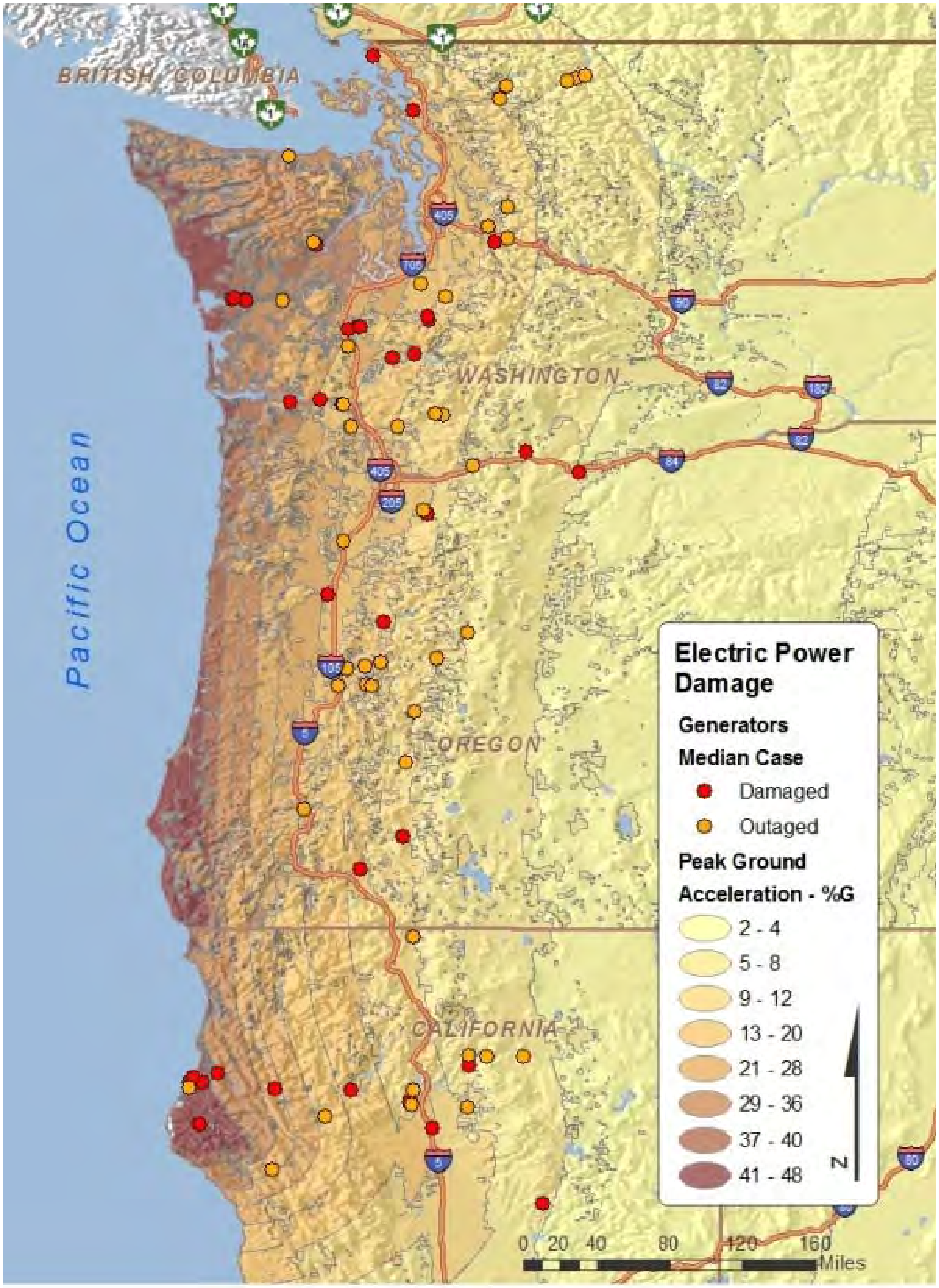

Figure 5-6. Earthquake-induced damage (including outaged assets) to electric power generators for the median damage case

Table 5-6 lists the number of electric power assets in each damage category for the maximum damage case. Of these assets, 63 generation units are undamaged but out of service, resulting in a loss of 4.0 GW, while 557 essentially undamaged substations are expected to be out of service, resulting in 6.5 GW of unserved load. A total of 123 generators are removed from service by the earthquake, resulting in a loss of 6.8 GW of generation to the electrical system. A total of 1,142 substations are removed from service by the earthquake, resulting in of 11.8 GW unserved customer demand.

Table 5-6. Asset counts, lost generation, and unserved load for each damage state using the maximum damage case

Damage State	Electric Generators			Substations		
	Outaged	Damaged	Generation Lost (GW)	Outaged	Damaged	Unserved Load (GW)
None/Slight	63		4. 0	557		6. 5
Moderate		44	1. 9		378	3. 5
Extensive		2	0. 3		74	0. 6
Complete		14	0. 6		133	1. 2

The locations of damaged and outaged substation (and generator) assets for the maximum damage case are shown in Figure 5-7 and Figure 5-8, respectively.

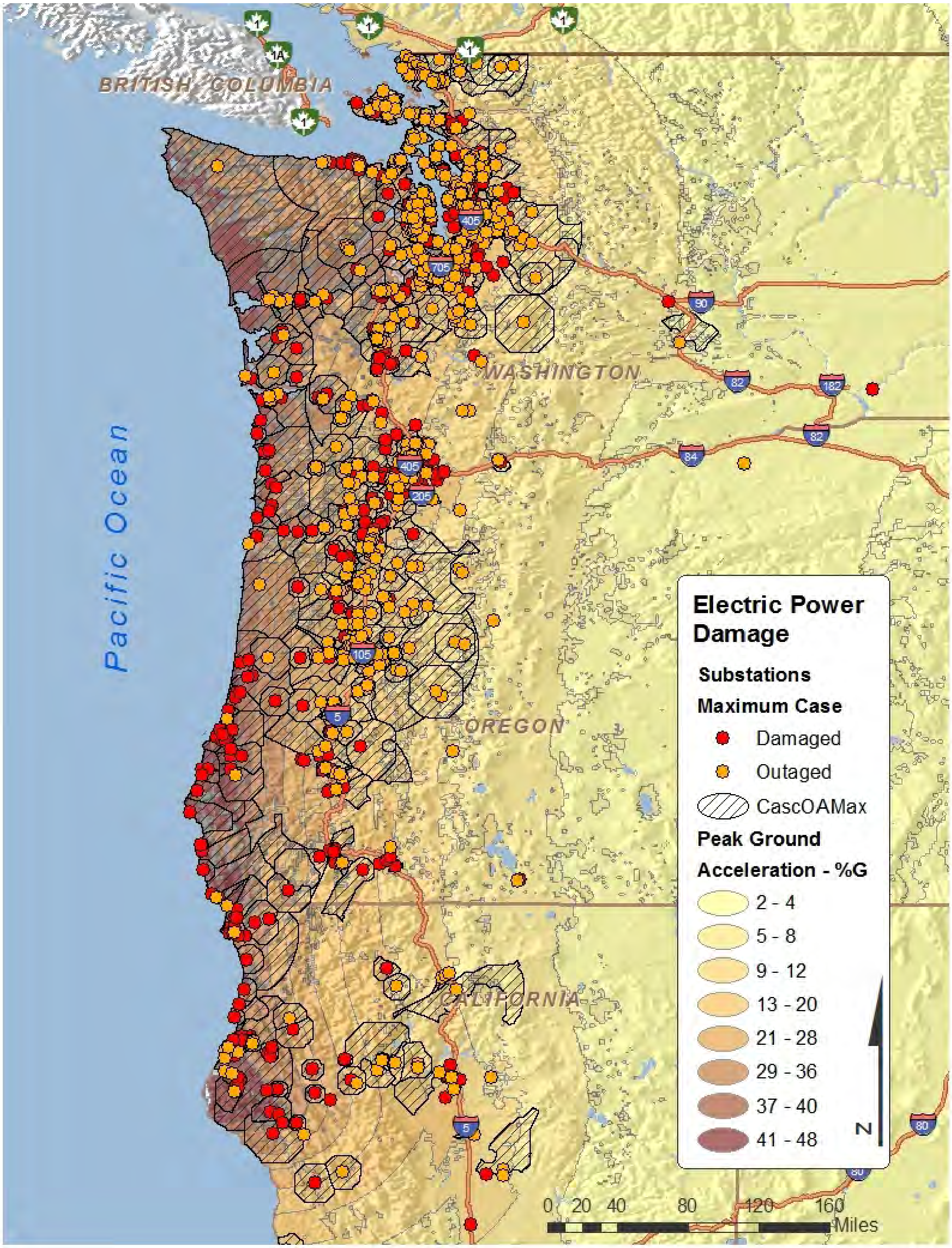

Figure 5-7. Predicted outage areas and earthquake-induced damage (including outaged assets) to electric power substations for the maximum damage case

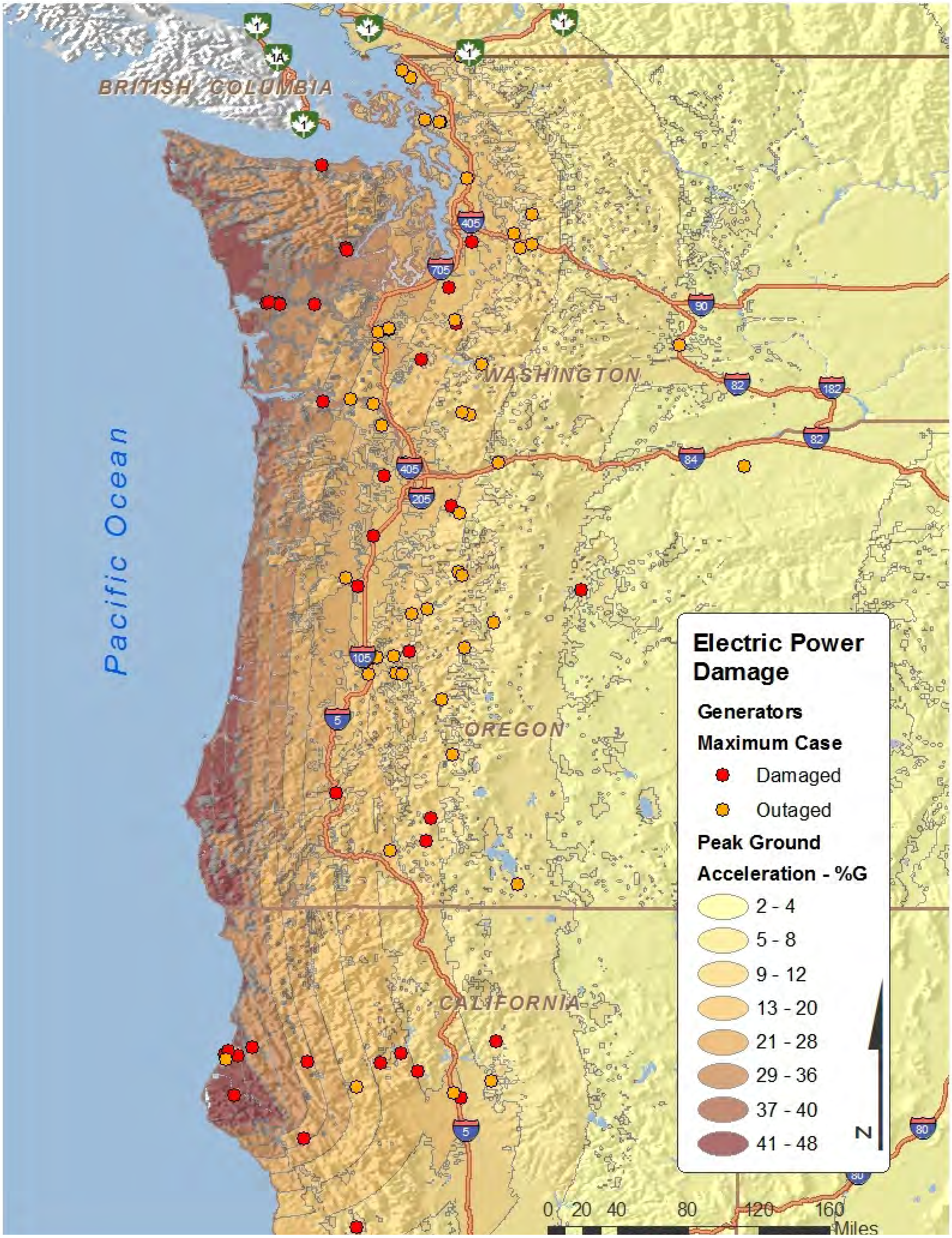

Figure 5-8. Earthquake-induced damage (including outaged assets) to electric power generators for the maximum damage case

On average over the 20 cases, the electric power system loses 6 GW of generation and 11 GW of demand out of a total system load of 170 GW. This results in a surplus generation of 5 GW. A generation surplus in an electric power system will cause operating generators to spin faster, a situation the system will not tolerate. The system is designed to automatically self-correct by taking units off line. This will happen within minutes of the earthquake event. All of the cases (Seattle and Tacoma, WA; Portland, OR; Vancouver Island, British Columbia, and every city within 100 miles of the Pacific coastline in Oregon and Washington) will experience partial blackout, with a few additional blackout areas in northwest California. Depending on the power utilities' ability to inspect damage and restore assets, power will be restored in one to eight days, beginning after the damage assessment is completed. Some additional electrical islanding, i.e., system breaking into collections of smaller isolated pieces, could occur. A small possibility of a complete blackout of the West Coast exists, but it is not yet quantified. This analysis is performed using tools based on the assumption of steady-state network conditions; thus, transient condition effects are not modeled.

5.3.1.2 Cascading Effects in Electric Power

The loss of a large portion of the electric grid in the northwestern United States within a relatively short timeframe would have a profound effect on the functioning portion of the electrical system. Analysis results indicate that earthquake damage would result in an excess of 5 GW of generation compared to demand. Under these circumstances, because generation and demand must balance for the grid to remain stable, the grid is designed to automatically rebalance by generators tripping offline. System operators may attempt to dispatch generating plants to prevent an automatic removal of generating plants from service, which could result in transmission line overloads, exacerbating an already serious situation.

Because the electric power solver (the modeling tool) operates on a steady-state basis, these results are a snapshot in time. In this case, the snapshot corresponds to the state of the system at its peak demand. The results that are obtained at this time represent the worst case, when the system is normally under the most stress. If the earthquake were to occur at a less stressful time, such as in the morning, on the weekend, or in the spring or fall, the effect would be much less pronounced. For example, on a summer day in the early morning, the total system demand for the western grid is only about two-thirds the demand at summer peak—usually in the late afternoon of the hottest day of the year. The system can withstand much more of a shock at off-peak times.

When the topology of the electrical system is changed due to the loss of generation and demand, system problems can result. The system must have energy balance or it will collapse (blackout). Transmission-line and transformer overloads and low voltages can also result. Unmitigated transmission-line overloads can lead to severe system effects, because an unattended overload eventually results in the transmission line being removed from service. This can cause other transmission lines to overload, resulting in a cascading effect that can lead to system collapse. This was the cause of the 2003 blackout of the northeastern United States and Canada.

Low voltage is also an unstable condition. A low-voltage condition is present when the lights dim. Although it does not damage light bulbs, electrical motors can be damaged if the voltage is not maintained at proper levels. Utilities will open breakers and shed load to protect customers from the effects of low voltage if they are unable to mitigate through other means. These include switching capacitors online, adjusting taps on tap-changing transformers, and dropping interruptible customers.

In approximately 50 percent of the modeled cases, the major western tie between the United States and Canada would be damaged. During the system peak demand in the summer months, the United States imports over 2 GW of power from Canada; during the winter, the United States imports about a half GW at the system peak. In the spring, Canada imports nearly 1 GW of electric power from the United States at the system peak. If the tie were lost, the United States and Canadian systems would electrically isolate from one another;[12] thus, in the summer, the United States would have an excess of 3 GW of generation while Canada would have an excess of 2 GW of generation. In the spring, the United States would have extra generation that would need to be taken off line to maintain U.S. system stability.

Potential cascading effects on the electric power grid were examined by running the maximum damage case in the electric-power solver model to determine whether the solution contained any transmission-line or transformer overloads or buses with low system voltage. Under the outage scenario, there were several transmission-line and transformer overloads. Most of the overloads were less than 10 percent over the emergency line rating, giving the affected utilities ample time to respond to the situation. Generators can be dispatched to shift the power flows, and transformers have cooling mechanisms that can be operated to increase their power flow capacities. Because the electrical model represented the system at its peak demand, the transmission lines and transformers would not be overloaded under most conditions. Those transmission lines and transformers that experienced power flows greater than 10 percent over emergency line ratings would require the affected utilities to take more immediate action to relieve the overloads. This requirement could result in further load shedding to prevent cascading that might ultimately lead to individual sections of the grid being isolated from one another.

Analysts also identified potential areas of low voltage following the earthquake scenario. Most involved a limited number of substations in isolated regions that lost higher voltage power feeds (transmission lines) due to the earthquake. If none of the schemes mentioned above for improving voltage were effective, utilities would be forced to shed load. In the maximum damage case, portions of Portland would be at risk for further load-shedding due to low voltages.

5.3.1.2.1 Cascading Effects to Other Infrastructures

The majority of infrastructure sectors depend on electric power to function fully. Much of this infrastructure will be disrupted until clean up and repairs can be completed. Some facilities, including wirecenters, hospitals, and water treatment plants, will have backup generation capability. These resources generally require fuel and can run until the fuel source is exhausted. For those areas where restoration of electric power may take several days and where roads and bridges sustain heavy damage, it is possible that local fuel supplies may be depleted and backup generators run out of fuel. Communities along the coast are at greatest risk from this cascading effect. Government and emergency service functions may degrade due to loss of electric power and communications.

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[12] Actions taken following the loss of the United States-Canadian tie are described in the document "BC Hydro Operations Support Operating Order 7T – 18 Custer – Ingledow 500 kV Interconnection" found at transmission.bchydro.com/nr/rdonlyres/f56489b9-f09a-452b-a0aa-6100a8f13aaf/0/7t18.pdf.

5.3.1.3 Restoration

Restoration of the electric power system is the reconnection of electric power to those places where electricity is no longer flowing. It is not the reinstatement of the pre-event conditions. Utilities work to restore power to a devastated area in the fastest manner possible that can be accomplished safely. A system will not be immediately restored to its pre-earthquake condition. Workarounds and temporary repairs will be accomplished if power can be restored in a safe and timely manner. The electrical system may be in a somewhat fragile condition during and immediately following restoration until time and effort can be expended to return the system to its original condition. A completely damaged substation will not be restored in a week, but a mobile substation can be placed nearby in less than a week to serve customers while the damaged substation is being repaired.

Restoration proceeds on a priority basis. Areas that are completely damaged do not need electric power until buildings and services are restored. As in any disaster, areas that have the highest priority for power restoration are those that contain hospitals and emergency services, such as police stations, fire stations, etc. The electric power restoration analysis model (EPRAM) ranks substation service areas by the number of priority facilities and also accounts for population and customer demand. An input to the model is the number of crews that are available to perform the restoration. A debris module is used to calculate the amount of debris that must be cleared before restoration can commence. RDMB-NISAC initially developed and validated EPRAM based on hurricane damage.[13] The Cascadia analysis is the first case for which RDMB-NISAC used EPRAM to evaluate the restoration of the electric power system with an earthquake as the cause of damage. The EPRAM tool is appropriate for restoration estimation as it recognizes and addresses damages to the electric power system the same way, regardless of the initiating event. The issue is whether any special circumstances related to the initiating event would affect restoration time and/or priorities. Due to the potential for extreme damage with a strong earthquake, such special circumstances exist: i.e., heavy debris, communities isolated by landslides, and road and bridge damage. EPRAM can accommodate these conditions with existing parameters, although the appropriate value for the parameters in the case of an earthquake is uncertain. However, it was beyond the scope of this project to calibrate EPRAM to earthquake damage. As a result, the restoration times shown in Figure 5-9 are based on the assumption that road access has been restored, permitting repair crews to access damaged facilities.

[13] National Infrastructure Simulation and Analysis Center, “EPRAM Model Methodology Overview” (2006).

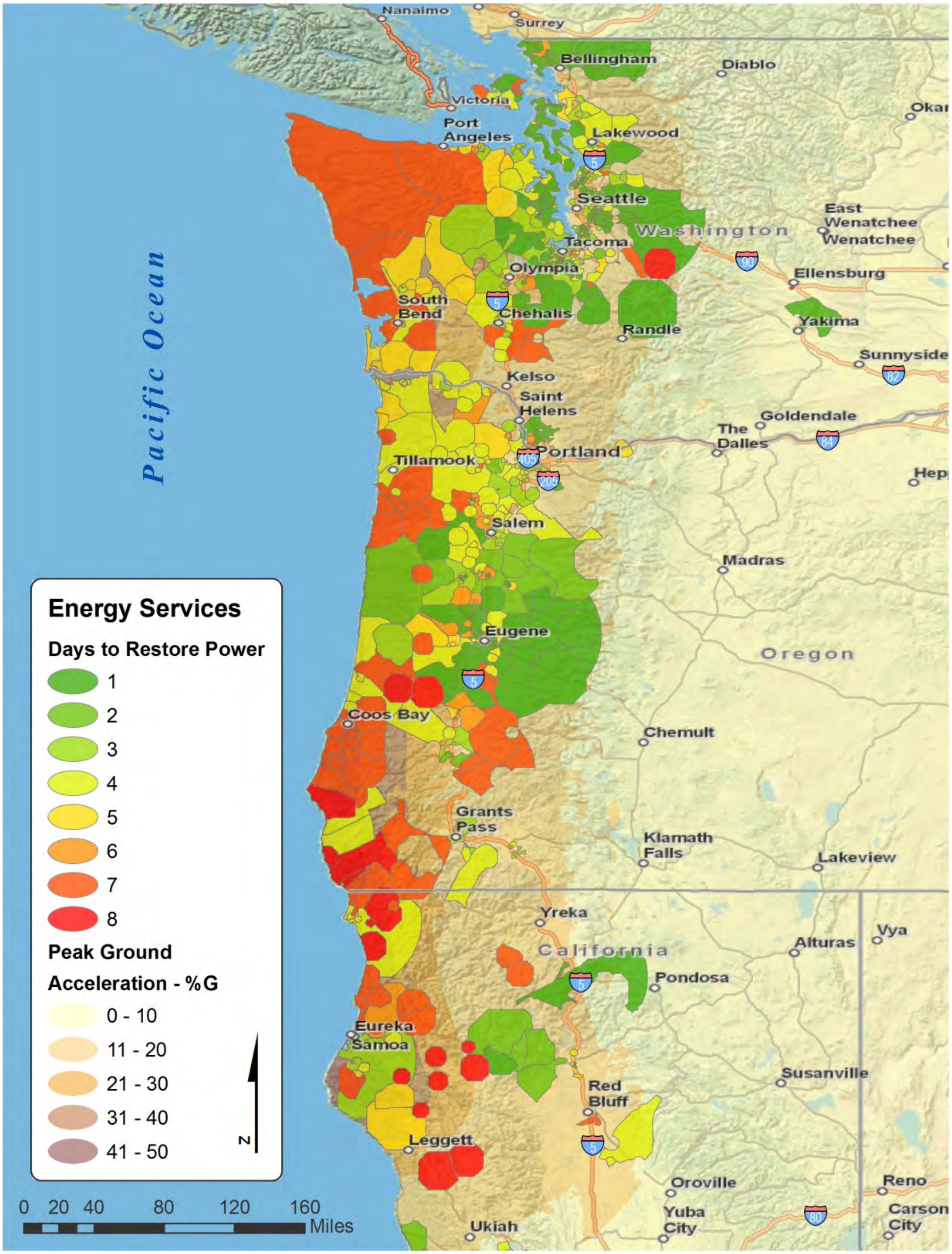

Figure 5-9. Restoration times for damaged and outaged substations under the maximum damage case

The Cascadia scenario requires a considerable recovery effort. Electric power restoration will involve not only utility personnel, but also electrical contractors in the immediate area and crews willing to travel large distances. The same type of response is witnessed following hurricanes. Under interagency agreements, utilities draw from a pool of workers from across the country. As such, the restoration is assumed to have an adequate number of crews. In the case of the Cascadia earthquake scenario, the restoration effort hinges on the ability of crews to access the devastated areas. Inhibiting factors, such as blocked roads and transportation restrictions, were not considered in the electric-power restoration process for two reasons. First, Hazus currently has no method to estimate landslide debris for damaged roadways. Second, landslide debris is not a recognized debris type for EPRAM, so debris removal rates could not be estimated. Due to these limitations, in some areas, particularly the coastal regions, the restoration times are underestimated. Communities in coastal areas and in the coastal mountain range may lack electric power for several weeks before restoration can be completed.

RDMB-NISAC used the damaged and outaged areas that resulted from the maximum damage case as input to EPRAM and chose an appropriate crew size based on engineering expertise. Figure 5-9 above shows the results of the EPRAM calculations. In general, areas that experienced the highest amount of ground shaking (those closer to the Pacific coast) were more heavily damaged and took longer to restore. Areas near Portland and Seattle-Tacoma were more populous and contained a larger number of critical facilities and therefore were restored more quickly. Restoration times ran from one to eight days. Again, this corresponds to the amount of time before power is restored to a service area, not the amount of time until the substation is functioning at pre-earthquake conditions.

5.3.2 Natural Gas

As shown in **Error! Reference source not found.**, segments of the backbone natural gas transmission pipeline serving western Washington and Oregon, as well as the compressor stations along that pipeline, are at risk of being damaged by this event.

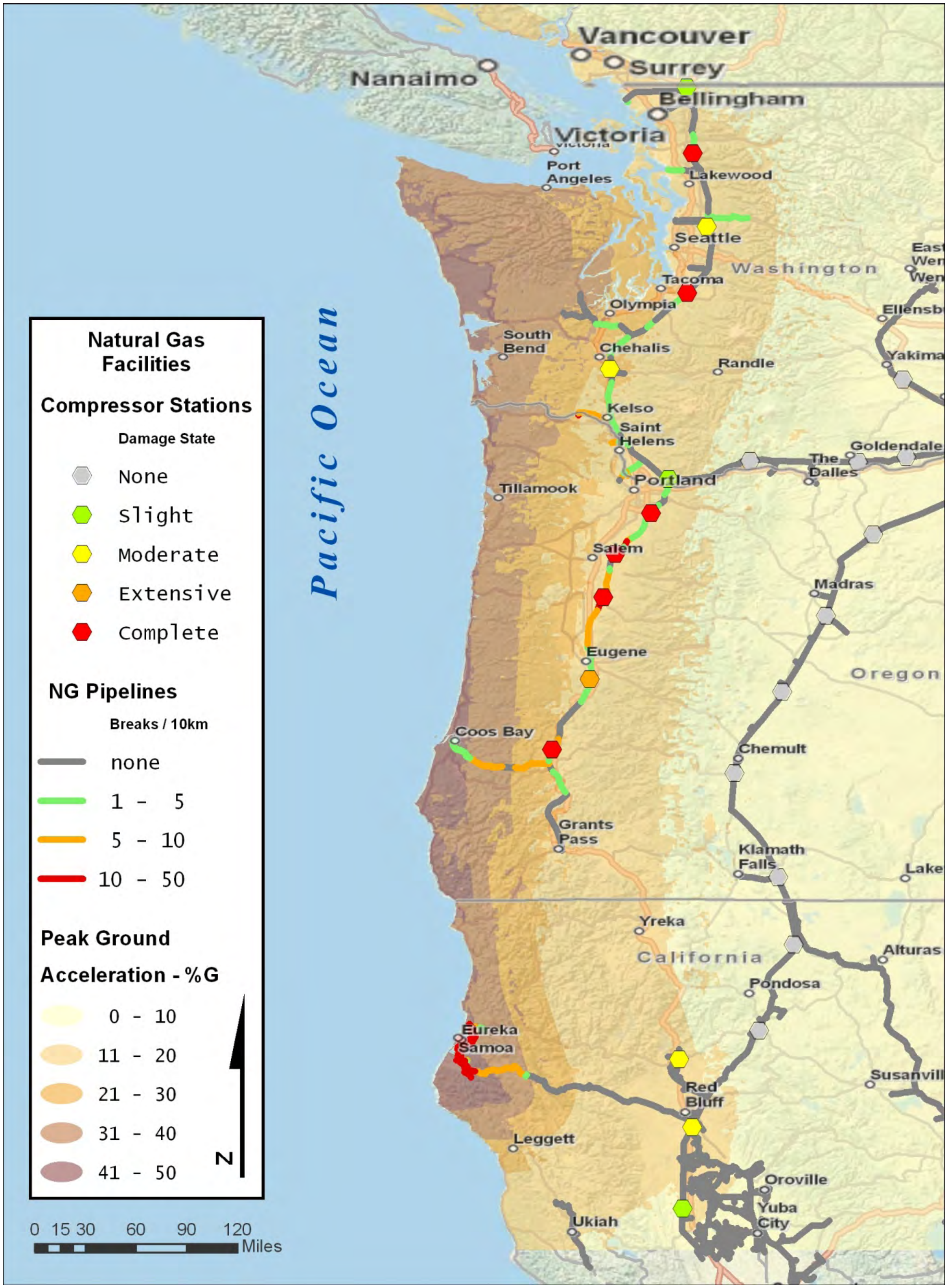

Figure 5-10. Hazus run of estimated damage to natural gas pipelines and compressor stations for the median damage case

The frequency of pipeline breaks and damage to compressor stations shown in Figure 5-10 above were calculated in a Hazus run based on assumptions of ground shaking intensity, areas of liquefaction, and pipeline/compressor station fragility. RDMB-NISAC analysts caution that the map in **Error! Reference source not found.** should be viewed as a possible outcome, rather than as a prediction of how assets in specific locations would be damaged. A detailed geotechnical study would be necessary to gain more certainty as to how specific pipeline segments or other assets may be impacted. Whether breaks actually occur depends largely on the type and quality of the pipeline welds and whether soil liquefaction under the pipeline takes place. Generalized liquefaction maps and fragility curves cannot adequately account for these factors.

However, it is reasonable to assume that this north-south transmission line in western Washington and Oregon is at risk of damage. This analysis, therefore, should be viewed as an exploration of the consequences of such damage.

5.3.2.1 Northwest Pipeline System

As part of the Northwest Pipeline system, the pipeline in question extends from the Canadian border (at Sumas, WA) down to southwestern Oregon. The northern and southern segments of this pipeline join in the Columbia River Gorge at the Washougal Station (near Washougal, WA). The southern segment terminates in southwest Oregon, and therefore exists only to serve demand in Oregon. Even if this segment of the pipeline is damaged, impacts to other parts of the system (beyond the earthquake damaged zone) are likely to be minimal due to the ability to route gas through alternative lines.

The northern segment primarily exists to serve customers in western Washington; however, it does play a role in serving other areas as well. During the winter, northwestern Washington (mainly the Seattle metropolitan area) receives gas from the interconnect with Canada at Sumas, but it also receives gas from Wyoming through another path in the Northwest Pipeline system. During the summer, instead of receiving gas through this path in the Northwest Pipeline, the northern segment facilitates the transit of Canadian gas in the other direction, to customers in eastern Washington.

In this winter scenario, there would be a surplus of gas in British Columbia and in parts of the Northwest Pipeline east of Plymouth, WA (where there is an important juncture in the Northwest Pipeline). As the southern transmission pipeline segment (which services western Oregon) serves only to distribute natural gas to end customers, it is reasonable to conclude that damage to the north or south portions of the backbone transmission pipeline in the winter would not impact parts of the network beyond the damaged region.

5.3.2.2 Consequences of Damage Within Region Directly Impacted by Earthquake

Customers in western Washington or western Oregon could receive natural gas service only if the transmission line servicing their local distribution company (LDC) is functional and the distribution network is operational. It is possible the transmission line could be operational, but a large number of breaks in the distribution network would require the distribution company to shut down its entire network, or large portions of it, while repairs are made.

Note that only about one-third of the households in Washington and Oregon use natural gas for home heating;[14] most homes use electricity. Natural gas is used by industrial and power-generation consumers in both states. The potential impact on electricity production is discussed below.

5.3.2.3 Consequences of Damage to Other Areas

In the summer and early fall, the backbone transmission pipeline in western Washington facilitates the transit of Canadian gas to customers in eastern Washington. If the northern segment were damaged in the summer or early fall, then Canadian gas received at Sumas could not be routed to eastern Washington. Therefore, the consequences of damage to this pipeline in a different scenario could extend beyond the area immediately impacted by the earthquake.

RDMB-NISAC used a natural gas pipeline model to see whether the pipeline network can reroute gas flows to compensate for the loss of this route. RDMB-NISAC therefore performed a natural gas network model run to determine whether the network might be able to reroute flows to eastern Washington in the event of a disruption of the westernmost north-south transmission pipeline.

Customers in eastern Washington, in this scenario, received the same amount of gas as they received in the undisrupted scenario. Additional flows from the Rocky Mountains, along with additional flows from northern Idaho (from Canada), allow supply to eastern Washington to remain at the same level (projected to be around 220 MMcf/day) in both cases.

Not only can the network reroute to provide enough gas to eastern Washington, but also it sends 450 MMcf/day from Plymouth to Washougal, supplying both western Oregon and western Washington – but with less than they would normally consume. Both western Oregon and western Washington receive between 65 to 70 percent of their normal supply.

The ability to supply western Washington presupposes that it is possible to close a valve south of the hypothetical break between Sumas, WA, and Seattle. While RDMB-NISAC views this as a likely option, it should be verified with the Northwest Pipeline System. Also note that this scenario assumes that only the Sumas to Seattle pipeline is damaged; all other sections of pipeline remain intact. Supplying western Washington and Oregon from the east, even though the gas supply would likely be available, could occur only to the extent the backbone transmission pipeline in western Washington and Oregon allows gas to reach distribution companies and industrial customers.

5.3.2.4 Impacts to the Natural Gas Sector From Other Sectors

The main impacts on the natural gas sector from other sectors are likely to come in the area of transmission pipeline and gas distribution network restoration. If roads are impassable, the time for pipeline and distribution network restoration will be increased as access by utility vehicles would be problematic. If transportation fuels are in short supply, impact restoration time may be affected (depending on how the scarce resources are allocated).

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[14] EIA State Energy Profiles, Oregon and Washington, http://ei-01.eia.doe.gov/cfapps/state/state_energy_profiles.cfm?sid=WA, accessed on 10 June 2011.

5.3.2.5 Impacts of the Natural Gas Sector on Other Sectors

If the main north-south natural gas transmission pipeline along the I-5 corridor experiences multiple breaks, then the largest impact on other sectors would likely be felt in the electrical power sector. If certain gas-fired power plants are unable to receive gas, the absence of these gas-fired plants (which provide valuable reserve capacity) might pose a threat to the reliable operation of the grid in the Pacific Northwest as the percentage of energy from variable generation increases over time.

For Washington State in 2009, the nameplate (design maximum) natural gas-fired generation was about 3,300 MW, versus a system installed capacity of about 27,000 MW.[15] Natural gas-fired generation therefore represents about 12 percent of the installed capacity in the state.[16] The total share of electricity generation in Washington that same year by natural gas-fired plants was also 12 percent. As almost all of this capacity is along the I-5 corridor, virtually all of it would be at risk.

For Oregon in 2009, the nameplate natural gas-fired generation was about 3,600 MW, versus a system installed capacity of about 14,500 MW.[17] Natural gas-fired generation therefore represents about 25 percent of the installed capacity in the state. The total share of electricity generation by natural gas-fired plants was 28 percent.[18] Of the total nameplate capacity of about 3600 MW in natural gas-fired plants, about 900 MW (or about 25 percent) would be at risk.

Given that the Pacific Northwest is a net exporter of power and that it has strong interties with Canada and California, the judgment of RDMB-NISAC analysts is that the temporary absence of natural-gas fired generators in Washington and Oregon is unlikely to lead to a power system failure.

The main caveat to this judgment is that because most of the population of Washington is in the western part of the state and most of the generation is along the Columbia River to the east, most power consumed in western Washington is transmitted over long power lines crossing the Cascade mountain range. If the natural-gas fired generation in western Washington is unavailable at the same time the coal-fired plant in Centralia, WA, is unavailable (the western Washington plant, which is the state's only coal-fired plant, is scheduled to close entirely by 2025)[19], then although in aggregate enough power is supplied to meet demand, voltage in western Washington may be insufficient.

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[15] EIA dataset, "State Historical Tables for 2009," released 2010, revised January 2011. Accessed at: http://www.eia.gov/electricity/data.cfm#gencapacity, "By Energy Source, by Producer, by State (EIA-860)," accessed 7 September 2011.

[E]EIA dataset, http://www.eia.gov/cneaf/electricity/st_profiles/washington.html, accessed 21 June 2011

[17] EIA dataset, "State Historical Tables for 2009," released 2010, revised January 2011. Accessed at: http://www.eia.gov/electricity/data.cfm#gencapacity, "By Energy Source, by Producer, by State (EIA-860)," accessed 7 September 2011.

[18] EIA dataset, http://www.eia.gov/cneaf/electricity/st_profiles/oregon.html, accessed 21 June 2011

[19] http://www.psr.org/news-events/press-releases/psr-helps-negotiate-closure-washington-states-only-coal-plant.html, accessed 22 June 2011.

5.3.2.6 Impact of Future Power Sector Developments

Washington and Oregon are moving aggressively to increase the percentage of electrical power produced by renewable sources, which they define to not include hydroelectric generation. For Washington and Oregon, renewable generation has primarily come in the form of wind generation. As the percentage of generation from variable sources (such as wind) increases, it becomes necessary to have more dispatchable generation to make up for unexpected shortfalls, to have energy storage to smooth out the peaks and valleys in variable generation, or to have agreements and market structures in place to allow entities outside of these two states to receive the variable generation.

In ten or twenty years, the level of variable generation will likely present a challenge to grid operators. Even if the impact of temporarily losing dispatchable natural gas-fired power plants is small today, if the earthquake were to happen ten or twenty years from now when the grid will likely require more dispatchable generation, this conclusion may be different.

5.3.2.7 Areas for Investigation

RDMB-NISAC does not currently have information on whether the natural gas transmission pipelines at risk (the westernmost portion of the Northwest Pipeline system) have automatic or remote shut-off valves installed. Such valves are important for mitigating damage due to fire after a pipeline rupture.

In the San Bruno, CA, accident of September 2010, the fire burned for 90 minutes after the gas pipeline rupture. If remote shut-off valves had been present, Pacific Gas & Electric Company estimates it could have shut off gas within 20 minutes of the rupture. [20] Although Department of Transportation guidelines recommend the installation of such valves, they are not mandatory.

5.3.3 Petroleum

5.3.3.1 Petroleum Fuel Supply Chain Impact Analysis

The Seattle area is the principal refining center for the Pacific Northwest (see Figure 5-11). There are five refineries in the region with a combined operable capacity of 627.85 thousand barrels per day (Kbpd) of crude oil. Applying the average PADD V[21] refinery use of 85 percent, the crude oil requirements for these plants is about 535 Kbpd. Located on the shore of Puget Sound, the region's refineries receive most of their crude oil feedstock by ship from Alaska. Waterborne shipments are also received from Canada and other foreign sources. In addition, about 10 percent of Washington crude oil demand is filled by a 24-inch diameter trans-mountain pipeline artery that moves crude and refined products from Edmonton, Canada. [22]

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[20] Levin, Alan, "PG&E Rejected Safety Warning for Shut-off Valves," USA Today, March 1, 2011, http://www.usatoday.com/news/nation/2011-03-01-pipeline-explosion-san-bruno_N.htm, accessed August 2011.

[21] There are five Petroleum Administration Districts for Defense (PADDs). PADD V consists of the West Coast, Alaska and Hawaii; a map of the PADD regions can be found at ftp://ftp.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/paddmap.htm, accessed August 2011

[22] Source: http://www.eia.gov/state/state-energy-profiles.cfm?sid=WA, accessed August 2011.

Figure 5-11. Crude and refined product pipelines in the region

Based on the average U. S. refinery yield, Seattle refineries produce about 460 Kbpd of finished motor gasoline, aviation gasoline, kerosene-type jet fuel, kerosene, distillate fuel oil, and residual fuel oil. Refined products are shipped to Portland, OR, and Eugene, OR, markets by a refined products pipeline artery that consists of a 14-inch diameter segment between Seattle, WA, and

Portland, OR, and an eight-inch diameter segment between Portland, OR, and Eugene, OR. Waterborne transportation is also used to move refined products from Seattle to terminals in Portland and along the Columbia and Snake Rivers.

Washington refinery output is augmented by refined products originating outside the region. For example, the Spokane, WA, market receives refined product through a 10-inch diameter ConocoPhillips pipeline from Billings, MT, refineries. Similarly, the Kennewick-Richland, WA, markets are linked with an eight-inch diameter pipeline from Salt Lake City, UT, refineries.

5.3.3.1.1 Defining Product Demand Regions

The demand for refined products in the impacted region can be calculated using daily state-level consumption data published by the Energy Information Administration (EIA).[23] Using refined product consumption data from 2007 through 2009, the estimated daily consumption rate of fuel for refined products in the Pacific Northwest is about 503 Kbpd. Fuel consumption rates by product type are presented in Table 5-7.

Table 5-7. Average refined product demand (Kbpd)

Refined Product	Washington	Oregon	Total
Motor Gasoline	178. 37	98. 57	276. 94
Aviation Gasoline	0. 46	0. 14	0. 60
Kerosene-Type Jet Fuel	48. 12	15. 14	63. 25
Total distillate and Kerosene	74. 90	51. 85	126. 75
Residual Fuel Oil	32. 15	3. 04	35. 20
Total (Kbpd)	**334. 01**	**168. 74**	**502. 74**

However, because the goal of this work is to understand how specific infrastructure damage will affect fuel availability, it was necessary to recast state-level demand estimates into market-level demand regions that correspond to endpoints of the petroleum supply chain network. Based on the location of refineries, pipeline network branches, products terminals, rail and highway network topologies, and general population distribution data, six market demand regions were defined (Figure 5-12).

[23] www.eia.doe.gov/state/state-energy-profiles.cfm?sid=WA, accessed 05/19/2011.

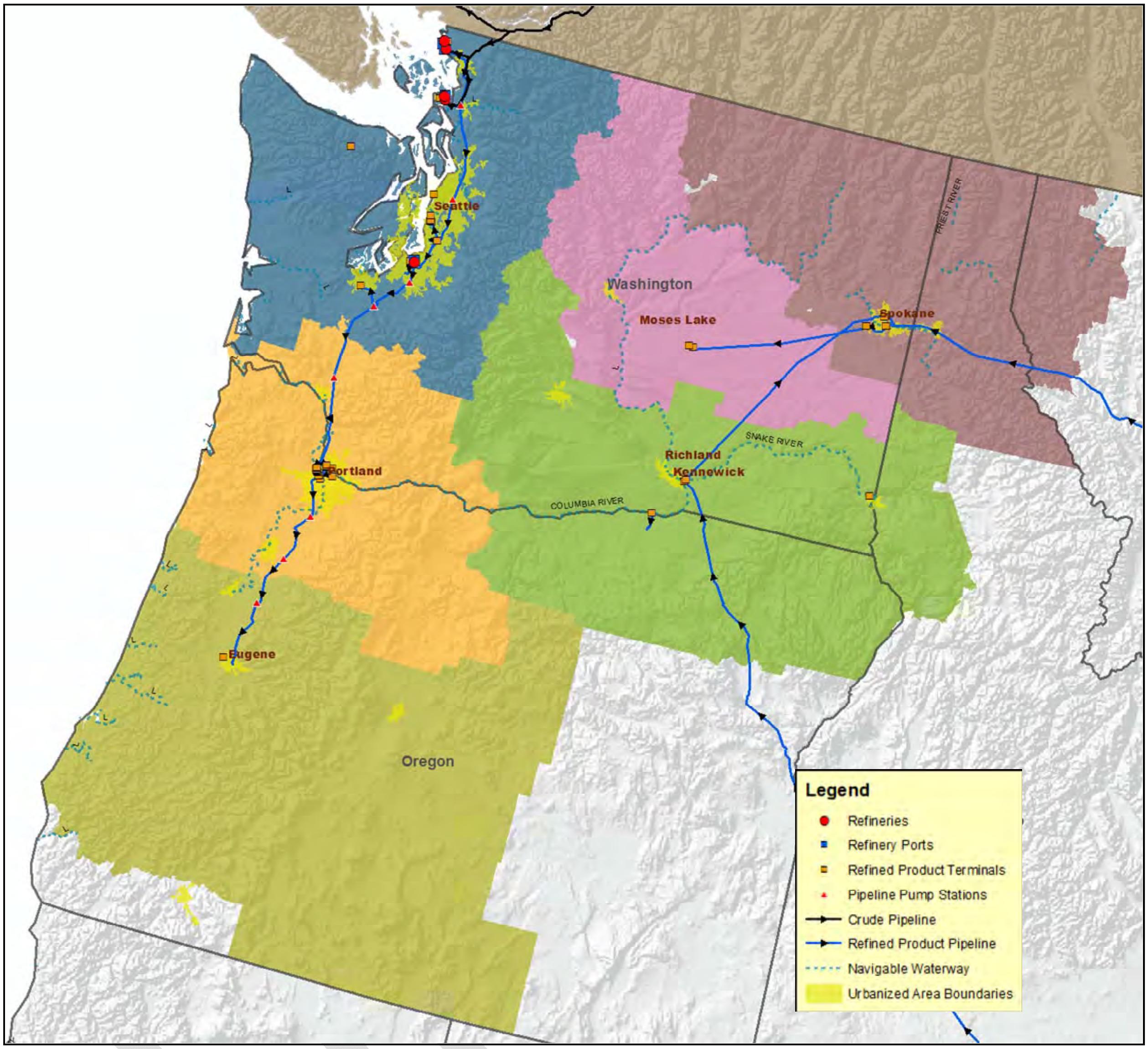


Figure 5-12. Refined product demand regions formed for supply chain analysis: Seattle, Portland, Eugene, Kennewick-Richland, Spokane, and Moses Lake

To estimate the demand within each region, state-level per capita product consumption estimates were multiplied by census block population data. Table 5-8 shows the estimates for each market region considered in this analysis.

Table 5-8. Average refined product demand

Demand Region	Refined Product Demand (Kbpd)	Percent of Total Refined Product Demand
Seattle	223. 5	46
Portland	123. 8	25
Eugene	46. 7	10

Demand Region	Refined Product Demand (Kbpd)	Percent of Total Refined Product Demand
Moses Lake	11. 4	2
Kennewick-Richland	42. 4	9
Spokane	38. 4	8

Based on the system level flow rates and product demand regions discussed above, a simplified network representation of the region's petroleum supply chain can be constructed. Illustrated in Figure 5-13, this network model provides a rough sketch of the region's major petroleum arteries that can be used to consider regional level fuel disruptions caused by damage to refineries, pipelines, terminals, and other major system components. This network is not yet balanced at all nodes. For example, refined product inflow and outflow values for the Portland demand region have a differential of about 100 Kbpd in this model.

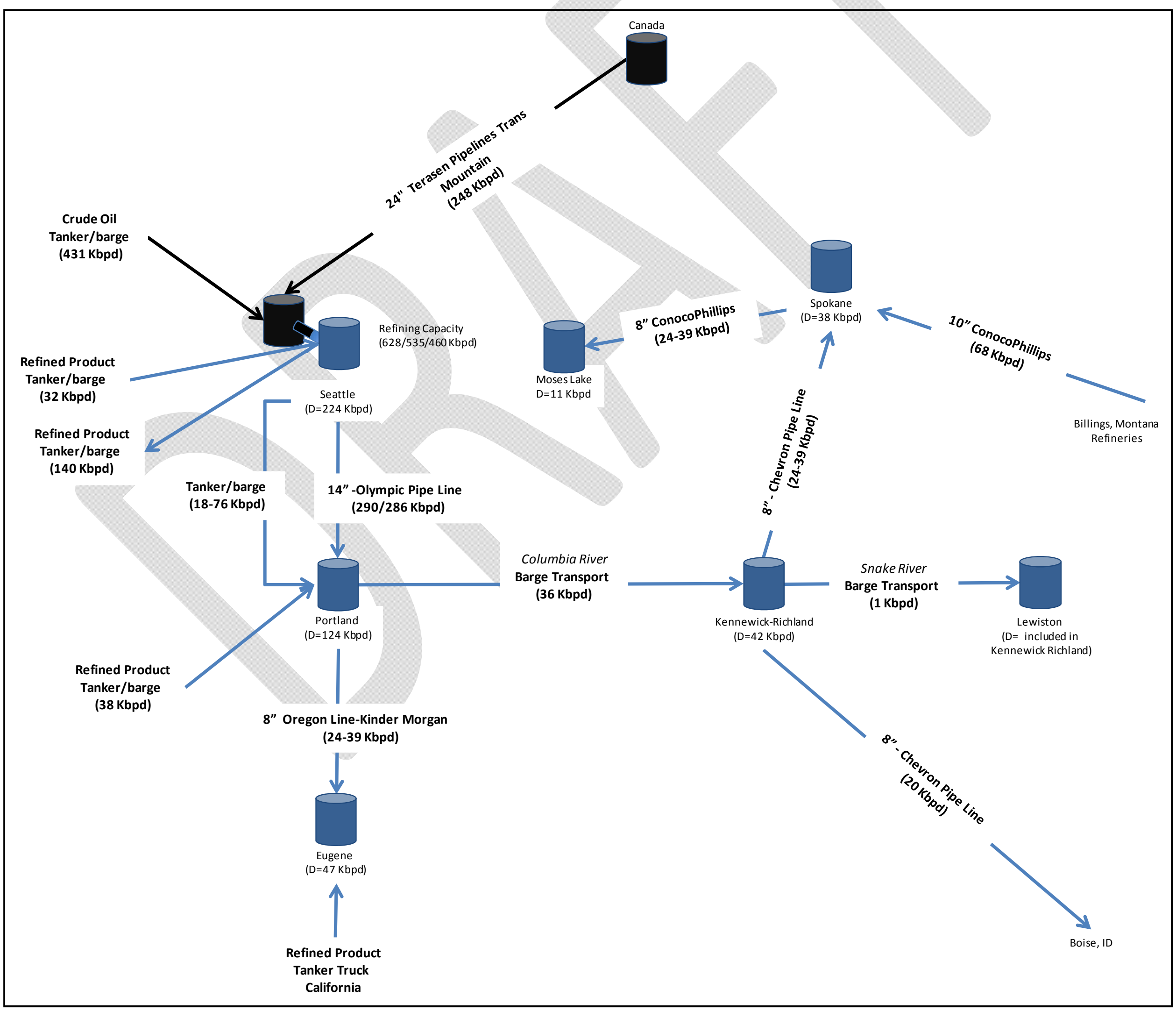


Figure 5-13. Simplified petroleum network (pipeline flow rate range, based on diameter)

5.3.3.1.2 Hazus Analysis Results for Key Petroleum Supply Chain Components

A Hazus analysis of Seattle area refineries was conducted as part of the petroleum fuel supply network analysis. Given earthquake scenario assumptions, an expected damage level was calculated for each system component (Damage State 50). In addition, an extreme damage case was calculated as a bounding condition (Damage State 90). Table 5-9 lists the five Hazus refinery damage categories. If the refinery sustains only Slight damage, operations should resume within days of the disruption. However, if the refinery sustains Complete damage, the disruption will likely be measured in months to years.

Table 5-9. Refinery Hazus Damage Categories

Component	Damage Level	Damage Description
Refineries	None	No damage to components.
Refineries	Slight/Minor	Defined by malfunction of plant for a short time (few days) due to loss of electric power and backup power, if any, or light damage to tanks
Refineries	Moderate	Defined by malfunction of plant for a week or so due to loss of electric power and backup power (if any), extensive damage to various equipment, or considerable damage to tanks
Refineries	Severe	Defined by the tanks being extensively damaged, or stacks collapsing
Refineries	Complete	Defined by the complete failure of all elevated pipes, or collapse of tanks

Table 5-10 and Figure 5-14 illustrate the expected damage to each regional refinery on day one of the disruption. Fortunately, 52 percent of Washington’s refining capacity will not be damaged in the earthquake scenario. Another 42 percent the region’s refining capacity will be only slightly damaged and should recover within days of disruption. However, the small 38-Kbpd refinery located in Tacoma will be completely damaged and will be inoperable for months to years.

Table 5-10. Refinery Hazus damage analysis results

Refinery	Location	Total Operable Capacity (Kbpd)	DMG_STATE 50	DMG_STATE 90
U. S. Oil & Refining Co.	Tacoma, WA	37. 85	Complete	Complete
Shell Oil Products U. S.	Anacortes, WA	145	Slight	Moderate
Tesoro West Coast	Anacortes, WA	120	Slight	Complete
ConocoPhillips	Ferndale, WA	100	None	Moderate
BP West Coast Products LLC	Blaine (Cherry Point), WA	225	None	Moderate

Figure 5-14. Expected refinery damage levels

5.3.3.1.3 Cascadia Petroleum-related Ports

A Hazus analysis of ports that transfer crude and refined products within the Cascadia impact region was conducted as part of the petroleum fuel supply network analysis. As with the refinery analysis, Hazus defines five damage categories ranging from Slight to Complete damage. Unlike the refinery damage categories, however, no indications of repair/replace times are given for the port damage categories. Table 5-11 lists each of the five port damage categories and corresponding damage description.

Table 5-11. Port Hazus damage categories

Component	Damage State	Damage Description
Ports - fuel facilities, unanchored equip	None	No damage to components
Ports - fuel facilities, unanchored equip	Slight/Minor	Elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e., to diesel generators, if available)
Ports - fuel facilities, unanchored equip	Moderate	Elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, or loss of commercial power for few days and malfunction of backup power (i.e. , diesel generators, if available)
Ports - fuel facilities, unanchored equip	Severe	Weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts)
Ports - fuel facilities, unanchored equip	Complete	Tearing of tank wall or implosion of tank (with total loss of content) or extensive /complete damage to pump building

Table 5-12 and Figure 5-15 illustrate the expected damage to petroleum-related ports on day one of the disruption. Fortunately, the most important ports along the petroleum supply chain are only slightly damaged by the earthquake event. The ports that feed regional refineries in the Seattle region and ports that ship/receive refined products in the Portland area should not have a significant impact on the flow of crude and refined products. However, for the extreme damage scenario (Damage State 90), regional ports will have a much higher damage level, which means the flow of petroleum crude and refined products will be impacted by the inability to ship and receive petroleum products for an extended period. For example, all petroleum-related ports in the Portland area will be completely damaged.

Table 5-12. Expected damage to petroleum ports, on day one of the disruption

Port Name	Location	DMG_STATE 50	DMG_STATE 90
Chevron U. S. A. , Point Wells Term.	Woodway , WA	Slight	Severe
UNOCAL Corp. , Edmonds Term Wharf	Edmonds , WA	Slight	Moderate
*The Shell Anacortes Refining Co	Anacortes , WA	Slight	Moderate
*Texaco Refining and Marketing	Anacortes , WA	Slight	Moderate
Time Oil Co. , Seattle Wharf	Seattle , WA	Slight	Moderate
Ballard Oil Co. , Fuel Pier	Seattle , WA	Slight	Moderate
*U. S. Oil & Refining, Tacoma Term	Tacoma , WA	Slight	Moderate
*U. S. Oil & Refining, Tacoma Term	Tacoma , WA	Slight	Moderate
*ARCO Products Co. , Cherry Point Ref	Ferndale , WA	Slight	Slight
*Tosco Refining Co. , Ferndale Ref. Wh	Ferndale , WA	Slight	Slight
Rainier Petroleum Corp. , Equilon Ente	Seattle , WA	Slight	Severe
Port of Vancouver, Oil Terminal Dock	Vancouver , WA	Slight	Severe
Chevron U. S. A. , Coos Bay Wharf	Coos Bay , OR	Complete	Complete
James River Corp. , Wauna Mill, Fuel Oil	Wauna , OR	Complete	Complete
Premier Edible Oils Corp Dock	Portland , OR	Slight	Complete
ARCO Products Co. , Linnton Term. Wh	Portland , OR	Slight	Complete
Mobil Oil Corp. , Linnton Term. Wh	Portland , OR	Slight	Complete
Time Oil Co. , Linnton Term Wh	Portland , OR	Slight	Complete
Pacific Northern Oil, Portland Term.	Portland , OR	Slight	Complete
Chevron U. S. A. , Willbridge Term. Pier	Portland , OR	Slight	Complete
Unocal Petroleum Products and Chem.	Portland , OR	Slight	Complete
McCall Oil and Chemical Co.	Portland , OR	Slight	Complete
Texaco Refining and Marketing	Portland , OR	Slight	Complete
Carmichael-Columbia Oil, Astoria Wharf	Astoria , OR	Complete	Complete
Tosco Refining Co. , Eureka Term Wh	Eureka , CA	Moderate	Complete
Chevron Products Co. , Eureka Term Wh	Eureka , CA	Complete	Complete

* Ports connected to refineries.

Figure 5-15. Expected damage to petroleum-related ports on day one of the disruption

5.3.3.2 Crude Pipeline System

The crude pipelines within the Cascadia Region are those that bring crude from Canada. A total of 62 miles (99 kilometers) of pipeline run from the U. S.-Canadian border to the refineries in northern Washington.

Based on calculations of pipe damage from ground shake (PGV) and ground displacement (PGD) used by the Hazus software, the pipeline systems delivering crude to the refineries could experience as many as 15 breaks and 6 leaks along the length of the system. The vast majority of the damage is the result of ground displacement as a result of possible liquefaction.

Restoration of the pipeline system is based in large part on the number of repair crews available to fix the pipeline damage (Table 5-13). Using the restoration functions provided with the Hazus software, analysts estimated the time to recover the crude pipeline delivery system, shown in the table below. Again, the number of available workers is the major factor in the restoration time.

Table 5-13. Restoration time for crude pipeline system (based on available workers)

Number of Workers	Small Pipe Breaks	Small Pipe Leaks	Large Pipe Breaks	Large Pipe Leaks	Days to Restoration
4	6	3	9	3	11. 7
6	6	3	9	3	7. 8
12	6	3	9	3	3. 9
20	6	3	9	3	2. 3
30	6	3	9	3	1. 6

5.3.3.3 Refined Product Pipeline System

The refined product pipelines within the Cascadia region are those that deliver refined product to the Seattle-Tacoma industrial region and further south to the Columbia River and into Oregon. Workers take the refined product off the pipeline system at the Columbia River and ship it up river by barge for consumption in inland Washington and Idaho. There are a total of 383 miles (616 kilometers) of refined product pipeline running from the refineries of northern Washington to the Columbia River and an additional 139 miles (223 kilometers) of pipeline running south from the Columbia River serving the Portland metro area and the Willamette Valley of central and southern Oregon. According to the Hazus pipeline analysis, the refined product pipeline system in northern California did not experience any damage as a result of the earthquake.

Using the same repair rate function used to calculate damage to the crude pipeline system, analysts performed calculations of pipe damage from PGV and ground displacement PGD to estimate the damage to the pipeline systems delivering refined product from the refineries of northern Washington (

Table 5-14).

Table 5-14. Restoration time for refined product pipeline system to Columbia River (based on available workers)

Number of Workers	Small Pipe Breaks	Small Pipe Leaks	Large Pipe Breaks	Large Pipe Leaks	Days to Restoration
4	96	39	22	9	77. 8
6	96	39	22	9	51. 9
12	96	39	22	9	25. 9
20	96	39	22	9	15. 6
30	96	39	22	9	10. 4
40	96	39	22	9	7. 8
50	96	39	22	9	6. 2

RDMB-NISAC estimated that the system from northern Washington to the Columbia River could experience as many as 135 breaks and 48 leaks along the length of the system. The refined pipeline system serving Oregon could experience as many as 115 breaks and 34 leaks along the length of the system (Table 5-15). As in the case of the crude pipeline system, ground displacement as a result of possible liquefaction is responsible for the vast majority of the damage.

Table 5-15. Restoration time for refined product pipeline system for Oregon (based on available workers)

Number of Workers	Small Pipe Breaks	Small Pipe Leaks	Large Pipe Breaks	Large Pipe Leaks	Days to Restoration
4	115	34	0	0	66. 0
6	115	34	0	0	44. 0
12	115	34	0	0	22. 0
20	115	34	0	0	13. 2
30	115	34	0	0	8. 8
40	115	34	0	0	6. 6
50	115	34	0	0	5. 3

5.3.3.4 Refined Product Pipeline Pump Stations

A Hazus analysis of the Olympic and Oregon Line pipeline system pump stations was conducted as part of the overall refined product pipeline analysis. Pump stations are designed to overcome head loss caused by friction along the pipeline, allowing the operator to control the flow rate of the pipeline system. There are nine pump stations critical to maintaining refined product flow from Seattle refineries to markets along the 350-mile pipeline transport network. For pipeline pump stations, the Hazus framework defines five damage categories ranging from Slight to Complete damage. As with the port damage categories, no indications of repair/replace times are given for the port damage categories.

Table 5-16 lists each of the five pump station damage categories and corresponding damage descriptions.

Table 5-16. Pump station Hazus damage categories

Component	Damage State	Damage Description
Pumping Stations	None	No damage to components
Pumping Stations	Slight/Minor	Light damage to building
Pumping Stations	Moderate	Considerable damage to mechanical and electrical equipment, or considerable damage to building
Pumping Stations	Severe	Building extensively damaged, or pumps badly damaged
Pumping Stations	Complete	Building in complete damage state

Table 5-17 and Figure 5-16 illustrate the expected damage to each pump station on day one of the disruption. Given the characteristics of the Cascadia earthquake event, many of the pump stations critical to moving refined product along the Olympic and Oregon Line pipeline system will be completely damaged. Thus based on pump station operability alone, it is reasonable to assume a disruption in pipeline functionality measured in months. Additional analysis is required to develop pump station recovery estimates.

Table 5-17. Refined product pump station Hazus damage results

Pump Station	Owner	State	DMG_STATE 50	DMG_STATE 90
Woodinville	Enbridge Inc.	WA	Complete	Complete
Allen	Enbridge Inc.	WA	Complete	Complete
Tacoma Barge	U. S. Oil and Refining Co.	WA	Complete	Complete
Castle Rock	Enbridge Inc.	WA	Moderate	Severe
Olympia Jct.	Enbridge Inc.	WA	Moderate	Severe
Tacoma	Enbridge Inc.	WA	Moderate	Severe
Salem	Kinder Morgan Inc.	OR	Moderate	Moderate
Morgan	Kinder Morgan Inc.	OR	Complete	Complete
Fargo	Kinder Morgan Inc.	OR	Complete	Complete
Rocklin	Kinder Morgan Inc.	CA	None	None
Feather	Kinder Morgan Inc.	CA	None	Slight
Colfax	Kinder Morgan Inc.	CA	None	None
Cisco Grove	Kinder Morgan Inc.	CA	None	None

Figure 5-16. Petroleum pump stations damage level on day one

5.3.3.5 Refined Product Terminals

A Hazus analysis of Pacific Northwest product terminals was conducted as part of the petroleum fuel supply network analysis. Refined product terminals serve a critical storage and inventory management function by receiving and storing product from pipelines and/or waterborne transport for downstream distribution to local distributors who in turn deliver them to end-users and retail outlets. The Hazus terminal analysis included 32 regional terminals: 19 in Washington, 11 in Oregon, and 2 in California. For refined product terminals, the Hazus framework defines five damage categories ranging from Slight to Complete damage. As with the refinery damage categories, limited information on repair/replace times are given for the terminal (tank farms/storage facilities) damage categories. Table 5-18 lists each of the terminal damage categories and corresponding damage descriptions.

Table 5-18. Refined product terminals Hazus damage results

Component	Damage State	Damage Description
Tank Farms/Storage Facilities	None	No damage to components
Tank Farms/Storage Facilities	Slight/Minor	Malfunction of plant for a short time (less than three days) due to loss of backup power or light damage to tanks
Tank Farms/Storage Facilities	Moderate	Malfunction of tank farm for a week or so due to loss of backup power, extensive damage to various equipment, or considerable damage to tanks
Tank Farms/Storage Facilities	Severe	Tanks extensively damaged or extensive damage to elevated pipes
Tank Farms/Storage Facilities	Complete	Complete failure of all elevated pipes, or collapse of tanks

Table 5-19 and Figure 5-17 illustrate the expected damage to each petroleum terminal on day one of the Cascadia earthquake event. Given the characteristics of the Cascadia earthquake event, many of the terminals located along the Olympic and Oregon Line pipeline system, including Seattle and Portland area terminals, will be completely damaged. Thus based on terminal operability alone, the ability to distribute refined products fuels along the Pacific Northwest corridor will be significantly reduced. Given the nature of the damage to the refined product terminals, a conservative estimate of the disruption of terminal functionality would likely be measured in months. Additional analysis will be required to develop terminal recovery estimates.

Table 5-19. Petroleum terminal Hazus damage results

Terminal Owner	Location	DMG_STATE 50	DMG_STATE 90
Tesoro	Anacortes, WA	Moderate	Moderate
Shell	Anacortes, WA	Moderate	Severe
BP	Blaine, WA	Moderate	Severe
Chevron	Edmonds, WA	Complete	Complete
ConocoPhillips	Ferndale, WA	Moderate	Severe
ConocoPhillips	Renton, WA	Complete	Complete
BP	Seattle, WA	Complete	Complete
Swissport	Seattle, WA	Moderate	Severe
Shell	Seattle, WA	Complete	Complete
Kinder Morgan	Seattle, WA	Complete	Complete
ConocoPhillips	Tacoma, WA	Complete	Complete
Sound Refining	Tacoma, WA	Complete	Complete
NuStar	Tacoma, WA	Complete	Complete
U. S. Oil & Refining	Tacoma, WA	Complete	Complete
Shell	Tumwater, WA	Complete	Complete
Tesoro	Vancouver, WA	Complete	Complete
Tidewater	Vancouver, WA	Complete	Complete
NuStar	Vancouver, WA	Complete	Complete
NuStar	Vancouver, WA	Complete	Complete
Kinder Morgan	Eugene, OR	Moderate	Severe
Kinder Morgan	Millersburg, OR	Complete	Complete
ConocoPhillips	Portland, OR	Severe	Complete
Chevron	Portland, OR	Severe	Complete
BP	Portland, OR	Complete	Complete
Aircraft Service	Portland, OR	Complete	Complete
Time Oil	Portland, OR	Complete	Complete
Shell	Portland, OR	Severe	Complete
Kinder Morgan	Portland, OR	Complete	Complete
NuStar	Portland, OR	Complete	Complete
McCall	Portland, OR	Complete	Complete
Kinder Morgan	Chico, CA	None	Slight
Chevron	Eureka, CA	Complete	Complete

Figure 5-17. Petroleum terminals

5.3.3.6 Crude Oil and Refined Product Supply Disruptions

Figure 5-18 shows a basic schematic of the petroleum products supply system. In the short term, the ability of the system to withstand unexpected shocks is a function of how much inventory coverage exists at each node in the supply chain and how much remains available to flow to downstream customers. Therefore, *where* the disruption occurs is of critical importance. In the long term, the system's ability to withstand unexpected shocks is a function of recovery time. No matter how much planned inventory coverage exists in the system and is available, if downstream consumption exceeds the system's net production/distribution rate, eventually inventories will depleted.

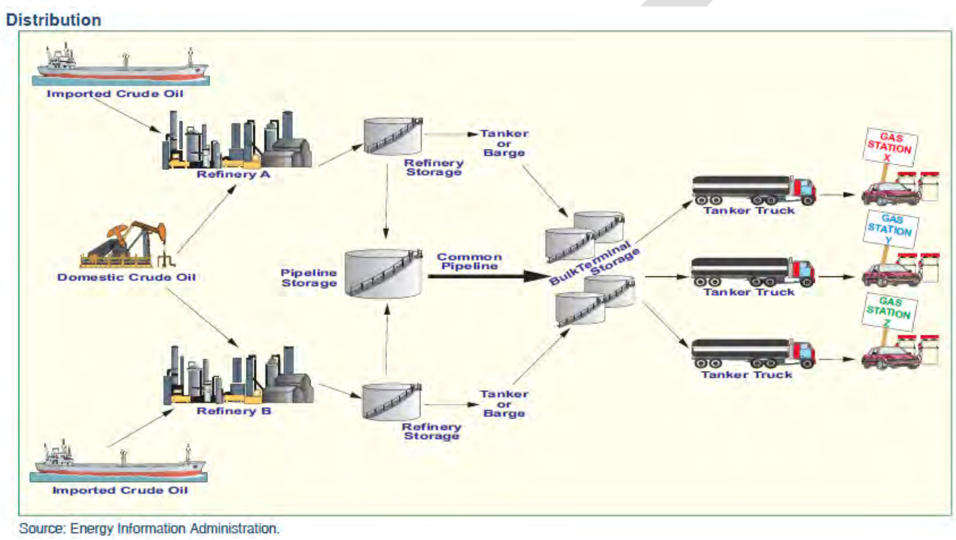
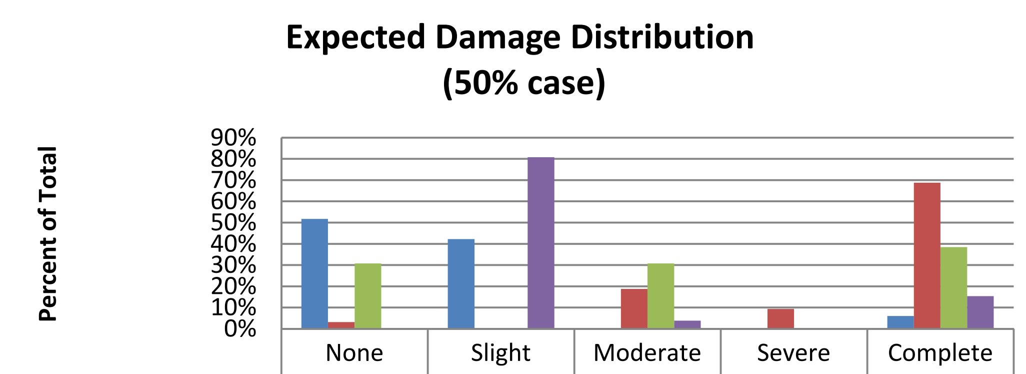


Figure 5-18. Petroleum products distribution system

The crude oil coverage at Seattle refineries can be calculated by taking the ratio of the total PADD 5 refinery crude inventory and total PADD 5 operable capacity. Accounting for the average refinery utilization and yield values, the crude coverage for PADD 5 refineries is approximately eight days. Similarly, about six production-days of refined product fuels are stored at the refinery before being shipped to downstream terminals by pipeline and barge. At the system level, refined product inventories are about equally distributed between refineries and terminals. Pipelines contain about ten percent of the refined product at any given time.

Given these inventory estimates, the expected damage to the Trans Mountain crude oil pipeline from Canada should not significantly impact refinery crude supplies. As discussed above, repairs to this pipeline can be completed in about a week, depending on the resources available to conduct pipeline repairs. The damage assessment for the product pipelines flowing from Seattle refineries is less optimistic. The Hazus analysis indicates that the 350-mile refined product pipeline between Seattle, WA, and Eugene, OR, will incur substantial damage in the form of leaks and breaks and will likely take several weeks to repair.

Figure 5-19 presents Hazus damage estimates for refinery capacity, ports, refined product terminals, and pump stations as a fraction of the total number of components or capacity. As with the crude and refined product pipelines, refineries and petroleum ports remained relatively unscathed by the earthquake event and therefore will not significantly impact the flow of petroleum products. About 94 percent of Seattle's refining capacity is unharmed or is only slightly damaged. Likewise, about 81 percent of the area's ports that process crude and refined products had only slight damage to their facilities. For these system components, it is reasonable to assume a recovery measured in days to weeks.



	None	Slight	Moderate	Severe	Complete
Refinery Capacity	52%	42%	0%	0%	6%
Refined Terminals	3%	0%	19%	9%	69%
Pump Stations	31%	0%	31%	0%	38%
Petroleum Ports	0%	81%	4%	0%	15%

Figure 5-19. Expected damage distribution

Similarly, in the short-run, refinery disruptions caused by power blackouts should not significantly impact the region's ability to deliver refined products. According to current estimates, power production and transmission capacity should be restored within a few days of the earthquake event. Existing inventories will absorb much of the impact of the temporary refinery shutdowns caused by power loss.

The major bottlenecks in the system post-event are the pipeline pump stations and product terminals located along the Olympic and Oregon Line pipeline systems in Seattle, Portland, and (to a lesser extent) in Eugene. In both cases, the expected damage is extensive and the repair or replace estimates are likely measured in months to a year or more.

For example, nearly 80 percent of the product terminals are expected to be severely damaged or completely damaged. Tank farms that serve as vital aggregation nodes will not be operational for a protracted period. The Hazus damage categories indicate this level of damage is characterized by tank failure, spillage, and loss of product. Similarly, pump stations, and therefore the pipelines themselves, will not be operational for an extended period likely measured in several months. Nearly half of the refined product pipeline pump stations will be completely damaged. Given what is known about the expected damage to system components, the Pacific Northwest corridor will experience significant fuel shortages for an extended period after the earthquake event.

The Seattle demand region receives a total of 492 Kbpd of refined product from refinery production output and external waterborne shipments. With the loss of pipeline transportation function from Seattle to Portland, the refined products inventory at Seattle refineries will increase and eventually force refineries to reduce production output.

In the Seattle demand region, tanker truck terminals located at refineries will remain operational and should be able to supply fuel directly to local distributors and retail locations. However, some areas will not be able to receive these supplies due to road system damage. As indicated in the road transportation analysis, some areas within the impact zone will incur extensive to complete damage to road segments, bridges, and tunnels. For these areas, it is likely that significant fuel shortages will be realized.

The Portland demand region will experience significant reduction in fuels supplies. Aside from the loss of supplies from the Olympic pipeline, the inability to store and distribute fuels locally will significantly impact the region.

With the Portland fuel transfer center out of commission, fuel supplies to the Eugene and Kennewick-Richland demand regions will be significantly impacted. For western Washington demand regions, this problem becomes even more complicated by the reduction or loss in the ability to move waterborne transportation into the Columbia River system as discussed in the Ports and Maritime Infrastructure Direct Impacts section. In turn, shortages in Kennewick-Richland will cause downstream disruptions in Boise, ID, markets. Further analysis is required to estimate the magnitude of the shortages in these markets.

The Spokane and Moses Lake demand regions are fed by pipelines originating from Kennewick-Richland terminals and Billings, MT, refineries. Even assuming that 100 percent of Kennewick-Richland supplies are cut off, the 10-inch diameter ConocoPhillips pipeline likely has sufficient capacity to meet demand. Further analysis is required to verify that product availability from Billings would be sufficient to meet this increased demand.

5.3.4 Transportation

5.3.4.1 Road Transportation

The roadway transportation system includes road segments, bridges, and tunnels. It does not include ferries. Water and rail transportation networks are reported separately.

5.3.4.1.1 Earthquake Direct Impacts on Roads, Bridges, and Tunnels

For roadway transportation, RDMB-NISAC computes direct effects from the earthquake on road segments, bridges, and tunnels using Hazus. In this analysis, the expected damage level and the 90th-percentile damage level are provided to inform planners of the average versus more extreme damage levels. Table 5-20 shows the estimated average and 90th-percentile damage states for road segments, bridges, and tunnels in the affected area.

Table 5-20. Estimated average and 90th-percentile damage states from earthquake for road segments, bridges, and tunnels in the affected area

Damage State	Number of Road Segments		Number of Road Bridges		Number of Tunnels	
	Average	90th-percentile	Average	90th-percentile	Average	90th-percentile
None	6,010	5,343	10,884	10,039	38	36
Slight	1,093	350	1,204	737	1	2
Moderate	419	364	758	815	1	1
Extensive	286	0	460	1,122	2	1

Damage State	Number of Road Segments		Number of Road Bridges		Number of Tunnels	
Complete	260	2,011	841	1,434	0	2

Table 5-21,

Table 5-22, and Table 5-23 show the damage to transportation road infrastructure for each Cascadia state. In California, about 93 percent of the assets receive None or Slight damage in the expected damage case and 66 percent for the 90th-percentile case. Oregon receives None or Slight damage for 75 percent of assets in the expected damage case and 56 percent for the 90th-percentile case. Washington receives None or Slight damage for 87 percent of assets in the expected damage case and 72 percent for the 90th-percentile case.

Table 5-21. Estimated average and 90th-percentile damage states from earthquake for road segments, bridges, and tunnels, California

Damage State	California Number of Road Segments		California Number of Road Bridges		California Number of Tunnels	
	Average	90th-percentile	Average	90th-percentile	Average	90th-percentile
None	1,575	1,562	4,555	4,313	4	3
Slight	12	9	83	215	0	1
Moderate	12	4	25	49	0	0
Extensive	10	0	11	58	0	0
Complete	90	124	214	253	0	0

In each state, road damage is most severe along the coast and in the coastal mountain chain. Some damage occurs along the Interstate 5 (I-5) corridor, and far less damage is incurred east of I-5. Road damage has the potential to disrupt traffic flows, leading to widespread economic impacts. It affects repair, restoration, and emergency response activities. Remote communities that rely on one or two roads to connect to the rest of the road network may be isolated by road and bridge damage. Such cases can make the delivery of emergency supplies of food, water, medicine, fuel, and materials impossible by ground transportation, until sufficient road restoration occurs. In urban areas, loss of bridges and overpasses will require the use of alternate routes, typically increasing travel time and increasing traffic congestion.

Table 5-22. Estimated average and 90th-percentile damage states from earthquake for road segments, bridges, and tunnels, Oregon

Damage State	Oregon Number of Road Segments		Oregon Number of Road Bridges		Oregon Number of Tunnels	
	Average	90th-percentile	Average	90th-percentile	Average	90th-percentile

Damage State	Oregon Number of Road Segments		Oregon Number of Road Bridges		Oregon Number of Tunnels	
None	1,464	1,122	1,842	1,656	7	7
Slight	516	189	391	166	1	0
Moderate	221	121	297	313	0	1
Extensive	218	0	264	447	1	0
Complete	108	1,095	263	475	0	1

Table 5-23. Estimated average and 90th-percentile damage states from earthquake for road segments, bridges, and tunnels in Washington

Damage State	Washington Number of Road Segments		Washington Number of Road Bridges		Washington Number of Tunnels	
	Average	90th-percentile	Average	90th-percentile	Average	90th-percentile
None	2,971	2,659	4,487	4,070	27	26
Slight	565	152	730	356	0	1
Moderate	186	239	436	453	1	0
Extensive	58	0	185	617	1	1
Complete	62	792	364	706	0	1

Figure 5-20 and Figure 5-21 show highway bridge and tunnel locations that are expected to experience moderate to extensive damages under the average and 90th-percentile damage cases, respectively.

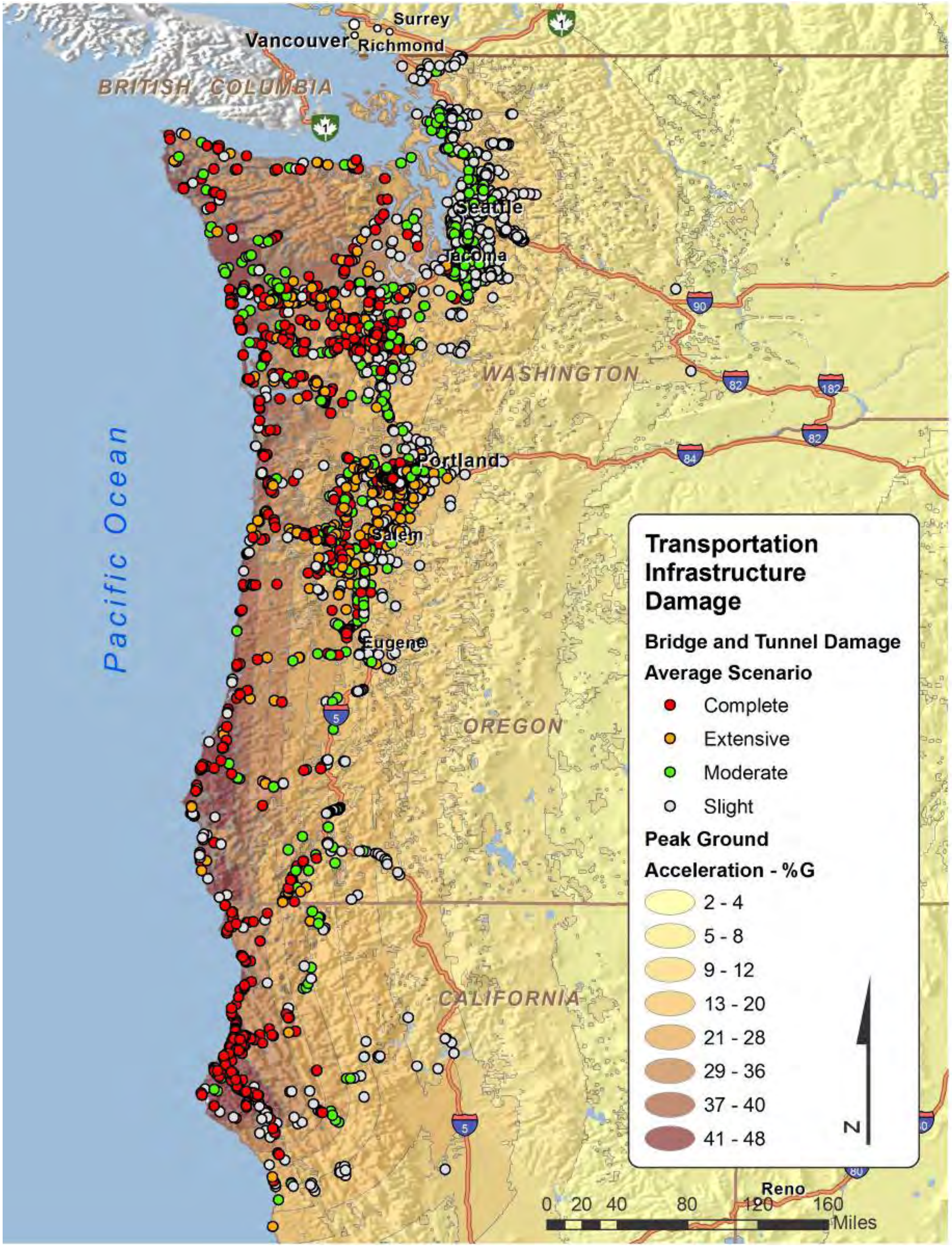


Figure 5-20. Highway bridges and tunnels in the Cascadia region with expected damage states of slight or more under the average case scenario

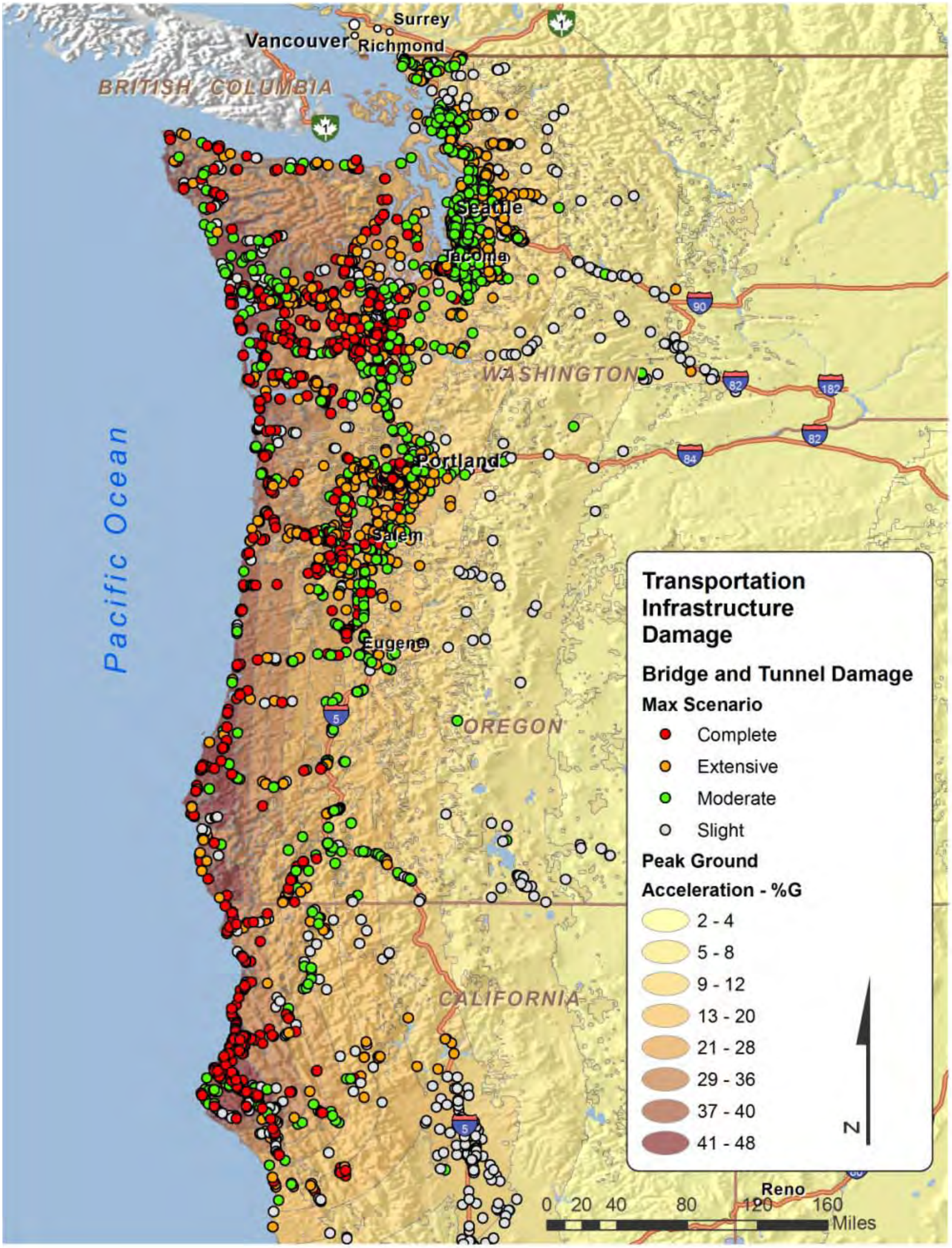


Figure 5-21. Highway bridges and tunnels in the Cascadia region with expected damage states of slight or more under the 90th-percentile case scenario

Figure 5-22 and Figure 5-23 show locations of highway road segments that are expected to experience moderate to extensive damages under the average and 90th-percentile damage cases, respectively.

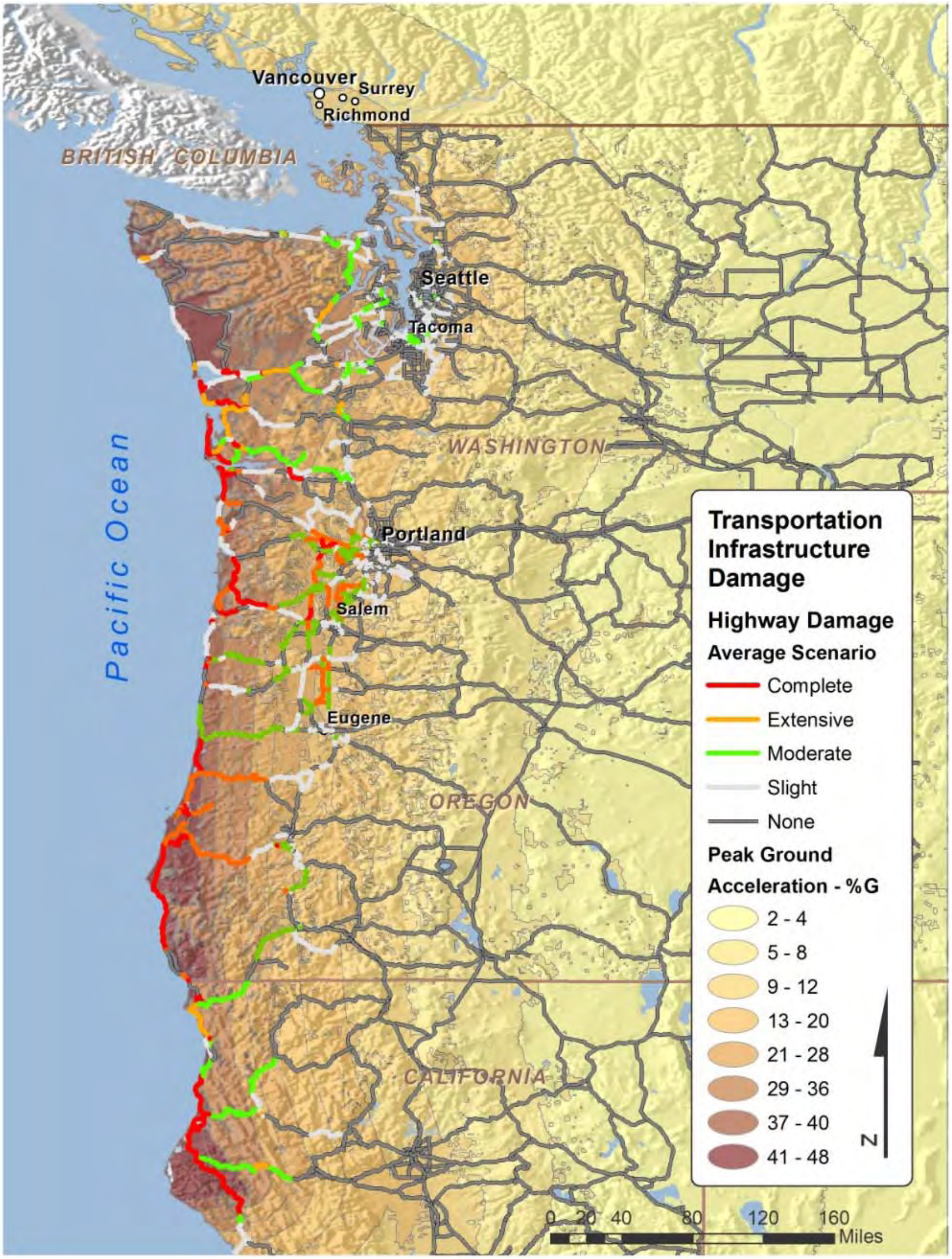


Figure 5-22. Highway road segments in the Cascadia region with expected damage states of slight or more under the average case scenario

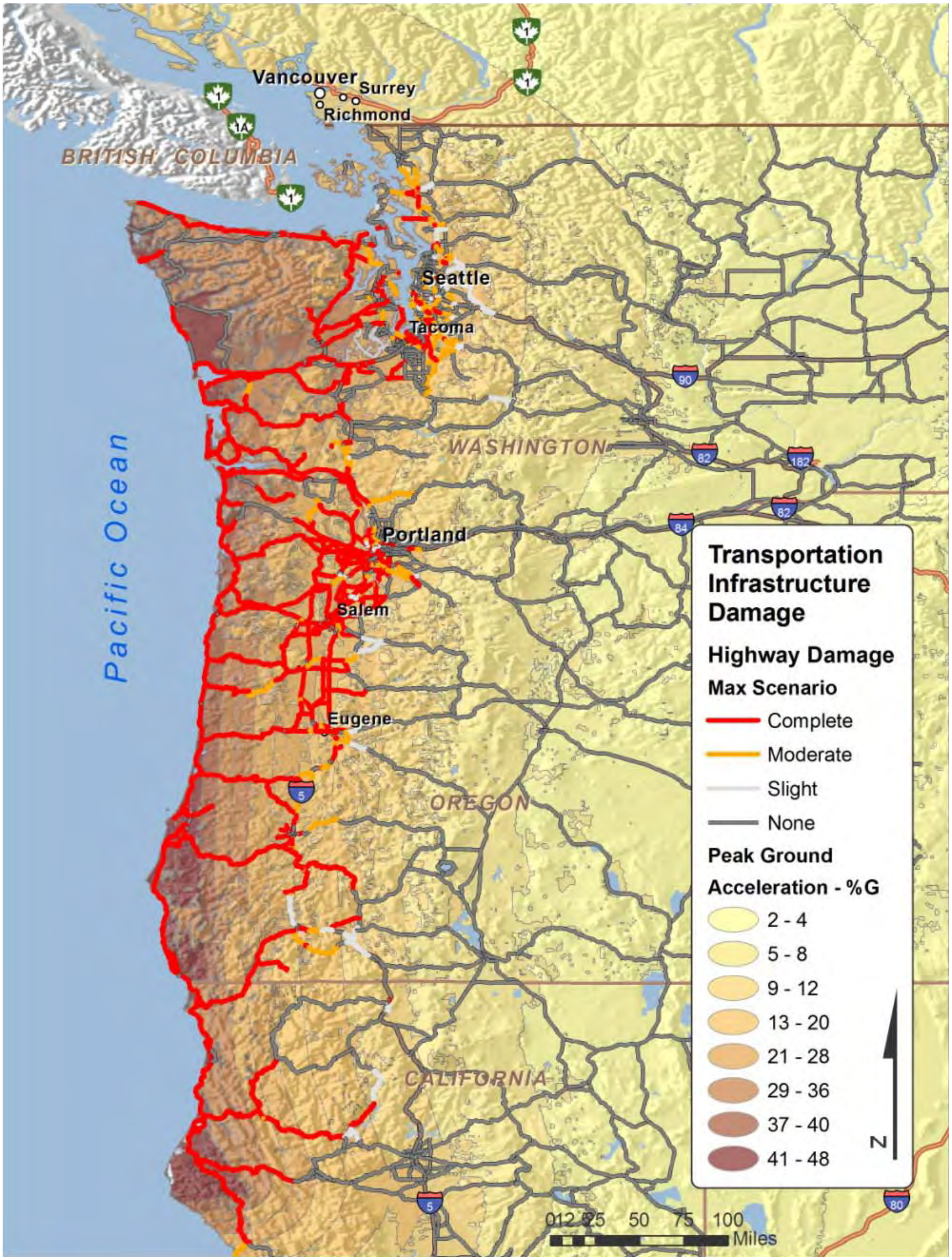


Figure 5-23. Highway road segments in the Cascadia region with expected damage states of slight or more under the 90th-percentile case scenario

5.3.4.1.2 Tsunami Effects on Roads, Bridges, and Tunnels

Table 5-21 shows the number of tsunami-inundated highway roads, highway bridges, and highway tunnels located within the Cascadia study region. RDMB-NISAC analysis results showed no inundated road segments for any of the sites in Alaska. For more detailed information on flood depths and road/bridge/tunnel names, along with inundation maps, refer to Appendix D of this report.

Table 5-21. Inundated major highway roads, highway bridges, and highway tunnels located within the Cascadia study region

Study Area	Number of Roads Inundated*	Number of Bridges Inundated*	Number of Tunnels Inundated*
Alaska			
State	0	0	0
California			
Crescent City	6	2	0
Humboldt	2	0	0
Oregon			
Cannon Beach	1	3	0
East Astoria	4	0	0
Newport Beach	0	1	0
Port Orford	0	1	0
Gearhart–to–Seaside	5	4	0
Warrenton	9	6	1
Rockaway Beach	3	0	0
Lincoln City	1	3	0
Waldport–to–Yahcats	2	0	0
Washington			
Moclips–to–Westport	3	10	0
Grays Harbor	3	2	0
Southbend–to–Raymond	2	1	0

* Because the height of a facility structure may be higher than the estimated flood depth, an inundated facility does not necessarily imply the facility is completely submerged. This table presents the number of facilities located within a region with a positive flood depth. Information on the facility's structure height and the specific flood depths is needed to determine if a facility is completely submerged.

5.3.4.1.3 Restoration of Bridges

For this analysis, the focus is on the 90th-percentile damage case.

Table 5-22 defines bridge damage and repair activity, per the Hazus technical manual.[24] Figure 5-20 shows the geographic location of damaged bridges.

[24] Federal Emergency Management Agency, *HAZUS MH MR4 Flood Model Technical Manual*, www.fema.gov/library/viewRecord.do?id=3726, (2006).

Table 5-22. Damage state definition for roadway bridges

Damage State	Description	Repair Actions
None	No damage	No repair costs or interruption of traffic.
Slight	Minor cracking and spalling of the abutment, cracks in shear keys at abutment, minor spalling and cracking at hinges, minor spalling of column requiring no more than cosmetic repair, or minor cracking of deck.	Minor repair costs but no shoring is needed. No interruption of traffic.
Moderate	Any column experiencing moderate shear cracking and spalling (with columns still structurally sound), moderate movement of abutment (< 2 inches), extensive cracking and spalling of shear keys, connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of approach.	Bridge damage is repairable, but shoring will be needed before repairs proceed. Shoring must be sufficient to totally support all dead loads and full traffic loads during repairs. Any jacking or ramping needed at locations of moderate settlement and offset will be done while shoring is proceeding. Bridge will be fully closed to traffic during shoring, and then fully reopened to traffic while repairs proceed. Moderate repair costs will be incurred.
Extensive	Any column degrading without collapse (e.g., shear failure) but structurally unsafe, significant residual movement of connections, major settlement of approach fills, vertical offset, or shear key failure at abutments, or differential settlement.	Some bridge elements are irreparably damaged and must be replaced. However, replacement of these elements can occur without replacing entire bridge. Bridge will first be extensively shored so that all dead loads and full pre-earthquake traffic loads are completely supported during replacement of damaged elements. Any jacking or ramping needed at locations of significant offset or settlement will be done while shoring is proceeding. Bridge will be fully closed to traffic during shoring, and then fully reopened to traffic during replacement of damaged elements. Major costs for replacement of damaged elements will be incurred. The shoring requirements for extensively damaged bridges will be more extensive than the shoring for moderately damaged bridges.
Complete	Collapse of any column, or unseating of deck span leading to collapse of deck. Tilting of substructure due to foundation failure.	Irreparable damage is sufficiently extensive to require replacement of entire bridge.

RDMB-NISAC used the data shown in Table 5-23 to provide coarse estimates of the time and cost to repair bridges. Actual time and cost will depend on resource availability (crews, specialty machines, and materials), accessibility of the bridge damage (bridges that cross major rivers have accessibility constraints that may increase time and cost), extensiveness of non-roadway damage (damage to adjacent buildings and co-located infrastructure may increase time and cost), as well as the efficiency with which contracts are approved. The time and cost estimates given here do not account for these complicating factors.

Table 5-23. Repair time and cost ratios for bridges damaged by ground shaking[25]

Damage State	Number of Spans	Bridge Repair Time	Underlying Roadway Repair Time	Repair-Cost-Ratio
None	-	0	0	0
Slight	-	0	0	0.03
Moderate	-	4	4	0.25
Extensive	-	12	12	0.75
Complete	≤ 3	140	30	1.0
	4	180	30	1.0
	≥ 5	220	30	1.0

Figure 5-24 and Figure 5-25 depict the estimated repair costs for bridges damaged by state for the average damage case and the 90th-percentile damage case. On average, the bridge repair costs for the 90th-percentile case are about twice that of the average damage case. Table 5-24 shows the estimated total repair cost by state.

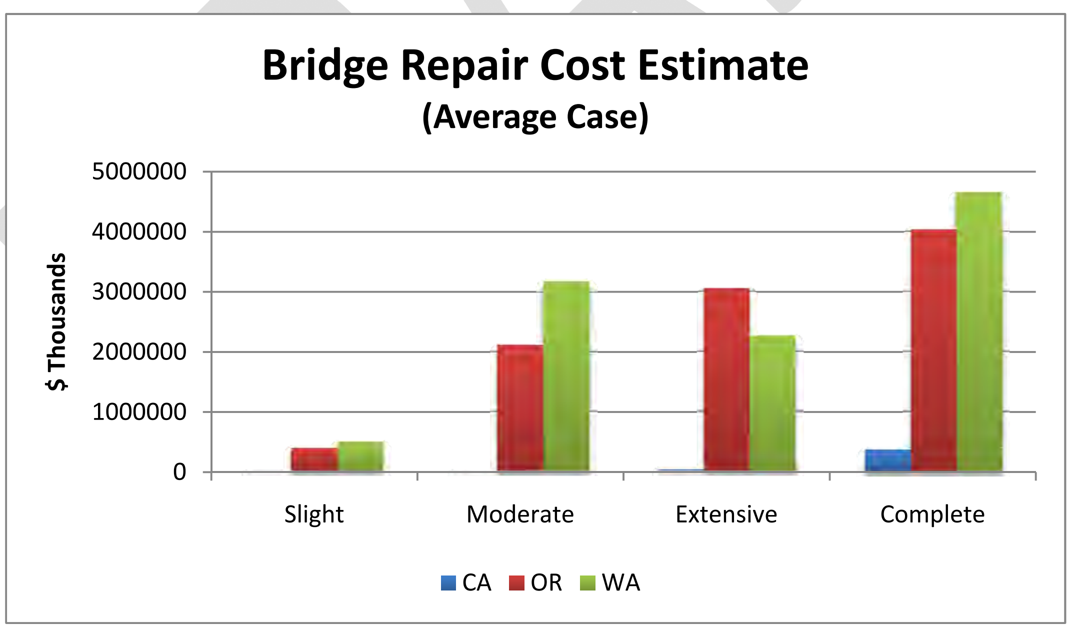


Figure 5-24. Estimate of cost to repair damaged bridges in the average damage case

[25] Werner, S.D., Cho, S., Taylor, C.E., Lavoie, J-P, Huyck, C.K., Chung, H., and Eguchi, R. *Technical Manual: REDARS™ 2 Methodology and Software for Seismic Risk Analysis of Highway Systems,* Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, (2006).

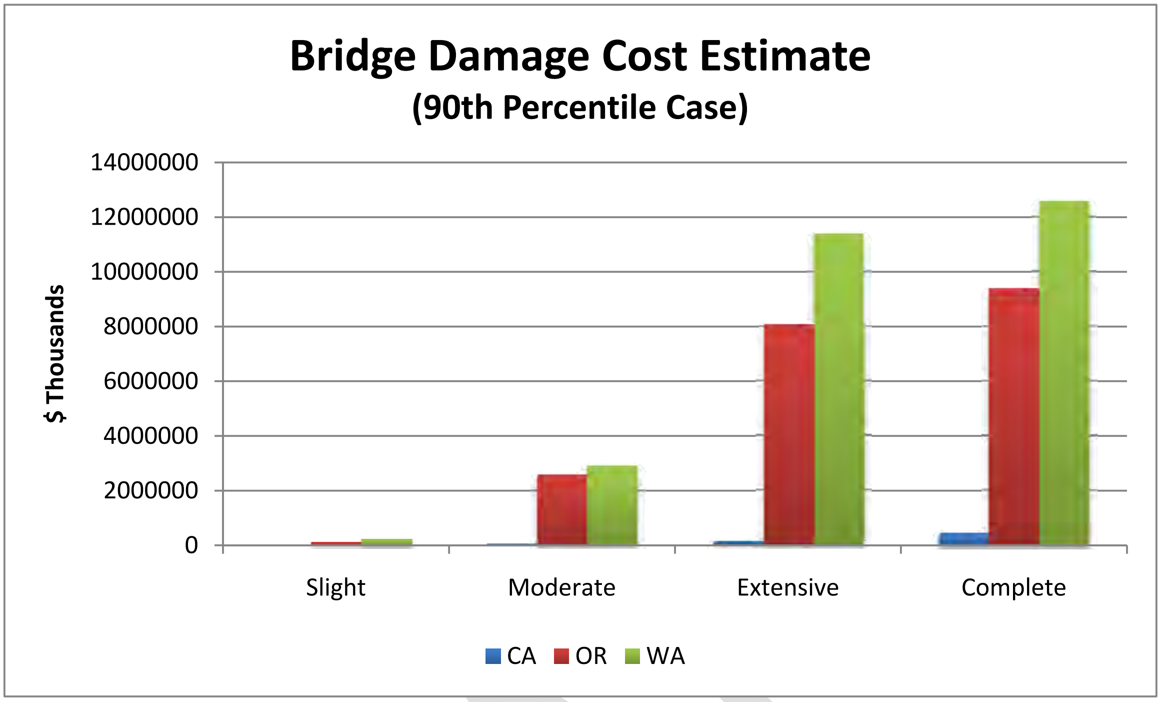


Figure 5-25. Estimate of cost to repair damaged bridges in the 90th-percentile damage case

Table 5-24. Estimated repair cost for highway bridges ($ millions)

Total Cost ($ millions)	Average Damage Case ($ millions)	90th-percentile Case ($ millions)
CA	$426	$594
OR	$9,602	$20,162
WA	$10,584	$27,187

Figure 5-24 and Figure 5-25 show the estimated time to repair the damaged bridges in crew days (time for a dedicated crew to repair), for both the average damage case and the 90th-percentile damage case. The actual number of repair days depends on the specific allocation of crews. Repair time is represented for the repair to the bridge structure as well as the repair of the road surface on the bridge. This estimate does not account for the period of damage assessment, which is nominally a week, but could extend to longer times given that some damage will be located in difficult-to-access areas of the region.

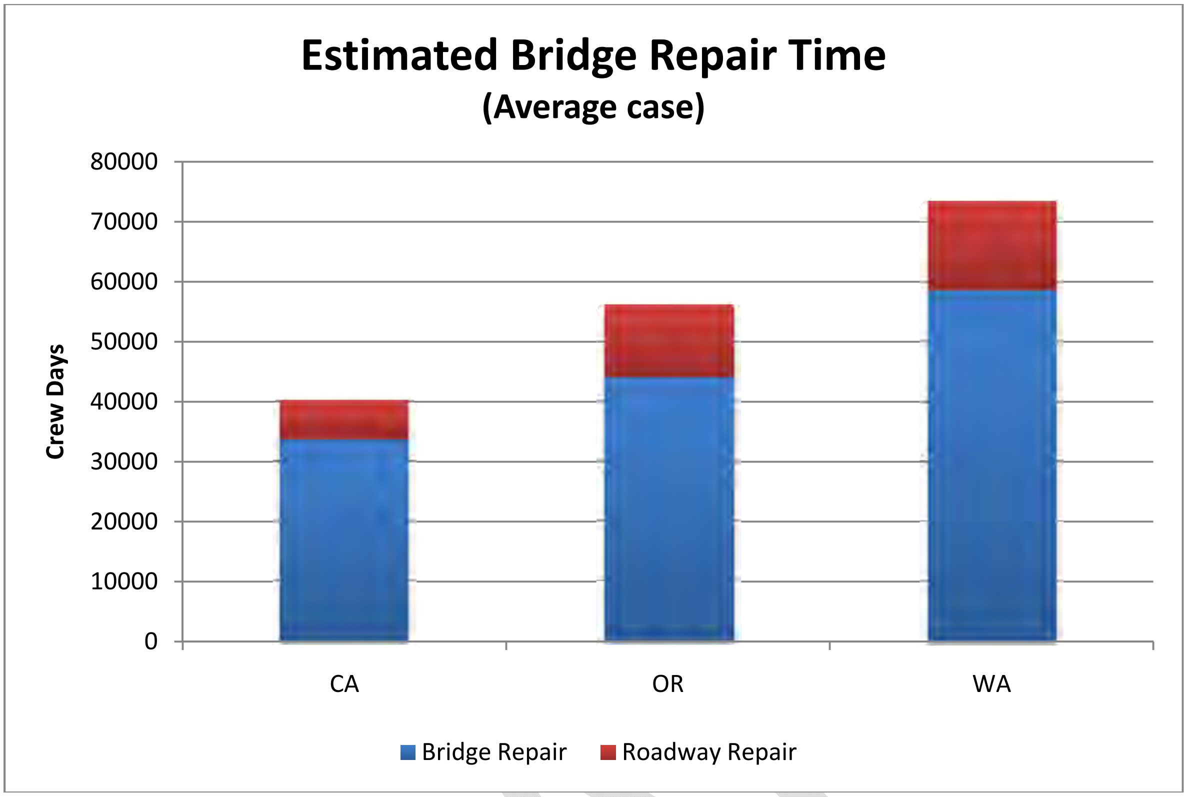


Figure 5-26. Estimated bridge repair time for the average damage case

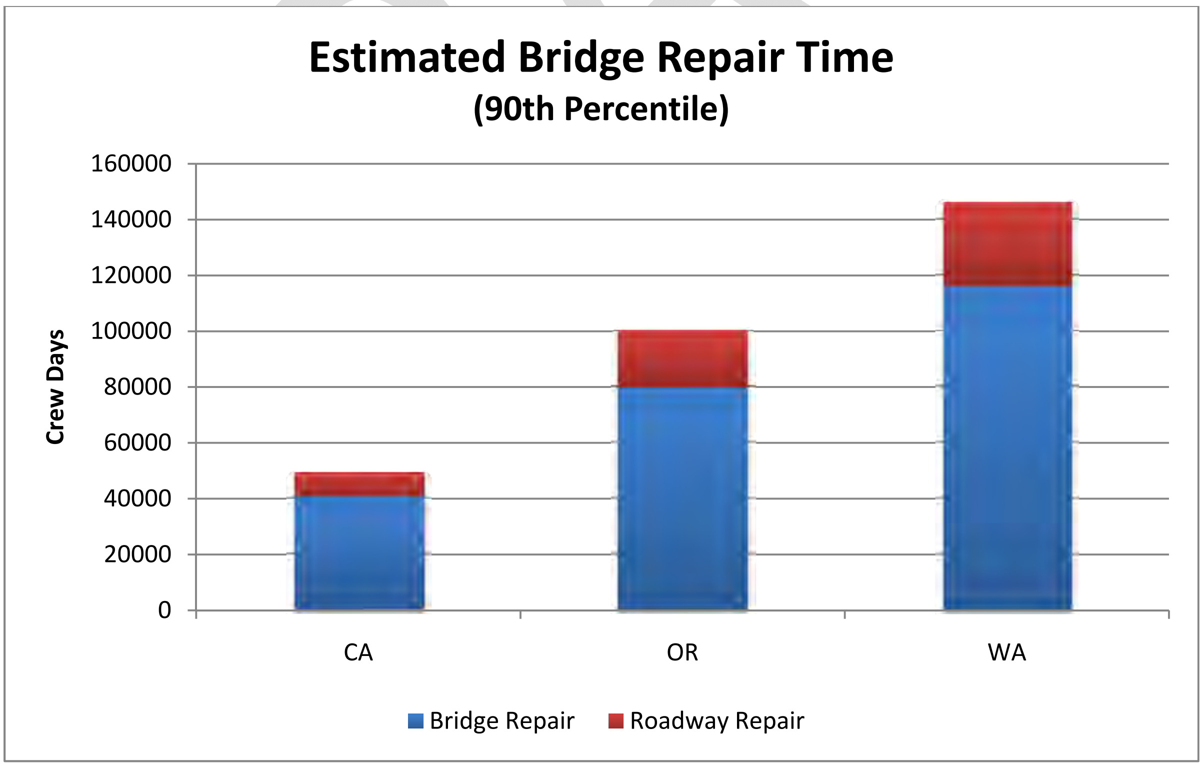


Figure 5-27. Estimated bridge repair time for the 90th-percentile damage case

5.3.4.1.4 Restoration of Roads

Damage to road segments is due to lateral spreading, vertical displacement, or horizontal displacement. Table 5-25 describes the damage and repair times for road segments (from Werner et al., 2008).[26]

Table 5-25. Groundshaking damage to roadways and repair times

Damage	Permanent Ground Displacement (inches)	Description	Repair Procedure	Repair Time (days)	Repair Cost per lane-mile ($)
None	<1	No repairs needed	None	0	0
Slight	1 ≤ and < 3	Slight cracking or movement. No interruption of traffic	Horizontal displacement: crack/seal. Vertical displacement: mill and patch	0-1	50,000
Moderate	3 ≤ and < 6	Localized moderate cracking or movement. Reduced structural integrity of pavement surface	No repair needed for sub-base. If asphalt pavement, or if damage to concrete pavement extends over long length, use asphalt concrete overlay. If damage to concrete pavement is localized, replace concrete slab.	1–3	100,000
Extensive	6 ≤ and < 12	Failure of pavement structure, requiring replacement. Movement but not failure of subsurface soils.	Rebuild pavement structure and sub-base. Provide soil improvement for subsurface materials.	1–7	300,000
Complete	≥ 12	Failure of pavement and subsurface soils	Remove and replace existing pavement structure and subsurface materials.	1–49	600,000

Roadway damage for the 90th-percentile case is extensive throughout the coast and coastal mountain range, as seen in Figure 5-23. Most primary and secondary roads from the I-5 corridor to the coast are completely damaged, putting many coastal communities in near isolation with respect to ground transportation. However, as the road network is highly interconnected, alternate routes may exist, although they may require use of tertiary roads. Damage to the tertiary road system was not modeled in this analysis. Forces sufficient to damage primary and secondary roads also damage tertiary roads, potentially to a greater degree. Local damage to the tertiary road system is expected to be commensurate with or worse than local damage to the

[26] Werner, S.D., Cho, S., Eguchi, R., “Analysis of Risks to Southern California Highway System,” www.colorado.edu/hazards/shakeout/highways.pdf, (2008).

primary and secondary road system. This still leaves the possibility of routes using tertiary roads, as they are typically more extensive and interconnected than the primary and secondary system.

Estimating the time and cost of repair for the roadway segments is a challenge. Each segment has a unique length and while damage is assigned to the segment based on the evaluation of conditions at a specific point on the road segment, the extent of the damage is unknown. Damage could be due to lateral or vertical displacement, liquefaction, or landslide debris. Under the assumption that for each damaged road segment, one mile of road requires repair, an estimate of repair time and cost (in units of thousand dollars) for the 90^{th}-percentile damage case is given in Table 5-26, using the maximum repair time and costs given in Table 5-25. The same information is depicted graphically in Figure 5-28 and Figure 5-29 for the average damage case.

Table 5-26. Repair time (days) and cost ($ thousands) for damaged highway road segments (90^{th}-percentile)

State	None		Slight		Moderate		Extensive		Complete	
	Time	Cost $ 000	Time	Cost $ 000	Time	Cost $ 000	Time	Cost $ 000	Time	Cost $000
CA	0	0	0	450	12	400	0	0	6,076	74,400
OR	0	0	0	9,450	363	12,100	0	0	53,655	657,000
WA	0	0	0	7,600	717	23,900	0	0	38,808	475,200

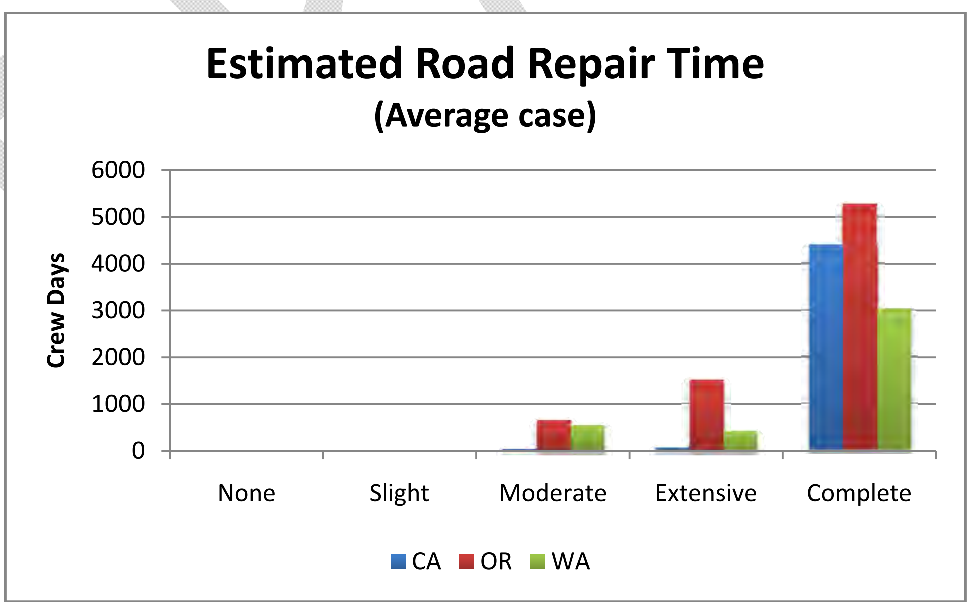


Figure 5-28. Estimated road repair time per state by damage class, average damage case

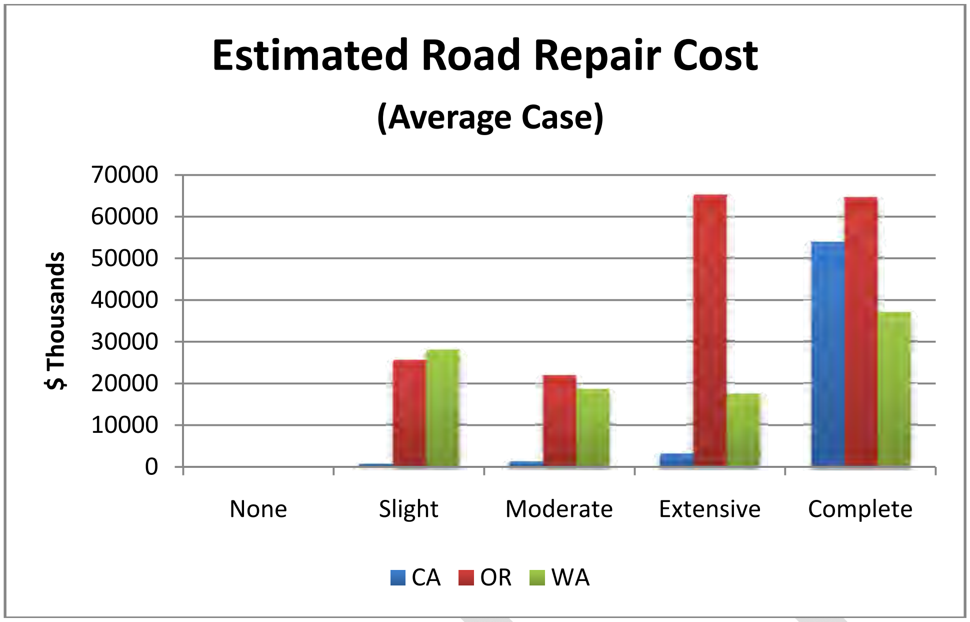


Figure 5-29. Estimated road repair costs per state by damage class, average damage case

5.3.4.1.5 The Coast Road: US 101

From Leggett, CA, to Neah Bay, WA, most of the coastal highways sustain complete damage. Several bridges on U.S. 101 are extensively or completely damaged. Trafficability will be very poor along the coast. Damage to the major route on the coast, U.S. Highway 101, may be extensive. For this analysis, the focus is on the 90th-percentile damage case. Figure 5-30 shows the damaged roads and bridges on the northern coast of California. Highway 101 is damaged south from Eureka to Leggett, where it intersects California State Highway 1. Damage to bridges and primary and secondary roads will isolate Eureka, Humboldt, and Crescent City. Routes 96, 299, 36, and 101 are significantly damaged. Alternate routes may exist along tertiary roads. However, this study did not assess damage against these roads and the tertiary road network may have severe damage as well.

In some locations where transportation asset damage occurs, the probability of landslide [Pr(Landslide)] is assessed to be 1 (i.e., certain). Figure 5-30 represents these locations with an icon representing a landslide. Sites with probability of landslide less than 1 are not indicated in the figure.

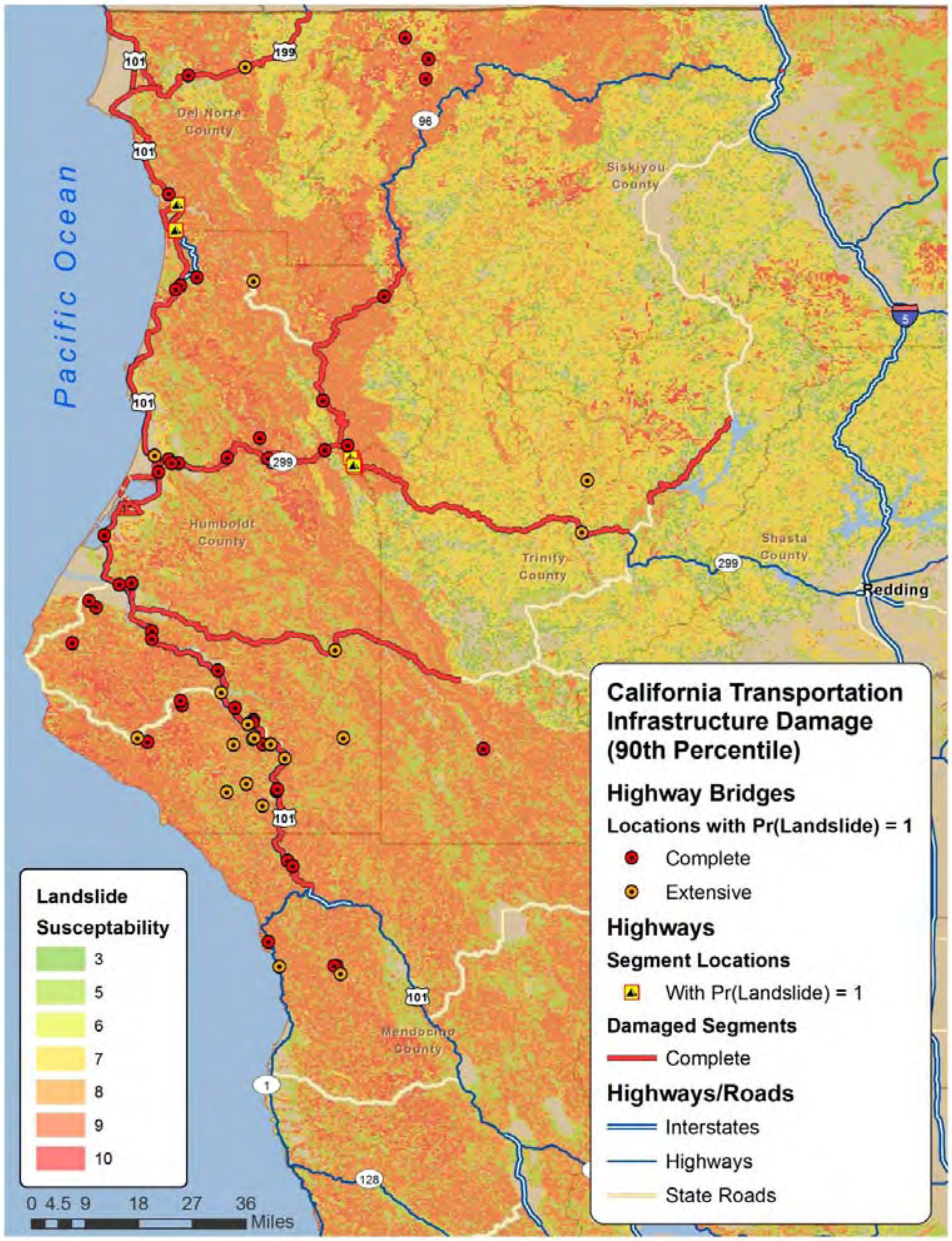


Figure 5-30. California transportation infrastructure damage for 90th-percentile case

Figure 5-31 shows damage to the road infrastructure in the Oregon coastal region for the 90th-percentile case. U.S. 101 is completely damaged for its full extent along the Oregon coast. Multiple bridges along U>S>101 are extensively or completely damaged. Routes connecting U.S. 101 to I-5, such as U.S. 199; Oregon state highways 42, 38, 126, 34, 20, 18, 22, and 6; and U.S. 26 and U.S. 30, all sustain complete damage. Some have landslides (Oregon 42, U.S. 199, and U.S. 30) with probability of 1. The road and bridge damage effectively isolates the coastal communities from the central I-5 corridor. Alternate routes may exist using the tertiary road system, but it too may have sustained considerable damage.

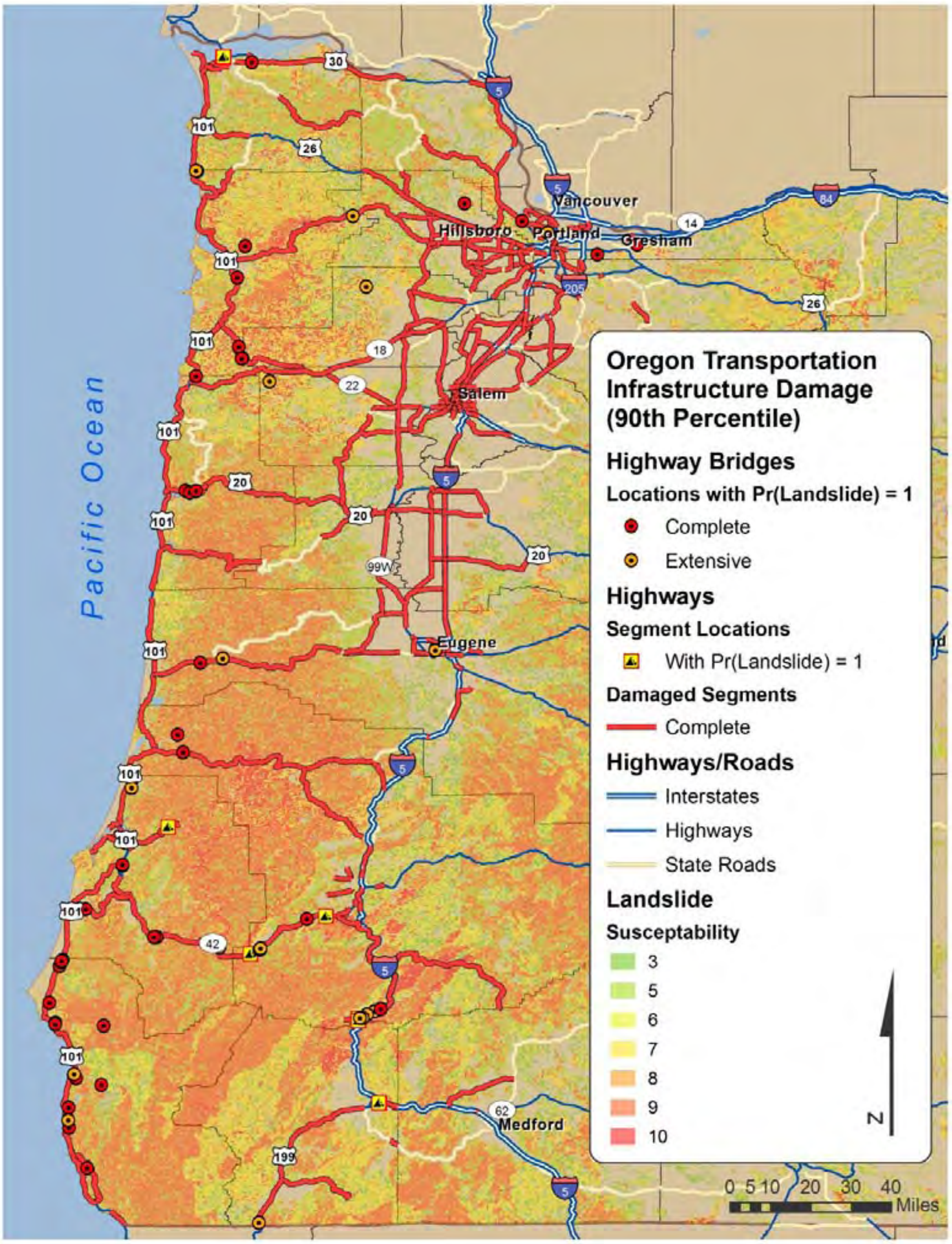


Figure 5-31. Oregon transportation infrastructure damage (90th-percentile case)

Figure 5-32 shows the damage to Washington transportation assets for the 90th-percentile damage case. Along the coastal corridor, much, but not all of U.S. 101 is completely damaged. However, Oregon highways 4, 6, 8, 105, 109, and 112, as well as U.S. 12, all sustain complete damage along their extent, limiting access between the interior of the state and the coastal regions. Landslide damage is indicated near Chinook, Hoquiam, Port Angeles, Shelton, and several places in the Seattle urban area. Many bridges sustain extensive or complete damage. For example, Oregon 6 from Chehalis to Raymond loses multiple bridges.

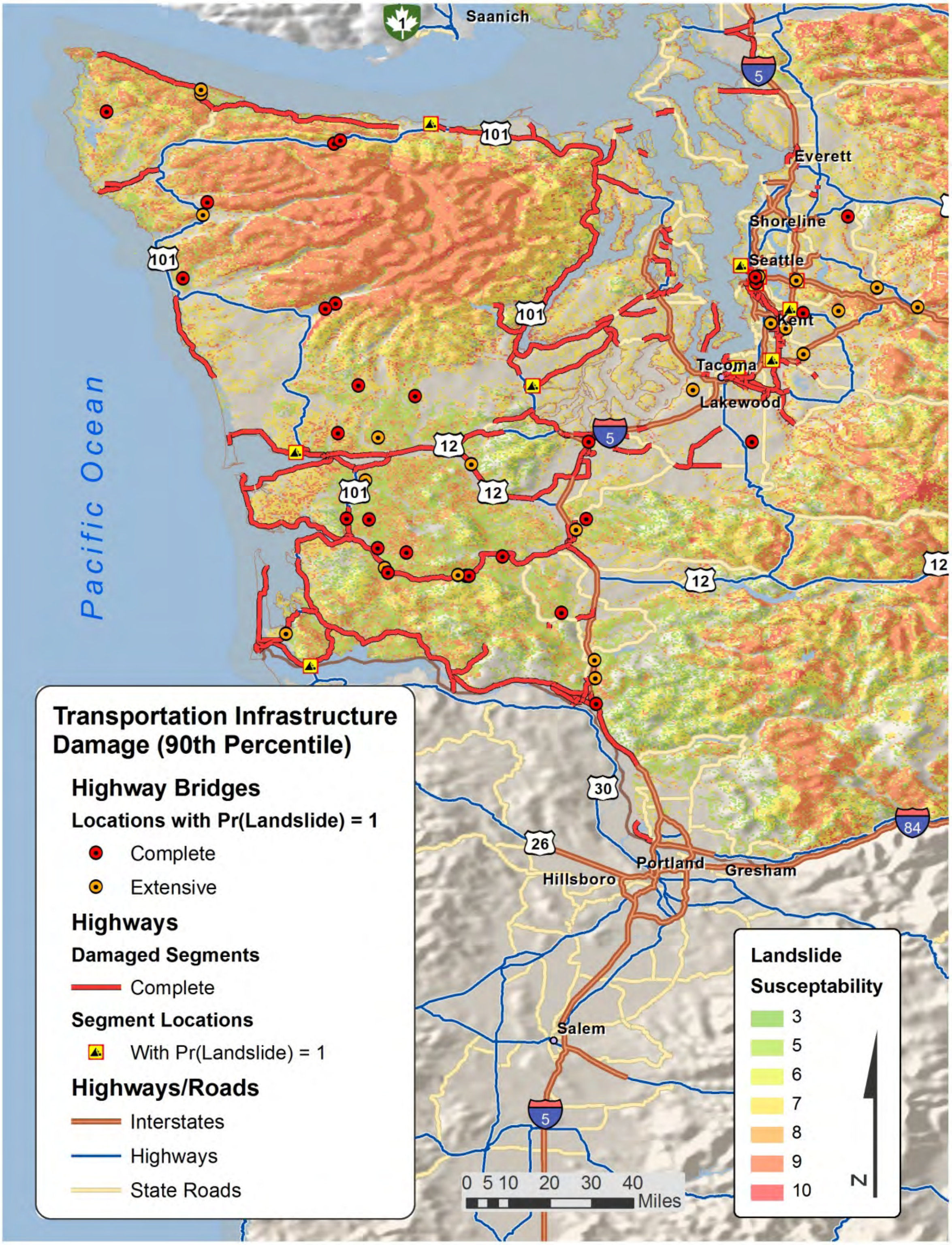


Figure 5-32. Washington transportation infrastructure damage (90th-percentile case)

5.3.4.1.6 The I-5 Corridor

The I-5 is a major roadway running from Los Angeles through Seattle to the U.S. border with British Columbia. Even in the 90th-percentile case, there is no complete damage for any road segments of I-5 in California. In Oregon, roughly half of the I-5 roadway system is completely damaged. Wolf Creek to Sutherlin sustains complete damage. The sections from Eugene to Portland sustain complete damage over roughly 90 percent of the road sections. In Washington, roughly 40 percent of the I-5 sustains complete damage. Given the substantial damage to I-5, traffic between California and Portland or Seattle would likely be rerouted along U.S. 97 to I-84 to Portland or I-82 to Seattle.

5.3.4.1.7 Routes from I-5 to the Coast

Nearly all primary and secondary roads between the I-5 corridor and the West Coast communities are completely damaged, often with damaged bridges. For example, U.S. 20 from Corvallis, OR, to Newport, OR, is 50 miles in length. The entire length of the route sustains complete damage, as do three bridges. Given the suggested bridge and road repair times noted in Table 5-24 and Table 5-26, it will be a minimum of 140 days to repair a bridge and up to 49 days to repair the roadway. It will take 3 to 6 months to restore these routes, depending on resources and priorities. Coastal communities should expect to be isolated by ground transportation from the interior of the states for several months. However, access by sea and air will still be possible.

5.3.4.1.8 Impact on Major Urban Areas

Damage to roadways will have a significant impact on major urban areas. Figure 5-33 shows road damage to Portland (90th-percentile case). There will be significant disruption to traffic flow in downtown Portland due to damage to roadways and to bridges. It appears that five of the eight downtown bridges will sustain damage. Figure 5-34 shows road damage in Seattle (90th-percentile case). Many bridges sustain damage and many road segments have complete damage. However, the potential for viable alternate routes exists, enabling some degree of travel, albeit with considerable delays. Under this scenario, a bridge on Washington 518 between I-5 and SeaTac airport is completely damaged. This bridge appears to be easily avoided using alternate routes. In urban areas, the population should expect longer travel times and the need to use alternate routes. Repair of the urban road system will take months to years to complete.

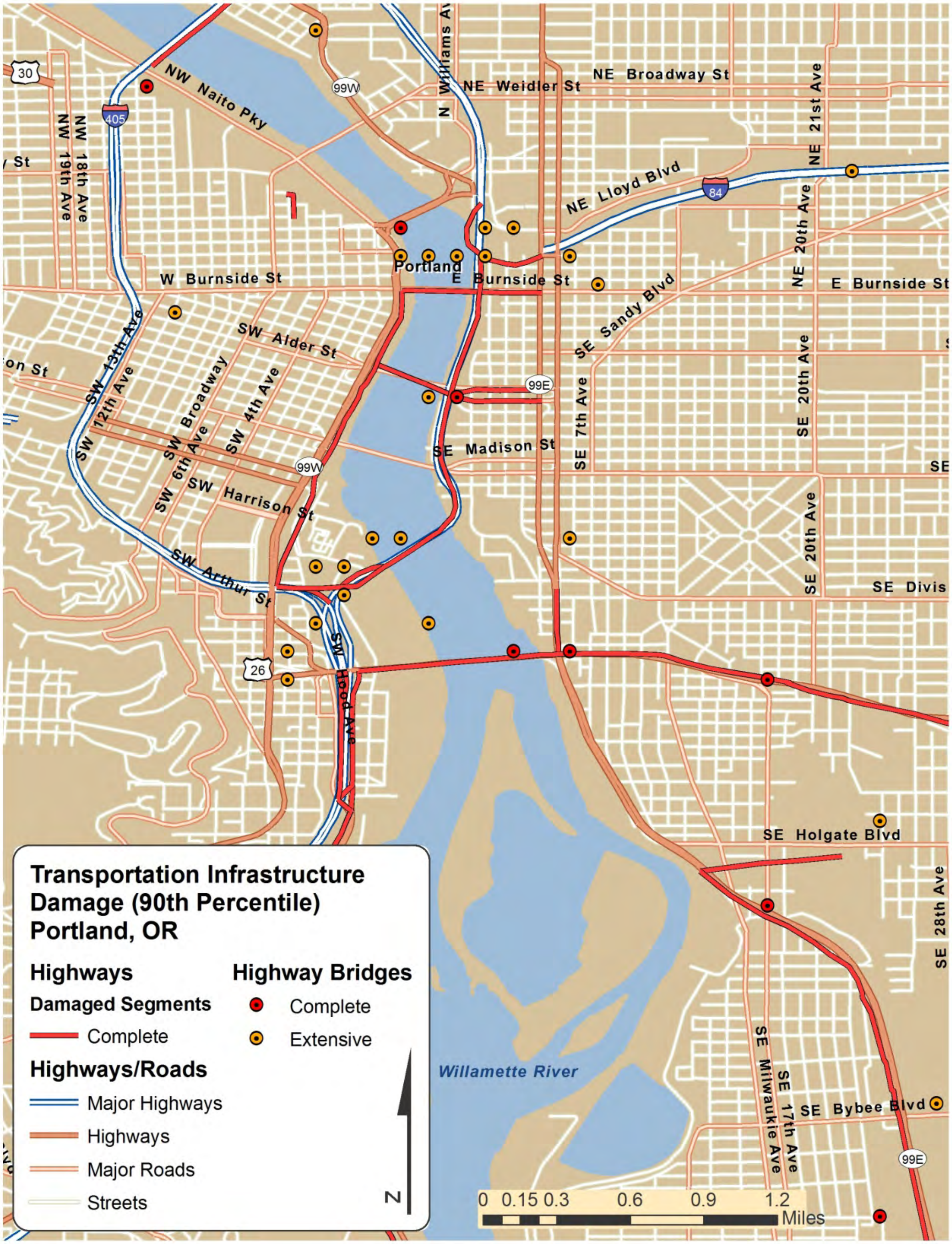


Figure 5-33. Roadway damage in Portland, OR (90th-percentile case)

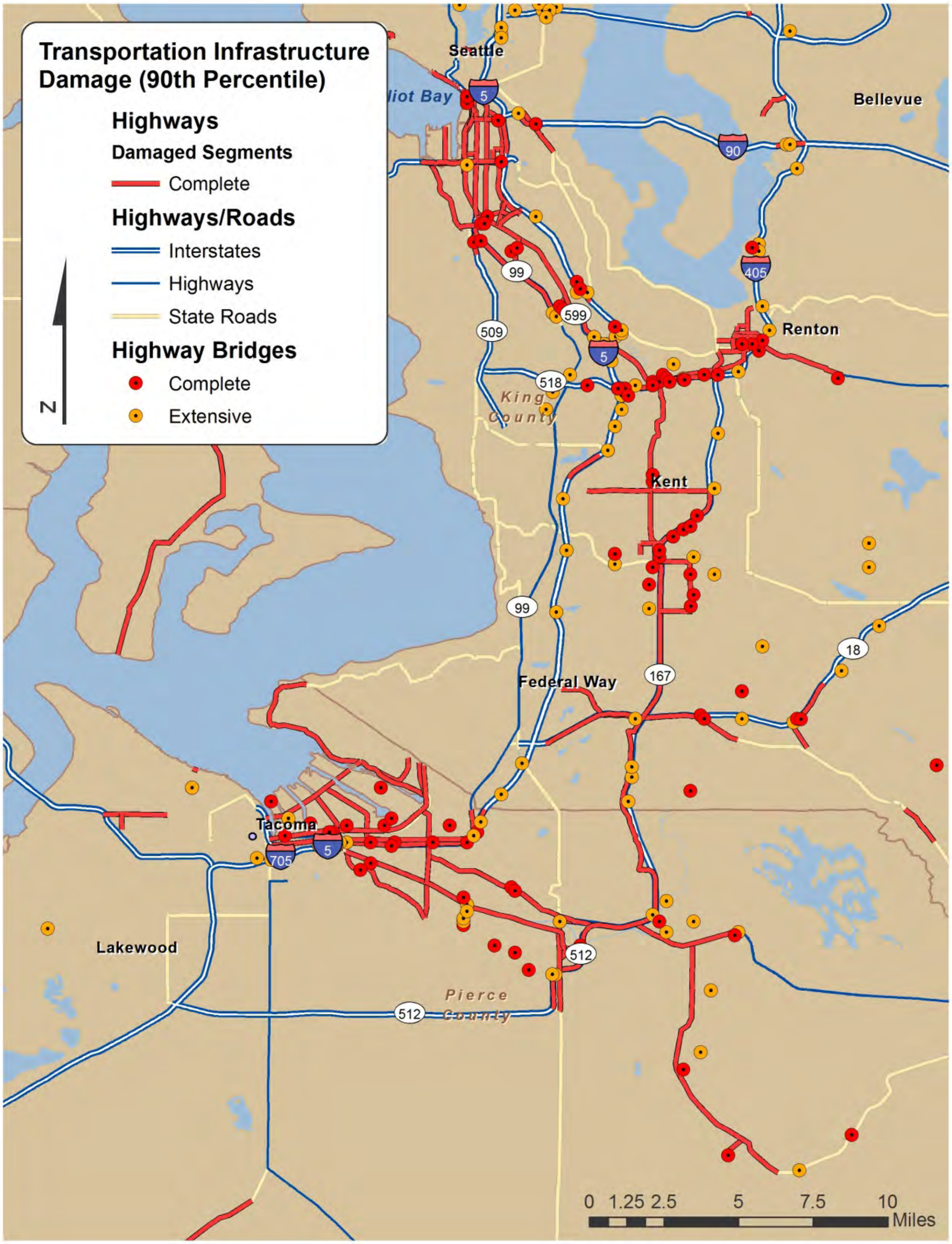


Figure 5-34. Roadway damage in Seattle, WA (90th-percentile case)

5.3.4.1.9 Cascading Effects

The effects of ground transportation isolation for coastal communities can include limited supplies of food, water, clothing, medicine, fuels, and repair materials. Limited access due to road damage will affect the ability of infrastructure owners, such as electric power utilities, to access and repair damaged equipment. Coastal inhabitants with severe injuries or chronic medical conditions will need to rely on sea or air transport for medical attention and supplies. Damage to the I-5 corridor will have modest effects on transport economics. Alternate routes exist for commercial shipments that do not use the damaged sections of I-5. Traffic along the I-5 corridor can expect delays and increased travel time due to repair of roads and bridges. It is likely that air and sea transport will experience an increase in usage while the ground transportation system is under repair as shippers temporarily shift to more efficient transport modes. Urban areas will experience trip delays due to damage to roads and bridges. Damage to the ground transportation system will affect emergency services, access to commercial centers, and repair and restoration activities.

5.3.4.2 Rail Transportation

5.3.4.2.1 Track and Bridges

For the expected case illustrated in Figure 5-35 and Figure 5-36, the railway system impacts due to the earthquake are most severe near the coast, although the coastal rail system is comprised primarily of spurs and does not include any main railway lines. In the state of Washington along the I-5 corridor, much of the rail system track remains intact and functional. A few segments in the Tacoma, WA, area suffer slight damage to include a few inches of track bed settlement. The larger concern in Washington is the severe-to-complete damage to several railway bridges south of Seattle and immediately outside of Olympia, as shown in Figure 5-37. Additionally, the main railway bridge crossing the Columbia River north of Portland suffers extensive damage (see Figure 5-38) that would likely prevent any through traffic along the I-5 corridor and would likely merit complete replacement, which could take several years.

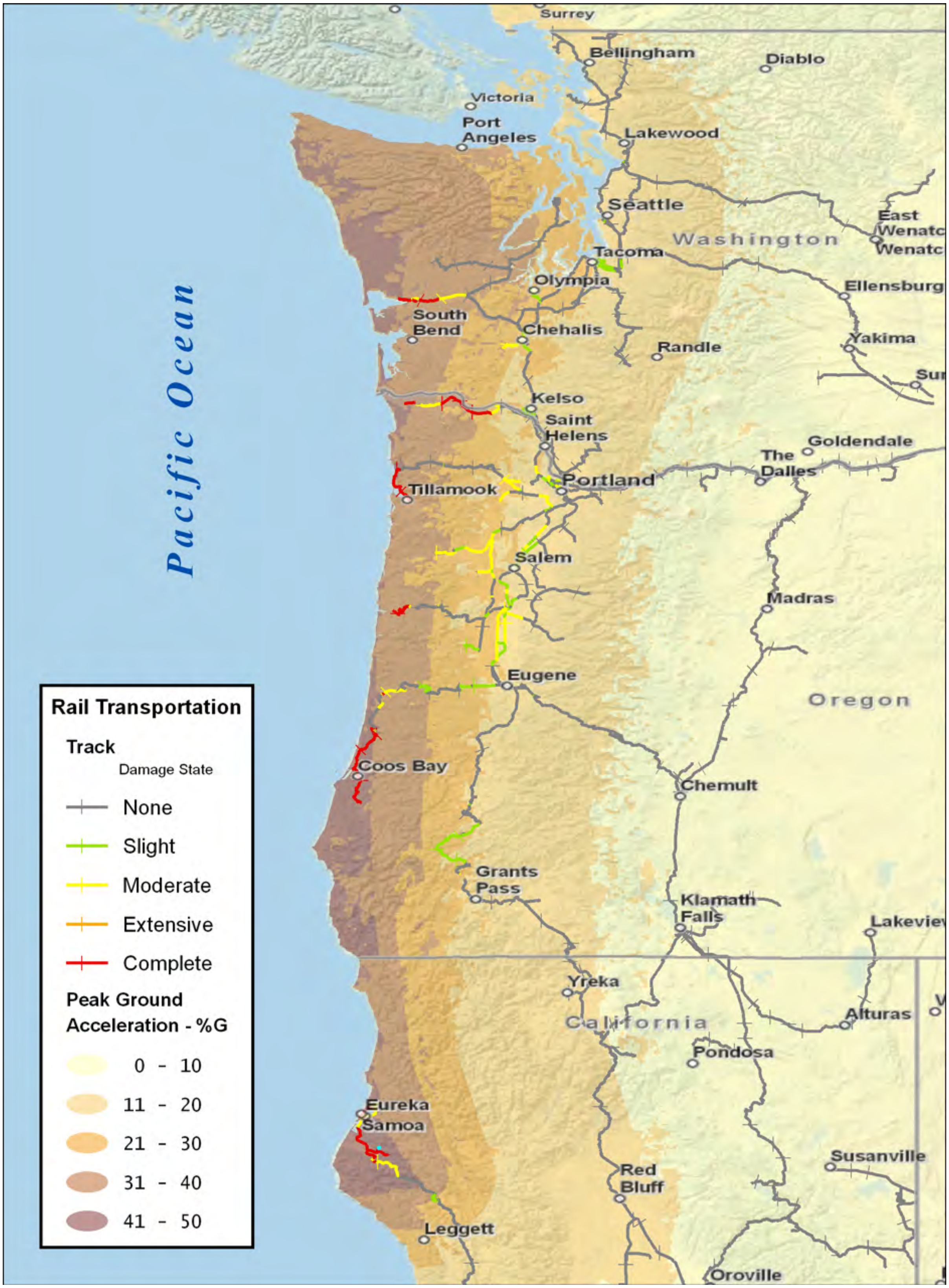


Figure 5-35. Damage to railroad track for the expected (50th-percentile) case

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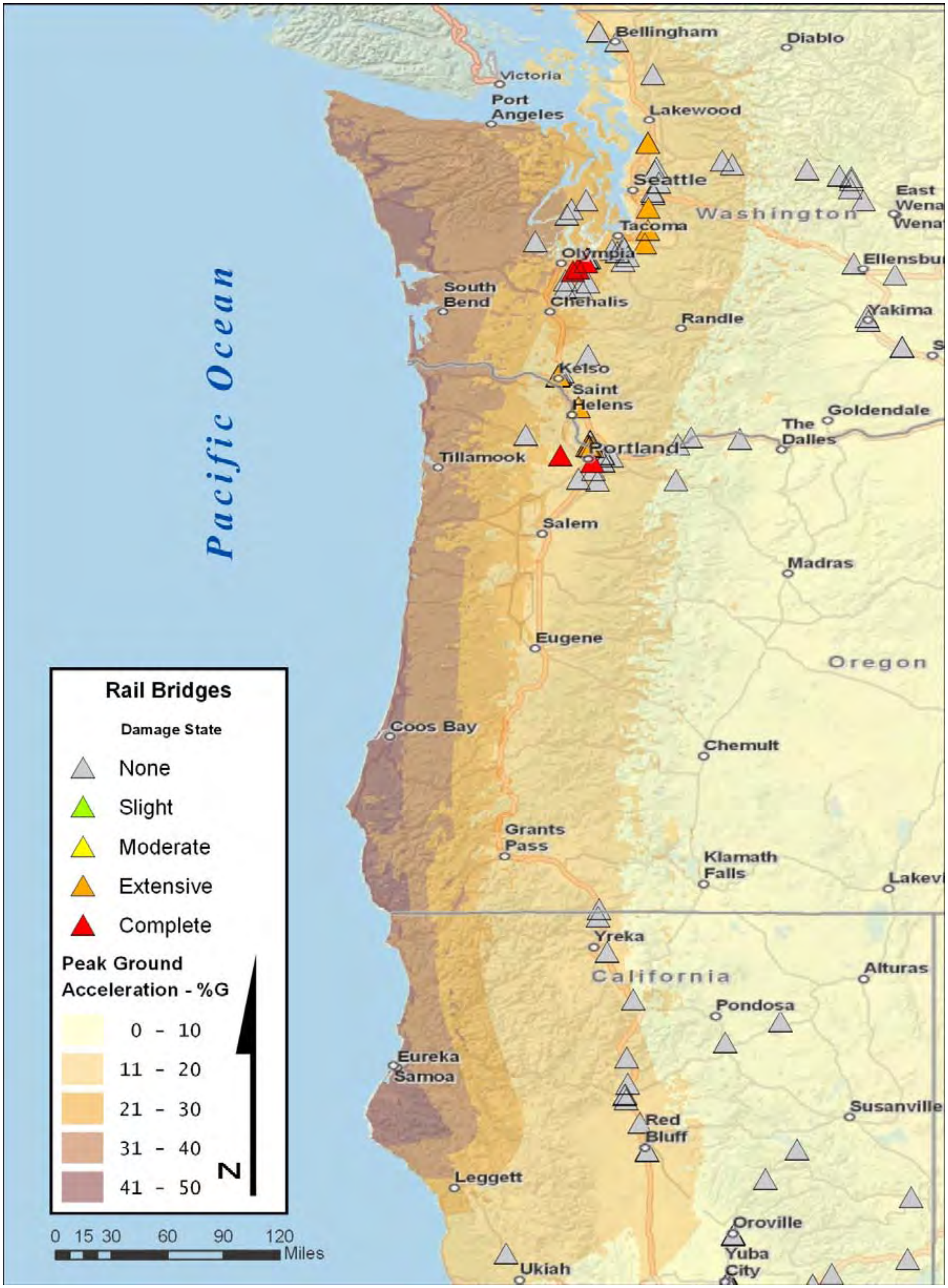

Figure 5-36. Damage to railway bridges for the expected (50th-percentile) case

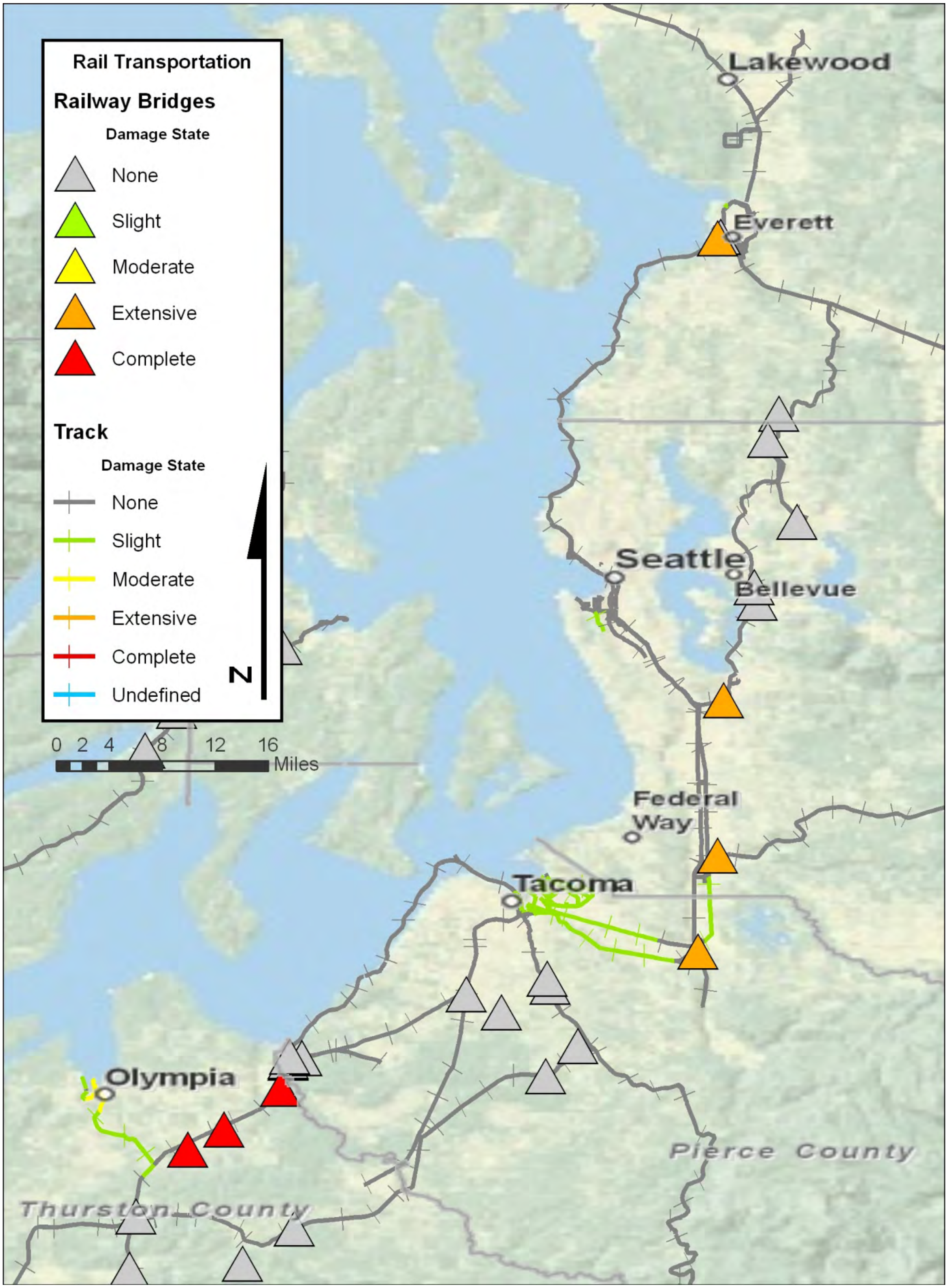

Figure 5-37. Railway track and bridge damage for the Seattle area for the expected (50th-percentile) case

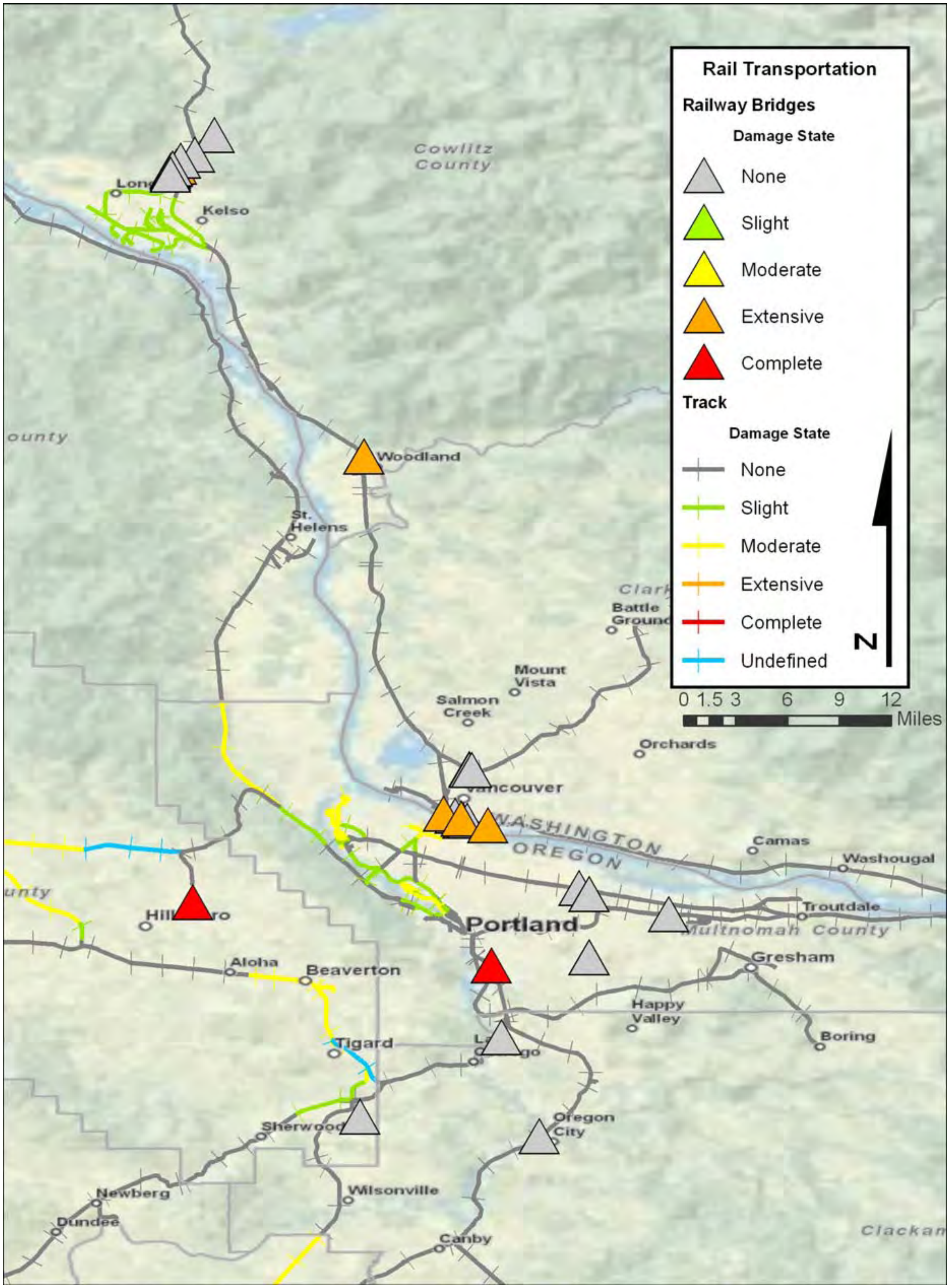

Figure 5-38. Railway track and bridge damage for the Portland area for the expected (50th-percentile) case

In Oregon's I-5 corridor, the level of damage is significant, particularly along the Willamette Valley between Portland and Eugene; this segment suffers moderate track damage, including several inches of track bed settlement and offset. There is also additional slight track damage along segments immediately north of Grants Pass. Otherwise, rail segments through and to the east of the Cascades for both Oregon and Washington remain unaffected by ground shaking.

Overall, rail transportation along the I-5 corridor and spurs to the west should expect a nearly complete shutdown of rail traffic due to either direct track damage, or loss of essential connectivity through sectors of damaged track and bridges up or down the line. The shutdown could last for several months, with restoration of the I-5 corridor taking five months or more due to the regional demand on repair crews, equipment, and replacement track supplies.

The larger issues are (1) the complete loss of key bridges in the Olympia and Seattle areas and (2) the loss of a bridge in downtown Portland, coupled with extensive damage to the critical bridge spanning the Columbia River immediately north of Portland. These losses will result in the complete shutdown of all through traffic along the I-5 corridor. Fortunately, Seattle and Portland are also serviced by rail lines coming from the east. With the relatively faster track repairs (several months) as compared with rail bridges, rail traffic should be able to be rerouted in and out of both Portland and Seattle using these eastbound lines to reach connectivity with the rest of the national railway network. Some communities, particularly between Portland and Seattle, could be isolated from through rail traffic until bridge replacements can be made.

Aside from some spur damage to the rail lines leading to Arcata and Eureka, the California rail system remains largely unaffected.

In a worse case (90-percent) scenario illustrated in Figure 5-39. Damage to railroad track for a worse (90th-percentile) case Figure 5-40, and Figure 5-41, significantly greater track and bridge damage result in much longer restoration times. Fortunately, the rail lines to the east of both Portland and Seattle still offer a rerouting alternative for the two metropolitan areas. Rail service along the I-5 corridor for communities and businesses between Seattle and Portland, as well as those between Portland and the California state line, could see complete rail service disruption for a year or more.

Figure 5-39. Damage to railroad track for a worse (90th-percentile) case

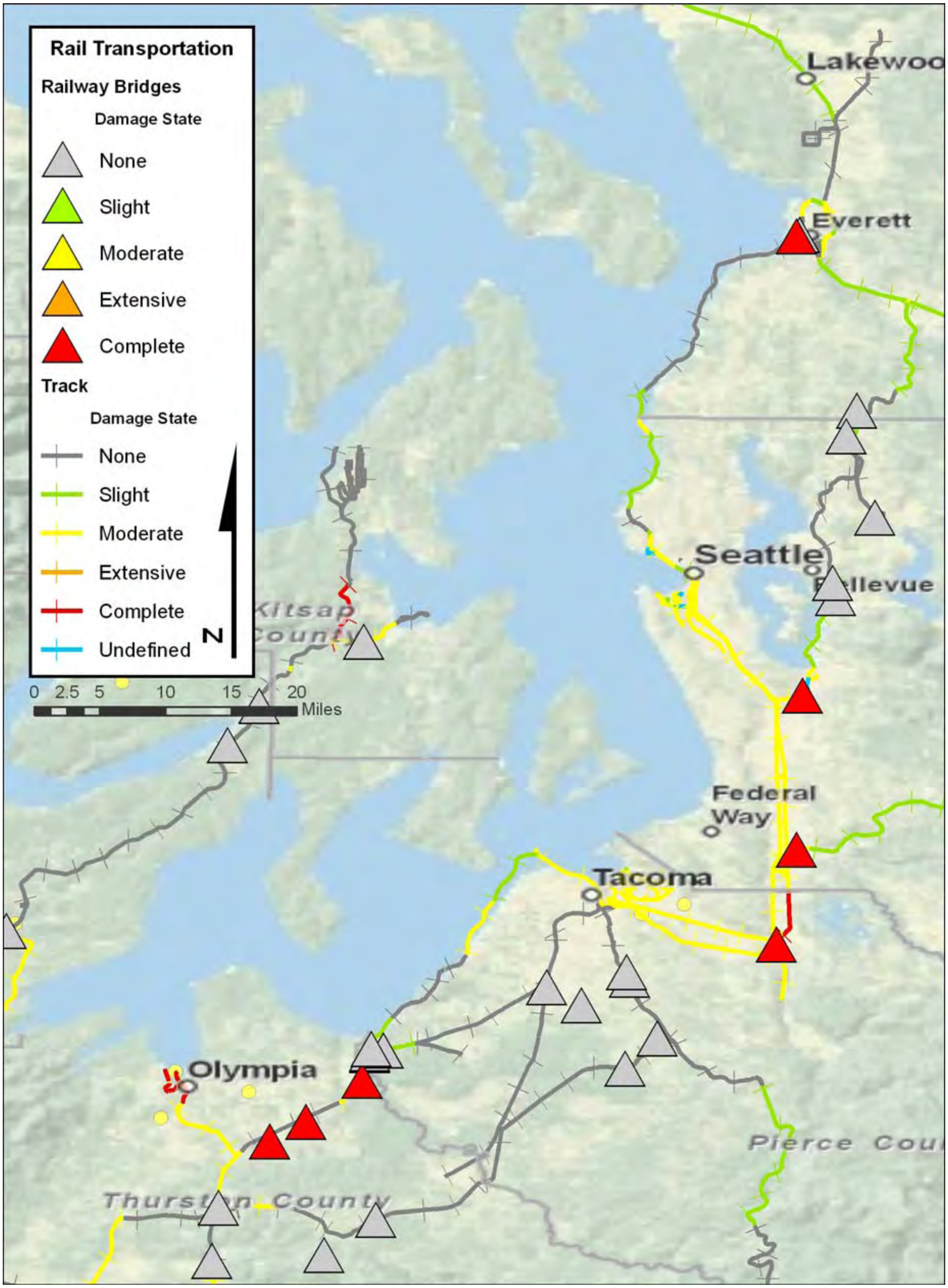

Figure 5-40. Railway track and bridge damage for the Seattle area for a worse (90th-percentile case

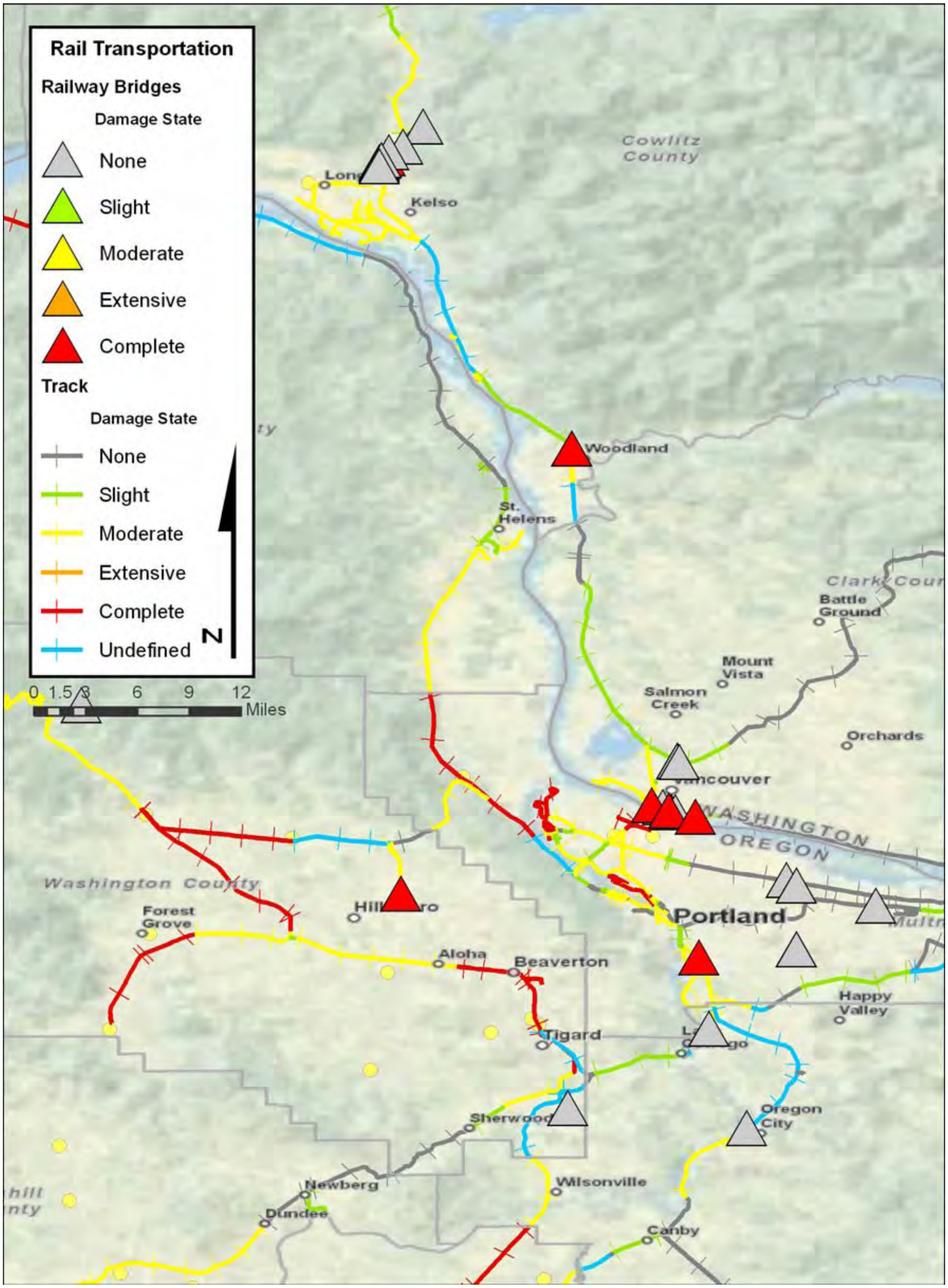

Figure 5-41. Railway track and bridge damage
for the Portland area for a worse (90th-percentile) case

5.3.4.2.2 Rail Facilities

Rail facilities are comprised of train stations, dispatch facilities, and fuel facilities. The vast majority of these facilities are along the major north-south corridor. Nearly all of these facilities receive slight damage; very few receive moderate damage (Figure 5-42). These damages should not significantly impact normal rail capacity and flow. Essential repairs should be accomplished in a short period of time. Long-haul fuel capacities should be adequate to support operation even if fuel becomes unavailable locally.

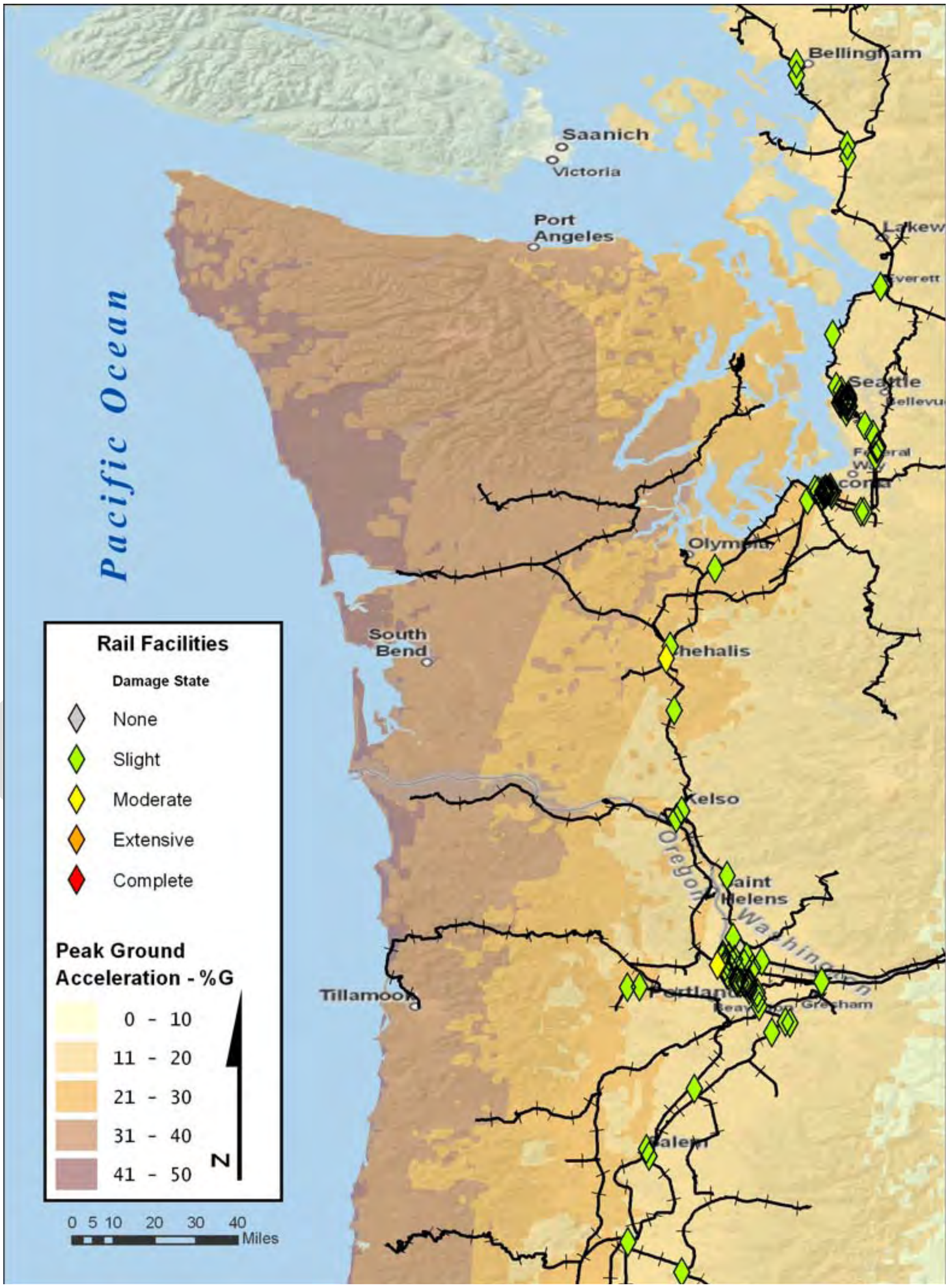

Figure 5-42. Rail facilities damage for the expected (50th-percentile) case

In a worse case (50th-percentile) the damage increases substantially, as shown in Figure 5-43, with most facilities suffering extensive-to-complete damage. This level of damage could significantly impact the ability to perform essential dispatch and switching control, although these functions could be relocated over the medium term. Rail facilities would likely be the quickest to be either replaced or relocated to achieve essential function, with track and bridges presenting the greatest time and resource demands for restoration of rail service.

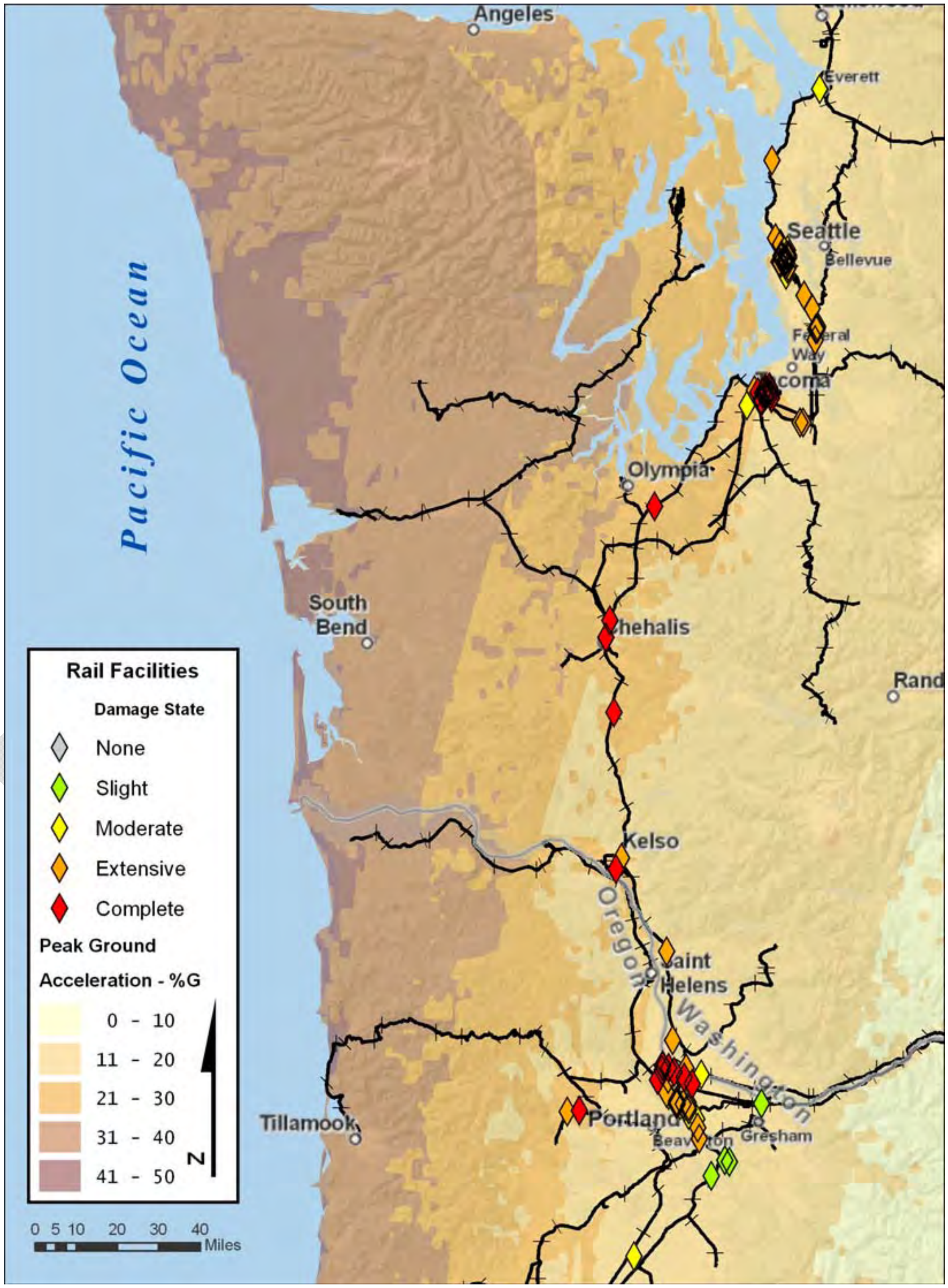

Figure 5-43. Rail facilities damage for a worse (90th-percentile) case

5.3.4.2.3 Rail Impact

In 2009, rail commodity flows in the region accounted for 4,607 carloads/day, with 4,100 carloads/day traveling to/from the region, and 507 carloads/day traveling within the region. In aggregate, this amounts to about 6.7 percent of national rail commodity flow.

Of these commodity flows, approximately 25 percent are farm products, 12 percent are intermodal, and 9 percent are chemicals (excluding inorganic). Farm products and intermodal commodity flows, which for the most part originate and terminate at the ports or related facilities, would likely be redirected to other container ports. Farm products, however, may be difficult to redirect to alternative ports without a significant increase in transportation overhead.

Farm products rail flows account for 1,120 carloads/day, almost entirely inbound to the region. Forty percent of these commodity flows travel to Seattle from three Transportation Analysis Zones (TAZs): Sioux Falls, SD (154 carloads/day), Fargo, ND (152 carloads/day), and St. Paul, MN (145 carloads/day), each equally contributing to this total. Fargo accounts for an additional 17 percent (188 carloads/day) of the carloads to the region in flows to Portland. This accounts for more than 10 percent of the national farm products rail traffic. If these rail flows were disrupted for a significant period of time, an impact on the economies of those producing regions is possible.

Containerized flows account for 567 carloads/day. Of those, 356 carloads travel mostly away from the region between Seattle/Tacoma and Chicago, representing the commodity flows to/from the Chicago reclassification yards. These commodity flows still only represent less than 5 percent of national containerized rail traffic. If these goods were redirected to/from other container ports, alternate corridors will provide these goods similar access to the Chicago switching yards.

Chemicals (excluding inorganic) reflect, at least partially, a regional flow, with 9 percent (34 carloads/day) traveling from Seattle/Tacoma to Portland. Unless regulation prohibits the transport of these chemicals on the highway network, many of these flows can be redirected to truck transport. Of the remaining 405 carloads/day in the impact region, 64 carloads/day travel to the region and 305 carloads/day travel out of the region, with 96 carloads/day going to Chicago and 77 carloads/day en route to Denver. This accounts for less than 3 percent of national chemical rail traffic.

Food and kindred products account for 267 of the impacted carloads, with 44 carloads/day traveling out of the region, 34 carloads/day traveling into the region from Omaha, NE, and 29 carloads/day traveling into the region from Chicago. This accounts for less than 3 percent of national food and kindred product rail traffic.

All 207 carloads/day of coal impacted are inbound to the region. The majority of those are destined for Seattle/Tacoma (97 percent, 201 carloads/day). Of these, 115 carloads/day originate in Denver and 93 carloads/day originate in Billings, MT. This accounts for less than 1 percent of national coal rail traffic.

In general, however, these disruptions are likely to be short term given the affected infrastructure. However, a longer-term disruption may cause some of the rail commodity flows to be redirected or lost as noted.

5.3.4.3 Air Transportation

5.3.4.3.1 Airport Operations

Generally, the immediate demands on airports in the areas of greatest impact are to support relief supplies, medical evacuation, and the import of rescue and medical personnel. These needs can be met without functioning facilities, so long as the runways remain intact and usable. Thus for high-impact areas, an undamaged runway becomes the critical resource, regardless of the condition of any of the collocated facilities.

The coastal areas with the most impacts due to both shaking and tsunami damage in many cases are least able to meet the need for import of supplies and critical personnel or the need to evacuate the injured. Airports will likely have usable open pavement space for staging some operations, but for most airports along the coast, the transport needs will have to be met by helicopters rather than fixed-wing aircraft. Although helicopters generally have less payload capabilities and are not as fast as heavier fixed-wing aircraft, they can generally land in any level clearing whether an airport is present or not.

Outside the area of significant damage, airports (particularly the larger regional airports) may serve as consolidation points for supplies and departure points for rescue personnel being sent into high-damage areas. Otherwise, these airports need to serve their normal function of supporting normal passenger, cargo, and commercial traffic in the area.

5.3.4.3.2 Airport Facilities

The category of airport facilities is comprised of terminal buildings, hangars, parking structures, fuel facilities, and control towers. The damage extents of the expected (50-percent) event on airport facilities (Figure 5-44) generally fall into three geographic areas:

1. **Coastal,** between the Coastal Range and the sea: The impacts to airport facilities along the coast are severe with nearly all facilities suffering extensive-to-complete damage.
2. **I-5 Corridor,** between the Coastal Range and the Cascade Range**:** Along the 1-5 corridor, the vast majority of facilities suffer only slight damage.
3. **East of the Cascades:** East of the Cascade Range there are no significant impacts to airport facilities.

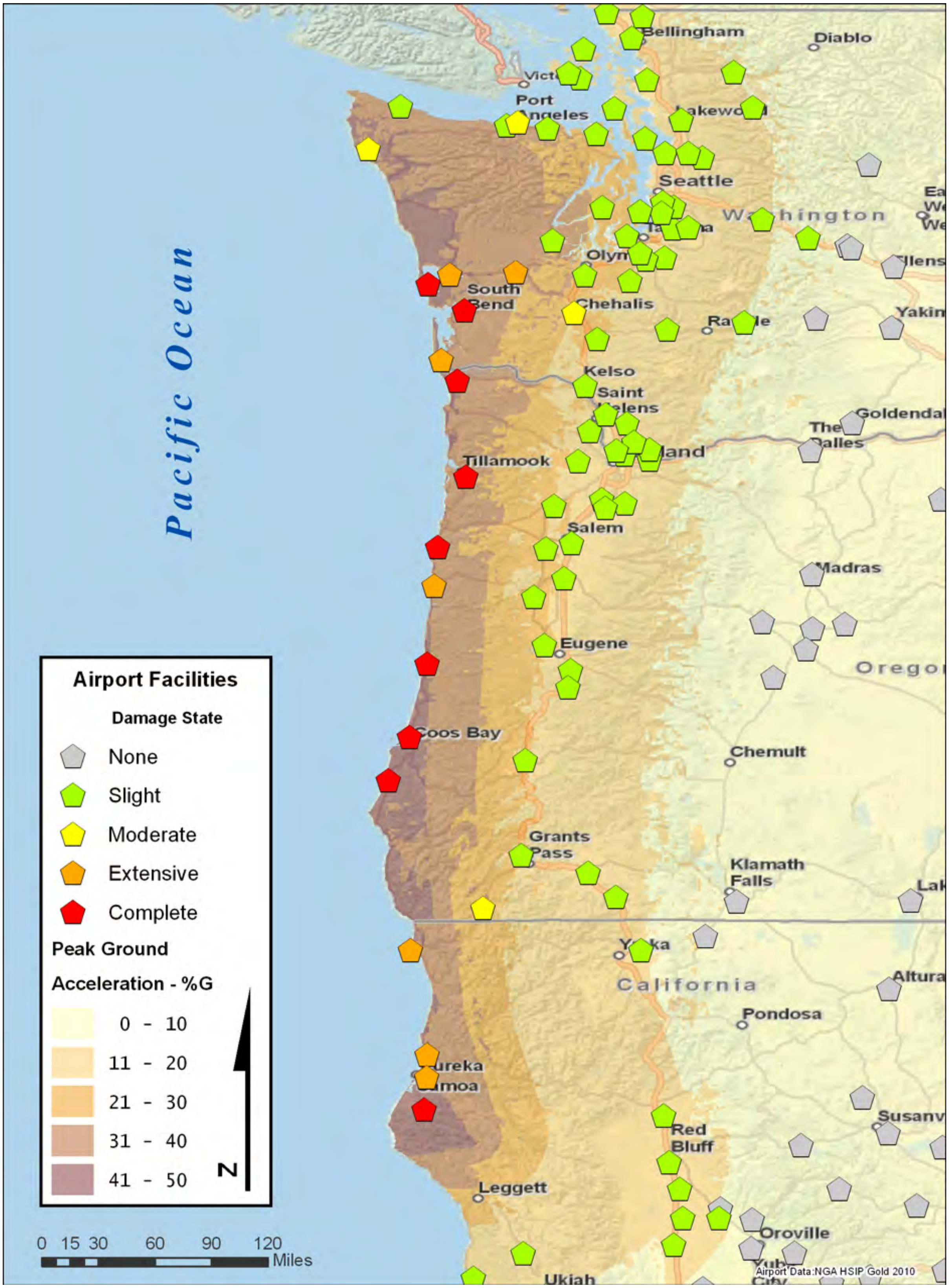

Figure 5-44. Airport facilities damage extent for the expected (50th-percentile) case

5.3.4.3.3 Airport Runways

With some exceptions, many of the airport runways along the immediate coastline suffer complete damage from deformation and heaving due to liquefaction and ground settlement (Figure 5-45). These runways will be completely unusable by fixed-wing aircraft for any emergency response, receipt of any relief supplies, or medical evacuation. The field may still be usable by helicopters. Otherwise, runway damage is not expected for areas further inland.

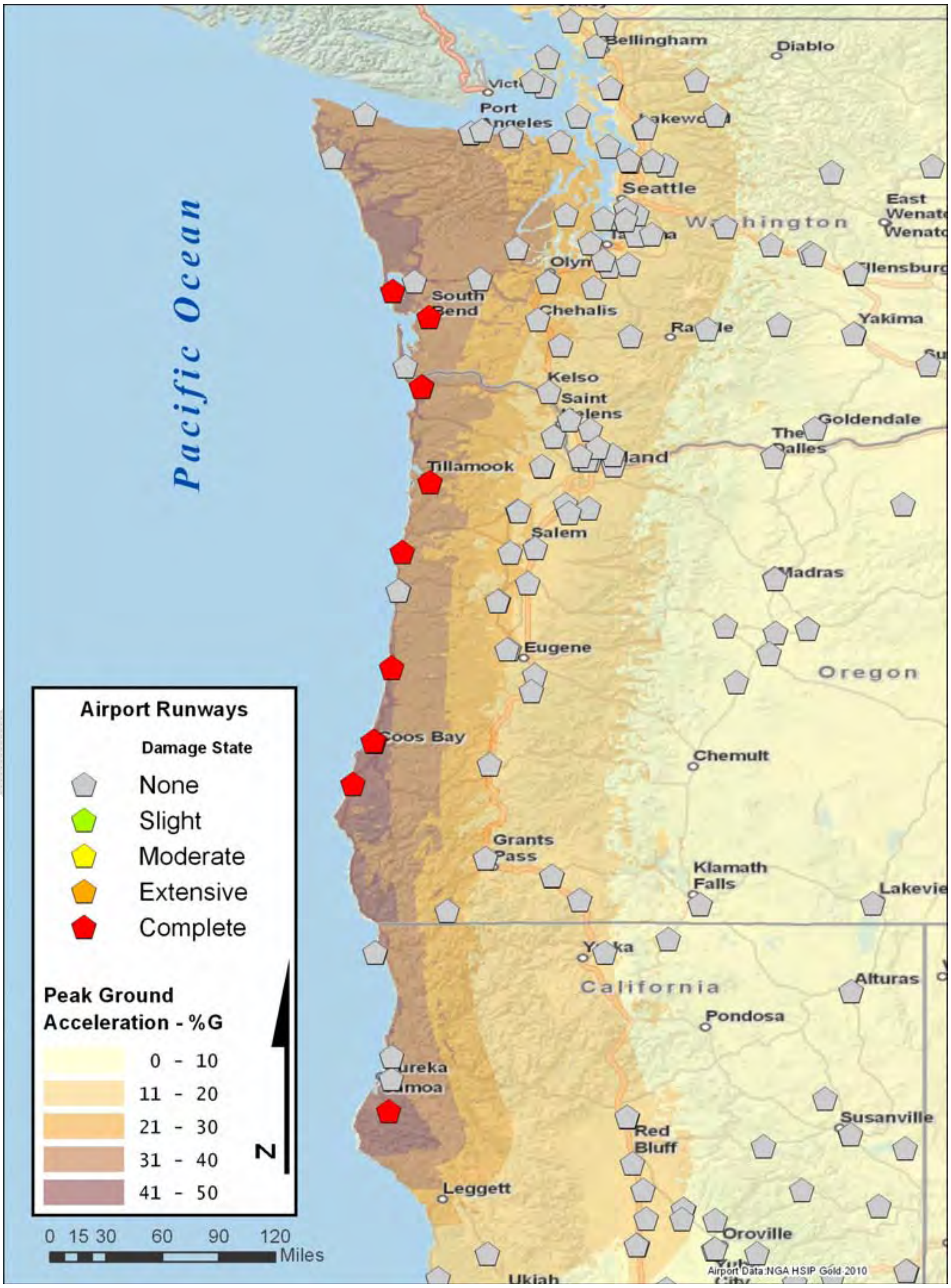

Figure 5-45. Airport runways damage extent for the expected (50th-percentile) case

5.3.4.4 Major Airports in the Region

Of the airports in the impact region, only two are significant to national domestic passenger flow - Portland International Airport (PDX) and Seattle/Tacoma International Airport (SEA). Both PDX and SEA will likely suffer disruption of pipeline-delivered Jet-A fuel over the medium term. Fuels can be trucked in any need repairs to access roads is completed. Alternatively, carriers could make capacity adjustments for short-haul flights to land with sufficient fuel on-board for their departures.

5.3.4.4.1 SeaTac International Airport

SEA, serving the Seattle and Tacoma metropolitan areas and the greater western Washington region, is expected to suffer only slight damage to the terminal and facilities, including some minor cracking of support columns and some toppling of unsecured equipment. The runways at SEA are not expected to incur any damage in either the expected (50^{th}-percentile) case or a worst (90^{th}-percentile) case; however, in the worst (90^{th}-percentile) case, the terminal and other facilities at SEA may suffer moderate damage, with most beams and columns exhibiting minor cracks and some showing larger stress cracks.

In 2010, SEA handled 12,788,360 enplanements. Of those, only 9,902,340 (77 percent) originated in SEA. In the case of limitation or loss of capacity at SEA, nearly three million passengers would require rerouting through alternate hubs. SEA serves as a significant hub for several terminations. Of the 23 percent of enplanements that represented pass-through passengers, 13 percent terminated at Anchorage International Airport (ANC), 7 percent terminated at PDX, and another 7 percent terminated at Spokane International Airport (GEG).

Of the 1,403,290 passengers who terminated at ANC, 26 percent travelled through SEA. As a result, a long-term impact to SEA may cause Anchorage-bound passengers to see a significant rise in ticket prices and/or a loss of available flights. However, impacts of shorter than a week are likely to be treated as standard weather delays. The system will be able to accommodate most passengers.

5.3.4.4.2 Portland International Airport

PDX, serving the greater Portland area and the northwest Oregon region, is expected to experience nearly the same level of damage as SEA: only slight damage to the terminal and facilities, including some minor cracking of support columns and some toppling of unsecured equipment. The runways at PDX are not expected to incur any damage in either the expected (50^{th}-percentile) case or a worst (90^{th}-percentile) case. In the worse (90^{th}-percentile) case, the terminal and other facilities may suffer moderate damage with most beams and columns exhibiting minor cracks and some showing larger stress cracks.

In 2010, PDX accounted for 5,875,500 enplanements. Of those, 5,063,990 (86 percent) originated at PDX. The remaining 14 percent represent pass-through passengers, who could be accommodated by other airports in the region if PDX were unavailable in the medium-to long-term.

5.3.5 Ports and Maritime

5.3.5.1 Ports and Maritime Infrastructure Direct Impacts

Maritime infrastructure in the area impacted by the Cascadian seismic event can be divided into three geographically distinct maritime provinces, illustrated in Figure 5-45: the Juan De Fuca Strait and Puget Sound area, the Columbia River System, and the Pacific Coast.

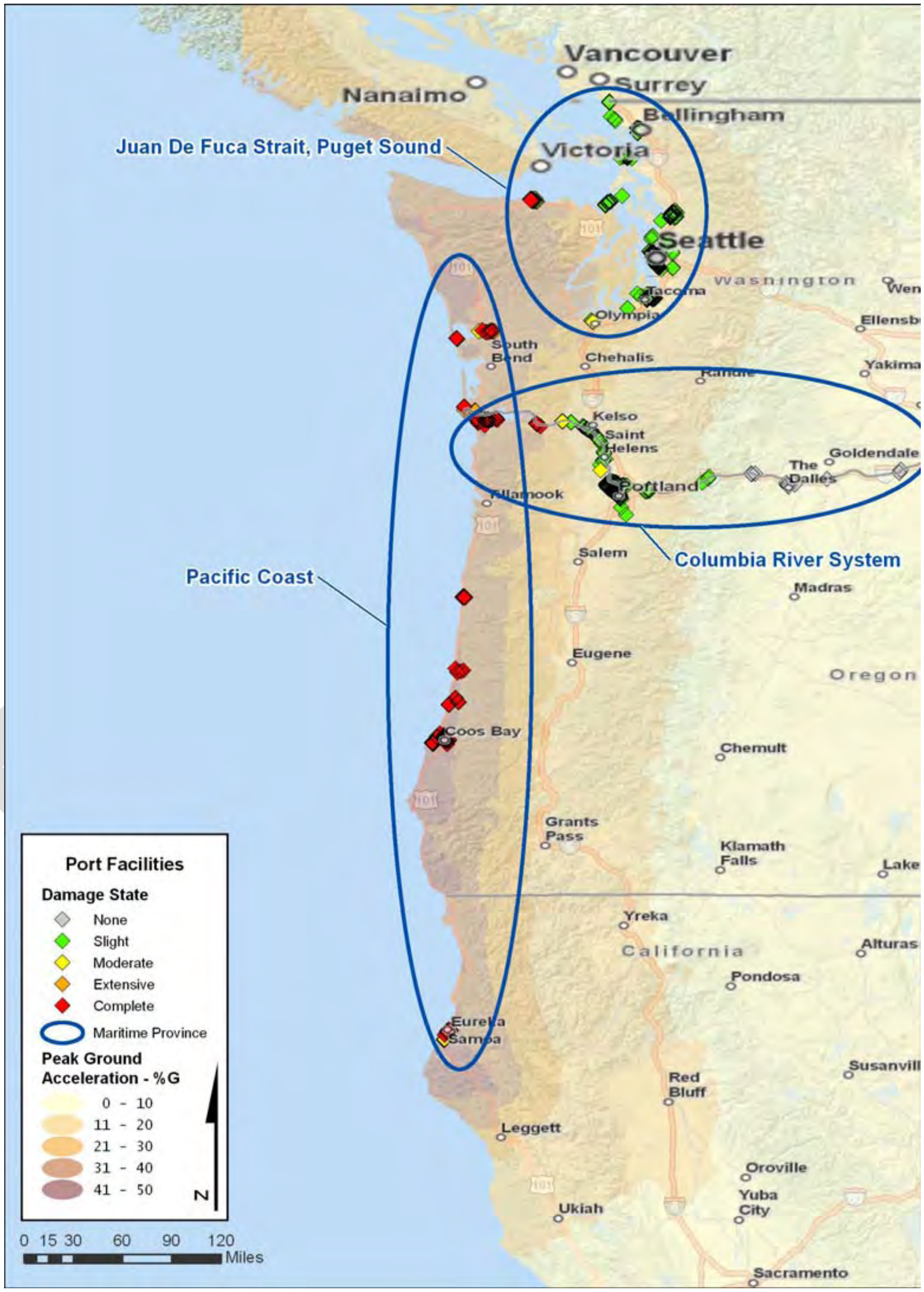

Figure 5-46. Maritime provinces and port facilities in the seismic impact zone

The port and maritime infrastructure analysis starts by selecting the major commercial ports in the impacted area from the United States Army Corps of Engineers' (USACE's) list of the 150 largest U. S. ports ranked by tonnage.[27] Ten ports in the impacted area appear on Table 5-27, which provides a list of the ports ordered by total tonnage and includes the domestic, export, and import tonnages that contribute to the total.

Table 5-27. Major commercial ports within the Cascadia impact zone

Port Name, State	Total Tons	Domestic Tons	Import Tons	Export Tons
Seattle, WA	24,607,832	5,162,695	6,881,937	12,563,200
Portland, OR	23,307,489	8,925,675	2,335,009	12,046,805
Tacoma, WA	23,165,295	5,558,302	4,634,259	12,972,734
Anacortes, WA	10,430,937	8,217,953	916,798	1,296,186
Kalama, WA	9,911,832	609,812	283,096	9,018,924
Vancouver, WA	6,818,889	1,691,264	762,702	4,364,923
Longview, WA	5,100,195	1,188,699	852,602	3,058,894
Grays Harbor, WA	1,162,441	245,967	56,765	859,709
Everett, WA	1,005,820	558,805	121,271	325,744
Olympia, WA	994,759	542,211	88,656	363,892
Total at Risk	**106,505,489**	**32,701,383**	**16,933,095**	**56,871,011**

Major container ports in the impacted area were selected from the USACE's list of container traffic ports ranked by loaded twenty-foot equivalent units (TEU), an inexact measure of cargo volume tonnage.[28] Table 5-28 provides a list of the ports with container operations ordered by total loaded TEUs and includes the domestic, export, and import loaded TEUs that contribute to the total.

Table 5-28. Major container ports within the Cascadia impact zone

Port Name, State	Total TEUs	Domestic TEUs	Import TEUs	Export TEUs
Seattle, WA	1,219,345		583,744	460,608
Tacoma, WA	1,150,675		481,378	400,869
Portland, OR	162,051		68,654	153,887
Dalles-McNary, OR	16,537		0	0
Everett, WA	13,939		10,191	2,747
Vancouver, WA	13,436		97	53
Total at Risk	**2,575,983**	**482,411**	**1,144,064**	**949,511**

Each major port is a complex assemblage of individual facilities, often spread out over a broad geographic land area in such a way that each facility has direct access to navigable water. The Hazus database used for this analysis identifies 741 individual port facilities within the impacted area, which is plotted in Figure 5-47.

[27] USACE, Navigation Data Center, Waterborne Commerce Statistics Center, Tonnage for Selected U. S. Ports in 2009, www.ndc.iwr.usace.army.mil//wcsc/portton09.htm.

[28] USACE, Navigation Data Center, Waterborne Commerce Statistics Center, U. S. Waterborne Container Traffic by Port/Waterway in 2009, www.ndc.iwr.usace.army.mil//wcsc/by_porttons09.htm.

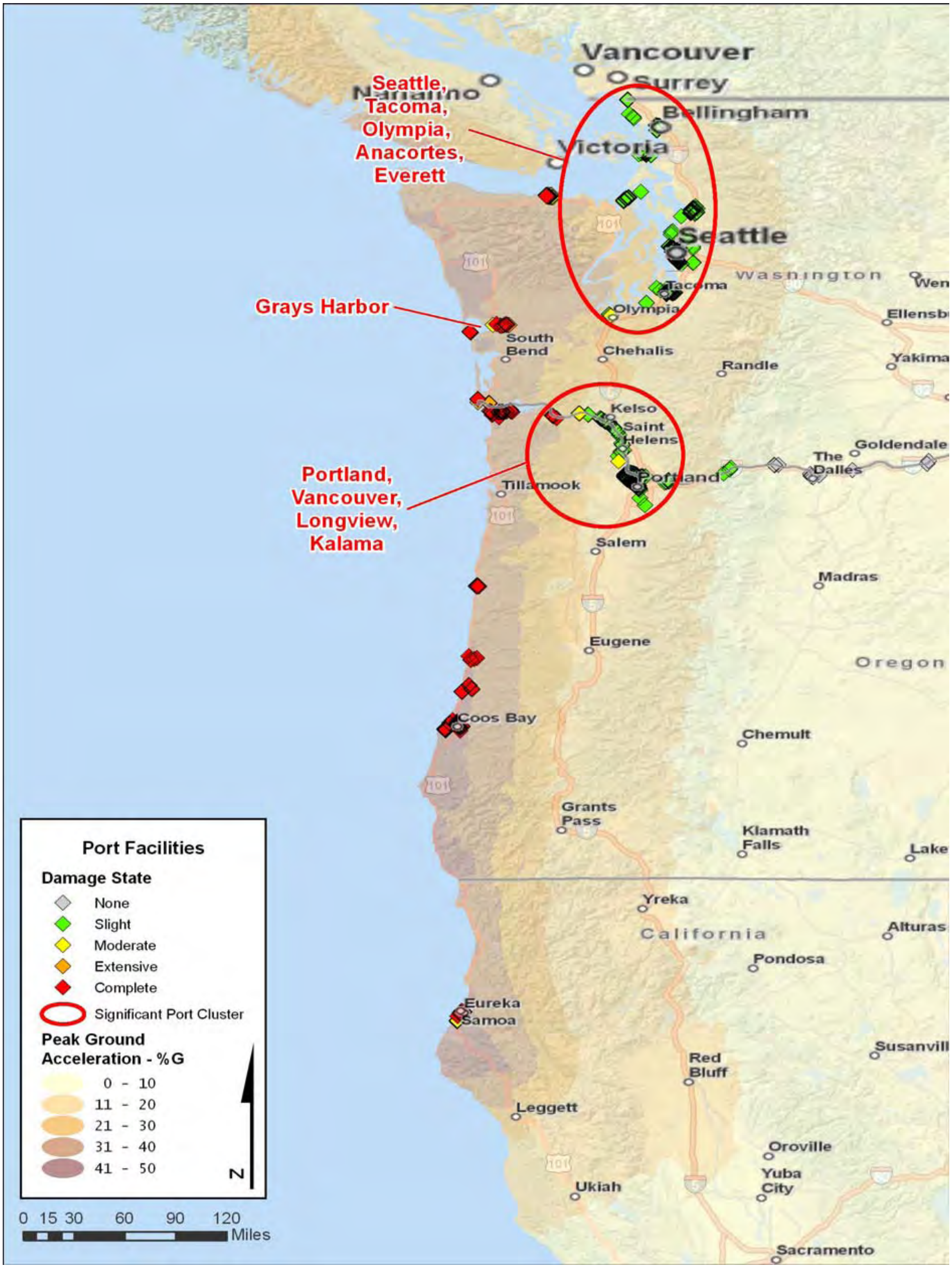

Figure 5-47. Locations of individual port facilities within the seismic impact zone; commercially significant port clusters are circled in red

Figure 5-47. Location above illustrates a number of important features of the overall port structure in the Pacific Northwest. Major commercial activity is clustered in two distinct areas located within the red circles in the figure. One is centered on Portland, OR, at the intersection of the Columbia River (which is a major inland waterway), the north-south Interstate 5 corridor, and the east-west Interstate 84. The second cluster is centered on Seattle, WA, adjacent to Puget Sound, where the north-south Interstate 5 intersects the east-west Interstate 90.

In Hazus, predictions of damage are referenced to the physical components of a given infrastructure. The physical components of port infrastructure considered by Hazus include waterfront structures (e.g., wharfs, piers, and seawalls), cranes and cargo-handling equipment, fuel facilities, and warehouses. Table 5-29 lists the individual components and provides a description of the damage that correlates to each one of the five damage states predicted by Hazus [None, Slight, Moderate, Severe (extensive), or Complete].

Table 5-29. Hazus port facility definitions of damage states

Component	Damage State (ds)	Damage Description
Waterfront Structures	None (ds1)	No damage to components
Waterfront Structures	Slight/Minor (ds2)	Minor ground settlement resulting in few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.
Waterfront Structures	Moderate (ds3)	Considerable ground settlement with several piles (for piers/seawalls) getting broken and damaged
Waterfront Structures	Extensive (ds4)	Failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.
Waterfront Structures	Complete (ds5)	Failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.
Cranes/Cargo-Handling Equipment	None (ds1)	No damage to components
Cranes/Cargo-Handling Equipment	Slight/Minor (ds2)	• Stationary Equipment: Slight damage to structural members with no loss of function • Unanchored or rail mounted equipment: Minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.
Cranes/Cargo-Handling Equipment	Moderate (ds3)	Derailment due to differential displacement of parallel track. Rail repair and some repair to structural members required
Cranes/Cargo-Handling Equipment	Extensive (ds4)	Considerable damage to equipment. Toppled or totally derailed cranes likely to occur. Replacement of structural members required
Cranes/Cargo-Handling Equipment	Complete (ds5)	Same as ds4
Warehouses	None (ds1)	No damage to components

Component	Damage State (ds)	Damage Description
Warehouses	Slight/Minor (ds2)	Slight building damage (check building module for full description of potential damage)
Warehouses	Moderate (ds3)	Considerable derailment due to differential settlement or offset of the ground. Rail repair is required
Warehouses	Extensive (ds4)	Major differential settlement of the ground resulting in potential derailment over extended length
Warehouses	Complete (ds5)	Same as ds4
Fuel Facilities with Anchored Equipment	None (ds1)	No damage to components
Fuel Facilities with Anchored Equipment	Slight/Minor (ds2)	Slight damage to pump building, minor damage to anchor of tanks, or loss of off-site power (check electric power systems for more on this) for a very short period and minor damage to backup power (i.e., to diesel generators, if available)
Fuel Facilities with Anchored Equipments	Moderate (ds3)	Elephant foot buckling of tanks with no leakage or loss of contents, considerable damage to equipment, moderate damage to pump building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available)
Fuel Facilities with Anchored Equipment	Extensive (ds4)	Elephant foot buckling of tanks with loss of contents, extensive damage to pumps (cracked/sheared shafts), or extensive damage to pump building
Fuel Facilities with Anchored Equipment	Complete (ds5)	Weld failure at base of tank with loss of contents, or extensive to complete damage to pump building
Fuel Facilities with Unanchored Equipment	None (ds1)	No damage to components.

Component	Damage State (ds)	Damage Description
Fuel Facilities with Unanchored Equipment	Slight/Minor (ds2)	Elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e., to diesel generators, if available)
Fuel Facilities with Unanchored Equipment	Moderate (ds3)	Elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, loss of commercial power for few days and malfunction of backup power (i. e. , diesel generators, if available)
Fuel Facilities with Unanchored Equipment	Extensive (ds4)	Weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts)
Fuel Facilities with Unanchored Equipment	Complete (ds5)	Tearing of tank wall or implosion of tank (with total loss of content), or extensive/complete damage to pump building
Fuel Facilities with Buried Tanks	None (ds1)	No damage to components
Fuel Facilities with Buried Tanks	Slight/Minor (ds2)	(PGD related damage) Minor uplift (few inches) of the buried tanks or minor cracking of concrete walls
Fuel Facilities with Buried Tanks	Moderate (ds3)	Damage to roof supporting columns, and considerable cracking of walls
Fuel Facilities with Buried Tanks	Extensive (ds4)	Considerable uplift (more than a foot) of the tanks and rupture of the attached piping
Fuel Facilities with Buried Tanks	Complete (ds5)	Same as ds4

Table source: Section 7. 5 Port Transportation System, Hazus-MH Technical Manual

HAZUS damage predictions for each individual port facility for the 50th-percentile scenario are shown in Figure 5-48.

Figure 5-48. HAZUS damage predictions (50th-percentile) to individual port facilities

Of the commercial ports of interest in this analysis, only the Port of Grays Harbor, located near the Pacific Coast, suffers significant damage.

Next, the analysis turns to maritime infrastructure, other than ports, that are required for commercial trade. There are two locations where critical maritime infrastructure that supports commercial traffic is exposed to the potential for significant damage. They are the lower reaches along the Columbia River (including the Columbia River Bar) and Grays Harbor. Figure 5-49 shows the location of aids to navigation that appear on an NOAA Chart US50R11M.[29] While Figure 5-49 serves to illustrate the complexity of maritime infrastructure that often goes unobserved, Figure 5-50 emphasizes the navigation channel.

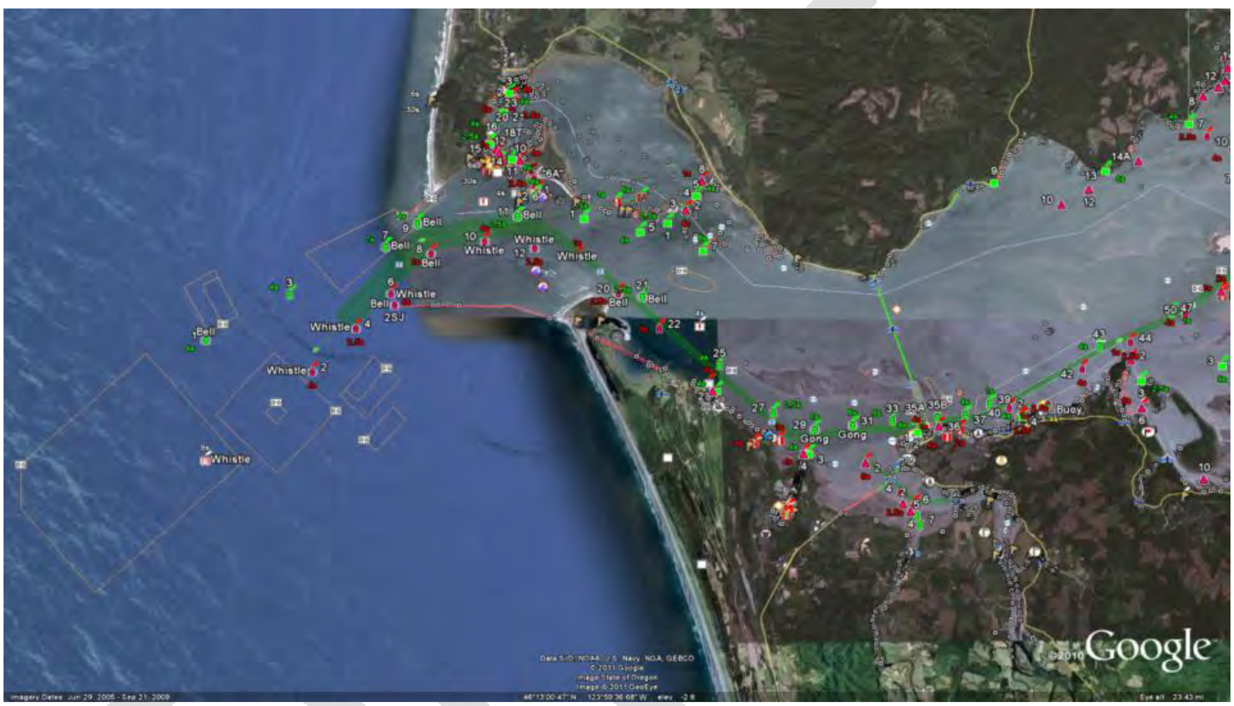

Figure 5-49. Locations of navigation infrastructure at the mouth of the Columbia River

[29] Downloaded as a keyhole markup language (KMZ) file from the EarthNC Nautical Chart Lis, earthnc.com/chartlist

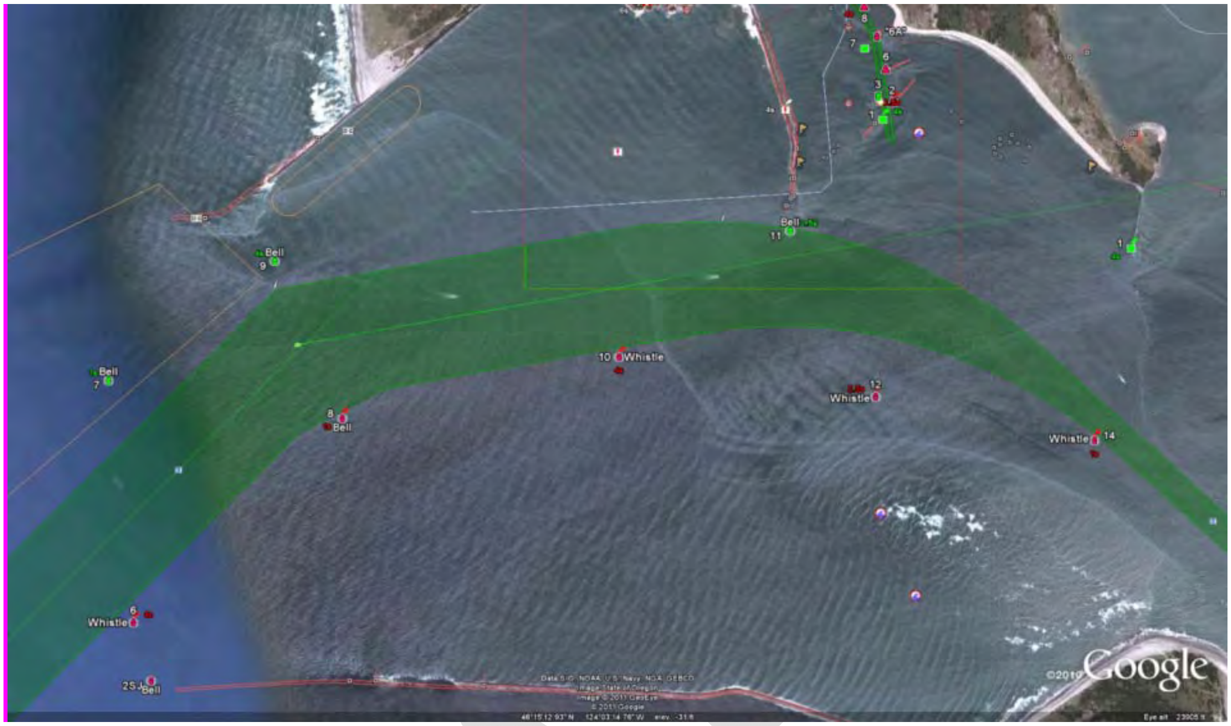

Figure 5-50. Location of the Columbia River deepwater navigation channel (shaded green line) at the mouth of the river; the channel continues upriver to Portland

The navigation channel is an engineered structure that continues 100 miles upriver to Portland, OR, and Vancouver, WA; the design depth of 43 feet and a design width of 600 feet accommodate the deep water vessels that command the import and export trade. In the area shown in Figure 5-49, debris entrained in the tsunami will damage or destroy many of the aids to navigation, and sediment, as well as sunken and floating debris, will compromise the navigation channel. Immediately following the tsunami, navigation will be difficult, if not impossible, within the area illustrated in Figure 5-50.

5.3.5.2 Port and Maritime Infrastructure Cascading Impacts

There is some risk that maritime transport of commercial and industrial supplies to Alaska could be disrupted. Totem Ocean Trailer Express, Inc. (TOTE) is a privately owned shipping company that services Alaska's freight and cargo market. TOTE operates a fleet of roll-on/roll-off cargo ships offering twice-weekly service between the Port of Tacoma, WA, and the Port of Anchorage, AK. TOTE's active fleet consists of two custom-built vessels, the M.V Midnight Sun and the M.V North Star. One ship sails from Tacoma every Thursday for Anchorage and one ship sails every Saturday from Tacoma to Anchorage.[30]

The Port of Anchorage services 90 percent of the consumer goods entering Alaska – almost 5 tons per year per Alaskan.[31]

[30] www.totemocean.com/default.htm, accessed August 2011.
[31] www.portofanchorage.org/ov_project.html, accessed August 2011.

Damage to the TOTE terminal and facilities is predicted to be minor. Contributing factors to risk include loss of direct access to the terminal from I-5, State Road 509, and U.S. 99 or access to I-90 using I-5 or State Road 18. The TOTE terminal also includes 140 reefer plugs that provide power for refrigerated containers. Some interruption in the shipment of refrigerated cargo to Alaska could occur.

Of greater concern under the current scenario is the potential for extended blockage at the mouth of the Columbia River deepwater navigation channel as a result of tsunami damage and the impact that would have on the upstream ports of Kalma, Longview, Portland, and Vancouver. These four ports, treated as one continuous port complex, constitute the third-largest center of grain (primarily wheat) exports in the world.[32]

If the scenario assumes market conditions for wheat similar to the current market (high prices for wheat on the global market), the uncertainty of when the channel could be reopened would likely result in a global increase in the price of wheat. Under the expected scenario, prices would return to market equilibrium once a timetable for reopening the channel is announced.

Under the 50th-percentile scenario, the Port of Grays Harbor sees significant damage to physical infrastructure. Recently, this port has experienced rapid expansion of trade. The Port of Grays Harbor has experienced growth in the value of exports over two of the past three years driven by trade with China. Table 5-30 provides the dollar value of exports from the Port for the calendar years 2008, 2009, and 2010 and the value of exports destined for China. Four commodities appear to be driving the increase in exports: soybean meal, distillers dried grains (a byproduct of corn ethanol production used for animal feed), automobiles, and lumber.[33]

Table 5-30. Value of total exports and exports to China for the Port of Grays Harbor, WA for calendar years 2008, 2009, and 2010[34]

	2010	2009	2008
Total	**$1,029,717,509**	**$254,254,368**	**$359,757,340**
China	$621,458,859	$3,028,531	$29,000

In the Cascadia earthquake and tsunami scenario, the increased trade and investment in new infrastructure that the port has realized over the past several years will be significantly impacted in the near term, but the same factors that have spurred the growth of Grays Harbor, direct and immediate access to the Pacific and to the Far East and China market, will likely result in rapid reconstruction.

5.3.5.3 Impacts on Containerized Shipping

The Ports of Seattle and Tacoma each support part of the landscape of containerized traffic. The Port of Seattle has increasingly become the port of choice for international flow in and out of the region, whereas the Port of Tacoma still transports a larger share of domestic flow.

[32] www.portofportland.com/fastfacts_marine.aspx, accessed September 2011.
[33] www.portofgraysharbor.com/news/Exports-Up-2010.php, accessed September 2011.
[34] World Port Source, 184.106.219.198/trade/exports/value/USA_WA_Port_of_Grays_Harbor_191.php, accessed September 2011.

In 2010, the Port of Seattle moved 897,224 full TEUs for import, 558,237 full TEUs for export, 380,114 empty TEUs for import/export, and 304,002 full/empty TEUs of domestic containerized traffic. Of the domestic TEUs, 67 percent travelled to/from Alaska, and 32 percent travelled to/from Hawaii. In total, the Port of Seattle moved 2,139,577 TEUs, a return to just above the 2005 total after a declining trend over the previous five years.

Compare this to the Port of Tacoma, which in 2010 moved 476,746 TEUs for import, 337,538 for export, 162,421 empty TEUs for import/export, and 478,762 TEUs of full/empty domestic containerized traffic. In total, the Port of Tacoma moved 1,455,466 TEUs, a 5.8 percent decline from the 2009 total, continuing a declining trend over the previous five years that may reverse in 2011.

The third largest port in the impact region is the Port of Portland, which plays a much less significant role in the transport of containerized goods. In 2010, the Port of Portland accounted for a total of 181,100 TEUs, approximately 5 percent of the total number of TEUs moved by the Ports of Seattle and Tacoma.

By vessel trade in U.S. dollars, the top four trade partners for the Port of Seattle in 2010 were China (53 percent), Japan (15 percent), Taiwan (5 percent), and South Korea (5 percent). Similarly, the top four trading partners for the Port of Tacoma in 2008 were China Mainland (41 percent), Japan (30 percent), China Taiwan (10 percent), and South Korea (9 percent).

These large commodity flows typically travel in a circuit. Container ships in these circuits typically take on mostly loaded containers and drop off mostly loaded containers at several ports throughout Eastern Asia. They then continue to ports in California, where the majority of their full containers are unloaded and replaced with empty ones. This lessens fuel requirements for the vessel as they continue north to ports in the northwestern United States and Canada. For example, one container ship may make calls at Busan, Hong Kong, Shanghai, Oakland, Long Beach, and Seattle, and then repeat the circuit.

In transportation models and analysis, the Ports of Seattle and Tacoma are often described as a pair, both because of their proximity and because local impacts that may affect the operation of one will similarly affect the other.

The consequence of the impact depends largely on restoration time. If port function can be restored quickly, containerized traffic will likely be held outside the port until operations resume, but will likely be processed at their original port.

In the case of a medium- or long-term loss of port operations, containerized goods originally destined for Seattle/Tacoma will most likely be unloaded earlier in the circuit, primarily at the Ports of Los Angles and Long Beach, which together accounted for 82 percent of TEUs to/from the United States in 2010. Other ports to which containers may be redirected are the Port of Oakland and the Port of Prince Rupert, in British Columbia.

The Port of Prince Rupert handled 343,366 TEUs in 2010 at the recently built Prince Rupert Container Terminal and is currently being developed to potentially quadruple the capacity of this terminal to two million TEUs per year. The port’s access to the Canadian National Railway, which enters the United States at Minnesota, makes it a viable alternative mode of transportation for containerized goods.

Even in the long term, commodity logistics costs are not likely to rise significantly outside the impact region. However, container flows directed to alternate ports may be slow to return to the Ports of Seattle/Tacoma, and may in fact never return to pre-event levels. Together, the ports account for hundreds of thousands of jobs in the Seattle metropolitan area.

5.3.6 Food and Agriculture

Analysis of the direct impact on Food and Agriculture of the Cascadia seismic event will focus first on geographic locations within the impacted zones where populations are at the greatest risk of being unable to access food or water following the event. Such locations are called food deserts. The U.S. Department of Agriculture (USDA) defines a food desert as "a low-income census tract where a substantial number or share of residents has low access to a supermarket or large grocery store."[35] The population in a food desert would likely encounter difficulty in obtaining food and water after the seismic event as a result of disruptions to surface transportation and disruptions to wholesale and retail food distribution channels. These problems are compounded in a food desert by lack of access to financial resources, limited household inventory, age, disability, and/or limited access to personal transportation.

Three figures are provided to indicate the census tracts labeled as food deserts. Figure 5-51 is a map of food deserts over the tri-state area impacted by the Cascadia seismic event; Figure 5-52 is an expanded view of food deserts in the Seattle-Tacoma metropolitan area; and Figure 5-53 is an expanded view of food deserts in the Portland metropolitan area.

[35] U.S. Department of Agriculture, "Food Desert Locator," www.ers.usda.gov/data/fooddesert/documentation.html#Definition, accessed May 14, 2011.

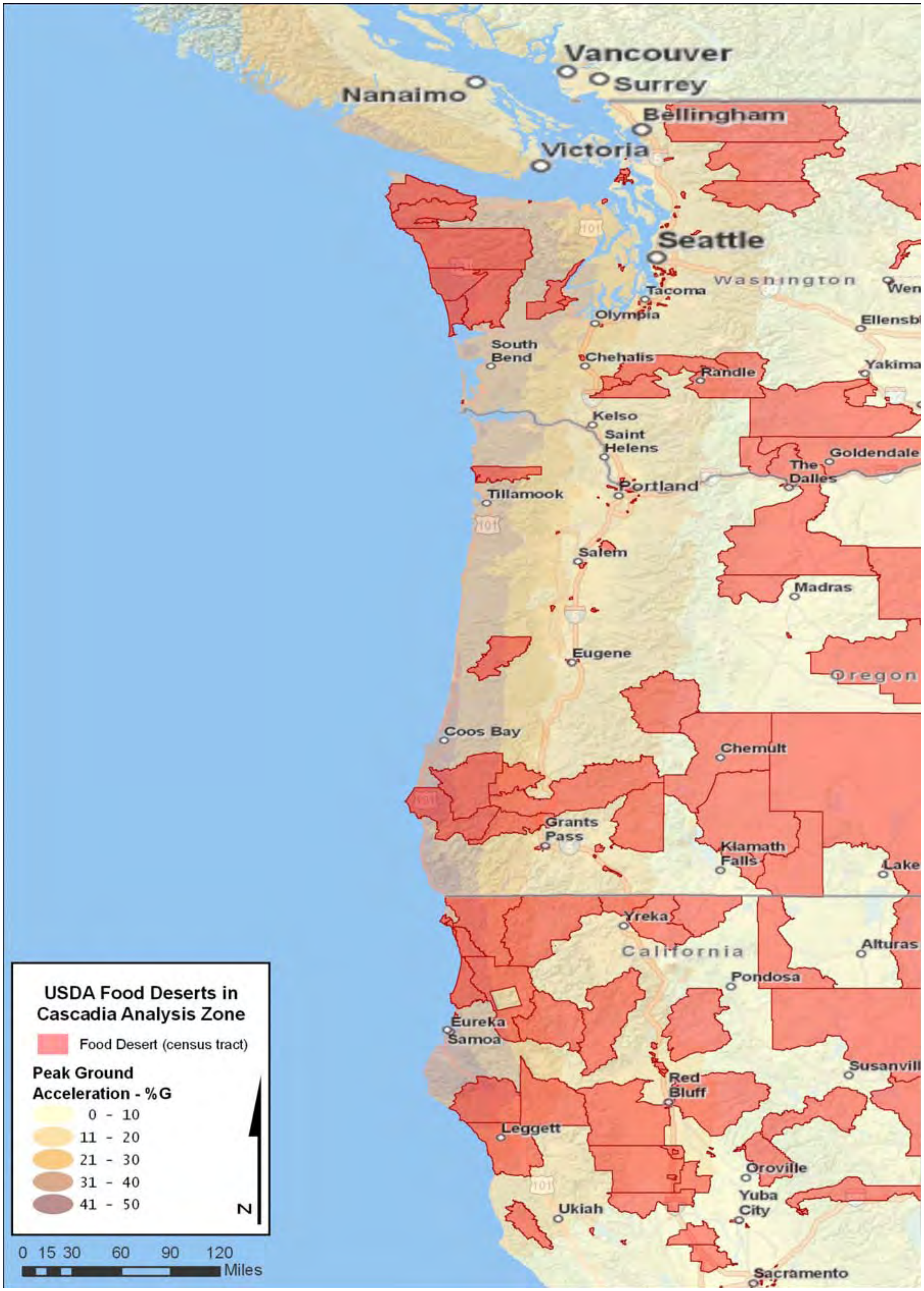

Figure 5-51. Census tracts in the impacted tri-state area classified as food deserts by the USDA

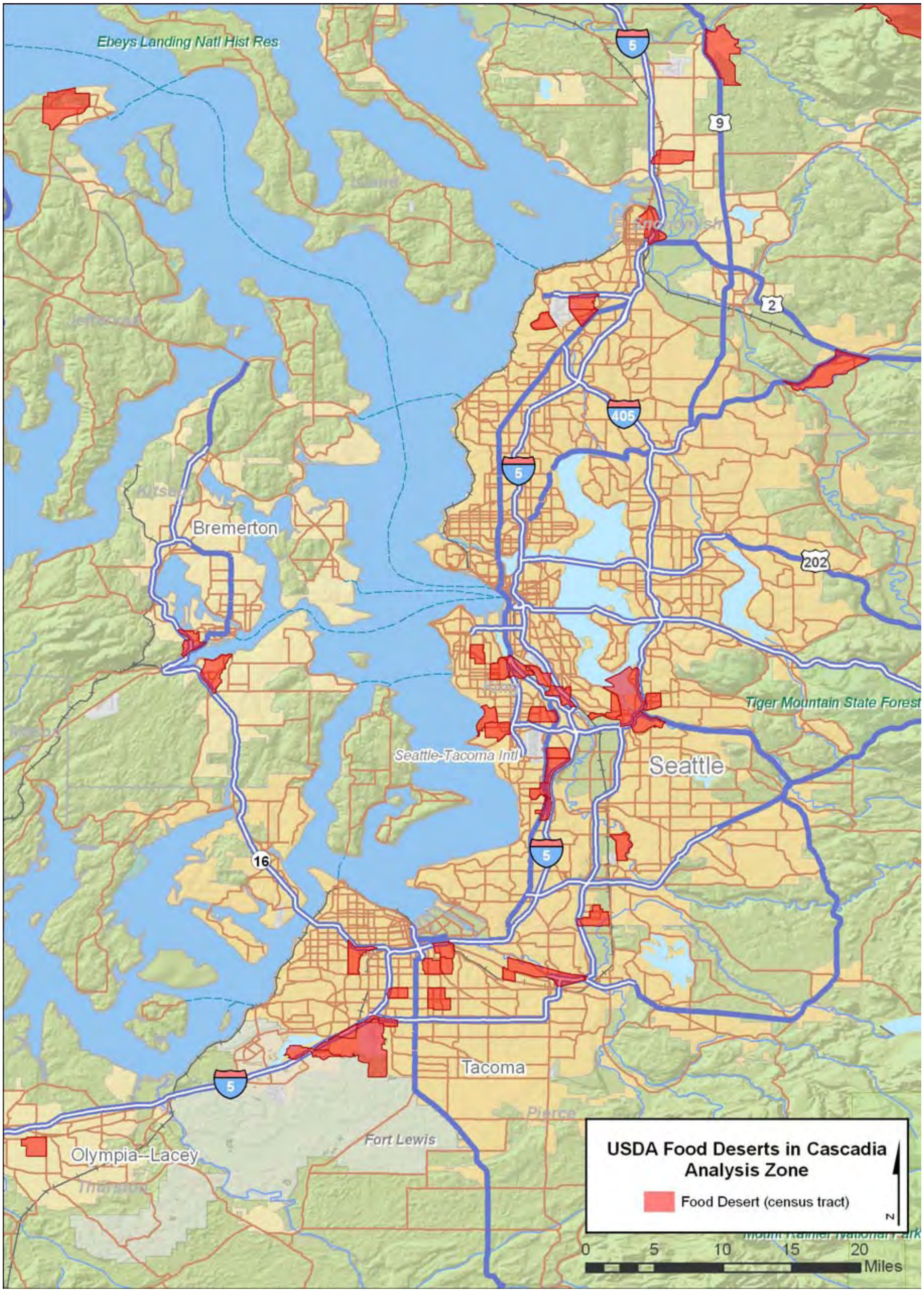

Figure 5-52. Census tracts in the Seattle-Tacoma metropolitan area classified as food deserts by the USDA

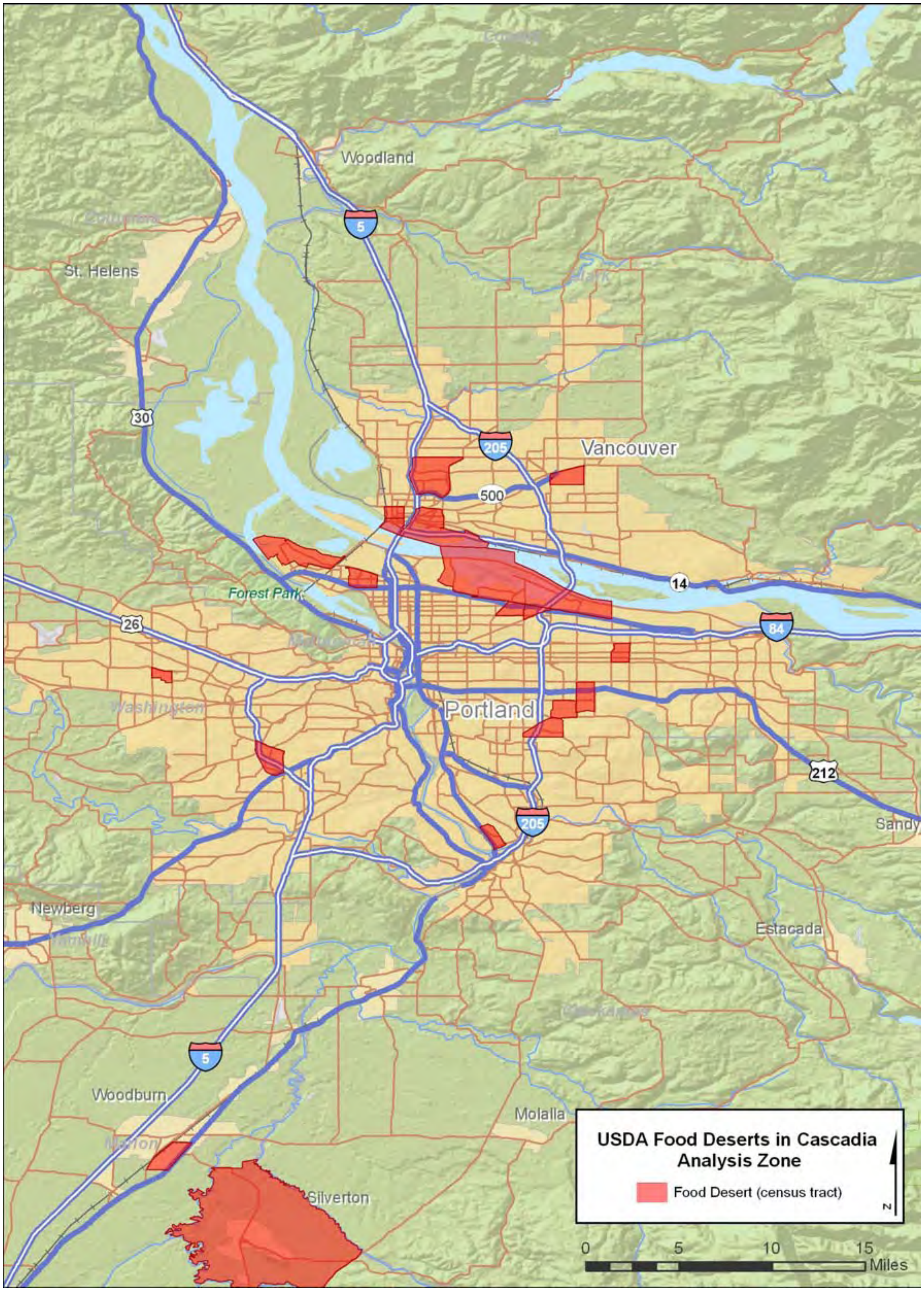

Figure 5-53. Census tracts in the Portland metropolitan area classified as food deserts by the USDA

The commanding agricultural contribution of the Pacific Northwest is the shipment of grain to export markets. This part of the analysis considers the distribution of major export grain terminals in the impact zone and estimates damage to individual facilities as predicted by Hazus. Table 5-31 includes the Hazus model damage estimate for each of the major grain terminals. Figure 5-54 shows the locations of the major grain terminals.

Table 5-31. Major grain terminals within the Cascadia impact zone

Major Grain Terminals	Port	Hazus 50th-percentile Damage Estimate	Hazus 90th-percentile Damage Estimate
Louis Dreyfus Grain Terminal	Seattle, WA	slight	moderate
TEMCO Cargill Grain Terminal	Tacoma, WA	slight	severe
AGP Terminal 2 Grays Harbor	Grays Harbor, WA	moderate	severe
Berth 9 Longview	Longview, WA	slight	complete
Kalama Export Company	Kalama, WA	slight	severe
Kalama Cenex/United Harvest	Kalama, WA	slight	severe
Columbia Grain Terminal 5	Portland, OR	slight	complete
Vancouver Terminal 2	Vancouver, WA	slight	severe

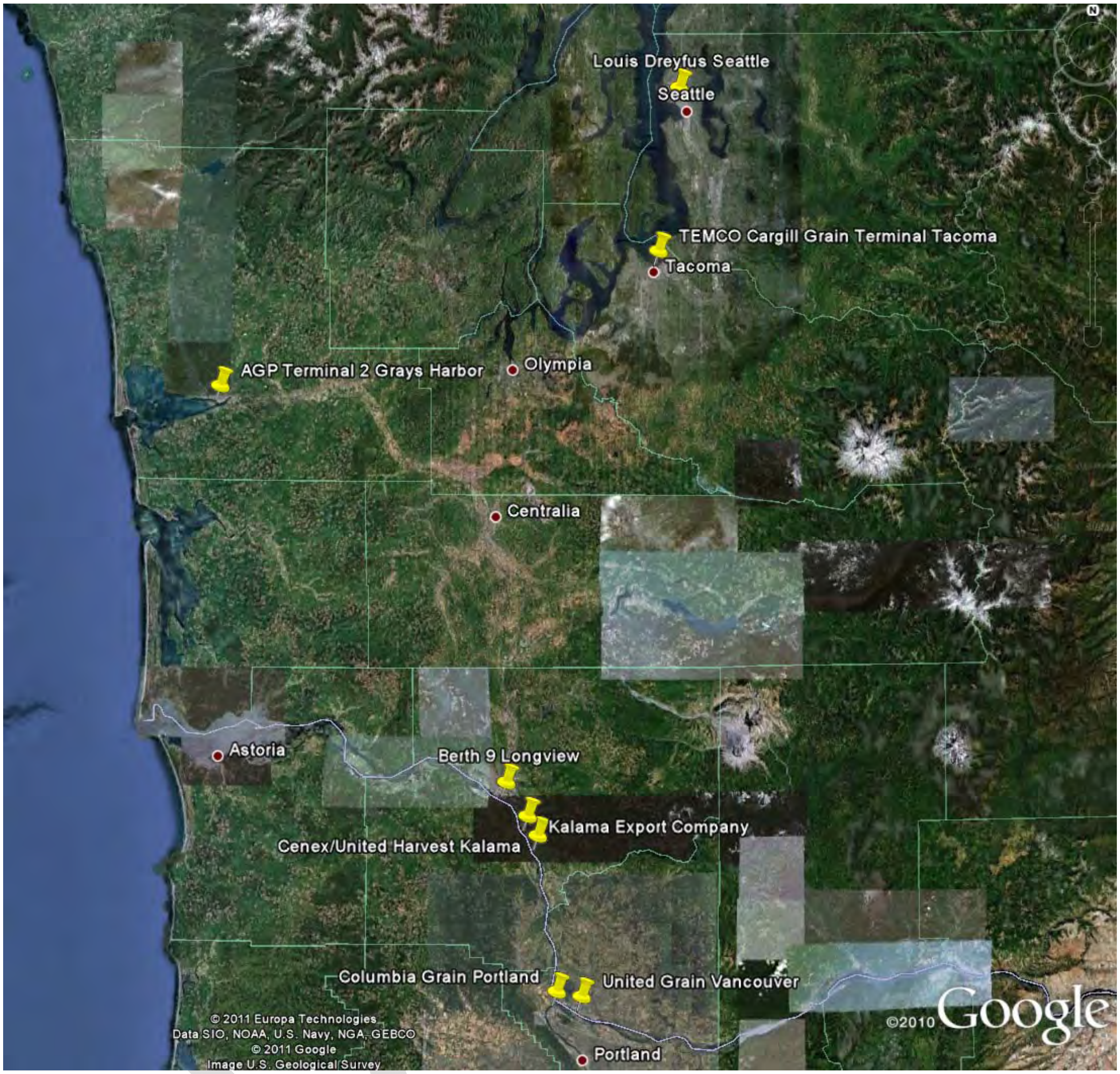

Figure 5-54. Major grain terminals in the Cascadia impact zone (marked by yellow pins)

AGP, a large farmer-owned processor of soybeans representing 200,000 midwestern farmers, is expanding its facilities at the Port of Grays Harbor to increase shipments of soybean meal, grains, distillers' grains, gluten meal, and beet pulp pellets to its Pacific Rim clients. Construction was expected to begin in the fall of 2011with completion scheduled for early 2012,[36] but would likely be delayed if this scenario were to take place.

Although damage is slight to all existing major facilities under the 50th-percentile damage scenario, there will be immediate impacts on grain exports from the facilities located at ports along the Columbia River System (Longview, Kalama, Portland, and Vancouver). Tsunami

[36] www.portofgraysharbor.com/news/AGP-Expand.php, accessed August 2011.

damage at the mouth of the Columbia will impact navigation and the ability to export agricultural commodities.

5.3.7 Emergency Services

The emergency services sector of police, fire, and ambulance services will experience logistical difficulty responding to the seismic event. Figure 5-55,Figure 5-56, and Figure 5-57 show that many of the facilities will be damaged in the earthquake, as well as the emergency vehicles housed at the facilities. Roads and bridges along the coast will be severely damaged or destroyed, rendering them impassable. In addition, the timeframe for responding to people requiring medical attention will be shortened because the event occurs during the winter. Aerial operations may be required to move personnel and the injured into and out of the affected area.

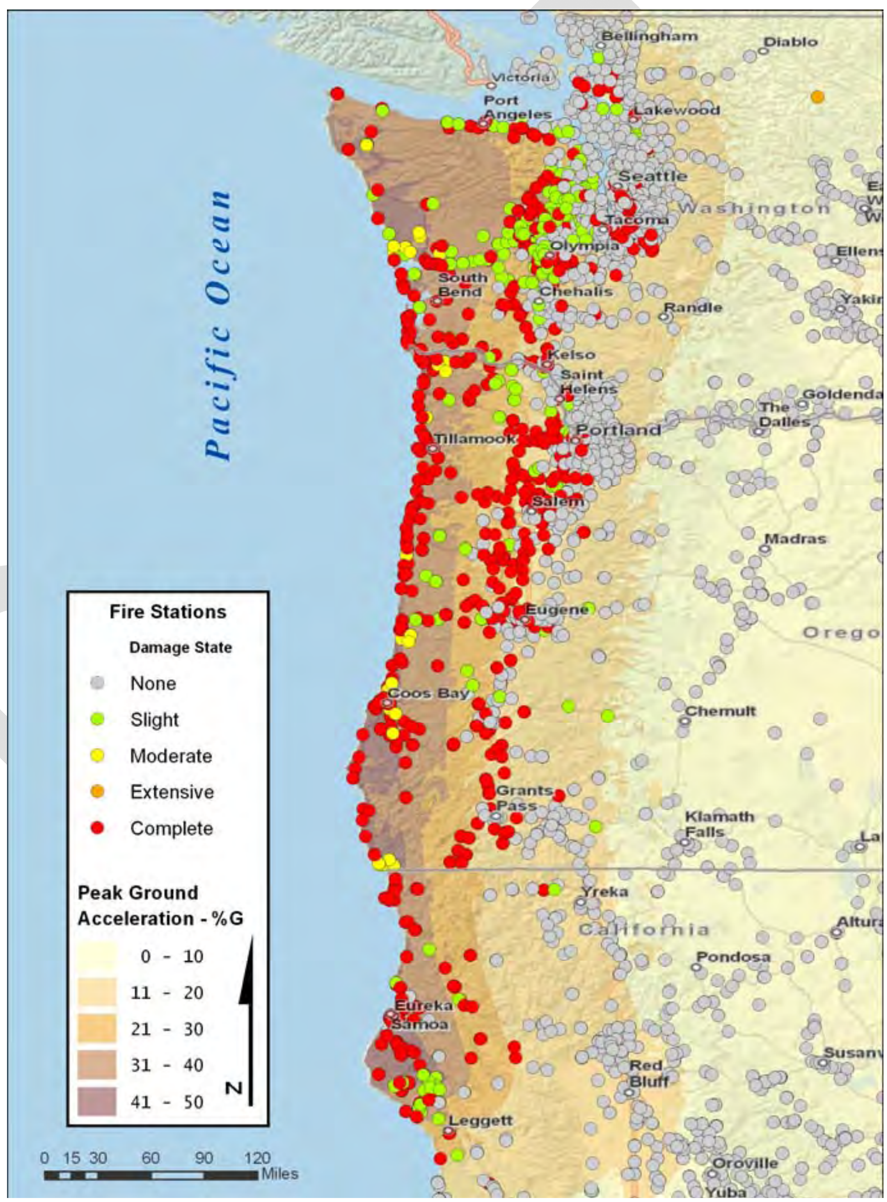

Figure 5-55. Fire station damage extent for the expected (50th-percentile) case

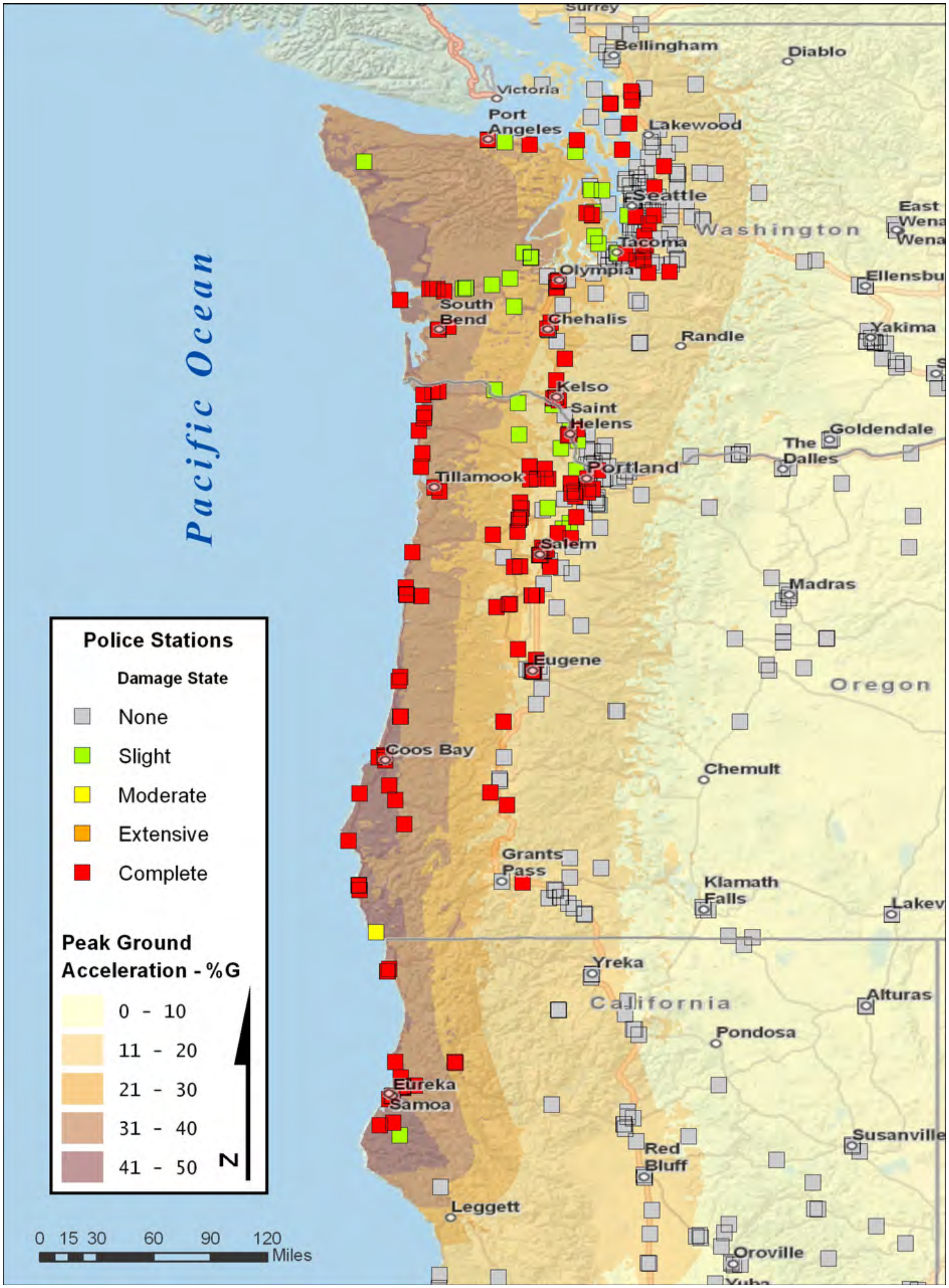

Figure 5-56. Police station damage extent for the expected (50th-percentile) case

Figure 5-57. Emergency operations infrastructure damage extent for the expected (50th-percentile) case

The population in the affected region will experience great difficulty reaching emergency services due to widespread failure of wireline and cellular communications infrastructure. Communications providers will require access to the region to deploy temporary cellular or wireline communications capability through cellular-on-wheels (COWs), cellular-on-light-trucks (COLTs), or wire centers on trucks as part of the emergency response effort.

The ability to use the Emergency Alert System (EAS) to broadcast important emergency announcements within the affected area will also be severely limited, which will contribute to the inability of the injured to get assistance. A general lack of information on appropriate actions that people within the affected area can take to minimize additional damage would be expected; the inability to communicate event-based information will also hinder both response and recovery efforts.

Similar to cellular networks and the EAS, antennas used in dispatch operations will likely be inoperable or mis-pointed, causing more communication difficulties for emergency responders. Ham radio operators may be helpful in assisting with communications.

Table 5-32, Table 5-33, and Table 5-34 provide damage statistics for fire stations, police stations, emergency medical services (EMS), and emergency operations centers (EOCs) in the region. The figures reflect the nominal damage scenario. In the worse-case scenario, the damage zones extend further to the east, making response and recovery efforts even more difficult.

Table 5-32. Damage to fire stations

Fire Stations and Ambulance		
Damage State	Facilities (50th-percentile case)	Facilities (90th-percentile case)
Complete	888	1126
Severe	1	84
Moderate	41	123
Slight	284	1037
None	2746	1590
TOTAL	**3960**	**3960**

Table 5-33. Damage to police stations

Police Stations		
Damage State	Facilities (50th-percentile case)	Facilities (90th-percentile case
Complete	151	200
Severe	0	9
Moderate	1	14
Slight	34	127
None	340	176
TOTAL	**526**	**526**

Table 5-34. Damage to emergency operations centers

Emergency Operations Centers		
Damage State	Facilities (50th-percentile case)	Facilities (90th-percentile case)
Complete	32	43
Severe	0	3
Moderate	0	3
Slight	11	35
None	81	40
TOTAL	**124**	**124**

Each of the preceding tables shows damage states at 50th-percentile and 90th-percentile, categorized as complete damage, severe damage, moderate damage, slight damage, and no damage at all. The 90th-percentile scenario damage estimate numbers are greater; thus the emergency response related to these damaged facilities will hinder overall performance of the emergency management system commensurately more in the worse-case (90th-percentile) scenario.

5.3.8 Water/Wastewater

The water and wastewater infrastructure includes the potable water storage and delivery system and the collection and conveyance of wastewater effluent to sewage treatment plants within a community.

Water/wastewater assets not damaged in the earthquake are likely to sustain a damage level of moderate or less. Figure 5-58 and Figure 5-59 show the water and wastewater assets that are expected to experience damage levels of moderate or more under the average and 90th-percentile damage states, respectively.

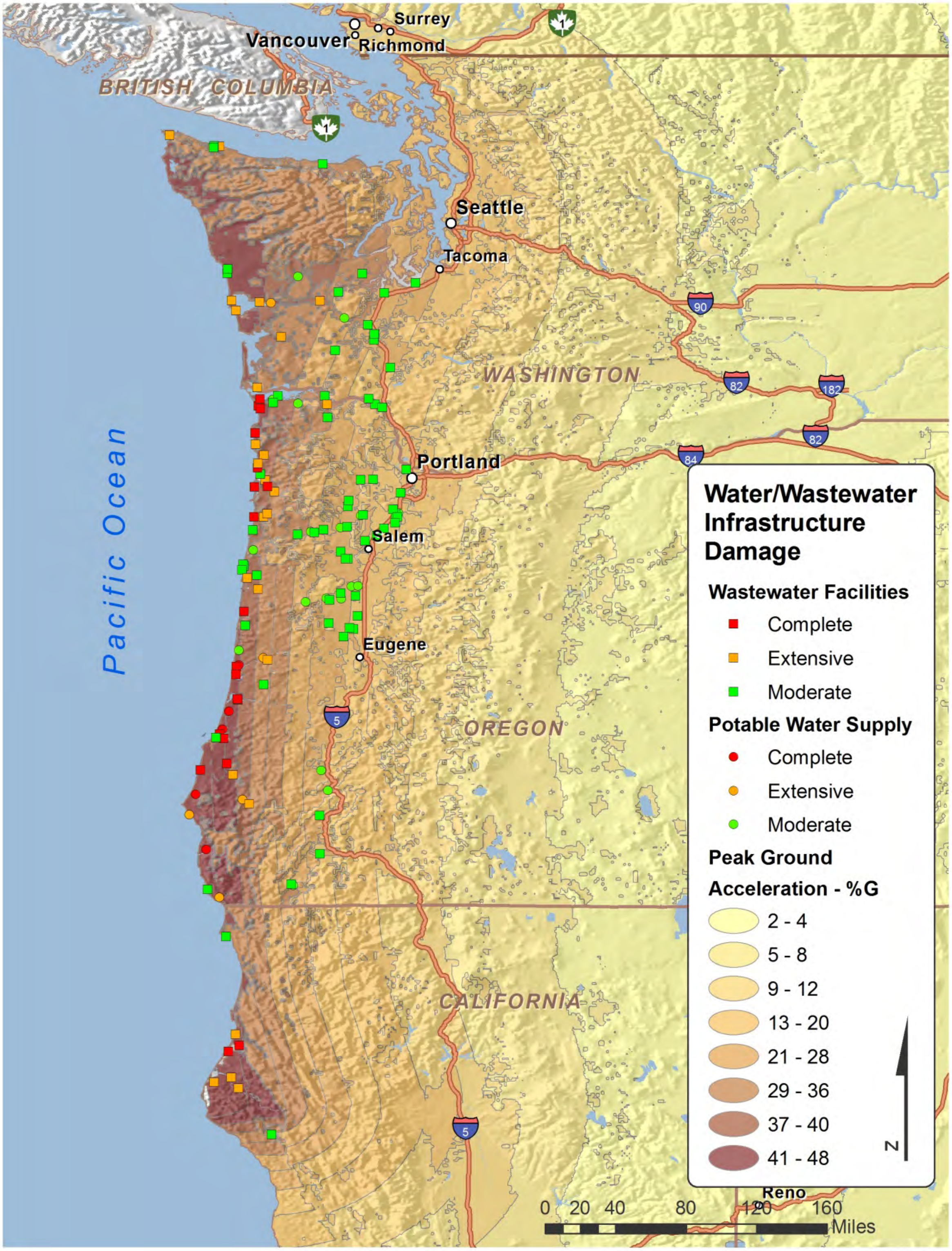

Figure 5-58. Water and wastewater facilities in the Cascadia region with expected damage state of moderate or more under the 50th-percentile case

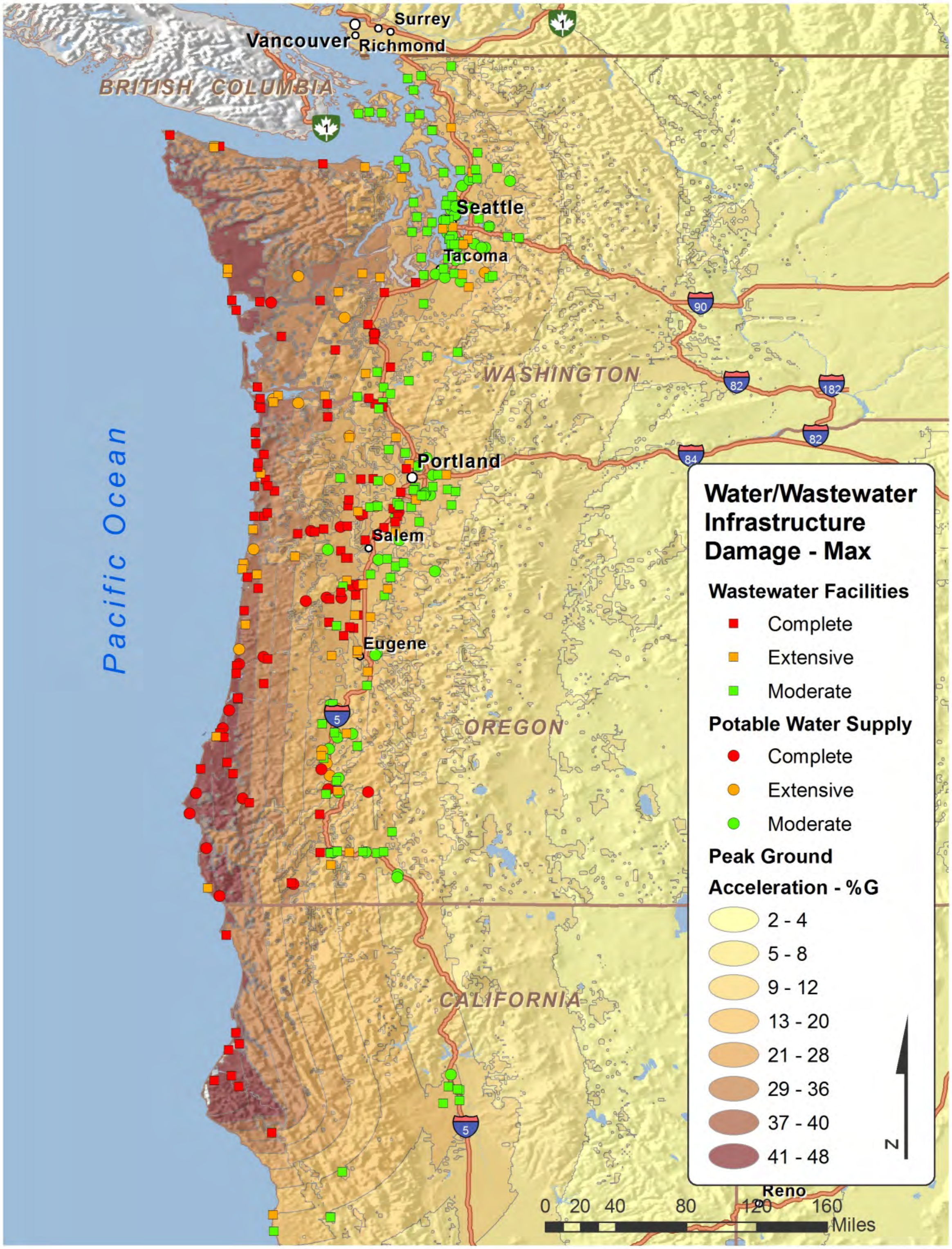

Figure 5-59. Water and wastewater facilities in the Cascadia region with expected damage state of moderate or more under the 90th-percentile case

Table 5-35 provides damage states for the 50th-percentile and 90th-percentile scenarios.

Table 5-35. Damage states for water/wastewater assets average and 90th-percentile damage states for earthquake

Damage State	Water Facilities		Wastewater Facilities	
	50th-percentile	90th-percentile	50th-percentile	90th-percentile
California				
Moderate	0	1	2	9
Extensive	0	0	4	1
Complete	0	0	2	8
Oregon				
Moderate	16	22	45	44
Extensive	4	13	13	36
Complete	5	22	17	64
Washington				
Moderate	3	28	20	61
Extensive	1	5	8	23
Complete	0	2	0	21
Total				
Moderate	19	51	67	114
Extensive	5	18	25	60
Complete	5	24	19	93

5.3.8.1 Potable Water

For potable water systems, most, if not all, of the coastal communities will sustain Severe (Extensive) to Complete damage, while the communities along the I-5 corridor have a mix of Moderate through Complete damage, except in Seattle, where the damage is Moderate to Severe (Extensive). Potable water systems are comprised of treatment facilities, the pipeline distribution system, pumping stations, valves, and holding tanks.

Table 5-36 lists the estimated repair times for potable water systems. Based on these estimates, water systems that sustain Complete damage will require at least three weeks to repair and may require 22 or more weeks. For Severe (Extensive) damage, the repair time will be about 1 to 13 weeks. It will be critical to supply water to these communities while the water system is being restored. In those areas where the ground shaking is most intense, usually the coast and coastal mountain areas, subject matter experts expect substantial damage to the water distribution systems, including widespread pipe breakage and leaks. Broken and leaking pipes can further extend repair times. For coastal communities that may be isolated due to road damage, it may not be possible to truck in potable water, so planners must consider alternatives to ensure adequate water supply. Similarly, it may be difficult to deliver repair materials.

Table 5-36. Estimated repair time for water systems in days

System	Repair Time (days) Moderate Damage	Repair Time (days) Severe (Extensive) Damage	Repair time (days) Complete Damage
Potable Water	1–3	10–90	26–155
Wastewater	1–6	30–80	100–220

For Seattle and Portland, much of the damage falls within the Moderate category, with relatively short repair times. Because these urban areas are not isolated by extensive road damage, water provision should follow established emergency supply procedures.

5.3.8.2 Wastewater

Wastewater treatment facilities are the final collection point in a wastewater system. Treatment plants treat raw sewage daily, after which the majority of the treated water is discharged into a nearby water system, such as a river or ocean. In some instances, sewage discharge can occur in homes, businesses, and government facilities due to pipeline system disruption. Such discharges carry the risk of higher rates of disease.[37]

Lift stations move raw sewage from lower elevations to higher elevations so that the sewer can flow by gravity to a wastewater treatment facility. If the lift station pumping capacity is insufficient or out of service, then the lift station is inoperable. As a result, sewers can back up and result in sewer-system failure. Lift stations are typically designed so that one pump or a set of pumps will handle normal peak flow conditions. These systems also typically have a built-in level of redundancy. If one or a set of pumps is out of service, through either failure or routine maintenance, the facility will have additional pumps that can handle the design flow.

Regardless of the cause of a system failure, loss of treatment capability typically results in the discharge of untreated sewage.

RDMB-NISAC also considered wastewater collection system pipeline infrastructure in an assessment of highest consequence infrastructure. An incident (e.g., blocked pipes, pipe failure, etc.) in a main trunk line is probably more harmful than a failure in a pumping station in an upper section of a sewer system with only a few connections.[38] The size of a pipe that fails is a factor in the magnitude of disruption. That is, larger pipes collect more sewage and, therefore, a failure affects a larger region.

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[37] Centers for Disease Control and Prevention Web site, "Global WASH-Related Diseases and Contaminants," www.cdc.gov/healthywater/global/wash_diseases.html.

[38] Moderl, M., Kleidorfer, M., Sitzenfrei, R., and Rauch, W. "Identifying weak points of urban drainage systems by means of VulNetUD," *Water Science and Technology*, 60(10), 2507-2513 (2009).

In a large-magnitude earthquake, a substantial fraction of sewer lines will be damaged and become inoperable. Sewage will back up into buildings and/or open areas, and broken water lines may become contaminated by sewage. If stoppage in sewer lines is suspected or obvious, the population should be notified to discontinue discharge of wastewater in houses or building sinks and drains and stop flushing toilets. The population should avoid contact with any overflow wastewater or sewage. An adequate number of chemical toilets should be provided for use until the wastewater system is repaired.

5.3.8.3 Water/Wastewater Cascading Effects

The disruption to the local population and community economy in the case of extensive or complete damage to water or wastewater systems will be large, as fundamental infrastructure that is often taken for granted will be lacking. As shown in Table 5-36, repair times are three weeks to seven months for facilities that sustain complete damage. The lack of functioning water infrastructure can disrupt commercial, industrial, and domestic activities and have major ripple effects upon a region's economy. Untreated wastewater has the potential to increase the incidence of waterborne diseases. Many critical facilities rely on water for operation (i.e., hospitals, fire and police stations, telecommunication assets). The lack of these essential services will be a significant impairment to the health and safety of the population.

5.3.8.4 Tsunami Effects

Only three sites are in the expected inundation area. Table 5-37 lists those sites.

Table 5-37. Water and wastewater facilities located within the expected inundation area

Facility	Location	Inundation Depth (feet)
Wastewater	Crescent City, CA	> 12
Public Water Supply	East Astoria, OR	6–12
Ocean Shores Sewer Treatment	Moclips-Westport, WA	6–12

5.3.9 Dams

5.3.9.1 Earthquake Effects

In this analysis, RDMB-NISAC used the Multi-Hazard Infrastructure Impact Analysis tool to perform fragility analysis on dams located within the Cascadia scenario region. The tool applies fragility curves that are a function of PGA.[39] The tool's damage algorithms yield damage probabilities analogous to Hazus.

Figure 5-60 shows the distribution of probability of damage for dams in the Cascadia seismic study zone.

[39] Lin, L., Adams, J., "Probabilistic Method for Seismic Vulnerability Ranking of Canadian Hydropower Dams," Canadian Dam Association Annual Conference, St. John's, NL, Canada, Sept. 22–27, 2007.

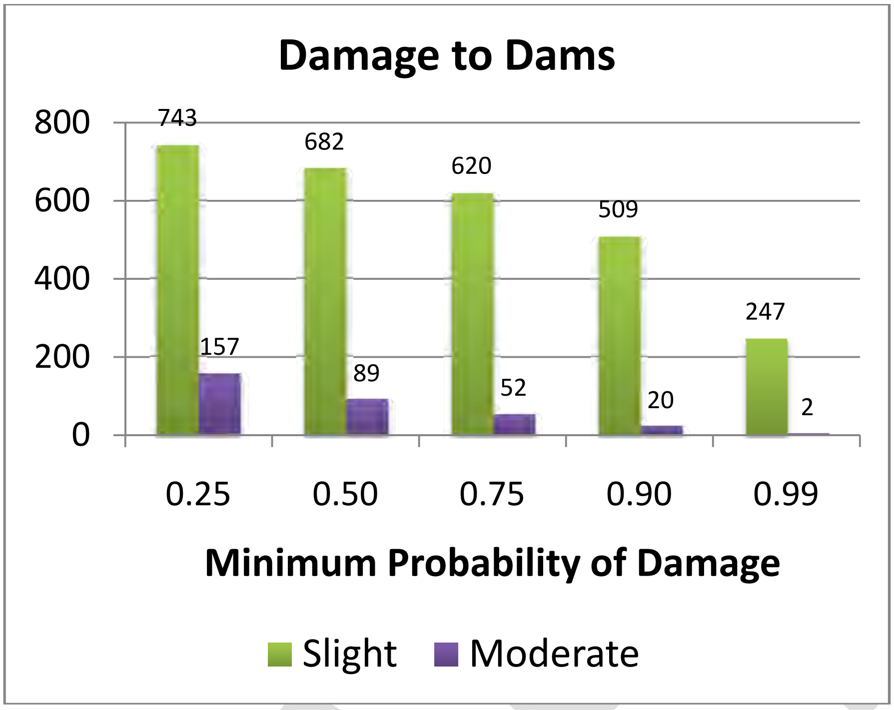

Figure 5-60. Distribution of dam damage states for the Cascadia earthquake scenario

As Figure 5-60 shows, of the 1,660 dams in the study region, analysis results indicate that no dams are severely damaged by the earthquake. However, 89 of these dams have a 50-percent or greater chance of moderate damage. Of these 89, 52 of the dams have a 75- percent or greater chance of moderate damage. Moderate damage is not considered catastrophic and most likely will not lead to a dam breach or failure; however, a moderately damaged facility will require substantial repairs.

Figure 5-61 and Figure 5-62 show the locations of dams with slight or moderate damage potential.

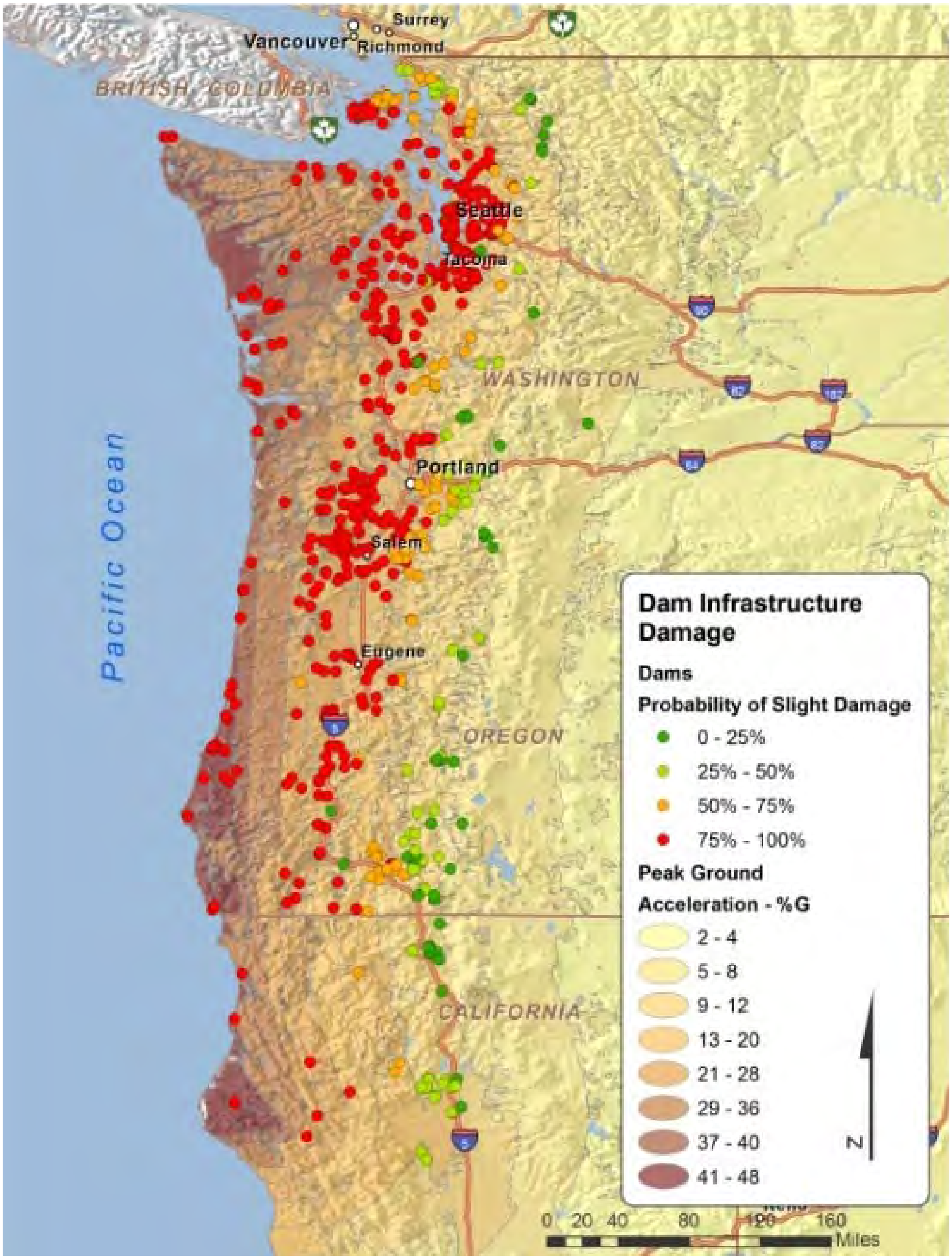

Figure 5-61. Cascadia dams with potential for slight damage

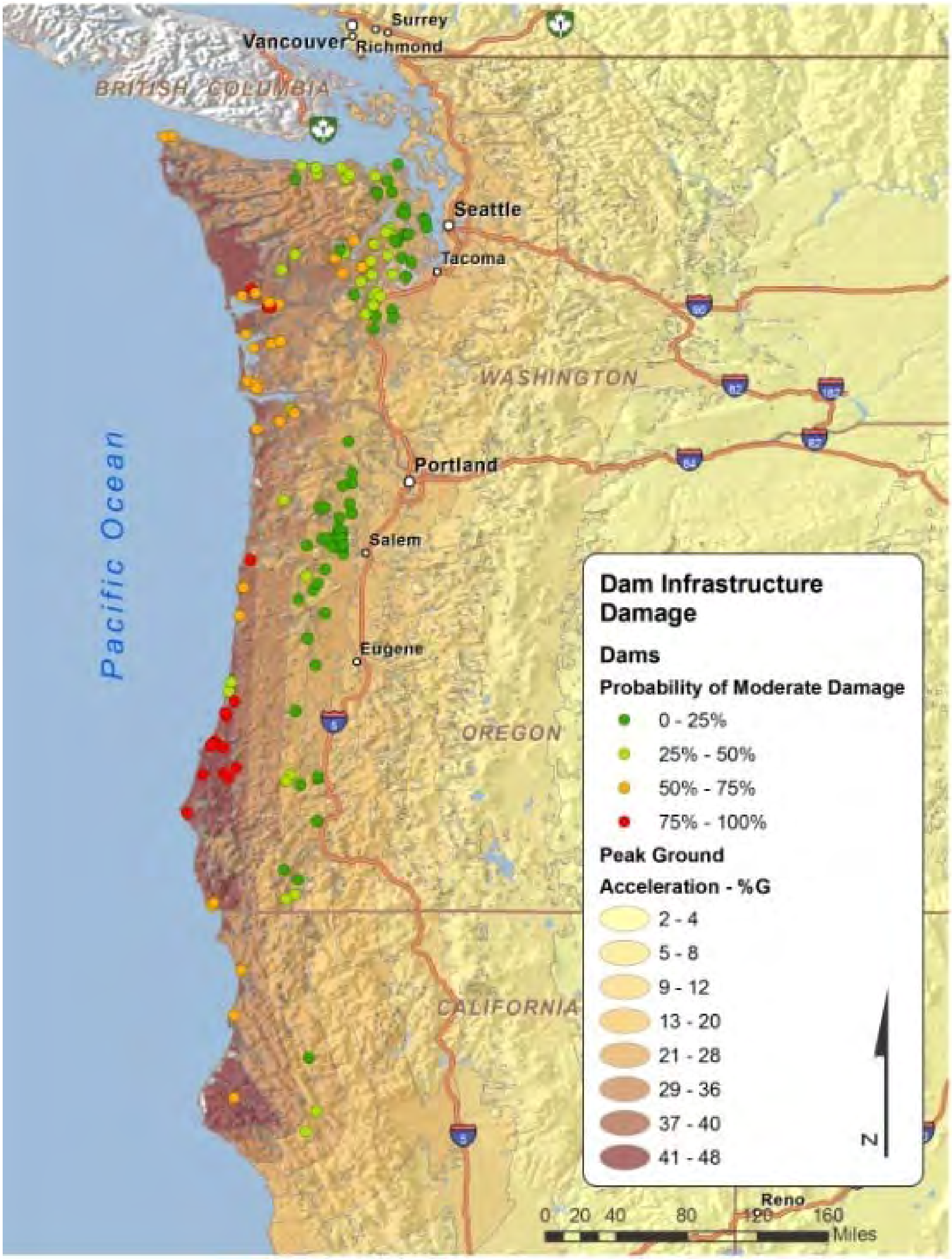

Figure 5-62. Cascadia dams with potential for moderate damage

5.3.9.2 Tsunami Effect

No dam sites were located within the inundation areas determined from the modeled tsunami marigrams. Hence, no dams are expected to be damaged due to tsunami-induced effects.

5.3.10 Banking and Finance

The CSZ earthquake will have minimal direct impacts on the banking and finance sector. However there will be larger, and potentially national impacts, due to the cascading impacts of other infrastructure sectors upon the banking and finance sector.

5.3.10.1 Banking and Finance Methodological Overview

The direct impact analysis for bank branches looks at those impacted on a county basis. The approach assumes that all branches within specific counties face a potential outage in functionality. For this analysis, the 14 counties listed in Table 5-38 face the largest impact from the CSZ scenario. It is important to note that the whole county may not be affected by this scenario. This analysis, therefore, represents an upper bound.

Table 5-38. Counties most impacted by the scenario

County	State	Deposits ($000's)
Del Norte	CA	$180,154
Humboldt	CA	$1,529,800
Clatsop	OR	$437,206
Coos	OR	$792,840
Curry	OR	$309,663
Douglas	OR	$1,507,749
Lane	OR	$4,151,973
Lincoln	OR	$762,683
Tillamook	OR	$305,967
Clallam	WA	$1,459,333
Grays Harbor	WA	$950,441
Jefferson	WA	$457,306
Pacific	WA	$456,097
Wahkiakum	WA	$40,470
Total		**$13,341,682**

For bank branch outage analyses, counties are input into the Federal Deposit Insurance Corporation (FDIC) Summary of Deposits (SOD) market share tool[40] to assess impacts to bank branches in the area. The output from this tool is then analyzed for important issues. After an earthquake, local infrastructure is devastated. It is assumed that people in the impacted area will

[40] Tool can be accessed at www2.fdic.gov/sod/sodMarketBank.asp?barItem=2, accessed August 2011.

be required to evacuate to gain access to funds. If an institution loses many or all of its branches, consumers may be inconvenienced in trying to access their funds as the bank would have lost significant portions of their infrastructure.

5.3.10.2 Access to Funds

5.3.10.2.1 Local/Regional Impacts

There are 1,319 branches that will be impacted by this scenario. Of these, 989 branches should be restored within eight days, as they are only impacted due to electrical outages. The other 330 branches managed by 35 institutions are likely to face some damage due to shaking and may take more time to reoccupy as inspections and any necessary repair or replacement is completed. This analysis focuses on these 330 branches. While electric power may be offline for 989 branches, retailers may still have electrical power allowing people to pay for goods, particularly if the banks' payment processing systems are not impacted by the scenario. Additionally, retailers without electrical power or telecommunications could chose to accept payments using manual credit card swipe machines. FEMA and other aid agencies can also provide assistance in the short term, depending on how long it will take them to muster resources to the area.

Of the 35 institutions managing the 330 impacted branches, 15 institutions are likely to lose half or more of their branch functionality. These 15 institutions represent approximately 20 percent of deposits in the 14-county area. The damage to branches and the bank's network could make it difficult for people to access their money in the near term. Significant loss in bank structures could result in some banks not returning to business after the incident. Table 5-39 lists the various banking institutions by their susceptibility to earthquake in this scenario. Figure 5-63 maps the impacts to bank branches in the region.

Table 5-39. Banks most impacted by the earthquake

Institutional Name	Branches Impacted	Deposits Held Within the Area (000's)	Institution Market Share (Impacted Area)	Percent Branches Impacted Area
First Federal Savings and Loan Association of Port Angeles	9	$555,808	4.17%	100.00%
Siuslaw Bank	10	$247,041	1.85%	100.00%
Redwood Capital Bank	2	$183,693	1.38%	100.00%
Oregon Pacific Banking Company dba Oregon Pacific Bank	5	$135,553	1.02%	100.00%
Oregon Coast Bank	5	$125,073	0.94%	100.00%
Summit Bank	1	$102,534	0.77%	100.00%
Century Bank	1	$74,793	0.56%	100.00%
Raymond Federal Bank	3	$53,414	0.40%	100.00%
Clatsop Community Bank	2	$31,270	0.23%	100.00%
Bank of The Pacific	12	$404,220	3.03%	70.59%
Shorebank Pacific	1	$100,607	0.75%	50.00%

Institutional Name	Branches Impacted	Deposits Held Within the Area (000's)	Institution Market Share (Impacted Area)	Percent Branches Impacted Area
Pacific Continental Bank	7	$613,178	4.60%	50.00%
Sound Community Bank	2	$136,237	1.02%	40.00%
Libertybank	6	$246,897	1.85%	37.50%
Anchor Mutual Savings Bank	6	$228,860	1.72%	37.50%
Evergreen Federal Savings and Loan Association	2	$37,965	0.28%	28.57%
Kitsap Bank	7	$149,654	1.12%	28.00%
Timberland Bank	6	$209,216	1.57%	27.27%
North Valley Bank	6	$149,702	1.12%	25.00%
Security State Bank	3	$38,510	0.29%	23.08%
Citizens Bank	3	$32,312	0.24%	21.43%
Umpqua Bank	34	$2,599,659	19.49%	19.32%
Sterling Savings Bank	26	$706,828	5.30%	14.86%
Premierwest Bank	6	$146,814	1.10%	13.95%
West Coast Bank	8	$201,172	1.51%	11.94%
Columbia State Bank	10	$183,987	1.38%	11.63%
Washington Federal Savings and Loan Association	7	$311,650	2.34%	4.29%
Tri Counties Bank	1	$35,629	0.27%	1.56%
U.S. Bank National Association	47	$1,415,111	10.61%	1.54%
Keybank National Association	13	$514,789	3.86%	1.26%
Bank of the West	5	$76,602	0.57%	0.76%
Union Bank National Association	3	$162,801	1.22%	0.75%
Bank of America National Association	27	$1,150,236	8.62%	0.45%
JP Morgan Chase Bank National Association	21	$736,204	5.52%	0.40%
Wells Fargo Bank National Association	23	$1,243,663	9.32%	0.35%
Number of Institutions in the Market: 35	**330**	**$13,341,682**		

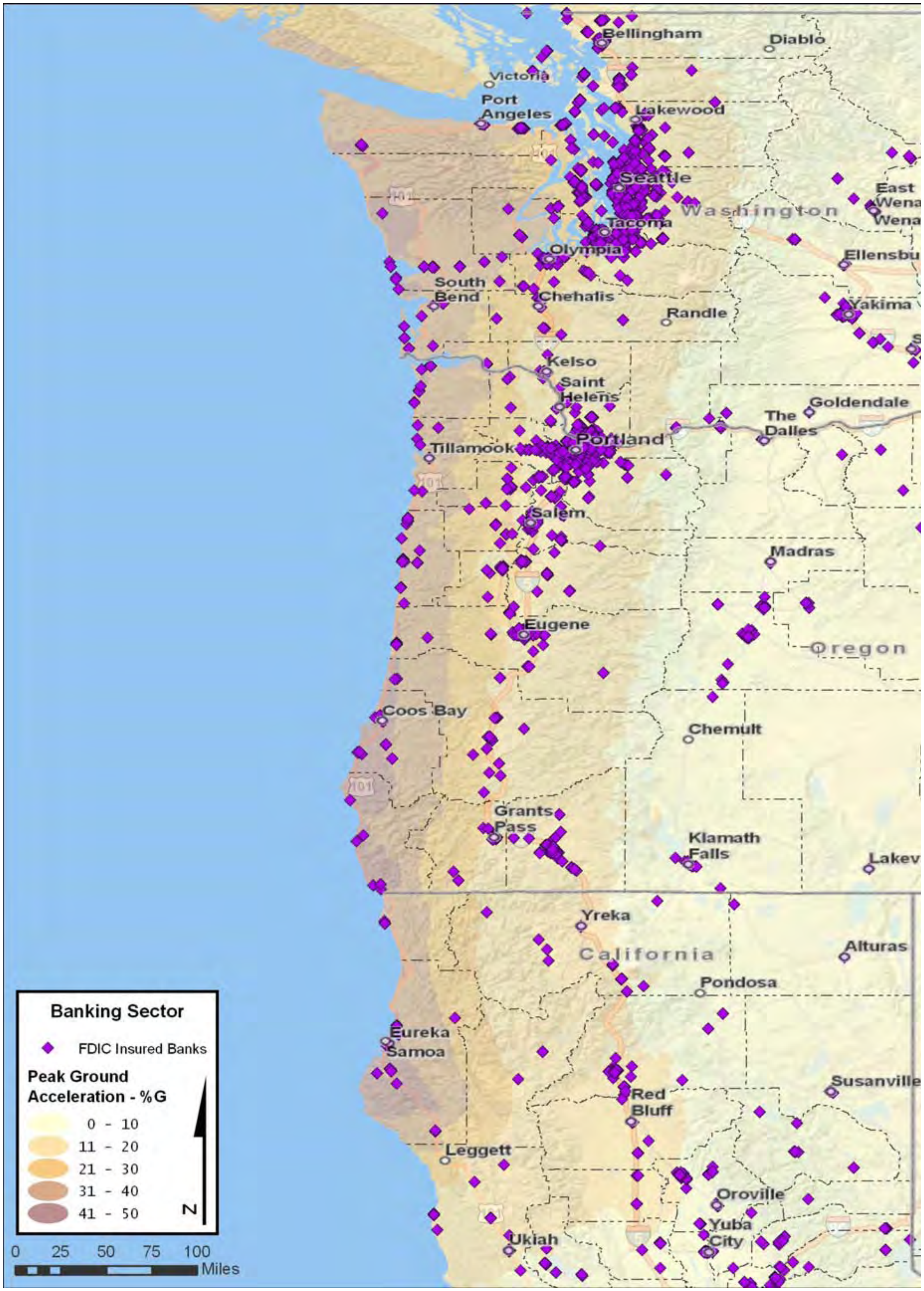

Figure 5-63. Bank branches and headquarters impacted by Cascadia earthquake

Banks have shown themselves to be adaptive in catastrophic situations. In the aftermath of Katrina, banks that could not access their electronic records allowed their customers $100 withdrawals if the customers could prove that they were members of the bank. Katrina also showed that banks were rapid in their recovery of EP through the procurement of mobile generators.

ATMs, credit cards, and debit cards are other sources for individuals to access funds locally. If the debit and credit network connections are lost, local businesses can use manual credit card machines to process transactions, thereby giving people access to funds. FEMA would also provide temporary assistance for people in the area through Electronic Benefits Transfer (EBT) cards and short-term loans.

The ATM network is largely dependent on the electricity and telecommunications infrastructures. ATM machines may survive damage in the area (due to sturdy construction) but without electricity and a communications link they will not function.

5.3.10.2.2 National Perspective

There is the potential for major impacts arising from the inability to access funds. The earthquake would likely disable the only high-speed communication links between Alaska and the contiguous United States. This represents a majority of the communications traffic to and from Alaska. About 40 percent of Alaskan deposits are in Alaska-based banks. The remaining 60 percent of deposits are held by two national institutions: Wells Fargo (48.79 percent of all Alaskan deposits) and Keybank (11.74 percent of all Alaskan deposits). These institutions may have Alaska-based infrastructure to process transfers and payments internal to Alaska. However, if either of these institutions do not have payment processing systems local to Alaska, people could have significant problems accessing funds. For employees of multinational and non-Alaska U.S. companies operating in Alaska, direct deposit services may not function due to the telecommunications outage. This could result in short-term delays in distributing payrolls.

5.3.10.3 Information Storage and Data Warehousing

RDMB-NISAC does not have access to data on banking data centers and their locations. It is possible that there may be some direct impacts on banking data centers in the area. However, data warehousing best practices suggest that data centers would have backups in geographically distant locations. After the September 11th attacks, medium-to-large banks invested in geographically distant data backups. Smaller institutions are likely to contract with larger banking data service providers (e.g. FiServ) who can provide distributed data facilities to mitigate geographic/co-location risk.

5.3.10.4 Revenue, Monetary, Clearing, and Settlement Functions

Settlement, check clearing, and revenue collections are likely to become difficult in Alaska until undersea linkages are restored. Institutions may be able to perform these functions through transferring data physically by air. Major banks could also try to secure satellite data uplinks. The major factor in acquiring these links is not cost, but constrained availability and contractual agreements.

5.3.10.5 Financial Markets

Major undersea cables to Southeast Asia, which comprise half the capacity of all transpacific undersea cables, would likely be damaged in this scenario. This scenario could yield high congestion on the remaining transpacific lines, resulting in significant impacts to trading on major exchanges due to lack of real-time data. Overseas and U.S. investors may choose to temporarily divest in positions they hold internationally due to uncertainty in being able to access their accounts or liquidity. Foreign investments in financial markets may return after congestions decrease and people feel confident in their ability to access their assets.

5.3.11 Telecommunications

5.3.11.1 Voice and Data Communications

Telecommunications and Internet services are likely to be severely disrupted across the regions experiencing liquefaction due to damage to the facilities and the loss of communication cables connecting those facilities. Thus while some facilities may suffer only a brief disruption to equipment, access to communications services could be severely limited for many customers in the regions shown in Figure 5-64. Localized communications outside the damage region will likely remain unaffected.

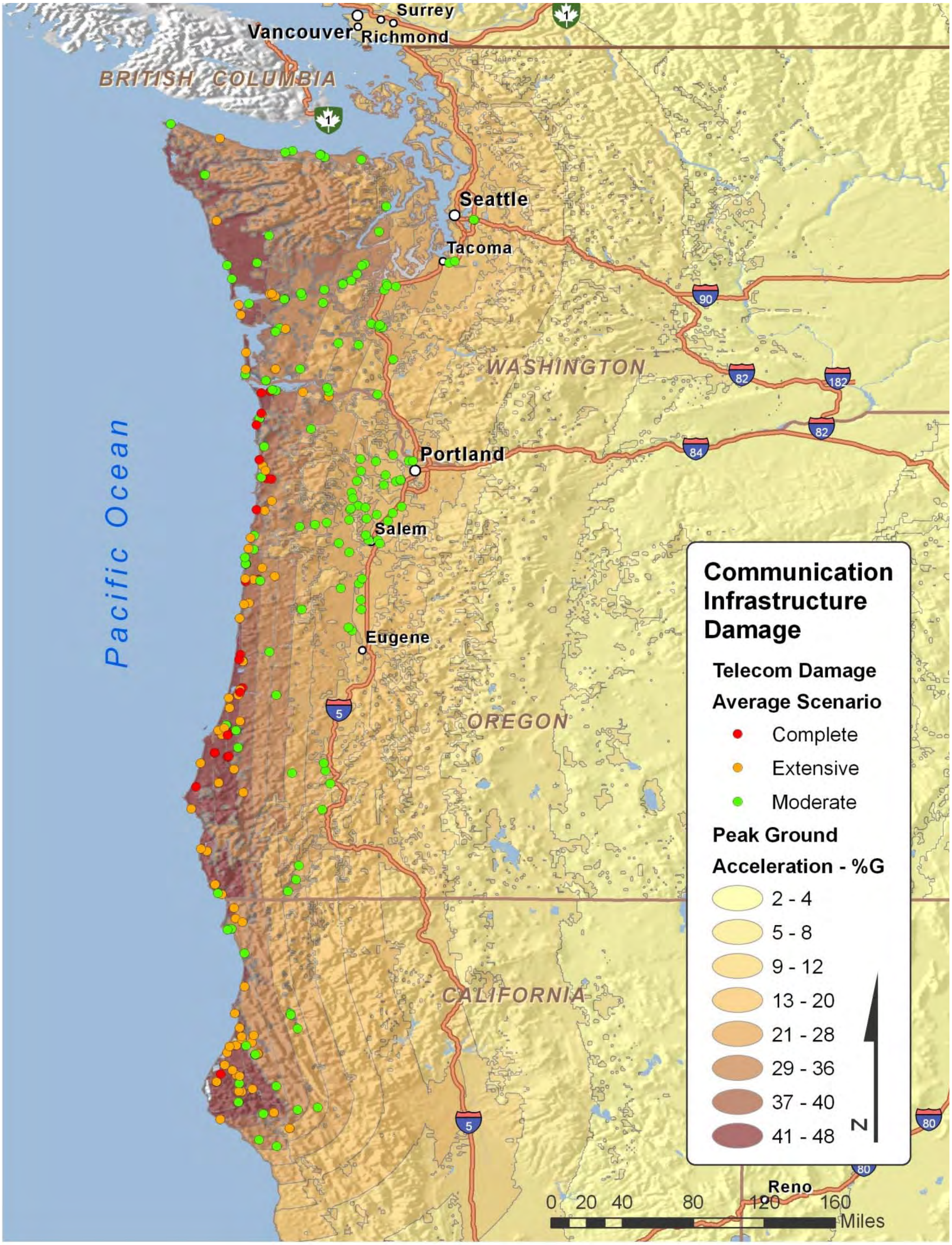

Figure 5-64. Wire centers potential for damage from liquefaction (50th-percentile case)

Undersea cables serving Alaska will likely be severed, causing severe communication disruptions between Alaska and the contiguous United States. The cables represent Alaska's primary communications links;[41] alternate routes using satellite and microwave communications exist, but bandwidth on those links is limited. Communication within Alaska will be unaffected and will continue to function.

Loss of several major transpacific undersea cables and regional long-haul fiber optic cables will likely cause disruption and severe delays in communication to and from East Asian countries. These delays and disruptions could cause regional and nationwide delays in Internet and long-distance communications as the network attempts to reroute around the affected area. Telecommunications service providers may have the option of routing some of the disrupted transpacific traffic to transatlantic cables; however that could spread the impact of the disruption if their networks across the lower United States are not capable of handling the additional traffic due to capacity constraints. This could have impacts on other infrastructures that rely on real-time or near real-time operation and timely large data transfers over transpacific networks.

The regions that will experience service disruption due to facilities and equipment failure include wire centers that serve over one million households. Those wire centers in liquefaction zones that may see cable breaks and potentially disrupted service serve an additional 1.7 million households. Due to potential breaks in the cables connecting these households to their corresponding wire centers and potential breaks in the interconnections between wire centers, the households are at risk of having no access to emergency services and telecommunications service. The largest wire center in Eugene, OR, EUGNOR53, will be completely damaged and the largest wire center serving Seattle, WA, STTLWA06, will suffer moderate damage and some service disruption.

For the 90th- percentile damage estimates, the number of directly affected households increases to 1.6 million with an additional 1.8 million potentially impacted by disruption to connecting cables. This is an increase of 700,000 potentially affected households.

Mobile switching centers (MSCs) providing cellular service in the liquefaction zones will also likely see breaks to fiber cables connecting those facilities to the network and connecting cellular base stations to their corresponding MSCs. Cellular service will see additional impacts in the earthquake region due to downed towers and mis-pointed antennas on towers. The number of cellular customers likely to be affected is unknown, due to an inability to link individuals or households to specific cellular towers or switching centers.

The number of damaged wire centers and MSCs and their associated damage levels are shown in Table 5-40, Table 5-41, and Figure 5-65. Damage to facilities uses the definitions shown in Table 5-42. Slightly damaged wire centers are likely to see an outage only if there is an associated power outage and backup power fails, and moderately damaged wire centers may see a brief outage due to some digital switch boards being dislodged or a loss of electric power and backup power. The 90th-percentile damage case increases the number of wire centers and households affected.

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[41] http://www.corp.att.com/alaska/about/profile.html , accessed September 2011.

Table 5-40. Damage states for wireline wire centers for both 50th- and 90th-percentile damage case

Damage State	Wireline Wire Center	
	50th-percentile	90th-percentile
None	316	228
Slight	78	56
Moderate	82	106
Severe	18	47
Complete	164	221

Table 5-41. Damage states for mobile switching centers for both 50th- and 90th-percentile damage case

Damage State	Mobile Switching Center	
	50th-percentile	90th-percentile
None	42	28
Slight	17	7
Moderate	26	26
Severe	6	15
Complete	35	50

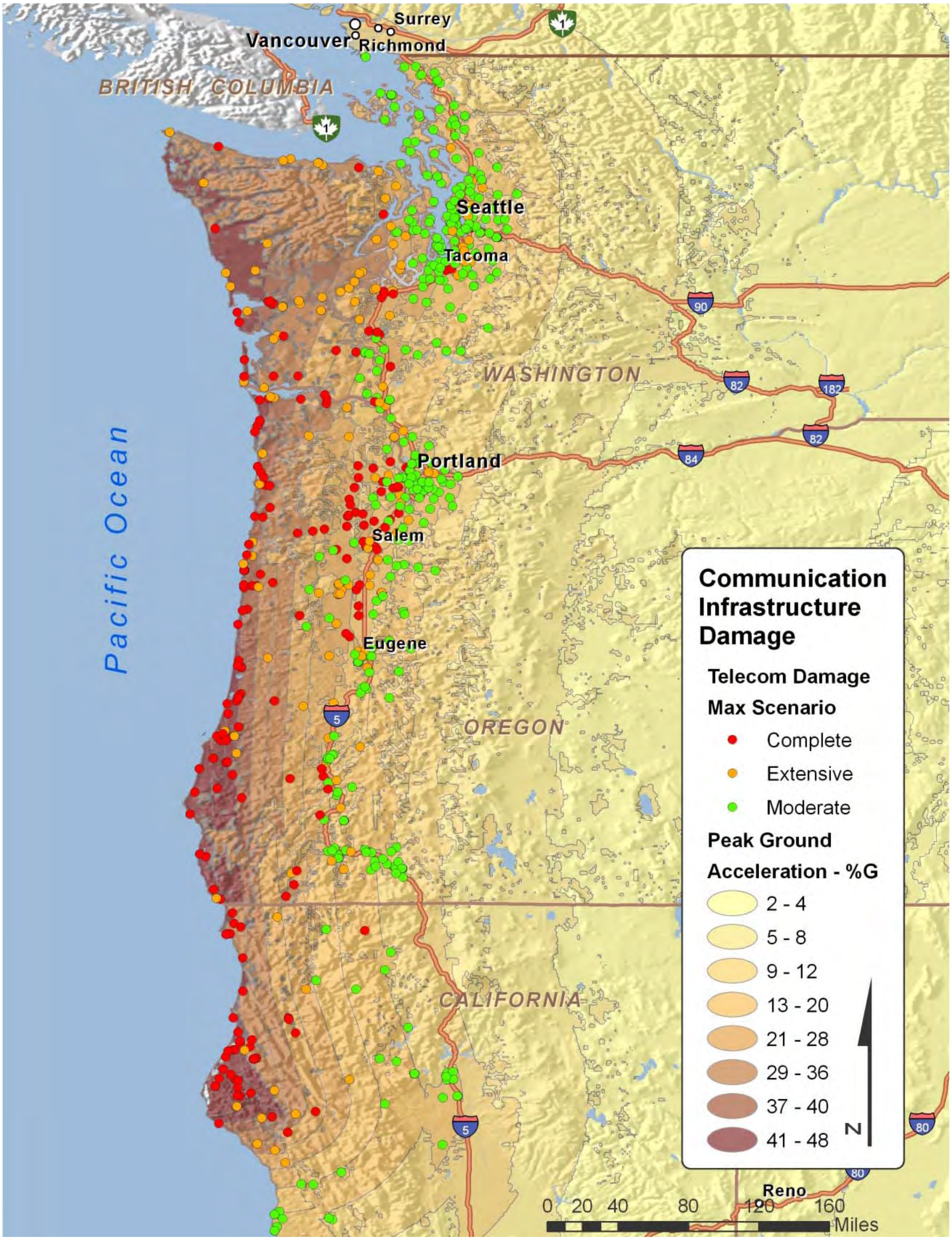

Figure 5-65. Wire centers potential for damage from liquefaction 90th-percentile case

Table 5-42. Damage states and descriptions for wire center buildings

Damage State	Damage Description
None	No damage to components
Slight	Defined by slight damage to the communication facility building or inability of the center to provide services during a short period (few days) due to loss of electric power and backup power, if available
Moderate	Defined by moderate damage to the communication facility building, few digital switching boards being dislodged, or the central office being out of service for a few days due to loss of electric power (i.e., power failure) and backup power (typically due to overload), if available
Severe	Defined by severe damage to the communication facility building resulting in limited access to facility or by many digital switching boards being dislodged, resulting in malfunction
Complete	Defined by complete damage to the communication facility building or damage beyond repair to digital switching boards

Wire centers and wireless equipment would continue to operate after any power outage using battery or backup generation. The percentage of backup generators that fail would likely be less than that expected for many other industry groups due to frequent testing and rigorous maintenance by most telecommunications companies. Initial failure in the network from loss of power would be primarily to individual customers who have phone systems that rely on electric power, such as VoIP or even wireline cordless handsets.

Figure 5-66 shows the long-haul fiber optic cables and submarine cable landings relative to the damage region. Long-haul cables typically run along roadways, railways, and bridges. So despite a cable appearing to lie just outside the earthquake damage region, it likely will be damaged because many of the rail lines and roadways and associated bridges will also be damaged. The cables most likely to incur damage lie within the red to yellow regions of the figure.

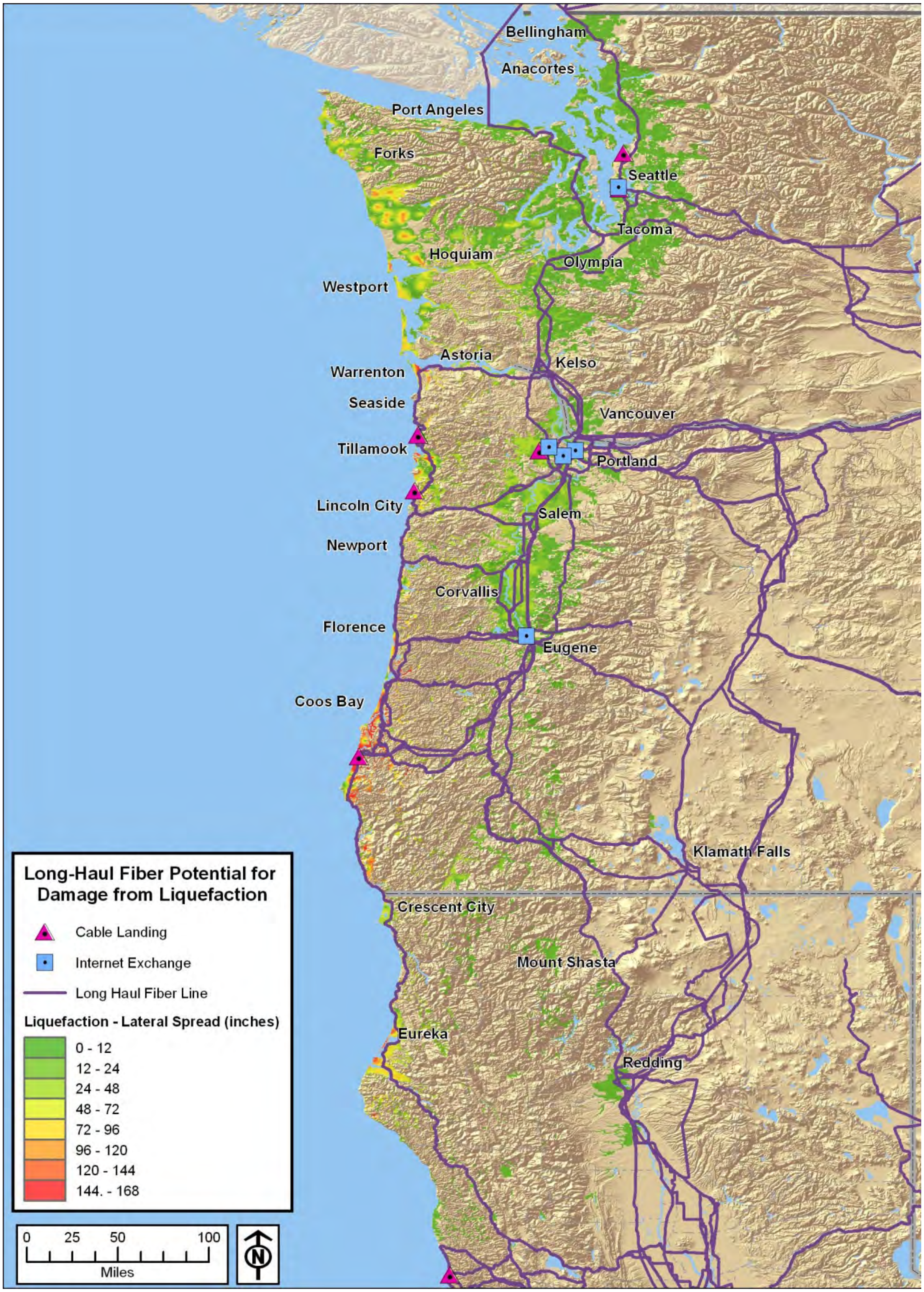

Figure 5-66. Long-haul fiber and submarine cable landing potential for damage from liquefaction

The damage to long-haul fiber optic cables could cause regional and nationwide delays in Internet and long-distance operation as the network attempts to reroute around the affected area. This could have impacts on other infrastructures that rely on real-time or near real-time operation over those networks. Localized communications outside the region will likely remain unaffected. If the region remains inaccessible for a long time after the earthquake, it is likely that domestic providers will upgrade capacity of the links that run around the region to restore normal service levels to other regions of the country.

Transpacific cables that traverse the offshore regions of the earthquake are likely to be severed due to underwater landslides and shifting of the ocean floor. If these cables are severed, restoration is likely to take two to three months depending on the number of cables disrupted, the number of segments of cable disrupted, the availability of cable ships to perform the repairs, and the difficulty of locating the damaged cables along the seafloor. These estimates are based in part on the December 2006, 6.7-magnitude earthquake that started an underwater landslide in the Luzon Strait off the southwest coast of Taiwan. This earthquake caused 21 faults in 9 out of 11 undersea cables in the area.[42] These faults required 11 cable ships (40 percent of the global fleet) and seven weeks to repair. The incident caused major disruptions in Taiwan, including a 60-percent loss of calling capacity to the U.S., 98-percent loss of communications to nearby East Asian countries, and serious impairment of Internet access to other Asian countries.

There are nine cable systems at risk (Table 5-43 and

Table 5-44), including cables that provide primary communication connections between Alaska and the contiguous United States. While alternate routes for communication to and from Alaska using satellite and microwave communications exist, bandwidth on those links is limited and there will likely be severe service disruptions. Communication within Alaska will be unaffected and will continue to function.

Table 5-43. Transpacific cable systems at risk

Cable Name	U.S. Landing	Capacity (Gbps)
China-US Cable	San Luis Obispo, CA	160
	Bandon, OR	
Pacific Crossing 1	Grover Beach, CA	1,060
	Harbour Pointe, WA	
Southern Cross	Nedonna Beach, OR	860
	Morro Bay, CA	
TPC-5	Bandon, OR	40
	San Luis Obispo, CA	
Tata TGN-Pacific	Hillsboro, OR	3,140
	Los Angeles, CA	
Trans Pacific Express	Nedonna Beach, OR	1,280

[42] www.kddi.com/english/corporate/news_release/2007/0213a/index.html, accessed September 2011.

Table 5-44. Alaska submarine cable systems

Cable Name	Landings	Capacity (Gbps)
Alaska-Oregon Network (AKORN)	Homer, AK	40
	Florence, OR	
Alaska United-AUFS	Juneau, AK	20
	Lynnwood, WA, Warrenton, OR	
Northstar	Juneau, AK	20

The two largest capacity transpacific cable systems, Tata TGN-Pacific and Trans Pacific Express, will likely see complete service disruption, because their transpacific routes travel directly through the fault zone. The remaining cable systems will see disruption on their northern transpacific routes, but the southern routes will remain functional, allowing rerouting of some traffic up to the capacity limits of the southern transpacific routes. Telecommunications service providers may have the option of routing some of the disrupted transpacific traffic to transatlantic cables; however that could spread the impact of the disruption if their networks across the contiguous United States are not capable of handling the additional traffic due to capacity constraints. Damage to undersea cables could cause regional and nationwide delays in Internet and long-distance operation as the network attempts to reroute around the affected area. This rerouting could have impacts on other infrastructure that rely on real-time or near real-time operation over those networks. Localized communications outside the damage region will likely remain unaffected.

5.3.11.2 Broadcast Communications

Broadcast services, which include AM/FM radio and television, are a part of the EAS. The EAS is a national public warning system that can be used by state and local authorities to deliver emergency information to specific regions. Broadcasters, cable television systems, wireless cable systems, satellite digital audio radio service (SDARS) providers, and direct broadcast satellite (DBS) providers are required to provide this communications capability.[43]

The EAS will be severely limited in its ability to reach people in the affected area due to power outages, misdirected antennas, and cable breaks. Many broadcast facilities along the coast will be severely damaged and unable to provide service. For facilities that are minimally damaged, the antennas required to relay and broadcast the signal will likely be mis-pointed or downed, further disrupting the ability to provide service. Due to line-of-sight limitations from the coastal mountain range, television and FM broadcast from undamaged areas further inland will likely be unable to reach the damage region. AM radio has a longer broadcast range, so it may be used to disseminate information into the damaged region to people with power or those who are attempting to listen in vehicles.

[43] transition.fcc.gov/pshs/services/eas/, accesses September 2011.

Figure 5-67 and Figure 5-68 show television and AM/FM radio broadcast facilities in relation to the 50th-percentile damage scenario. In the 90th-percentile scenario, inland populations may also be affected and unable to receive EAS messages.

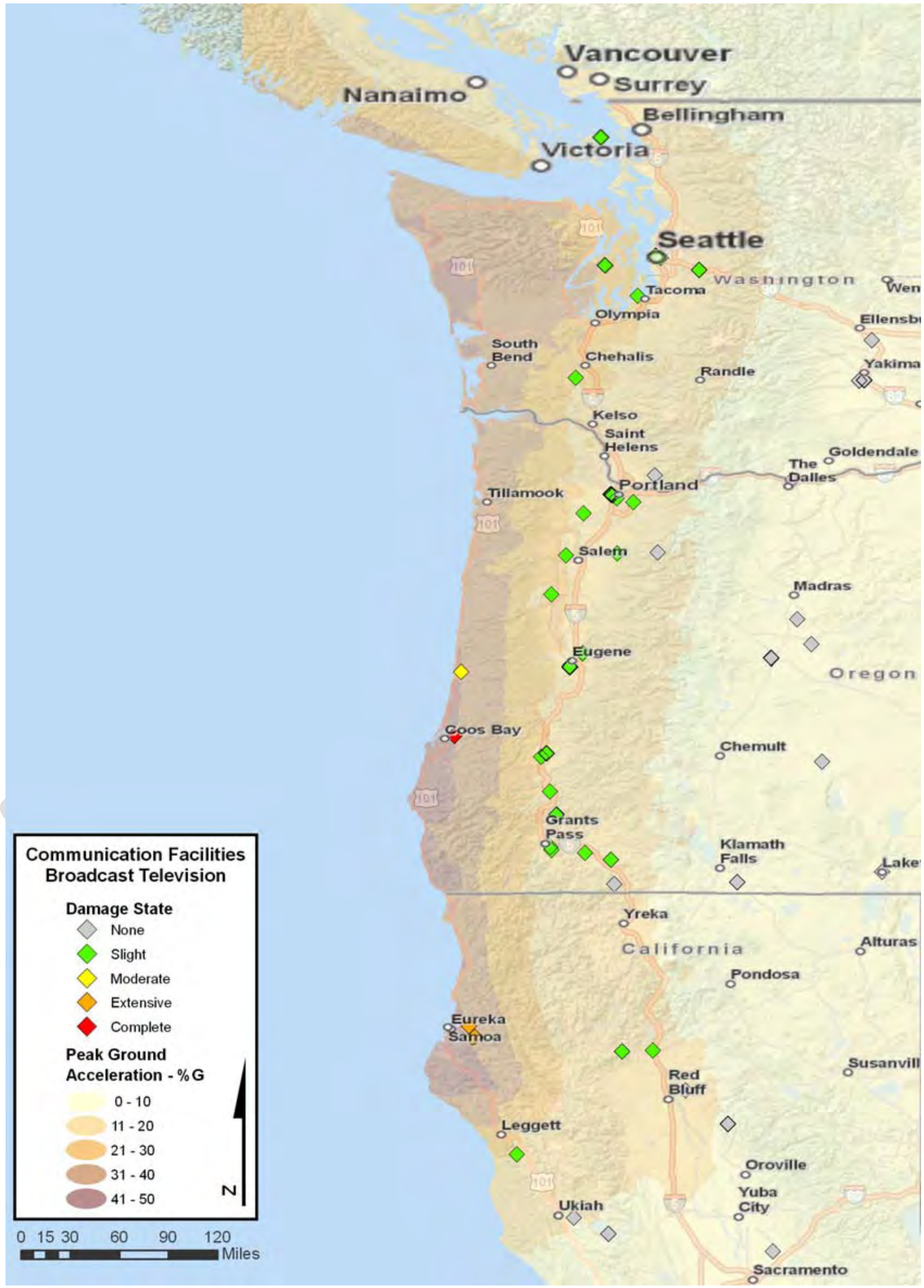

Figure 5-67. Broadcast television facilities (50th-percentile case)

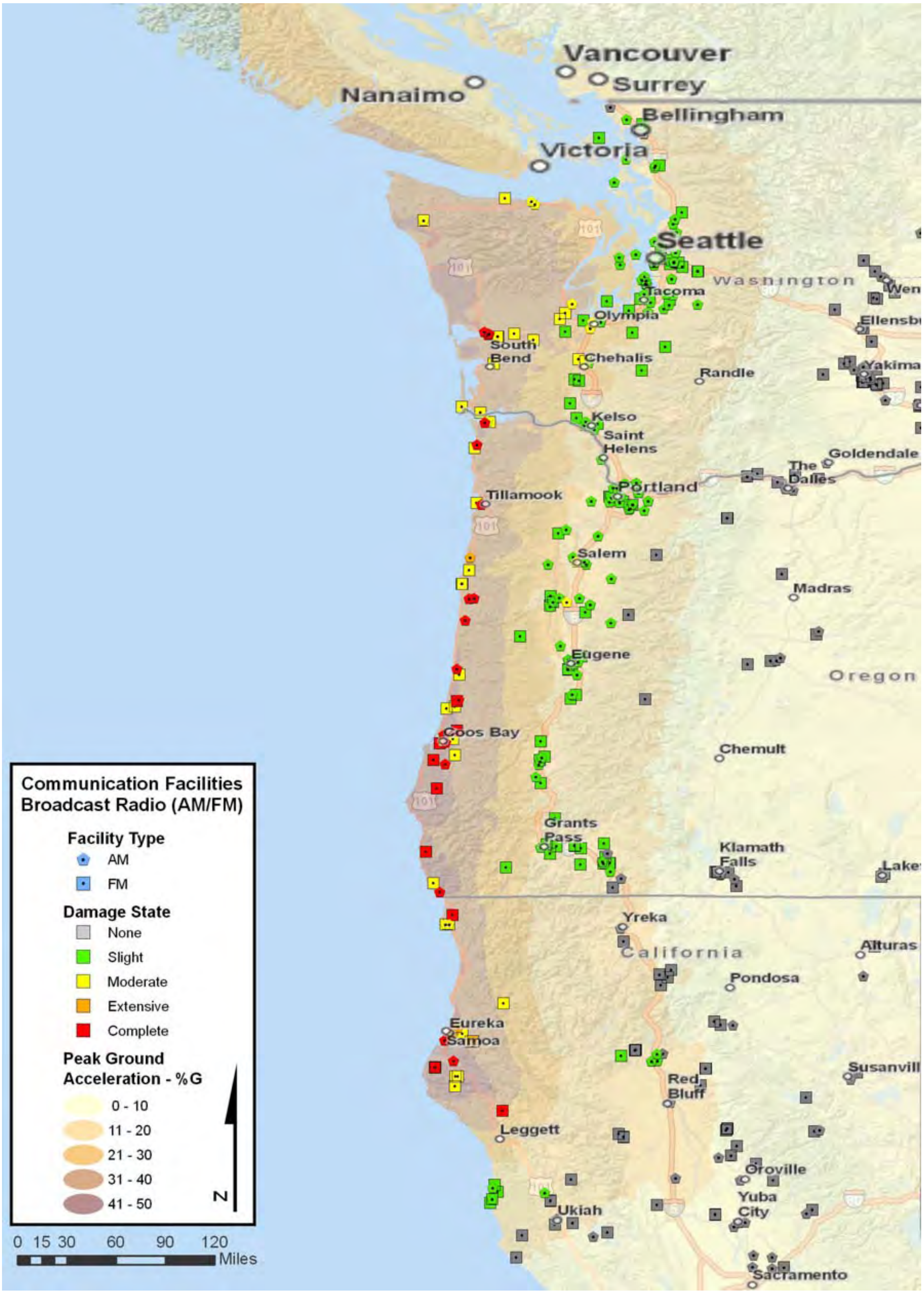

Figure 5-68. Damage to broadcast radio (AM/FM) facilities (50th-percentile case)

5.3.12 Chemical

There should be no direct impacts on the chemical sector due to the tsunami inundation. There are no facilities located within the area projected to flood. The inundation area tends to be on or very near the Pacific coast, which is not a common location for chemical manufacturing facilities.

In the 50^{th}-percentile damage case, there are 42 chemical manufacturing facilities that are expected to receive complete damage from the earthquake, with 2 receiving severe damage and 10 receiving moderate damage; see Figure 5-69. In the 90^{th}-percentile damage case, 50, 17, and 19 facilities will be completely, severely, and moderately damaged, respectively. The 54 facilities that are expected to receive complete, severe, and moderate damage in the expected case, along with their location and the chemicals they produce, are shown below in Table 5-45, Table 5-46, and Table 5-47, respectively. In almost all cases there are many domestic producers of the chemicals shown in Table 5-45, Table 5-46, and Table 5-47 and as such, national level affects and supply chain impacts are not expected. The potential exceptions are discussed in the following sections.

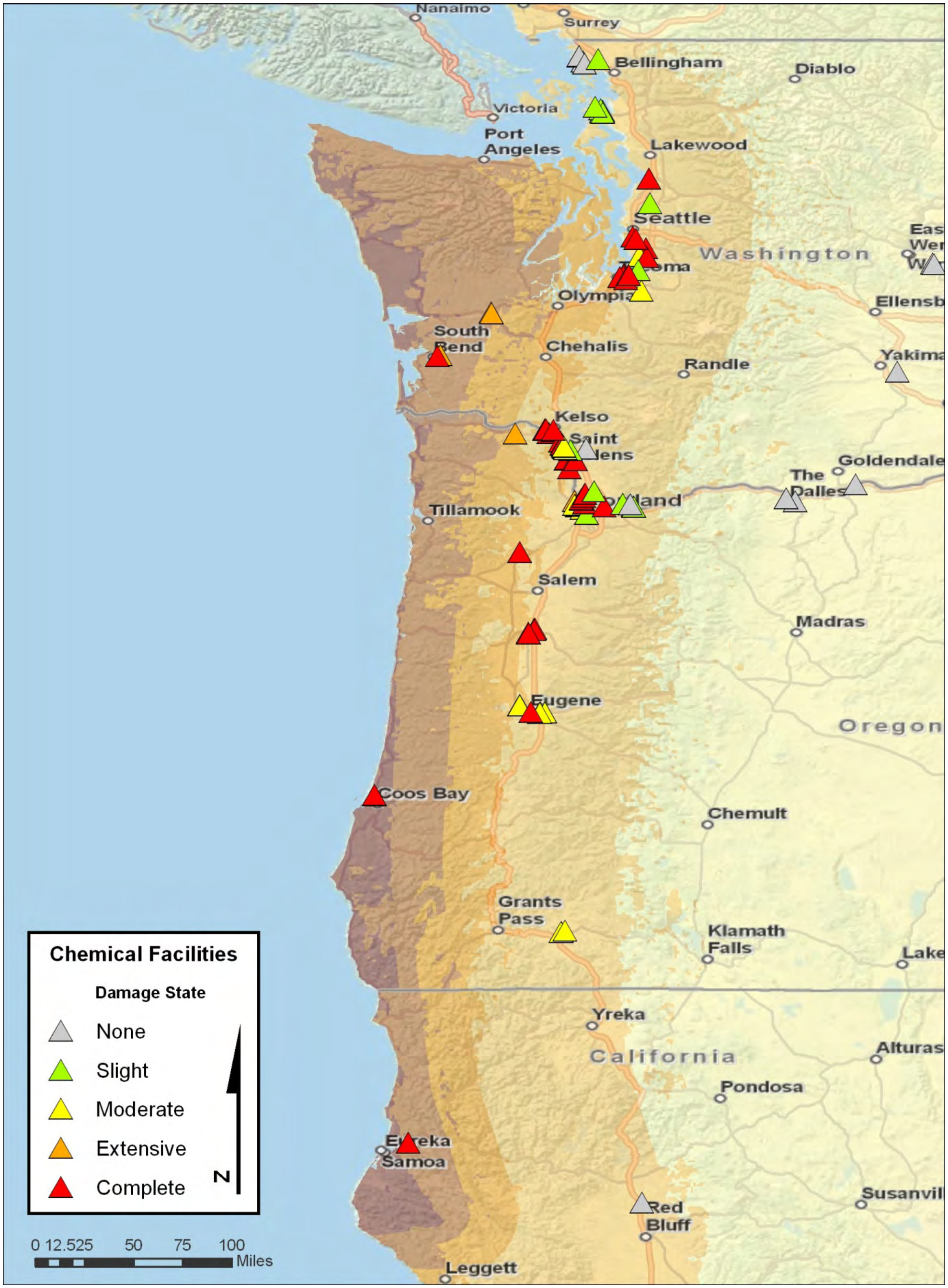

Figure 5-69. Damage to chemical facilities in a 50th-percentile scenario

Table 5-45. Chemical facilities expecting complete damage in a 50th-percentile scenario

Company Name	City	State	Chemicals Produced
Air Liquide America L.P.	McMinnville	OR	argon, nitrogen, oxygen,
Air Liquide America L.P.	Portland	OR	acetylene
Air Liquide America L.P.	Kent	WA	argon, nitrogen, oxygen,
Air Liquide America L.P.	Kalama	WA	argon, nitrogen, oxygen, hydrogen, ultra high purity liquid oxygen
Arclin	Portland	OR	PF resins, resin-impregnated paper
ATI Wah Chang	Albany	OR	zirconium, vanadium, hafnium, titanium, niobium compounds
BOC Group, Inc. (Linde Group)	Seattle	WA	argon, nitrogen, oxygen,
Calgon Carbon Corporation	Blue Lake	CA	(re)actived carbon
Chemtrade Logistics Inc.	Kalama	WA	bleaching chemicals, zinc oxide, sodium hydrosulfite
Columbia River Carbonates	Woodland	WA	calcium carbonate
Dyno Nobel Inc.	St. Helens	OR	ammonia, ammonium nitrate
Emerald Performance Materials, LLC	Kalama	WA	benzoic acid and benzene-related chems
Equa-Chlor LLC	Longview	WA	sodium hydroxide
General Chemical Corporation	Vancouver	WA	aluminum sulfate
Georgia-Pacific Chemicals LLC	Albany	OR	formaldehyde, UF, PH
Georgia-Pacific Resins	Eugene	OR	PH, UF, polyamide resins
Graymont Western US, Inc.	St. Helens	OR	calcium carbonate
Graymont Western US, Inc.	Tacoma	WA	calcium oxide
Hasa Chemicals, Inc.	Longview	WA	sodium hypochlorite
Hercules Incorporated	Portland	OR	defoaming compounds, polyamide, UF resins
Huber Engineered Materials	Longview	WA	silica
Huber Engineered Materials	Seattle	WA	silica
JCI Jones Chemicals, Inc.	Tacoma	WA	sodium hypochlorite
Kemira Water Solutions, Inc.	Kalama	WA	sodium aluminate, polyaluminum chloride

Company Name	City	State	Chemicals Produced
Kemira Water Solutions, Inc.	Longview	WA	polyacrylamide, water treating chemicals
Kimberly-Clark Corporation	Everett	WA	ammonium bisulfite
Koppers, Inc.	Portland	OR	pitch of tar
Koppers, Inc.	Longview	WA	pitch of tar
Lacamas Laboratories	Portland	OR	pharmaceutical intermediates, fine chemicals outside pharma
Nalco Company	Vancouver	WA	papermaking chemicals
Noveon, Inc.	Kalama	WA	specialty chemicals
Olin Corporation	Tacoma	WA	sodium hypochloride
Olympic Chemical Corporation	Tacoma	WA	sodium bisulfite, sodium sulfite
PQ Corporation	Tacoma	WA	catalysts
Praxair, Inc.	Fife	WA	argon, nitrogen, oxygen,
Rhodia Inc.	Portland	OR	aluminum sulfate
Solvay Chemicals Inc.	Longview	WA	hydrogen
Specialty Minerals Inc.	Longview	WA	calcium carbonate
Synthetech, Inc.	Albany	OR	specialty chemicals
Valspar Corporation	Seattle	WA	paints, sealants, coatings
Vanson Halosource, Inc.	Raymond	WA	chitosan, chitin
Weyerhaeuser Company	North Bend	OR	sodium sulfate

Table 5-46. Chemical facilities expecting severe damage in a 50th-percentile scenario

Company Name	City	State	Chemicals Produced
Momentive (Hexion Specialty Chemicals)	Portland	OR	polyvinyl acetate adhesives
Rohm and Haas Company	Elma	WA	hydrogen, potassium borohydride, trimethyl borate, sodium borohydride, sodium hydride

Table 5-47. Chemical facilities expecting moderate damage in a 50th-percentile scenario

Company Name	City	State	Chemicals Produced
Air Products and Chemicals, Inc.	Puyallup	WA	oxygen, nitrogen, argon
Arch Wood Protection, Inc.	Kalama	WA	copper azole wood preservative
Arclin	Springfield	OR	formaldehyde, MUF, MF, UF, PF, resorcinol-formaldehyde resins, aerospace phenolic resins, acetone-formaldehyde resins
General Chemical Corporation	Anacortes	WA	sulfuric acid
Georgia-Pacific Chemicals LLC	White City	OR	UF, PF, polyamide resins, epichlorohydrin based,
Georgia-Pacific Resins, Inc.	Springfield	OR	polyamide resins, epichlorohydrin based
Momentive (Hexion Specialty Chemicals)	Springfield	OR	MF, PF, UF, formaldehyde
Koppers, Inc.	Portland	OR	pitch of tar
Shell Oil Products US	Anacortes	WA	nonene, sulfur, propylene
Tesoro Petroleum Corporation	Anacortes	WA	sulfur

5.3.12.1 Bulk Chemicals

There are several producers of urea-formaldehyde (UF), melamine-formaldehyde (MF), and phenol-formaldehyde (PF) resins that are expected to receive moderate or greater damage. Approximately 25 percent of national capacity of UF resins and 10 percent of MF resins are produced by these facilities. While it is more difficult to estimate the national PF resins contribution of the impacted plants, it is not expected to be more than 20 percent. However, no more than 10 percent of domestic production capacity of any of the resins is in the complete damage zone.

UF resins are used predominately in the manufacturing of particleboard and fiberboard; MF resins are used in laminates, surface coatings, and wood adhesives; and PF resins are used predominately in granulated wood and plywood. Recent domestic production of UF resins, MF resins, and PF resins has been only about 70 percent, 50 percent, and 55 percent of domestic production capacity, respectively. In the event of more substantial damage and/or a longer plant shutdown, the potential loss of UF, MF, and PF resins manufacturing at impacted facilities could likely be made up at other domestic production facilities. However, because these resins have high water content, a disruption in local production could result in higher total costs due to an increase in shipping costs.

The Rohm and Haas facility in Elma, WA, is expected to receive severe damage in the expected scenario; it would be completely damaged in a worst-case scenario. This facility is one of what is believed to be a small number of domestic producers of sodium borohydride and potassium borohydride. The production capacity of this facility, or of any of the other domestic producers, is not explicitly known. Sodium borohydride is used in the removal of trace metal impurities during the manufacturing of bulk organic chemicals like alcohols, esters, and amines, and in effluent treatment systems. Potassium borohydride is used in the pharmaceutical industry in the purification of drugs. A portion of the potassium borohydride consumed domestically is imported, but the ability of imports to make up lost production is unknown. Damage to this facility (resulting in a long-term shutdown) could have national impacts on the pharmaceutical and bulk organic chemical manufacturing areas, and potentially other chemical manufacturing areas as well.

The Shell Oil Products facility in Anacortes, WA, is expected to receive moderate damage and would be completely damaged in a worst-case scenario. It represents about 15 percent of the national capacity for the production of nonene, a chemical used ultimately in the production of polyvinyl chloride (PVC; construction materials) and various surfactants. If significantly impacted, a large portion of lost nonene production could be made up through underutilized domestic production capacity. This facility also produces a small amount of propylene, less than one percent of national capacity, and should not have any national impact. Finally, Shell and several other oil refineries also produce elemental sulfur, but in total represent only approximately two percent of the national capacity of elemental sulfur. The loss of this domestic capacity will not have significant impacts nationally.

5.3.12.2 Specialty Chemicals

ATI Wah Chang in Albany, OR, which produces a variety of zirconium, hafnium, niobium, tantalum, titanium, and vanadium metal products, is expected to be completely damaged. Although they are not believed to be the sole producer of any of their products, there are only a few domestic producers. However, the relative production capacities of the various producers are not known. Increased prices and reduced availability of products containing these metals is possible if this production facility were to be lost for any significant period of time.

Lacamas Laboratories in Portland, OR, which produces six chemicals used as intermediates in the pharmaceutical industry, is expected to suffer complete damage. Although it is not believed to be the sole producer of any of these chemicals, production capacities are not known and the loss of this production facility could have supply chain impacts. In addition, Synthetech, Inc. in Albany, OR, produces a large number (hundreds) of pharmaceutical precursors and is also expected to be completely damaged. It is not known if there are other domestic producers of these chemicals, although it is highly likely Synthetech is the sole producer of a significant number of them. RDMB-NISAC has no information indicating that these chemicals are used in the production of currently available pharmaceuticals (beyond trials), and as such there is no indication of significant supply chain impacts. However, due to the large number and highly specialized nature of many of the chemicals produced, significant supply chain impacts are a possibility.

5.3.12.3 Industrial Gases

Several air separation facilities, which produce oxygen, argon, and nitrogen, are expected to receive moderate to complete damage. There are approximately 200 domestic air separation facilities in the affected zone, making it a regional market. Consequently, there could be some regional impact on the availability of these gases if all facilities were forced to cease operation, but no national impacts are expected; however, the regional impact could be significant. Large consumers are often supplied by pipeline; damage to the pipeline would most likely increase down times. Increased costs due to further shipping distances would also be expected. Nitrogen shortages could delay the restart of other chemical manufacturing facilities that require the compressed gas to clean pipes prior to restart.

5.3.12.4 Facilities Expecting Slight Damage

An additional 13 facilities are expected to experience slight damage. In most cases the quantities of chemicals produced at these facilities is not known. Even though quantities are not known, it is not believed that any one facility represents a significant share of any bulk chemical produced nationally. Slight damage may result in temporary (approximately two weeks) shutdowns. Existing inventories may be able to cover some or all of the lost production.

5.3.12.5 Cascading Impacts

The large number of facilities expecting complete damage will limit the indirect impact on the chemical industry because so many facilities will be recovering from the direct impact of the earthquake. The vast majority of cascading impacts are associated with the transportation infrastructures that link chemical facilities. In cases where both the chemical facility and its supporting transportation systems are extensively damaged, the time needed to repair the infrastructures will most likely be similar. Furthermore, the restoration of electric power should precede both the opening of transportation systems and chemical facilities with moderate or greater damage. Those facilities with slight or no damage may experience slight delays in operation due to the loss of EP, but impacts will be very minor.

Most chemical facilities are located on rail lines; a smaller but significant number are along waterways. Consequently, normal operation of these chemical facilities is dependent on the use of these transportation networks to receive materials and ship products. As discussed in the rail transportation section, the expected loss of several key rail bridges near Olympia, WA, the main railway bridge crossing the Columbia River north of Portland, and track damage along Oregon's I-5 corridor will most likely cause rail traffic to cease for several months. The loss of these bridges and other rail segments may result in significant delays and increased costs in the Northwest. Some shipments will be routed around damaged bridges, which take longer to replace, but would again result in delays and increased costs. Some facilities may be isolated from rail until all repairs are complete. Depending on the damage to the facility, this could result in its closure at that location. However, the market in this area of the country is largely regional, limiting the national-level supply chain impacts.

The loss of intermodal and port facilities will also impact the facilities that utilize them. These facilities are largely located around Portland, OR, and Seattle, WA, as discussed in the Ports and Maritime section. The losses of these ports will temporarily impact regional manufacturing, but the disruption should not be longer than the duration required for the restoration of other supporting infrastructure. Chemicals are not the top commodities that traverse these ports; however these ports play a significant role for certain chemicals. From a national perspective, Portland, OR, receives the fifth-largest amount of urea of any U.S. port and exports a significant amount of potash. Urea is used both agriculturally and in the manufacturing of resins and coatings used by the wood-based industries in the Northwest. The vast majority of potash is used as a fertilizer and is the most common source of potassium used agriculturally. Canpotex is the world's largest exported of potash and represents about one-third of global capacity. The majority of its exports travel through ports in Vancouver, British Columbia, and Portland, OR. The inability to ship potash could have worldwide impacts.

The high cost associated with transporting resins could result in significantly higher prices and/or shortages in the Northwest. Higher prices would subsequently be passed along to the construction and manufacturing industries. Specialty chemical and other small-volume manufacturers also rely on road transportation. As shown in the Transportation section, the greatest probability of damage and transportation delays will be between Eugene and Portland in Oregon and between Seattle and Tacoma in Washington. Similar to rail, this damage may result in delays and increased costs, but should be relatively minor as there are many more re-routing options with road than rail.

5.3.13 Healthcare and Public Health

5.3.13.1 Ground Shaking Effects

The public health system is comprised of doctors' offices, public health offices, clinics, special care facilities, long-term care facilities, and hospitals. For this analysis, the focus is on earthquake-induced damage to hospital facilities. Damages are computed using Hazus, resulting in a probability distribution on damage states. In Table 5-48, the number of hospitals assigned to the damage categories are listed for both the 50th-percentile damage case and the 90th-percentile case, as well as the number of regular and critical hospital beds lost due to damage to the facility. It is assumed that a hospital with extensive damage is no longer capable of functioning. However, less severe damage would allow some degree of facility operation.

Table 5-48. Damage states for hospital assets, giving both expected damage and 90th-percentile damage states and estimated regular/critical beds lost due to damage

Damage State	Hospitals		Regular Beds Lost*		Critical Beds Lost*	
	50th-percentile	90th-percentile	50th-percentile	90th-percentile	Average	90th-percentile
California						
Moderate	0	4	0	244	0	41
Extensive	1	0	49	0	6	0
Complete	0	6	0	72	0	10
Oregon						
Moderate	10	25	690	2,271	107	465
Extensive	10	2	260	195	40	24
Complete	1	9	15	971	4	139
Washington						

Damage State	Hospitals		Regular Beds Lost*		Critical Beds Lost*	
	50th-percentile	90th-percentile	50th-percentile	90th-percentile	Average	90th-percentile
Extensive	3	3	200	140	10	16
Complete	0	7	0	330	0	39
Total						
Moderate	14	34	809	3,143	132	597
Extensive	14	5	509	335	56	40
Complete	1	22	15	1,373	4	188

Figure 5-70 and Figure 5-71 show the locations of hospitals based on the 50th-percentile and 90th-percentile damage cases, respectively.

Figure 5-70. Hospitals located within the Cascadia region with expected damage states ranging from Moderate to Complete in the 50th-percentile damage case

Figure 5-71. Hospitals located within the Cascadia region with 90th-percentile earthquake-induced damage states ranging from Moderate to Complete

Figure 5-72 and Figure 5-73 show the locations of urgent care and blood/organ bank facilities based on the 50th-percentile and 90th-percentile damage cases, respectively.

Figure 5-72. Urgent care and blood/organ bank facilities located within the Cascadia region with expected damage states ranging from Moderate to Complete in the 50th-percentile damage case

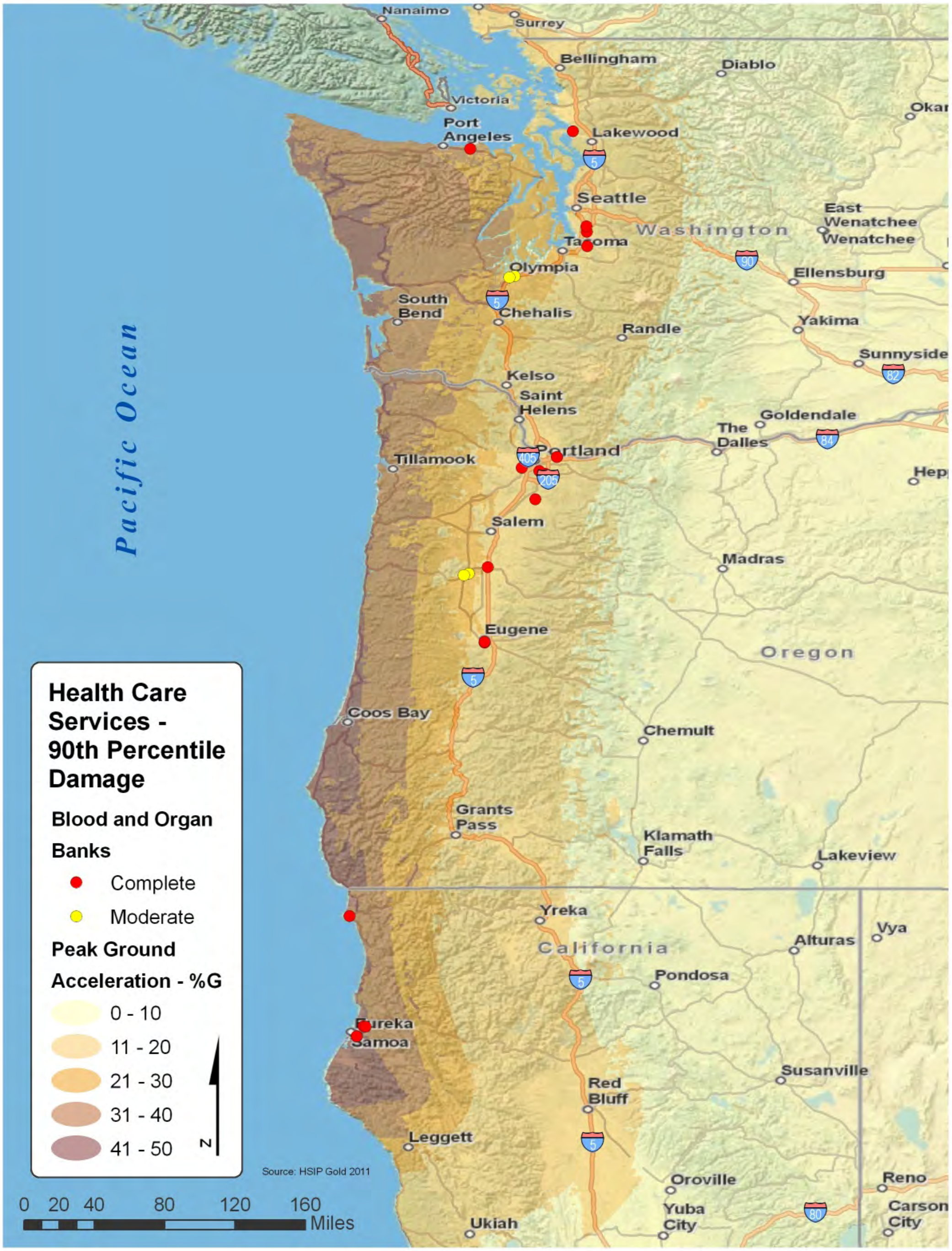

Figure 5-73. Urgent care and blood/organ bank facilities located within the Cascadia region with 90th-percentile earthquake-induced damage states ranging from Moderate to Complete

5.3.13.2 Hospital Impacts

RDMB-NISAC used its hospital impact model to analyze the potential impacts on hospitals in the Cascadia scenario study area. Figure 5-74 shows the basic workflow for the hospital impacts analysis. Fatalities and injuries are computed by Hazus 2.0 and by the RDMB-NISAC tsunami model. Damage to hospitals is computed by Hazus 2.0 as a probability distribution over the damage states: None, Slight, Moderate, Severe (Extensive), and Complete. First, the hospital damage data is refined to two cases: the 50th-percentile damage case and the 90th- percentile damage case. For each case, those hospitals with Severe (Extensive) or Complete damage states are deemed to be no longer operational, thus reducing the regional hospital bed capacity. This information is combined with data from the American Hospital Association (AHA), which specifies capacities and typical occupancies for individual hospitals in the United States.

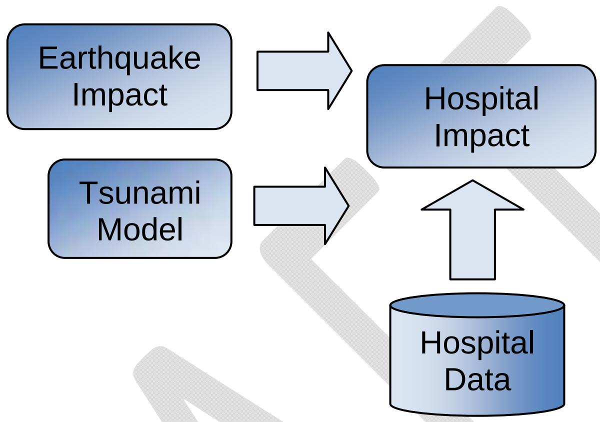

Figure 5-74. Workflow for the hospital impact model

5.3.13.2.1 Hospital Impact Model

The hospital impact model is a simulation to assess how well the regional hospital system responds to a mass casualty event. The model represents the operational hospitals, their capacity (beds and critical care beds), their average occupancy, and location. In general, only general medical and surgical hospitals or children's general medical and surgical hospitals are represented. Other types of hospitals exist, i.e., mental health care, alcoholism treatment, and so on, but these facilities are typically unable to respond with treatment for trauma patients. The model also represents patients, their treatment, length of hospital stay, and final disposition (death or recovery). In the model, hospitals give priority to admitting severely injured patients over moderately injured. The data for populating the hospital model comes from the 2008 AHA Annual Survey.[44] Lastly, the model includes an emergency medical service (EMS) system that delivers patients to the nearest hospital that has the capacity to admit. The EMS model may search up to a maximum distance from the location of the patient. For this study, that distance was set to 250 miles (about 400 km) or about the distance that a vehicle with an average speed of 55 mph (about 90 km/hr) can travel in about four-and-a-half hours.

5.3.13.2.2 Injury Characterization

There are two sources of traumatic injury for this type of event: earthquake and tsunami. Hazus assigns four levels of severity to earthquake casualties. Severity 4 is immediate death and

[44] American Hospital Association, AHA Annual Survey 2008 Database, www.ahadata.com.

Severity 1 is mild. NISAC-RDMB assumes that Severity 1 injuries can be treated locally and do not require any hospitalizations. Severity 2 is moderate and Severity 3 is severe; both require hospitalization. In the hospital impact model, moderate and severe injuries are interpreted in terms of the Injury Severity Score (ISS).[45] This permits the degree of injury to be associated with a fatality rate and a length of hospital stay based on National Trauma Data Bank (NTDB) data.[46] Table 5-49 shows match up of injury severity to ISS that is used in this study. Note that different treatments of trauma result in different fatality rates. Importantly for this study, non-treatment results in much higher fatality rates. If the hospital system becomes overwhelmed with trauma injuries, some patients will have either delayed treatment or no treatment. Both conditions will result in higher loss of life.

Table 5-49. Input injury severity and associated health outcome parameters

Severity	Injury Severity Score Range	Treatment	Fatality Rate (%)	Average Hospital Stay
Moderate	16–24	None	12	--
Moderate	16-24	Inpatient	7	5 days
Severe	>24	None	90	--
Severe	>24	Inpatient	60	5 days
Severe	>24	ICU	30	7 days

The tsunami model calculated injuries attributed to the tsunami; however, that model only produces projections of total injuries and deaths. Analysts used a two-step process to translate these figures to numbers of moderately and severely injured patients.

Based on a study of the 2004 Indian Ocean tsunami,[47] RDMB-NISAC estimates that about 80 percent of deaths estimated in the tsunami injury model would be immediate. The remaining deaths occur about a week later. Therefore, RDMB-NISAC assumed 20 percent of the estimated tsunami deaths would be delayed deaths from injuries suffered in the tsunami and added them to the number of injured.

5.3.13.2.3 Hospital Damage Characterization

As previously described, the hospital impact model marks hospitals with extensive and complete damage states by Hazus as inoperable. Hospitals with these damage states are modeled as evacuating their patients, who are subsequently added to the pool of injured patients waiting to be admitted to a hospital.

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[45] S.P. Baker et al., "The Injury Severity Score: A Method for Describing Patients with Multiple Injuries and Evaluating Emergency Care," *J. Trauma*, 14(1974), p. 187.

[46] National Trauma Data Bank, www.facs.org/trauma/ntdb/index.html, accessed 08/31/2011.

[47] Nishikiori, et al, "Who Died as a Result of the Tsunami?," *BMC Public Health*, 6(2006), www.biomedcentral.com/1471-245816/73.

In the tsunami damage model, hospitals are declared non-operational if the inundation depth at the site location is three feet or more. No hospitals in this study met this criterion.

5.3.13.3 Simulation Cases

RDMB-NISAC simulated four hospital impact cases. Because different injury calculations were obtained from Hazus based on the time of day at which the event occurred, analysts used estimates based on 2 a.m. and 2 p.m. event occurrences. Tsunami injuries were based on worst-case estimates of population exposure to the event. Table 5-50 shows the number of injuries and deaths by state.

Table 5-50. Deaths and injuries from Cascadia event

		CA	OR	WA	Total
Ground Shaking	Injuries	1,045	14,109	9,508	24,662
	Deaths	47	671	392	1,110
Tsunami	Injuries	790	897	659	2,346
	Deaths	920	643	195	1,758
Totals	Injuries	1,835	15,006	10,167	27,008
	Deaths	967	1,314	587	2,868

RDMB-NISAC combined these injury estimates with hospital damage estimates based on both 50^{th}-percentile and 90^{th}-percentile confidence measures. This gave four cases: 50th-percentile damage/2 a.m., 50th-percentile damage /2 p.m., 90th-percentile damage /2 a.m., and 90th-percentile damage /2 p.m.

5.3.13.3.1 Hospital Simulation Results

While overall estimates of injuries, deaths, and damage projected for the Cascadia event are reported in Table 5-50, this section specifically discusses hospital impacts. The number of deaths in the hospital impact scenarios may be somewhat different from those appearing elsewhere because of statistical variations in mortality calculated by the RDMB-NISAC trauma model and should not be considered discrepancies.

As expected from the extreme nature of the Cascadia event, all modeled cases showed severe impact on hospital infrastructure. The two cases associated with 2 p.m. occurrence are substantially worse than those occurring at 2 a.m.

Figure 5-75 is a plot of EMS demand for each of the four cases.

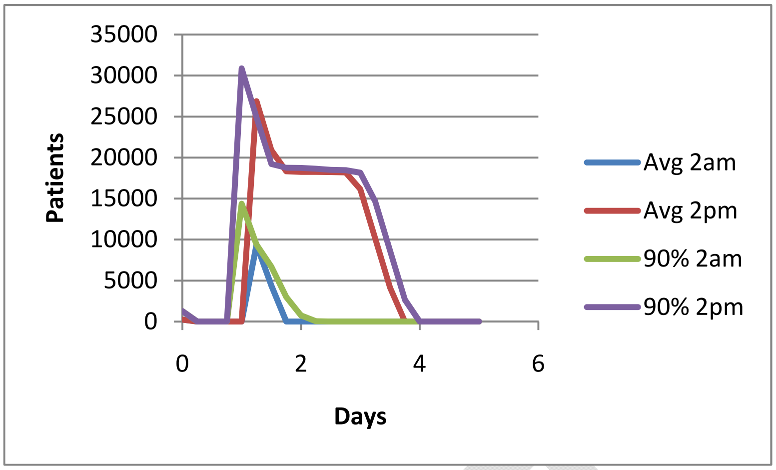

Figure 5-75. EMS patient demand over time for each of the four simulations

The plateaus occurring in the 2 p.m. cases are indications of saturation in hospital processing capacity. Although the timing of the plateau should not be taken as completely accurate because of the coarse nature of the EMS model, it is a likely qualitative feature that distinguishes the more severe 2 p.m. cases from the 2 a.m. cases. In each case, the initial population of displaced patients from damaged hospitals is small compared with the injuries directly caused by the event.

Figure 5-76 shows regular (i.e., not critical) hospital inpatients over time for each of the four cases. The patient volume and timing are similar to those seen for EMS patient demand. However, the traces for 2 p.m. occurrences have a shape that is truncated at the early stage. This is interpreted as a measure of how difficult it is for the EMS and the hospitals in the model to process such large numbers of patients. One interpretation is that the hospitals are at capacity and cannot admit new patients until a bed becomes available.

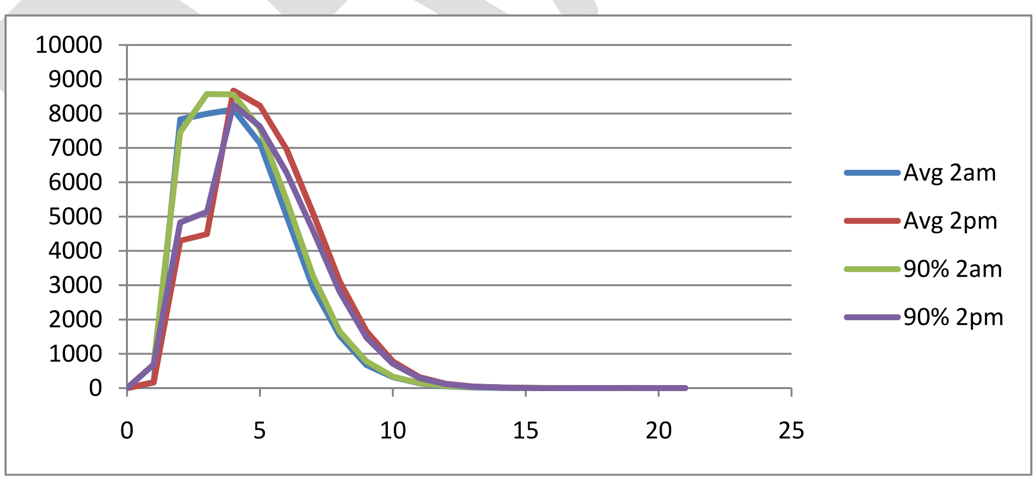

Figure 5-76. Regular inpatients over time for the four scenarios

The result of the bottleneck in available care can be seen in the fatality rates (number of deaths per number of casualties) of the four cases pictured in Figure 5-77. Because substantial numbers of seriously injured patients are unable to reach a hospital in time for life-saving treatment, the fatality rate is higher (18.5 percent) for the 2 p.m. scenarios than for the 2 a.m. cases (15 percent). This translates to approximately 1,100 "excess" deaths, given the very large number of casualties (more than 30,000) in the 2 p.m. occurrence scenarios.

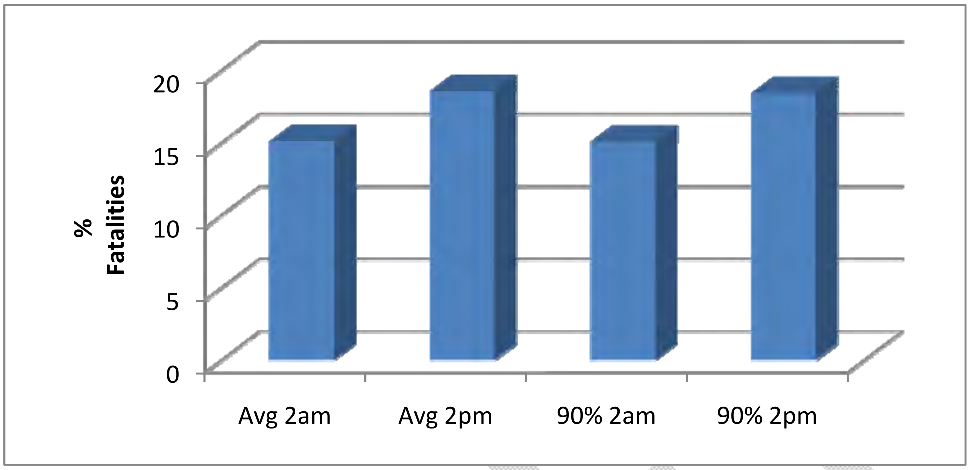

Figure 5-77. Percentage of overall fatality rates for the four scenarios

Finally, RDMB-NISAC looked at the impacts of these scenarios on surrounding hospitals. Table 5-51 lists a number of impact statistics. As shown in the table, most of these statistics are similar for all scenarios. One exhibits a qualitative difference between the 2 a.m. and 2 p.m. cases. All scenarios involve about 10,000 hospital admissions, with approximately 1,000 surrounding hospitals impacted. About the same number of hospitals exceed regular inpatient capacity. However, there is a substantial difference in the number of hospitals exceeding critical capacity, with roughly twice the number exceeding critical care resources in the much more severe 2 p.m. scenarios. The last column of the table is a metric that gives a sense of how far the EMS must extend its search in placing patients. This quantity is the maximum, over all impacted hospitals, of the average distance a person admitted to that hospital has traveled.

Table 5-51. Summary statistics on impacted hospitals

Case	Number of Hospitals Impacted	Total Number Admitted	Number of Hospitals Exceeding Regular Capacity	Number of Hospitals Exceeding Critical Capacity	Maximum Average Person-Distance (km)
Average 2 a.m.	928	8,989	273	150	304
Average 2 p.m.	1,103	10,327	247	309	398
90% 2 a.m.	939	9,558	288	148	386

Case	Number of Hospitals Impacted	Total Number Admitted	Number of Hospitals Exceeding Regular Capacity	Number of Hospitals Exceeding Critical Capacity	Maximum Average Person-Distance (km)
90% 2 p.m.	1,065	9,922	247	311	383

These figures indicate that all the scenarios are severe enough to have essentially reached the 250-mile limit, effectively saturating hospital capacity in the extended region. The 2 a.m. scenarios just reach capacity; the 2 p.m. scenarios show capacity is substantially exceeded. The number of casualties in the 2 p.m. scenarios is approximately twice as large as those at 2 a.m. These differences are due mainly to the increased size of the exposed population, resulting in a proportionally larger number of severe injuries. Hospitals also give priority to treating patients requiring critical care. Taking these factors into account, including the general fact that intensive care unit (ICU) capacity is usually about 10 percent of regular inpatient capacity,[48] it is clear why there is a much larger impact on critical care in the 2 p.m. scenarios than those occurring at 2 a.m.

5.3.13.3.2 Hospital Results Summary

The Cascadia earthquake and tsunami considered in this study clearly constitute a catastrophic event with 15,000 to 30,000 casualties. This number of mass casualties is sufficient to saturate the excess capacity of hospitals within a 250-mile range of where injuries occur.

About 1,000 hospitals are impacted by the demand for inpatient care. On average, about 10,000 patients are admitted as inpatients, and about 260 hospitals exceed their capacity for regular inpatient care. For the more severe scenarios (30,000 injuries), the number of hospitals that exceed critical care capacity is more than double (about 300 versus about 150). Because it takes several days for hospitalized patient outcomes to resolve, and unplaced patients die or recover in just two days (Table 5-49), the standing capacity of the hospital system seems to be the determining factor for how many patients can receive hospital care. Table 5-52 shows the number of unhospitalized patients due to capacity saturation of the hospitals. This clearly indicates the need for external medical treatment resources to be brought into the region to serve the excess demand and reduce the overall fatality rate.

Table 5-52. Hospitalized versus unhospitalized patients

Case	Total Hospitalized	Total Unhospitalized
Average 2 a.m.	9,128	5,476
Average 2 p.m.	11,834	19,277

48 This is an empirical result from examination of the 2008 AHA annual survey.

Case	Total Hospitalized	Total Unhospitalized
90% 2 a.m.	9,450	6,204
90% 2 p.m.	10,142	22,019

5.3.13.4 Public Health Cascading Effects

The loss of 15-27 hospitals comprising 524-1708 regular beds and 60-228 critical bed facilities, mostly along the coastal regions, will affect immediate and mid-term care in the region. In addition, the potential loss of medical personnel, doctors, specialists, and nursing staff in hospitals experiencing Extensive (Severe) or Complete damage sets the stage for degradation of health care services, particularly in the coastal regions. Large urban areas and communities east of the coastal mountains will be affected as hospitals deal with the surge of casualties from the earthquake. Access to healthcare will be more difficult in the near term, one to two weeks, as the system addresses the surge in trauma patients. Damage to the ground transportation system will make healthcare access more difficult, particularly for residents of the coastal regions. But even in urban areas access may take more time than usual. The healthcare system will gradually rebuild itself to pre-earthquake levels over one to two years.

The region may experience an increase in waterborne diseases due to contamination of drinking water. While the healthcare system focuses on treating the trauma casualties from the earthquake, other healthcare needs may be deferred. There may be temporary interruptions in the supply chain of healthcare supplies due to damage to ground transportation, but these can likely be rapidly resolved. Cascading effects from a mild reduction in healthcare services will likely manifest in increased absenteeism of workers in other infrastructures, but this is expected to have only minor effects at most.

5.4 Dynamic Prioritization Methodology

5.4.1 Overview

RDMB-NISAC has an established methodological framework designed to support resource allocation decision-making related to infrastructure disruptions from earthquakes.[49] This framework identified a set of overarching objectives at various points in time relative to the occurrence of an event for which the dedication of resources supporting infrastructure restoration should be considered. The framework then made recommendations on the dedication of resources (manpower, materials, and equipment) toward meeting these overarching objectives with specific needs for particular sectors of infrastructure identified.

This framework, the Dynamic Prioritization Methodology (DPM), can be applied to a 9.0-magnitude Cascadia event. At the core, it is necessary to determine:

[49] RDMB-NISAC (2010), “Foundational Methodology to Support Infrastructure Decision Analysis: Methodology Development Extension for Earthquakes,” February 2010.

- Whether the overarching objectives at various points in time relative to the event occurrence have changed as the result of the event, and if so, what changes need to be made;
- Whether the composition of infrastructure and composition of affected infrastructure is of the same nature as that previously studied, and if not, which infrastructure is more or less vital at various points in time relative to the event occurrence in comparison to previous analyses and methodology applications; and
- Whether the infrastructure resources identified for use by infrastructure with each overarching objective at various points in time relative to event occurrence differ from previous analysis as the result of the composition of infrastructure, the composition of affected infrastructure, and the damage profile associated with the 9.0-magnitude Cascadia event.[50]

5.4.2 Overarching Objectives

The RDMB-NISAC 2010 work on resource allocation decision-making suggested that a variety of priorities for resources would exist following an earthquake event, each designed to meet a time-specific objective. In the moments following such an event, actions (and resources) related to minimization of casualties would be most effective. After the effectiveness of resources for this purpose diminishes, resource allocation related to infrastructure restoration that supports minimization of public health and safety effects will become more significant. In the long run, once these respective issues diminish in significance, resource allocation for infrastructure restoration focused on minimization of long-run economic impacts to the affected area will become the most significant resource priority. Figure 5-78 provides a conceptual diagram of the relative value of activity prioritization in support of each of these objectives, as a function of time, specific to earthquake events.

[50] As identified in RDMB-NISAC (2011), "Analytical Baseline Study for the Cascadia Earthquake and Tsunami," August 2011.

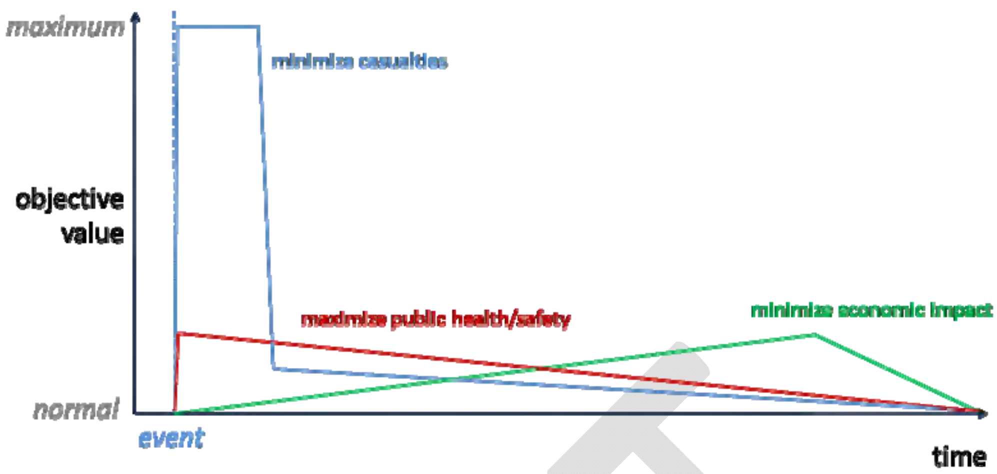

Figure 5-78. Value of resources for objectives relative to normal conditions as a function of time

For this analysis, the first question is whether or not these overarching objectives, or their importance, would change given the differences between the event analyzed here (a 9.0-magnitude Cascadia event) in comparison to the event postulated in RDMB-NISAC 2010, a 7.7-magnitude New Madrid seismic zone (NMSZ) event. As this prioritization schema was developed independent of the specific event but specific to the event type, no changes to the overarching objectives would be expected.

5.4.3 Composition of Infrastructure

RDMB-NISAC 2010 studied disruption to elements of infrastructure in a number of sectors/subsectors, specifically:

- **Public Health**: Hospitals, urgent care facilities, nursing homes, and retirement homes
- **Emergency Services**: Fire stations, law enforcement facilities, EMS facilities, and EOCs
- **Petroleum, Oil & Lubricants (POL)**: Refineries, tank farms, terminals, and pumping stations
- **Telecommunications**: Wire centers (with and without access tandems)
- **Water and Wastewater**: Water treatment systems

The implementation in RDMB-NISAC 2010 also considered other infrastructure sectors (transportation, for example) in prioritization of activities relative to the overarching objectives.

For this analysis, the next question which must be addressed is whether the composition of infrastructure in these sectors is of the same nature as that studied in RDMB-NISAC 2010, and if not, what differences exist that may propagate into the analysis of disruptive effects and subsequent resource prioritization.

In general, the composition of infrastructure closely follows the distribution and concentration of population, particularly population centers. The numbers of public health, emergency services, telecommunications, and water and wastewater facilities described above closely correlate with population figures. Similarly, POL facilities are correlated regionally, although these are typically concentrated near port or pipeline facilities where product can be moved between transportation methods (e.g., vessel to pipeline, pipeline to truck, rail to truck). Therefore the geography associated with a 9.0-magnitude Cascadia event would only vary in comparison to a 7.7-magnitude NMSZ event such as that identified in RDMB-NISAC 2010 to the extent that population distribution varies between the two regions.

The affected populations are strikingly similar despite the differences in geography. RDMB-NISAC 2010 was based on an earlier analysis that estimated 22,000 to 27,000 injuries and fatalities (depending on the time of day of occurrence of the earthquake), while RDMB-NISAC 2011 reported approximately 25,800 injuries and fatalities from ground shaking and another 4,100 injuries and fatalities from tsunami effects. Elements of the infrastructure systems are similar in many regards, which are discussed in more detail in the following section.

5.4.3.1 Composition of Affected Infrastructure

For this analysis, the next question which must be addressed is whether the composition of affected infrastructure in these sectors is of the same nature as that studied in RDMB-NISAC 2010, and if not, which infrastructure is more or less vital at various points in time relative to the event occurrence in comparison to previous analyses and methodology applications.[51]

Some of the infrastructure impacts are similar in nature between a 9.0-magnitude Cascadia event and a 7.7-magnitude NMSZ event. For the NMSZ event, 306 telecommunications wire centers are damaged to a functional extent within the expected case, while for the Cascadia event, 284 telecommunications wire centers are damaged to a functional extent within the expected case.

In other cases, the scale of infrastructure impact varies between the two cases:

- For the NMSZ event, 513 fire stations are damaged to a functional extent within the expected case, while for the Cascadia event, 930 fire stations are damaged to a functional extent within the expected case;
- For the NMSZ event, 420 law enforcement facilities are damaged to a functional extent within the expected case, while for the Cascadia event, 152 law enforcement facilities are damaged to a functional extent within the expected case; and
- For the NMSZ event, 87 hospitals with over 13,000 beds are damaged to a functional extent within the expected case, while for the Cascadia event, 29 hospitals with over 1,500 beds are damaged to a functional extent within the expected case.

Other less subtle differences exist for the POL subsector. In the NMSZ event case, effects are based primarily on pipeline disruptions; however most of these effects actually lead to impacts outside the damage zone, as the pipelines provide resources to other parts of the country. In the Cascadia event case, a combination of pipeline, port, and terminal damage creates effects within and beyond the damage zone, with the principal population centers being located within the damage zone. Each of these distinctions will be valuable in determining which resources are of most value to support the overarching objectives.

[51] It is not possible within the confines of this effort to examine additional infrastructure sectors/subsectors beyond those addressed in RDMB-NISAC 2010.

From these points, the following resource priority changes may be necessary:

- Additional fire equipment may be necessary.
- Fewer impacts, and therefore fewer additional resources, may be necessary for law enforcement and hospital services.
- Additional resources for the movement and storage of petroleum fuels and the repair of pipeline and storage facilities, may be necessary, in spite of relatively low (eight percent) of regional refining capacity being disrupted for an extended period of time.

5.4.4 Resource Requirements

RDMB-NISAC 2010 suggested a series of scenario-specific priorities for the dedication of resources to meet the overarching objectives. Table 5-53 shows a summary of these priorities. In this case it is important to note the value of transportation and transportation methods. The NMSZ area includes many transportation modes but the most likely to be restored quickly is rail transportation; thus its priority, especially to classification yards (where train cars can be moved between trains) near the center of the effects zone, for the purpose of moving materials and manpower in and moving the injured out is significant.

Table 5-53. Summary of scenario-specific priority activities for RDMB-NISAC 2010

Time Frame	Activity
Immediate Aftermath	Search and rescue in damage zone, focused on damaged facilities with susceptible populations (e.g., hospitals, nursing homes, large apartment complexes)
	Identification and clearance of paths from areas with functional public health and infrastructure to damage zone
	Evacuation of injured from damage zone to working medical facilities
	Movement (to outpatient facilities) or discharge of ambulatory patients at hospitals in areas with functional public health and infrastructure to clear bed space and shorten transportation times
	Repair of rail routes to yards in damage zone
	Coordination of truck and rail transport of POL (especially diesel fuel for emergency services vehicles and backup generators) from functional terminals to damage area and its perimeter
Second Stage	Expansion of transportation routes to/from damage area, especially rail
	Establishment of medical triage and resource allocation/shelter locations
	Evacuation of those lacking structurally sound housing or infrastructure resources from the damage area
	Repair of interstate POL pipelines to restore flows beyond the damage area
Long-term	Community-centric restoration of infrastructures: • Basic Infrastructure (water, power, fuels, commodity supplies) • Public Service (fire, police, schools)

5.4.4.1 Prioritization of Resource Requirements

The final question faced within this analysis is whether the infrastructure resources identified for use by infrastructure with each overarching objective at various points in time relative to event occurrence differ from previous analysis as the result of the composition of infrastructure, the composition of affected infrastructure, and the damage profile associated with the 9.0-magnitude Cascadia event.

Given the differences in affected infrastructure identified above in Composition of Affected Infrastructure, the resource requirements necessary to evacuate non-functional hospitals and the distance required to find functional hospitals may be significantly smaller. Major airport runways in Seattle and Portland are expected to remain functional, providing a means of entry for rescue and recovery workers and equipment into the affected area. Furthermore, the composition of the most-affected area for a 9.0-magnitude Cascadia event is somewhat remote in nature, with limited ground transportation paths. This is especially true for areas in projected tsunami damage zones. Thus additional air transportation means to these outlying communities – helicopter and/or seaplane dispatched from unaffected runways as staging areas – may provide an effective means of getting prompt resources into the affected area.

Increased damage to fire stations within this scenario relative to the NMSZ scenario is likely to have an immediate impact on the ability to place equipment at the scene of fires and to support search and rescue efforts. Additional external resources may be needed to provide support for this purpose.

Functional transport of POL supplies – especially where diesel fuel is required for localized generation in place of commercially supplied power – is vital. As storage at pipeline terminal sites is projected to be significantly damaged, additional means of transporting POL fuels and repair of the transportation systems to key facilities will be required. This requirement increases in importance both for the immediate aftermath as well as for maximizing public health and safety. As the POL pipeline system in the affected area is regional in nature, repairing POL pipelines to meet needs outside the affected area is less important.

Additionally, although rail is important for the metropolitan areas on the I-5 corridor, it is by no means the exclusive means of transporting resources into the affected area. Where damage to waterfront structures, port facilities, cargo-handling equipment, and warehouses is light or nonexistent, facilities can be used to bring in resources for recovery – provided personnel are available to staff the facilities (many functions at these facilities are usually performed by members of the International Longshore and Warehouse Union) and are not otherwise occupied with personal concerns.

A summary of the scenario-specific priorities for the dedication of resources to meet the overarching objectives for a 9.0-magnitude Cascadia event is shown in

Table 5-54

Table 5-54below.

Table 5-54. Summary of scenario-specific priority activities for 9.0-magnitude Cascadia event

Time Frame	Activity
Immediate Aftermath	Search and rescue in damage zone, focused on damaged facilities with susceptible populations (e.g., hospitals, nursing homes)
	Transport of emergency response surge capacity through major airports (SeaTac, Portland International) as staging areas for reaching more affected zones (by open roads, helicopter, seaplane), including fire suppression equipment to replace that destroyed by structural failure
	Identification and clearance of paths from areas with functional public health and infrastructure to damage zone
	Evacuation of injured from damage zone to working medical facilities
	Movement (to outpatient facilities) or discharge of ambulatory patients at hospitals in areas with functional public health and infrastructure to clear bed space and shorten transportation times
	Repair of transportation routes (truck, rail) to minimally damaged port facilities near damage zone
	Coordination of truck and rail transport of POL (especially diesel fuel for emergency services vehicles and backup generators) from functional terminals/refineries to damage area and its perimeter
Second Stage	Identify shelter/housing for key transportation workers and housing/evacuation for their families, to support operational flow of port facilities supporting recovery effort
	Evacuation of those lacking structurally sound housing or infrastructure resources from the damage area, especially those lacking means of home heating
	Repair of POL pipeline and terminal facilities to restore flows beyond the damage area. Rerouting of refined product from other western refineries as capacity allows by rail to undamaged areas
Long-term	Community-centric restoration of infrastructures: • Basic Infrastructure (water, power, fuels, commodity supplies) • Public Services (fire, police, schools)

5.5 Economic Impacts

The debris calculation module of the FEMA Hazus model and the damage to buildings module will be used as input into the economic analysis. The damage to buildings provides an estimate for impact to the commercial, banking, and industrial sectors. The debris calculation is used to estimate the level of effort required in cleanup operations.

The REAcct and FastEcon models are employed to provide rapid estimates of economic impacts. Considering areas disrupted by earthquakes and electrical outage, the lost economic activity will be assessed. This assessment can be broken down by county and by economic sector. For disruptions with long-term impacts, the Regional Economic Modeling Inc. (REMI) model can be employed.

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6 Data

6.1 Earthquake and Tsunami Data

Hazus was employed to provide ground shaking damage and impacts on population. RDMB-NISAC modeling was used for the onshore inundation from the tsunami. The data sources for the input to both are summarized in Table 6-1 below.

Table 6-1. Data sources for ground shaking and tsunami

Area	Data Set	Data Source
Ground Shaking: Hazus Input	ShakeMap	USGS: earthquake.usgs.gov/earthquakes/shakemap/global/shake/Casc9.0_se/
	Liquefaction Susceptibility	CA: derived from Hazus algorithm, modified to wet
		OR: preliminary data from DOGAMI, modified to wet
		WA: data provided by State of Washington in a Hazus run (2009)
	Landslide Susceptibility	Derived from Hazus algorithm
Tsunami	Marigrams	Developed in Pacifex 11 Pacific Marine Environmental Laboratory, NOAA
	Digital Elevation Measures	National Geophysical Data Center
	Infrastructure	HSIP Gold

6.2 Infrastructure Data

The Homeland Security Infrastructure Protection Gold (HSIP-Gold) database provides basic asset information for most of the infrastructure sectors. Data from private-sector providers, including Platts and SRI Consulting for the energy and chemical sectors respectively, provide information necessary for the construction of network models. Census data are used for locating population relative to disrupted areas. Dun & Bradstreet, IMPLAN, and Bureau of Economic Analysis (BEA) data are used to generate estimates of economic impacts. Other government data sources include the Federal Energy Regulatory Commission (FERC) for energy, and the Bureau of Transportation Statistics and Surface Transportation Board for transportation data. In addition, proprietary data are used by agreements with industry, such as the restoration data used in EPRAM and the data that are employed by GPCM.

It is important to note that these externally obtained datasets are virtually never used 'as is' in modeling. These databases generally require extensive transformation and manual annotation and checking before they are model-ready. Data sources are provided in Table 6-2 below. Note: Additional models will be added to the table below as they are identified.

Table 6-2. Data sources used by models

Product	Data Set	Data Source
Rail (R-NAS)	Bureau of Transportation Statistics (2008), "2002 Commodity Flow Survey"	www.bts.gov/publications/commodity_flow_survey
	Association of American Railroads, "Class I Railroad Statistics"	www.aar.org/IndustryInformation/IndustryStatistics/RailCostIndexes.aspx
	Surface Transportation Board (2007), "2005 Carload Waybill Sample"	www.stb.dot.gov/IndustryData/EconomicData/Waybill
All Models (Chemical Data)	World Petrochemicals Program 2008	SRI Consulting
	Chemical Economics Handbook 2008	SRI Consulting
	Directory of Chemical Producers 2008	SRI Consulting
	Oil & Gas Pipelines 2007	National Geospatial-Intelligence Agency (original publisher Penn Well Energy Inc.)
	Oil & Gas Facilities 2007	National Geospatial-Intelligence Agency (original publisher Penn Well Energy Inc.)
	Refinery Location Data	Argonne National Laboratory
	United States Census 2000	U.S. Census Bureau
	County Business Patterns 2002	U.S. Census Bureau
	County Business Patterns Employees Estimation 2002	U.S. Census Bureau
	Geographic Names Information System	U.S. Geological Survey (USGS)
	IMPLAN States Summary 2002	Minnesota IMPLAN Group (MIG)

Product	Data Set	Data Source
	2007 Foreign Trade Statistics	Foreign Trade Division, U.S. Census Bureau
	2002 Commodity Flow Survey, Department of Transportation (DOT)	2007 Waybill Sample, Surface Transportation Board
	2007 Class I Railroad Statistics, Association of American Railroads	2007 Producer Price Index, Department of Labor
FASTMap	All Sectors	HSIP Gold 2005, 2007
		Federal Deposit Insurance Corporation (FDIC) Institution Directory of Current FDIC-Insured Institutions, Bank Holding Companies, and Offices
		SRI Directory of Chemical Plants
		U.S. Army Corps of Engineers – National Inventory of Dams
		Platts
		DOT National Transportation Atlas Database (NTAD) 2005
		Argonne National Laboratory
		ESRI – Compiled from the 2000 Census
		LERG from Telcordia Joined with Map Info Corporation Wire Center Points
		Map Info Corporation
WorkBench	All Sectors	HSIP Gold
		Platts

Product	Data Set	Data Source
		Dun & Bradstreet
		Argonne National Laboratory
		Los Alamos National Laboratory
		Hazus
		DOT
		U.S. Army Corps of Engineers
		U.S. Census Bureau
		BEA
IEISS, EPANET, SWMM5	Energy, Water, Dams, Telecommunications	Multiples data sources depending on the sector. Predominant data sources FERC filings and HSIP Gold. The U.S. Environmental Protection Agency (EPA) developed EAPNET and SWMM5
FastPOP FastECON REAcct	All CIKR	BEA, Dun & Bradstreet, U.S. Census
EPRAM	Energy (Electric)	FERC 715 filing, HSIP Gold
HCSim	Healthcare & Public Health: resource demand information; population impacts; Cascading impacts within healthcare sector; Distance to closest hospital; economic impacts	HSIP Gold augmented with state data, primarily to ascertain seismic performance of the facilities. American Hospital Association (AHA) and Dartmouth Atlas of Healthcare (DAH) data.

Some data are not employed in models, but used to support analysis directly. This includes data used in the analysis of ports: USACE Port Facility database, U.S. Army Corps of Engineers (USACE) Waterborne Commerce database, NOAA navigation charts, Port Authority descriptions of port infrastructure including multi-modal connections, private industry descriptions of port facilities including 10-K information, and individual state DOT multi-modal information. For food and agriculture, the following sources are consulted: commodity import and export data from the United States International Trade Commission, as well as state and county agricultural profiles and county-level crop and livestock data from the Census of Agriculture.

Local sources of data will be integrated into the above data sets. Improvements to the analytical understanding of the local hospital network will be included. Knowledge of potential emergency staging areas, air and helicopter landing fields and lots, and sea ports will allow the identification of those key response areas that are likely to be operable.

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7 Conclusions

7.1 Ground Shaking

The 9.0-magnitude earthquake along the Cascadia fault line off the coast of northern California, Oregon, and Washington, along with a resulting tsunami, causes significant damage and loss of life along coastal regions of California, Oregon, and Washington. Further structural damage is experienced along the I-5 corridor from Seattle to Portland. The earthquake's effects are felt throughout the region, but the greatest damage is in the coastal areas and west of the coastal mountains of Washington and Oregon. Approximately 1,100 fatalities are forecast to result from ground shaking, primarily due to structure collapse.

7.1.1 Tsunami

Many communities along the northern California, Oregon, and Washington coast have as little as 15 minutes warning of the resulting tsunami. Almost two thousand lives could be lost due to tsunami inundation along the Pacific coast. The communities of Crescent City and Grays Harbor are particularly hard hit, although there are no significant tsunami impacts further into the Puget Sound or inner reaches of the Columbia River.

7.2 Transportation

7.2.1 Roads

Significant damage to roads can be expected, particularly those along the coast and connecting the coast to the I-5 corridor. Some coastal communities along U.S. 101 can expect to be isolated due to complete inaccessibility for the short term. U.S. 101 is expected to have substantial damage due to both shaking and tsunami and is expected to have limited capacity for several months. Road and bridge damage will likely impact accessibility of emergency services as well as essential repair crews for other sectors.

7.2.2 Rail

The complete loss of key rail bridges in the Olympia and Seattle areas, as well as the loss of a bridge in downtown Portland, and extensive damage to the critical bridge spanning the Columbia River immediately north of Portland will cause long-term disruption to rail traffic along the I-5 corridor for a year or more. Eastbound lines for both Seattle and Portland should suffer fewer impacts and offer alternate routes for those population centers.

7.2.3 Airports

Smaller airports along the coast are expected to suffer substantial runway damage, limiting fixed-wing access for emergency services. Seattle and Portland international airports should quickly regain functionality to near full capacity. There may be some near-term fuel supply issues.

7.2.4 Ports

Intermodal facilities are very hard hit as a result of being close to the coast and because they are located in areas susceptible to liquefaction. These facilities could take months to restore.

Tsunami damage at the mouth of the Columbia River will impact navigation and the ability to export agricultural commodities.

7.3 Banking and Finance

Loss of the Alaska telecommunications link would significantly impact the ability of Alaskan banks to process payments/ settlements. Satellite uplinks might not be an available option due to scarcity of bandwidth and contractual agreements.

Loss of major transpacific undersea cable capacity would affect transoceanic commerce, settlement, and transpacific financial market exchanges. With the loss of approximately half the undersea cable capacity, communications systems could face abnormally high congestion.

7.4 Water and Wastewater

Disruptions to potable water supply are expected with restoration times of three weeks to seven months with the greatest damage and longest restoration times near the coastline. There is some risk of release of untreated wastewater and sewer-line backups, which would cause a shutdown of the system until repairs can be completed. Availability of water supply and wastewater systems can delay economic recovery, particularly along the coastline. The region may experience an increase in waterborne diseases due to contamination of drinking water.

7.5 Health Care

The Cascadia earthquake and tsunami constitute a catastrophic event with 15,000 to 30,000 casualties. There is an expected loss due to damage of 15-27 hospitals comprising 524-1708 regular beds and 60-228 critical bed facilities particularly near the coast. The number of mass casualties is sufficient to saturate the excess capacity of other hospitals within a 250-mile range of the site of injuries. Restoration to pre-earthquake levels will occur over one to two years.

7.6 Electric Power

Extensive electric power outages are experienced throughout the region with medium-term outages forecast for the coastal areas. Seattle and Tacoma, Washington; Portland, Oregon; Vancouver Island, British Columbia: and all other Oregon and Washington cities within 100 miles of the Pacific coastline will experience at least partial blackout, with a few additional blackout areas in northwest California. Restoration of power proceeds on a prioritized basis with most areas having power restored within one to eight days.

7.7 Natural Gas

Segments of the backbone natural gas transmission pipeline serving western Washington and Oregon, as well as the compressor stations along that pipeline, are at risk of being damaged. Both the transmission pipeline and the networks of distribution pipelines are likely to suffer enough damage that the majority of customers in western Washington and western Oregon will not receive natural gas service until pipelines can be repaired. Combined with electrical outages, many homes may lose all sources of heating. Only 12 percent of electric power generation capacity is fueled by natural gas in the region, so disruption of natural gas is not expected to have a major impact in overall EP capacity, unless the transmission lines delivering hydroelectric power from the east fail.

7.8 Hospitals and Emergency Services

Widespread damage to hospitals, fire stations, police stations, and emergency services along with widespread bridge and road outages along the immediate coastal communities are expected to substantially limit the abilities of first-responders to assist in rescue and medical aid for victims.

7.8.1 Emergency Services

Widespread damage to police stations, fire stations, and hospitals is expected along the coast. Bridge and road outages will inhibit accessibility and emergency response capabilities. Communications disruptions will be a widespread problem for emergency response operations along the entire coast. Transportation fuels to key emergency operations centers may become be an issue until road access is restored.

7.9 Telecommunications

Telecommunications and Internet services are likely to be severely disrupted across the regions experiencing liquefaction due to damage to the facilities and the loss of communication cables connecting those facilities. Repair of the facilities and restoration of the cables is likely to take weeks to months.

The earthquake will likely sever undersea cables that primarily provide communications services to Alaska and major transpacific routes. This will cause severe communications disruptions between Alaska and the contiguous United States. The loss of the major transpacific communication routes will cause disruption and severe delays in communication to and from East Asian countries, which could have impacts on other infrastructures that rely on real-time or near real-time operation and timely large data transfers over transpacific networks. Restoration of these cable systems is likely to take two to three months depending on the number of breaks and the availability of cable ships to conduct the repairs.

7.10 Transportation Fuels

Petroleum refining capacity in the region will not be significantly impacted. However, many of the pump stations critical to moving refined product along the Olympic and Oregon Line pipeline system will be completely damaged. Thus, based on pump station operability alone, it is reasonable to assume a disruption in pipeline functionality measured in months.

A majority of refined product terminals are expected to be completely destroyed; as a consequence, the ability to distribute refined products fuels along the Pacific Northwest corridor will be significantly reduced. As a result, the Portland, Eugene, and Kennewick-Richland demand regions will experience a major reduction in transportation fuels supplies.

7.11 National, Regional, and Local Impact Summary

National infrastructure impacts resulting from the earthquake and tsunami are not expected to be severe; however, there will be longer term regional impacts to the telecommunication sector and increasing shortages of gasoline and refined petroleum products south of Seattle to Portland, Eugene, and beyond. Coastal areas taking the brunt of the earthquake and tsunami will experience a long recovery time; this is due to both limited access to begin restoration activities and the extent of structural damage of coastal communities.

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Appendix A: Acronyms, Initialisms, and Abbreviations

Acronym	Description
AHA	American Hospital Association
ANC	Anchorage International Airport
BEA	Bureau of Economic Analysis
COLTs	cellular-on-light-trucks
COWs	cellular-on-wheels
CREW	Cascadia Region Earthquake Workgroup
CSZ	Cascadia Subduction Zone
DAH	Dartmouth Atlas of Healthcare
DBS	direct broadcast satellite
DHS	Department of Homeland Security
DOT	Department of Transportation
ds	damage state
EAS	Emergency Alert System
EBT	Electronic Benefits Transfer
EIA	Energy Information Administration
EMS	emergency medical service
EOC	emergency operations center
EP	electric power
EPA	U.S. Environmental Protection Agency
EPRAM	Electric Power Restoration Analysis Model
FDIC	Federal Deposit Insurance Corporation
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GEG	Spokane International Airport
GPCM	Gas Pipeline Competition Model
GW	gigawatts
Hazus	FEMA's Hazus®-MH 2. 0 Multi-hazard Loss Estimation Methodology
HITRAC	Homeland Infrastructure Threat and Risk Analysis Center
HSIP-Gold	Homeland Security Infrastructure Protection Gold
I-5	U.S. Interstate 5
ISS	Injury Severity Score
Kbpd	thousand barrels per day
KMZ	Keyhole Markup Language
LDC	local distribution company
MF	melamine-formaldehyde
MIG	Minnesota IMPLAN Group

Acronym	Description
NISAC	National Infrastructure Simulation and Analysis Center
NMSZ	New Madrid seismic zone
NOAA	National Oceanic and Atmospheric Administration
NTAD	National Transportation Atlas Database
NTDB	National Trauma Data Bank
PADD	Petroleum Administration Districts for Defense
PDX	Portland International Airport
PF	phenol-formaldehyde
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
POL	petroleum, oil, and lubricants
PVC	polyvinyl chloride
RDMB	Risk Development and Modeling Branch
REMI	Regional Economic Modeling Inc.
SA	spectral acceleration
SDARS	satellite digital audio radio service
SEA	Seattle/Tacoma International Airport
SOD	Summary of Deposits
TAZ	Transportation Analysis Zones
TEU	twenty-foot equivalent unit
TOTE	Totem Ocean Trailer Express, Inc.
UF	urea-formaldehyde
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Appendix B: Glossary

Term	Definition
bathymetry	The measurement of the depth of bodies of water, particularly of oceans and seas
boundary condition	A condition specified for the solution to a set of differential equations
Hazus	A nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes
lateral spread	The relative distance that a point on the ground may move due to spreading and ground settlement
liquefaction	A phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading
marigram	Plot of tsunami wave amplitude as a function of time
peak ground acceleration	The maximum acceleration that any point on the ground would experience
peak ground velocity	The maximum speed that a point on the ground will achieve due to ground shaking in an earthquake
spectral acceleration	The maximum acceleration that a point on the ground would experience at a particular frequency
wave amplitude	The amplitude of an ocean wave is the maximum height of the wave crest above the level of calm water, or the maximum depth of the wave trough below the level of calm water

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Appendix C: Tsunami Marigram Substitution Error Analysis

For most of the modeled tsunami sites, RDMB-NISAC was able to obtain marigrams to use as boundary conditions in the higher-resolution two-dimensional inland inundation model. However, for some sites, no direct associated marigram was available. To minimize analysis time and proceed with the coastal tsunami modeling simulations, RDMB-NISAC used the nearest marigram to set the boundary conditions for those sites. This approach does inject some degree of error into the assessment of inundation and velocity values; however, as the error analysis presented here shows, the error in assessing infrastructure damages, injuries, and deaths is small, as long as the selected marigram is relatively close to the modeled site.

To provide sufficient justification for the approach mentioned in the previous paragraph, RDMB-NISAC selected two locations (Rockaway Beach, OR, and Lincoln City, OR) for additional analysis. These two regions were cross-analyzed using nearby marigrams for each city (Figure C-1).

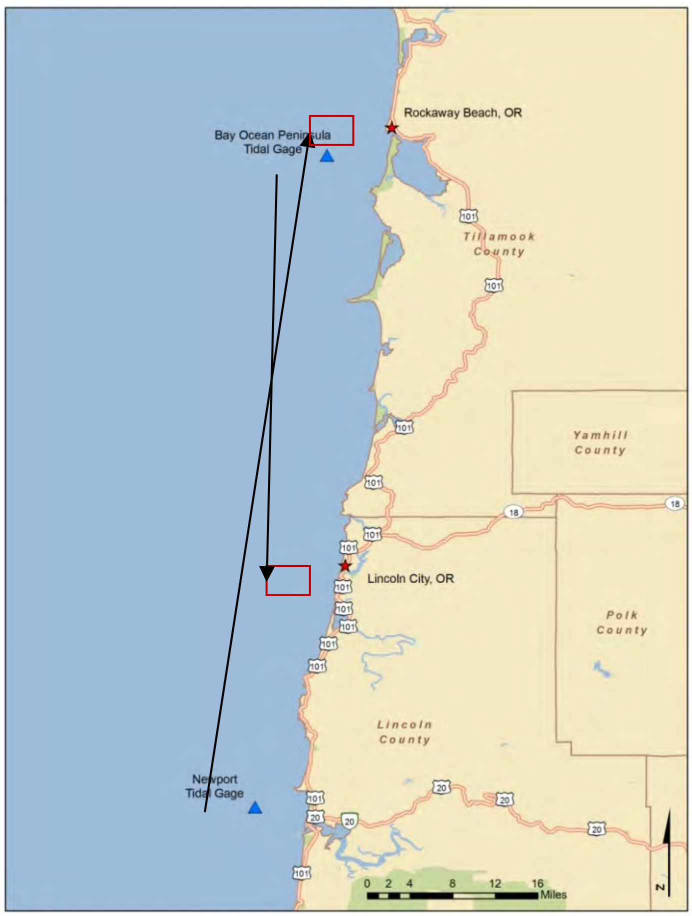

Figure C-1. Cross-comparison of Newport, OR, and Bay Ocean, OR, marigram substitution

The marigrams chosen for these analyses were obtained from tidal gauges for Newport and Bay Ocean Peninsula, OR. These marigrams have roughly the same maximum wave amplitude;

however, the Newport marigram has less wave dissipation then the Bay Ocean Peninsula marigram (Figures C-2 and C-3).

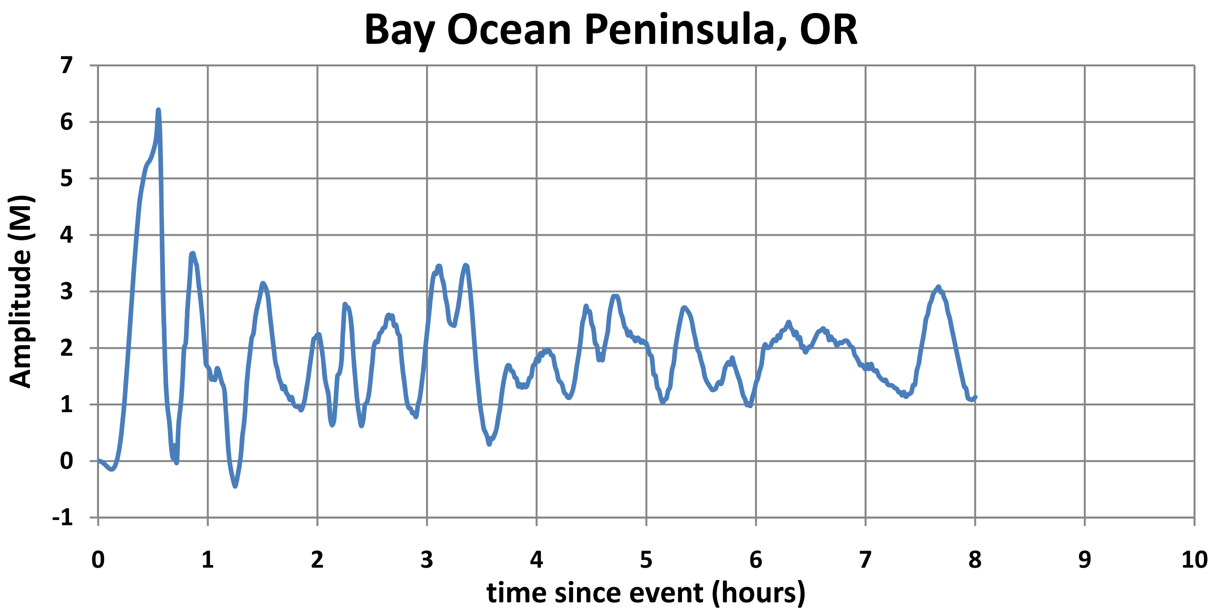

Figure C-2. Tide gauge marigram for Bay Ocean Peninsula, OR

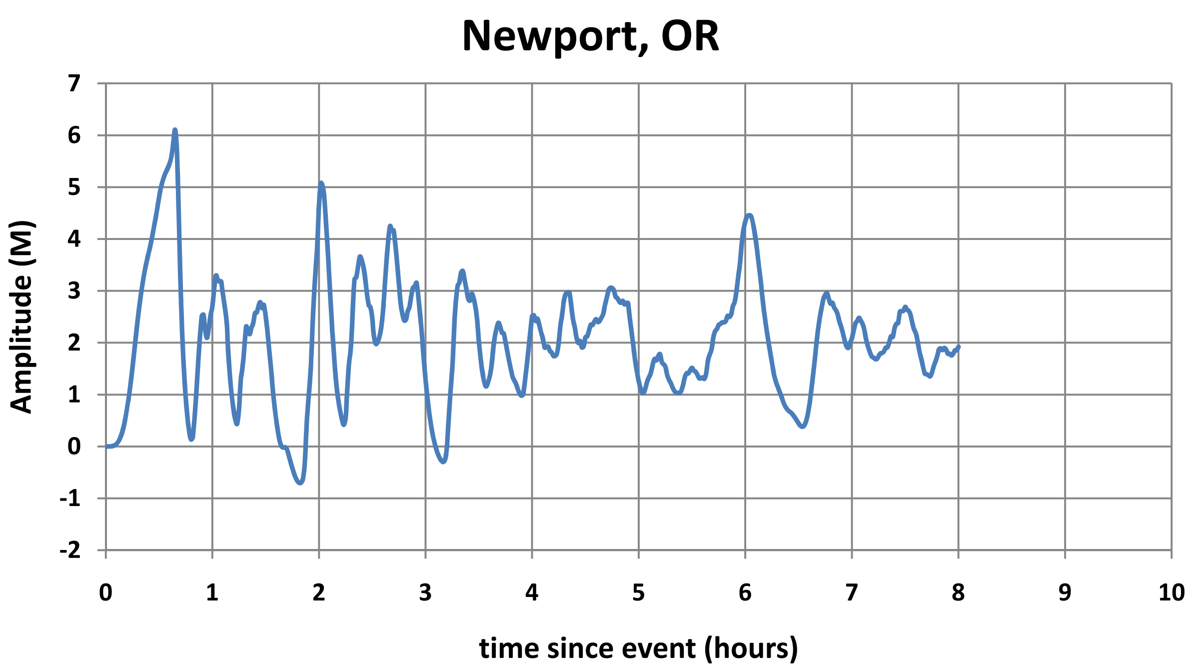

Figure C-3. Tide gauge marigram Newport, OR

The analyses results are compared in maps and tables describing direct infrastructure impacts. The error analysis for both Rockaway Beach, Oregon, and Lincoln City, OR, showed little change in the spatial extent and severity of the flooding and the infrastructures impacted. (See Figures C-4 and C-5 and Tables C-2, C-3, C-5, and C-6.) Due to the differences in marigram amplitudes, the population at risk (PAR) values are expected to differ. By comparing the casualties at each site to the corresponding day and nighttime populations, the percentage of casualty impacts to these PARs (see Tables C-1 and C-4) imply that these population differences are reasonable and consistent.

Rockaway Beach Error Analysis

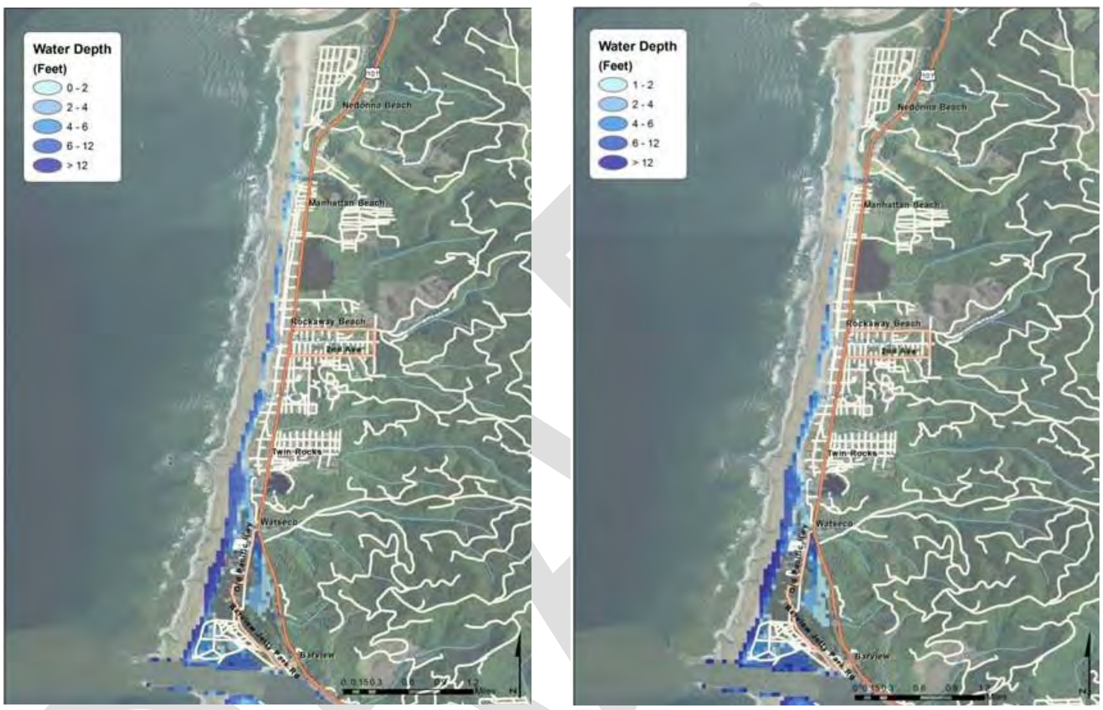

Figure C-4. Comparison of expected tsunami inundation in Rockaway Beach, OR, using Bay Ocean, OR, marigram (left) and Newport, OR, marigram (right)

Table C-1. Comparison of population at risk in Rockaway Beach, OR, using Newport, OR, marigram

Population Impacts	# People	Relative Casualty PAR Impacts [%]	# People	Relative Casualty PAR Impacts [%]
	Bay Ocean, OR		Newport, OR	
Daytime PAR	70	7.1	60	8.3
Nighttime PAR	75	6.7	70	7.1
Injuries	4		4	
Deaths	1		1	

Table C-2. Comparison of impacted sectors in Rockaway Beach, OR, usingthe Newport, OR, marigram

Asset	# Facilities	Sector	# Facilities
Bay Ocean, OR		Newport, OR	
Major Roads	3	Major Roads	3

Table C-3. Impacted roads in Rockaway Beach, OR, using Newport, OR, marigram

Road Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	2 - 4	Poorly Constructed
Old Pacific Hwy	2 - 4	Poorly Constructed
Barview Jetty County Roads	6 - 12	Poorly Constructed

Lincoln City Error Analysis

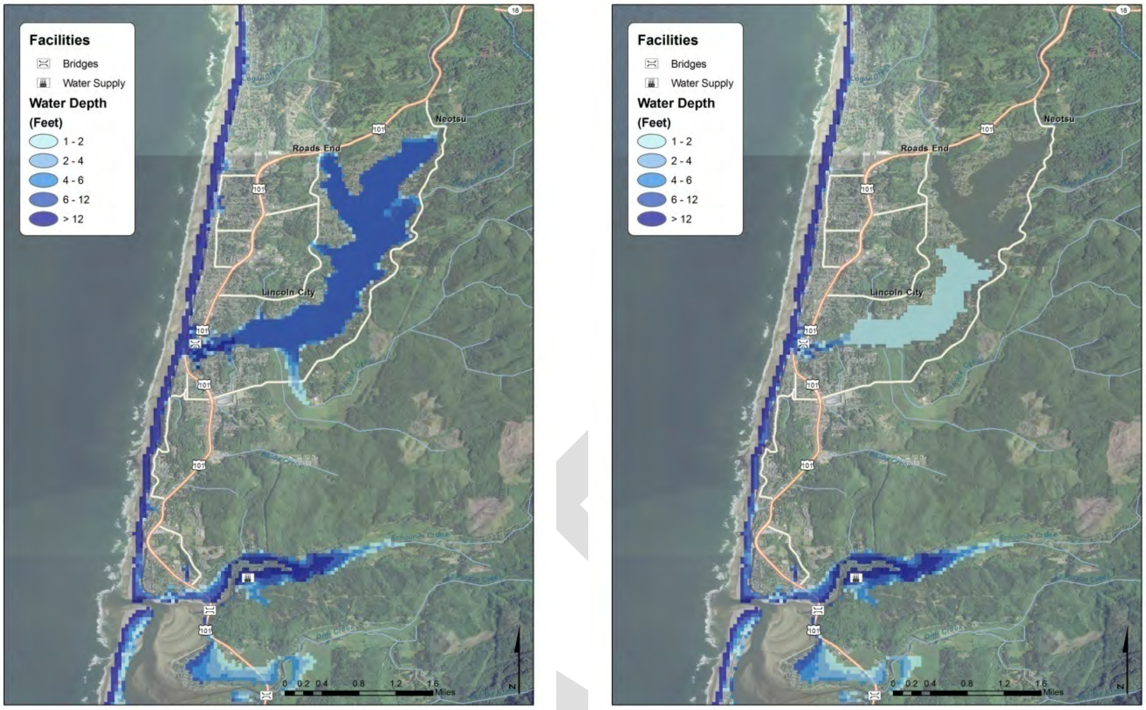

Figure C-5. Expected tsunami inundation and impacted facilities in Lincoln City, OR, using Newport, OR, marigram (left) and Bay Ocean, OR, marigram (right).

Table C-4. Comparison of population at risk in Lincoln City, OR, using the Bay Ocean, OR, marigram

Population Impacts	# People	Relative Casualty PAR Impacts [%]	# People	Relative Casualty PAR Impacts [%]
	Newport, OR		Bay Ocean, OR	
Daytime PAR	960	20.8	630	11.1
Nighttime PAR	900	22.2	560	12.5
Injuries	120		50	
Deaths	80		20	

Table C-5. Comparison of impacted sectors in Lincoln City, OR, using Bay Ocean, OR, marigram

Sector	# Facilities	Sector	# Facilities
Newport, OR marigram		Bay Ocean, OR marigram	
Bridges	3	Bridges	3
Major Roads	1	Major Roads	4
Water Supply	1	Water Supply	0

Table C-6. Impacted transportation facilities in Lincoln City, OR, using Bay Ocean, OR, marigram

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	n/a	> 12	Well-built Masonry
NW Inlet Avenue	n/a	4 - 6	Poorly Constructed
NW Jetty Avenue	n/a	6 - 12	Poorly Constructed
Oregon Coast Hwy	n/a	0 - 2	Poorly Constructed
U.S. 101	Drift Creek Bridge	0 - 2	Poorly Constructed
U.S. 101	Devil's Lake Outlet	2 - 4	Poorly Constructed
U.S. 101	Schooner Creek	2 - 3	Poorly Constructed

Appendix D: Tsunami Modeling Results

This appendix contains figures that depict the specific tsunami modeling scenario results, including marigrams, building stability, and expected tsunami inundation area for each of the 27 modeled locations. Where geospatial data were available, initial expected population and infrastructure impacts are provided. Geospatial population data were not available for regions in Alaska. The population at risk (PAR) included in the Tsunami Modeling section of this report for these areas is taken from the total population for the community or municipality reported in 2010 U.S. Census data.

Alaska

Homer, AK

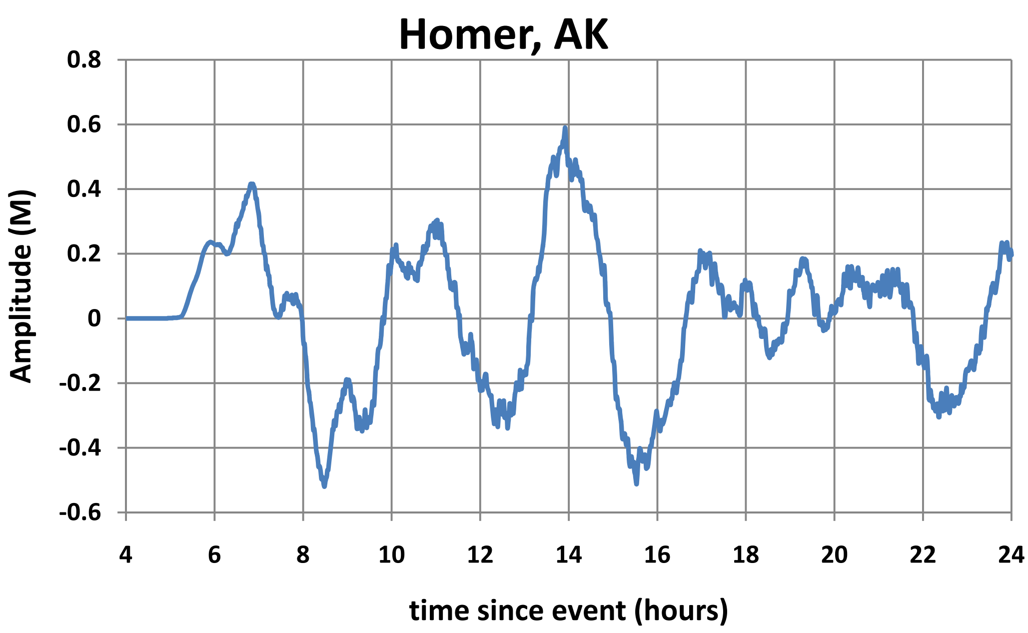

Figure D-1. Homer, AK, seismic event marigram

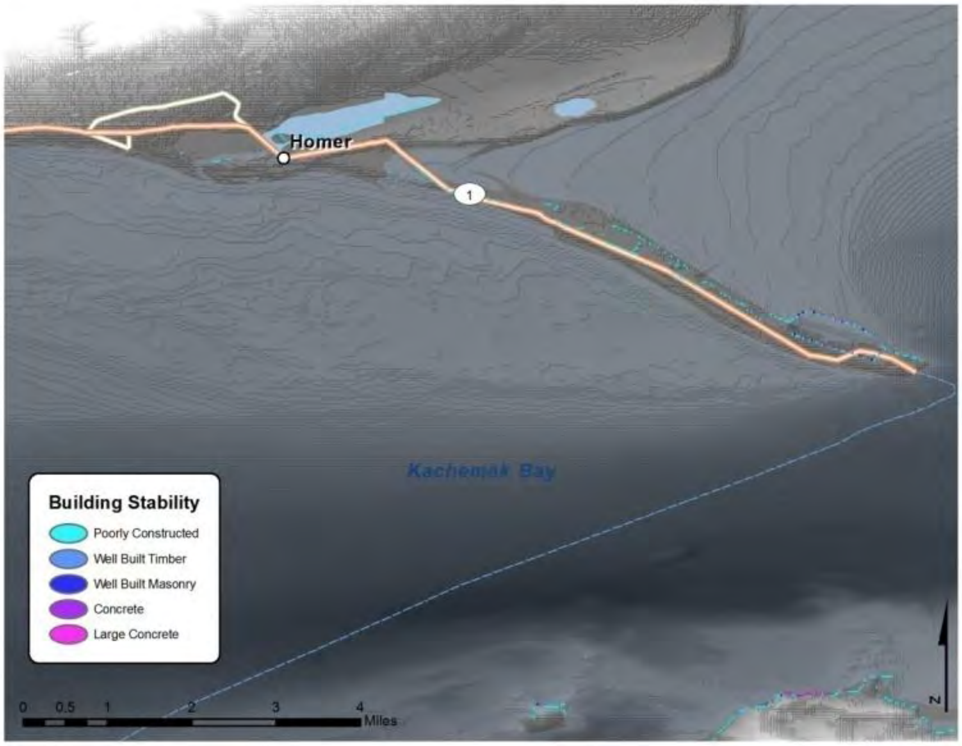

Figure D-2. Predicted building stability rating for Homer, AK

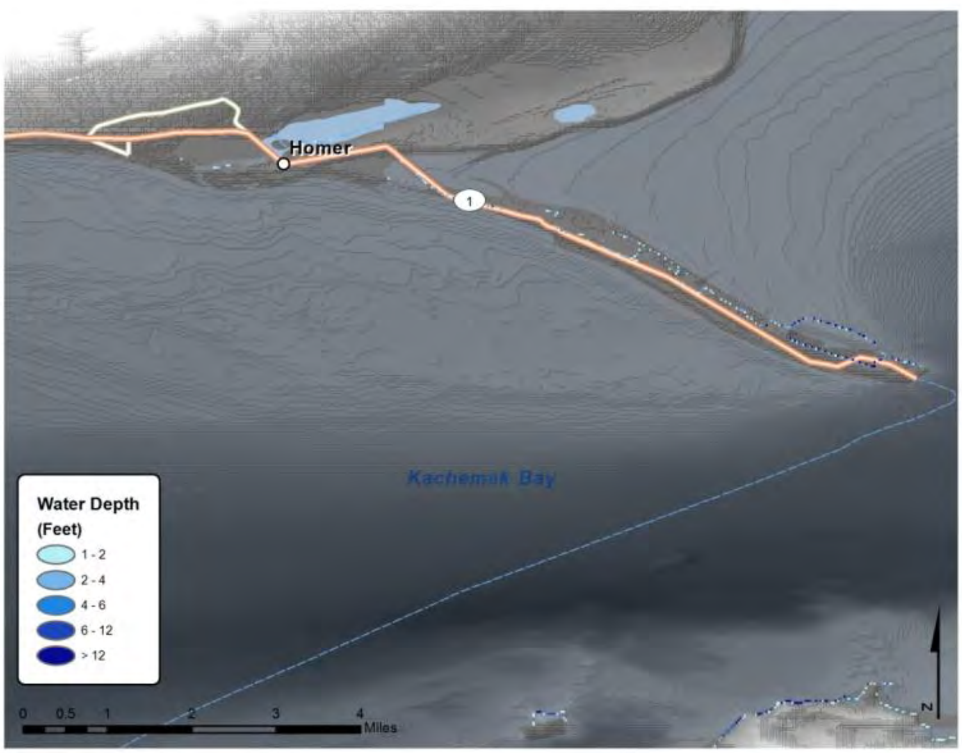

Figure D-3. Expected tsunami inundation depths for Homer, AK

Kodiak, AK

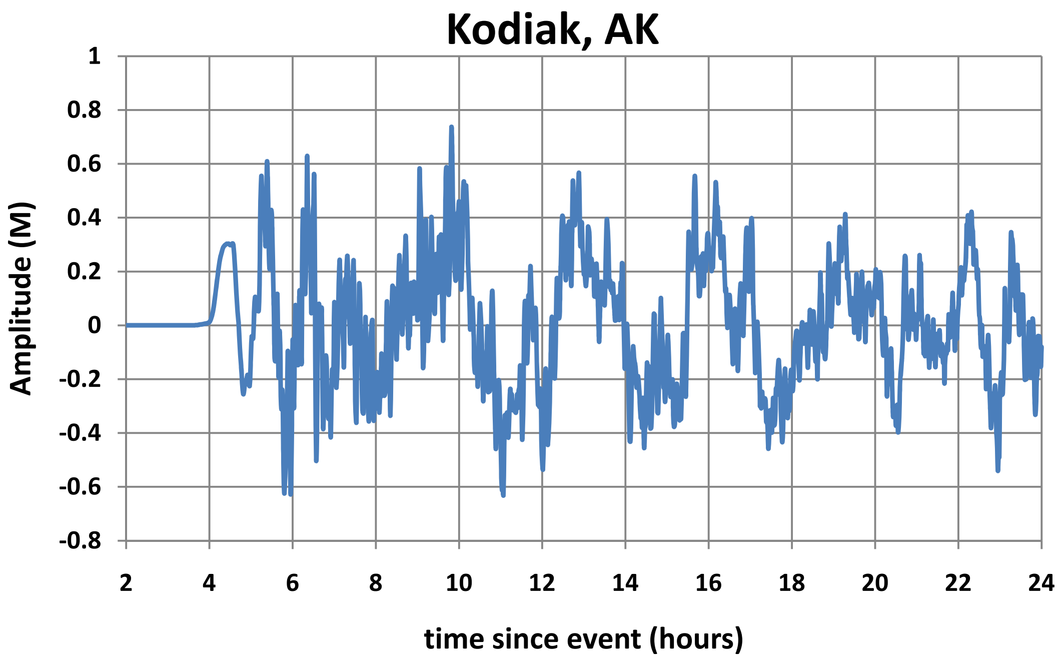

Figure D-4. Kodiak, AK, seismic event marigram

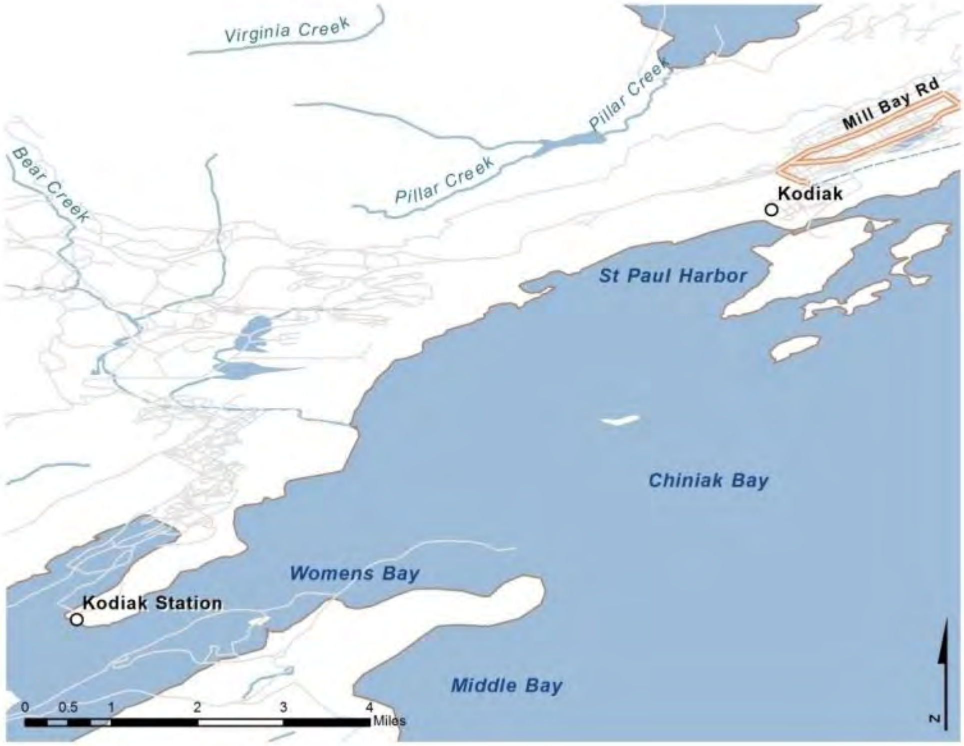

Figure D-5. No expected tsunami inundation or building stability rating for Kodiak, AK

Nikolski, AK

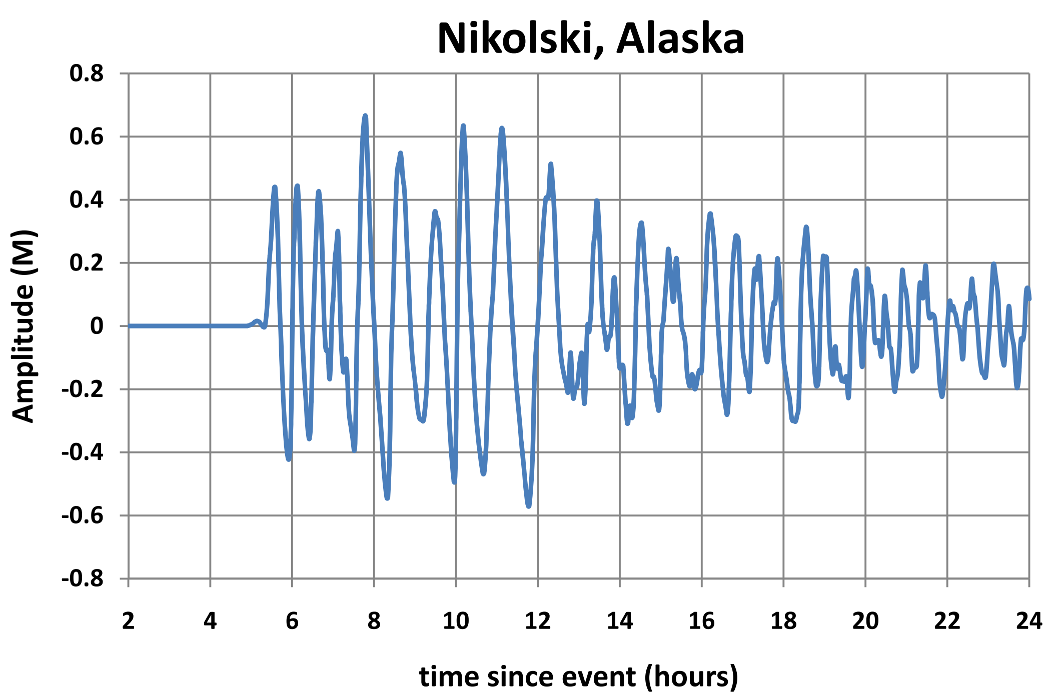

Figure D-6. Nikolski, AK, seismic event marigram

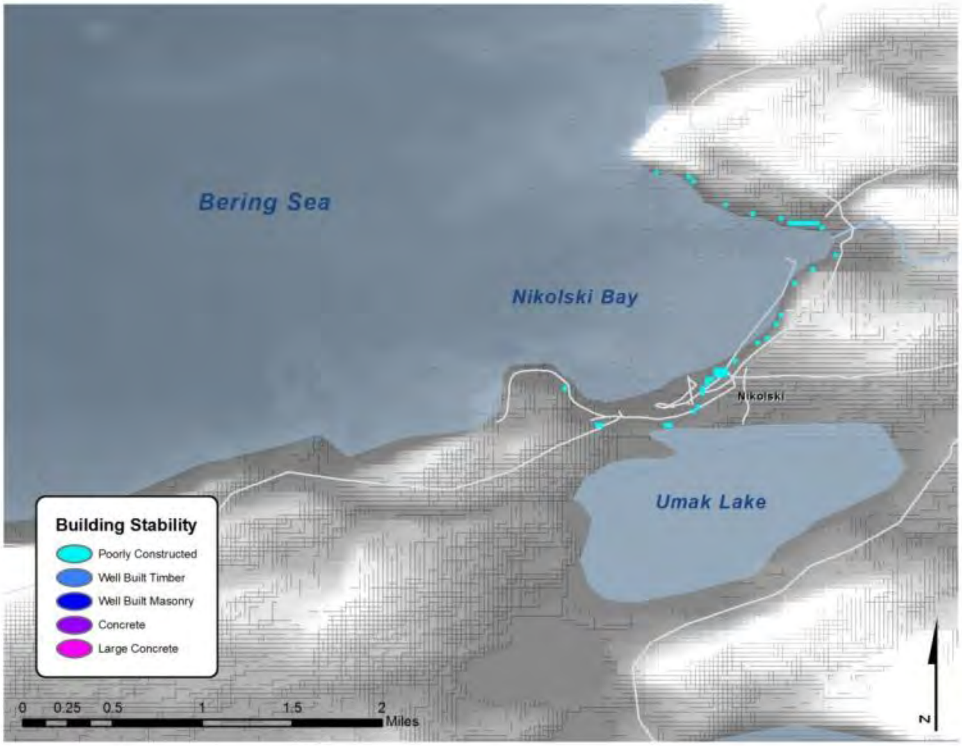

Figure D-7. Predicted building stability rating for Nikolski, AK

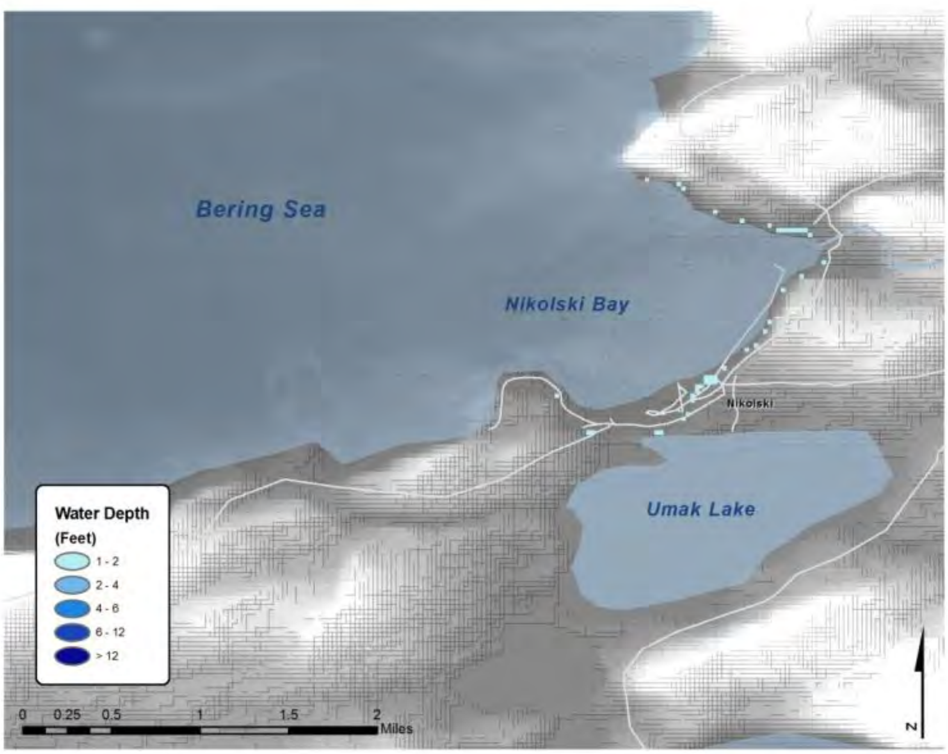

Figure D-8. Expected tsunami inundation depths for Nikolski, AK

Sand Point, AK

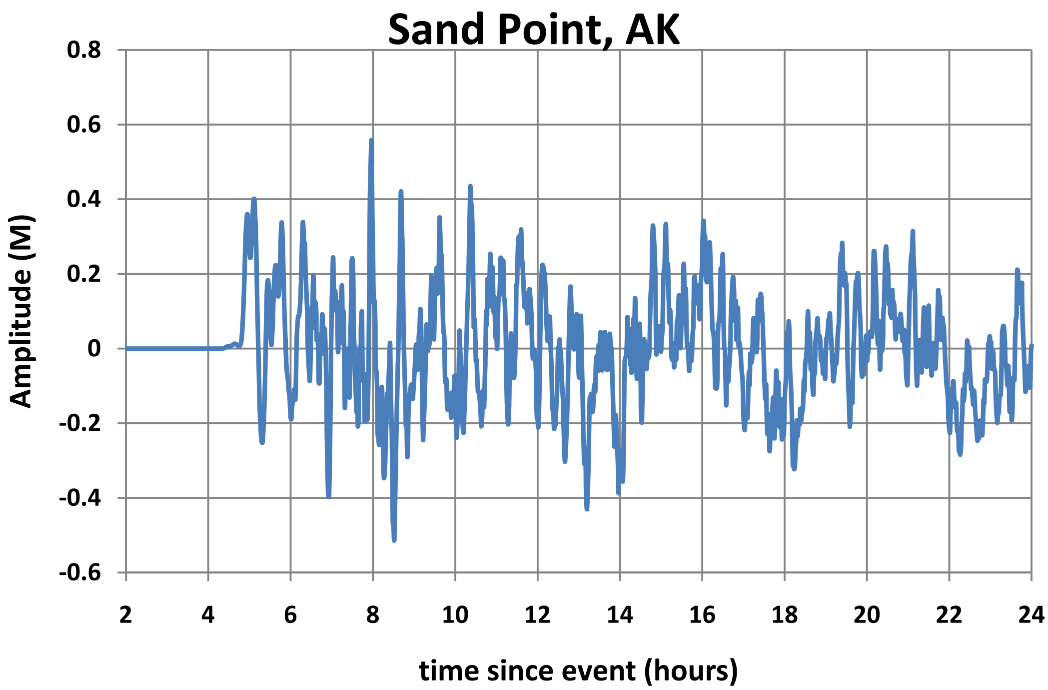

Figure D-9. Sand Point, AK, seismic event marigram

Figure D-10. Expected tsunami inundation depths for Sand Point, AK

Figure D-11. Predicted building stability rating for Sand Point, AK

Seward, AK

NOTE: Geospatial population and economic data do not extend to Seward, AK.

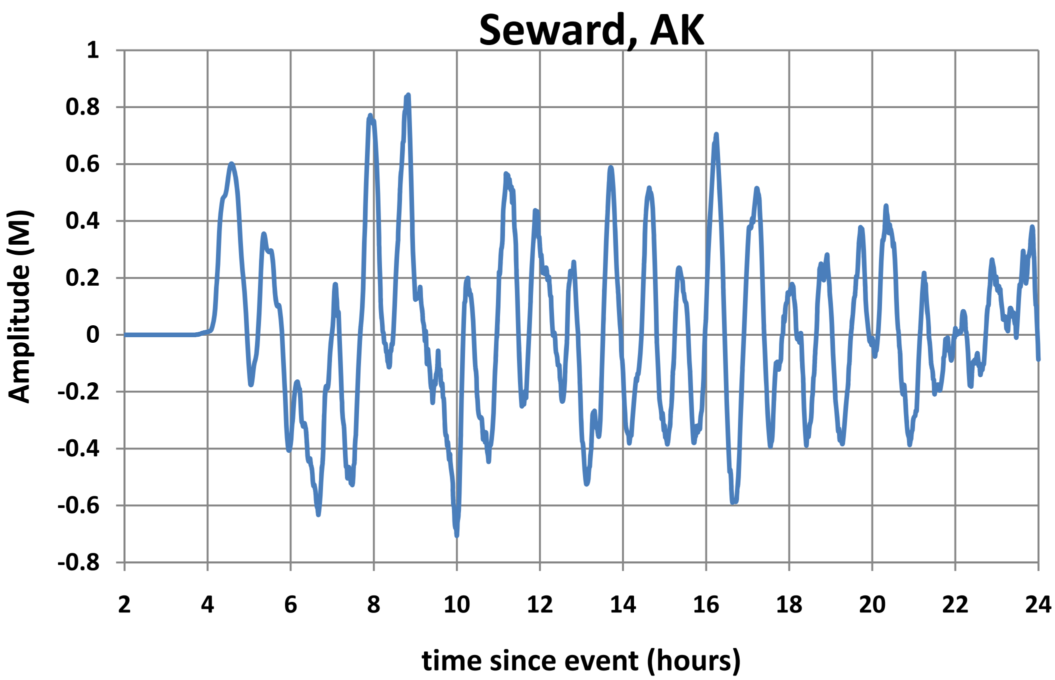

Figure D-12. Seward, AK, seismic event marigram

Figure D-13. No expected tsunami inundation or building stability rating for Seward, AK

Sitka, AK, Direct Infrastructure Impacts Analysis

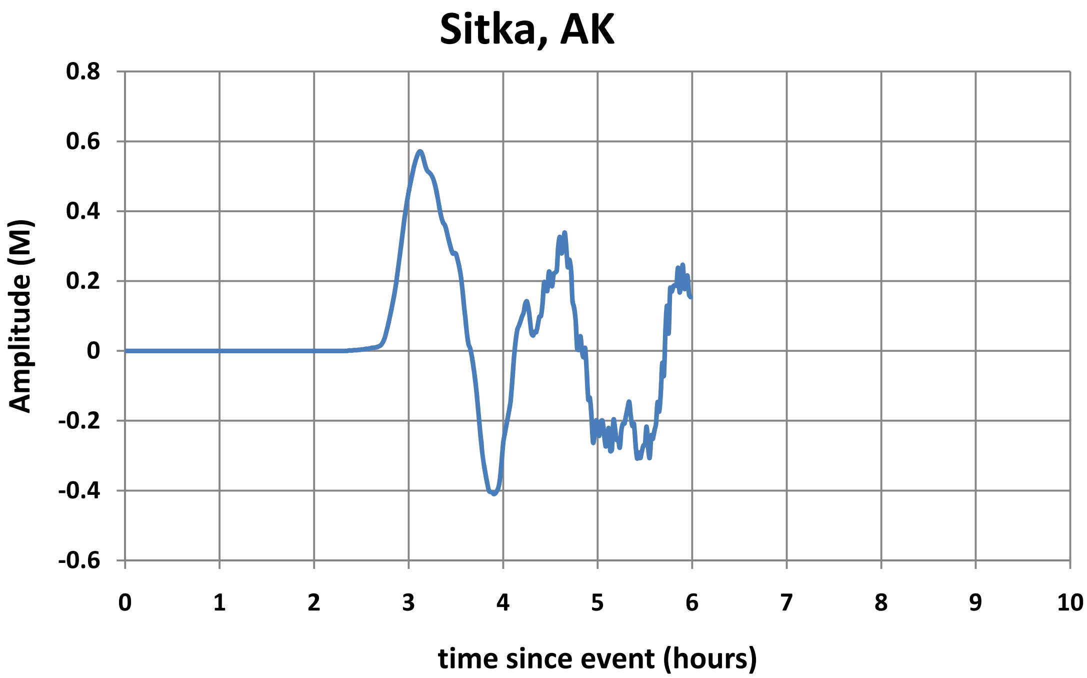

Figure D-14. Sitka, AK, seismic event marigram

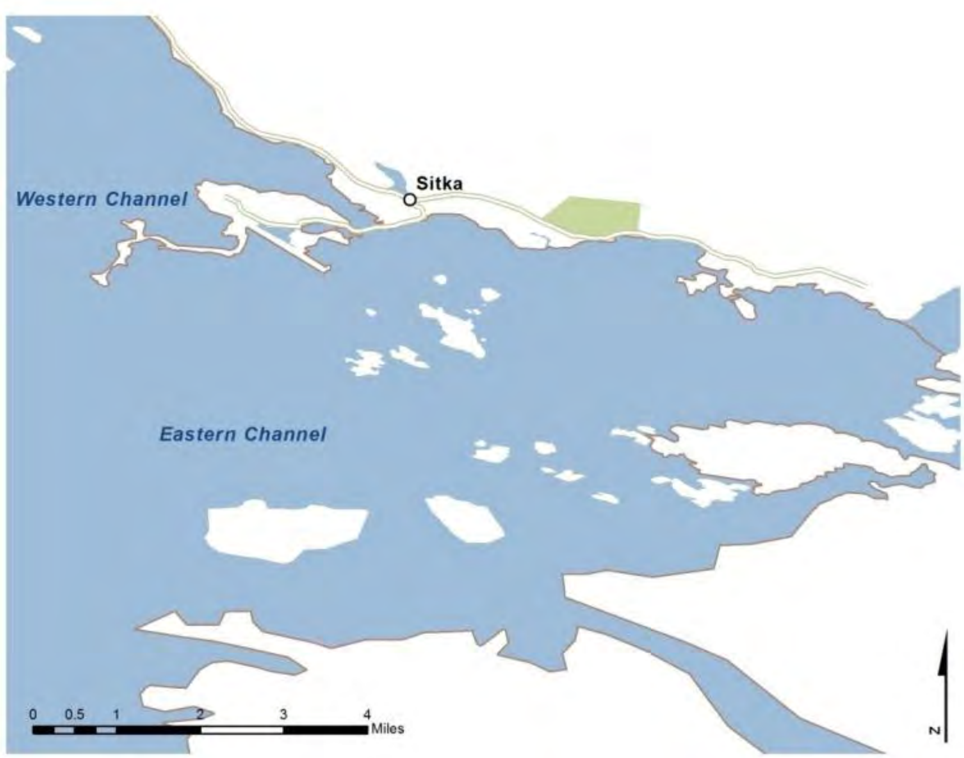

Figure D-15. No expected tsunami inundation or building stability rating for Sitka, AK

Unalaska, AK

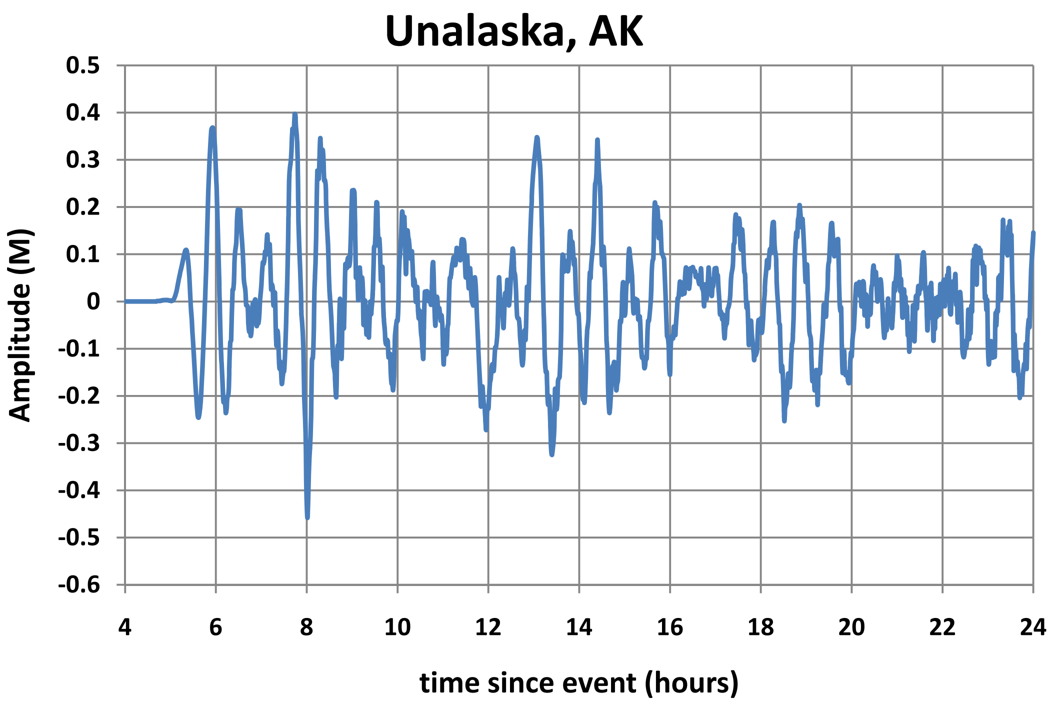

Figure D-16. Unalaska, AK, seismic event marigram

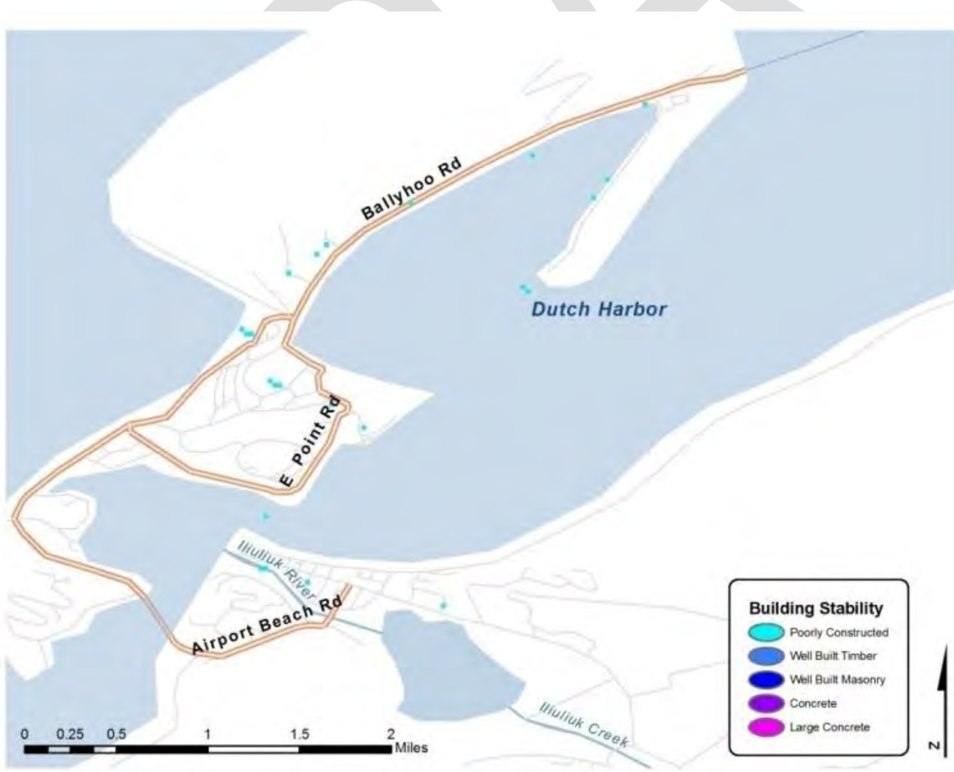

Figure D-17. Predicted building stability rating for Unalaska, AK

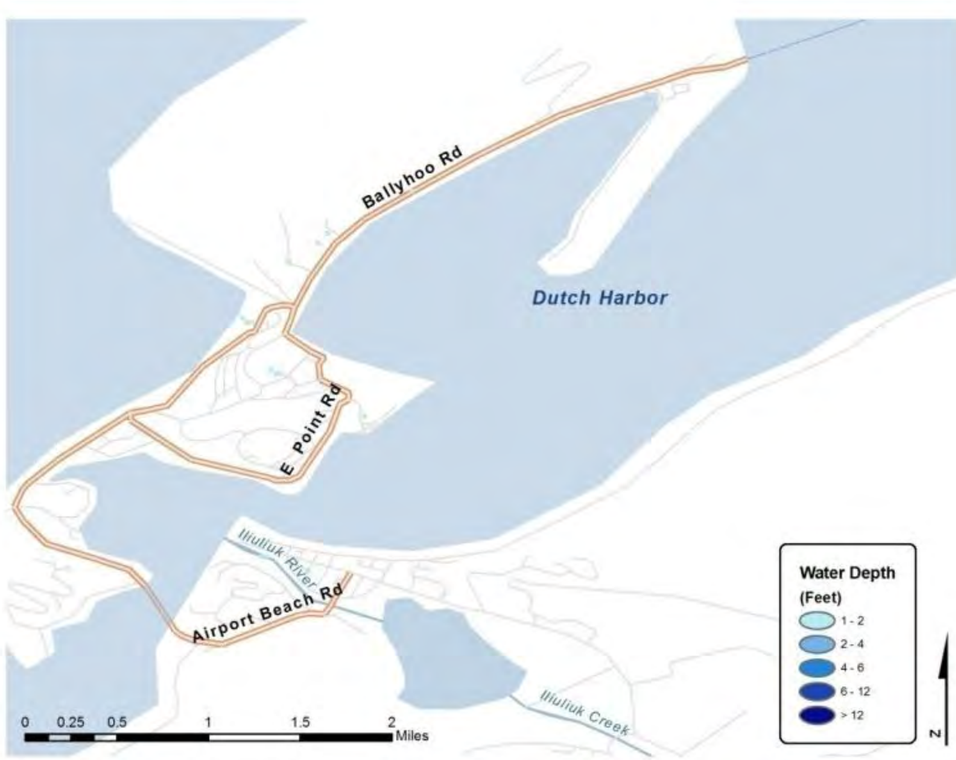

Figure D-18. Expected tsunami inundation depths for Unalaska, AK

Yakutat, AK

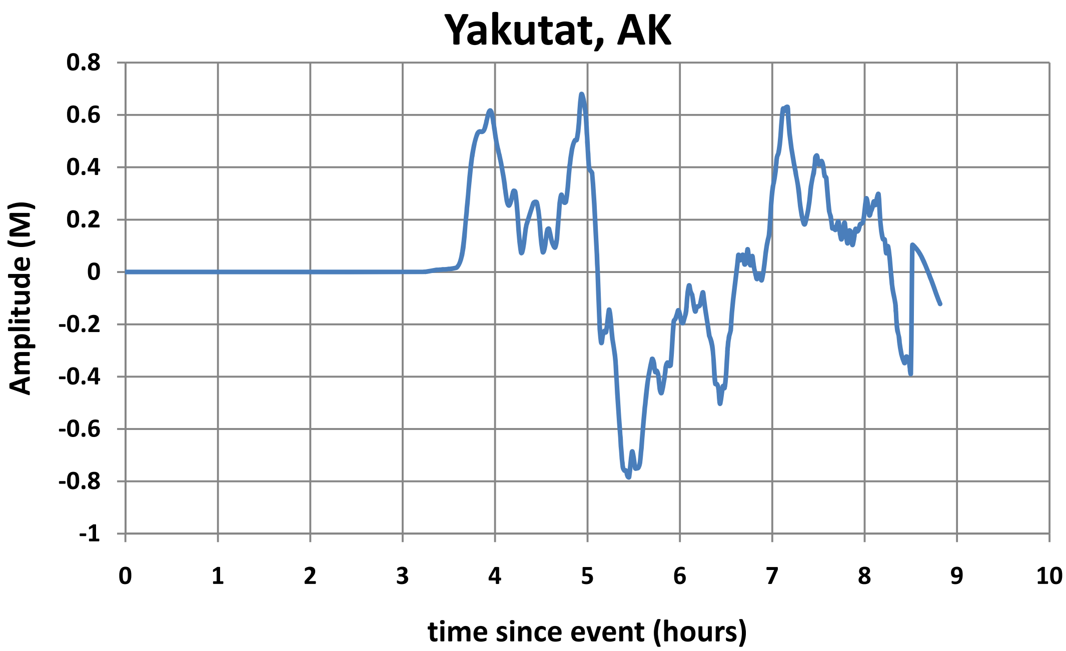

Figure D-19. Yakutat, AK, seismic event marigram

Figure D-20. No expected tsunami inundation or building stability rating for Yakutat, AK

California
Crescent City, CA

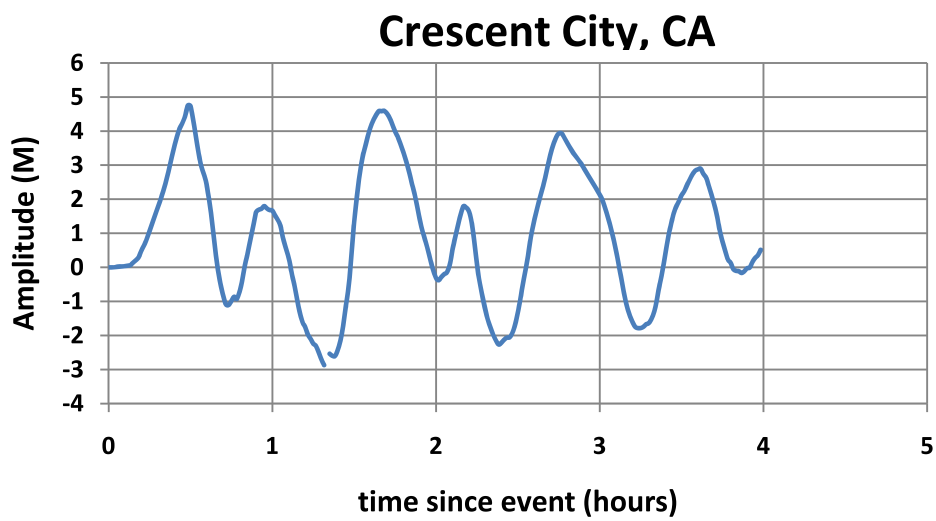

Figure D-21. Crescent City, CA, seismic event marigram

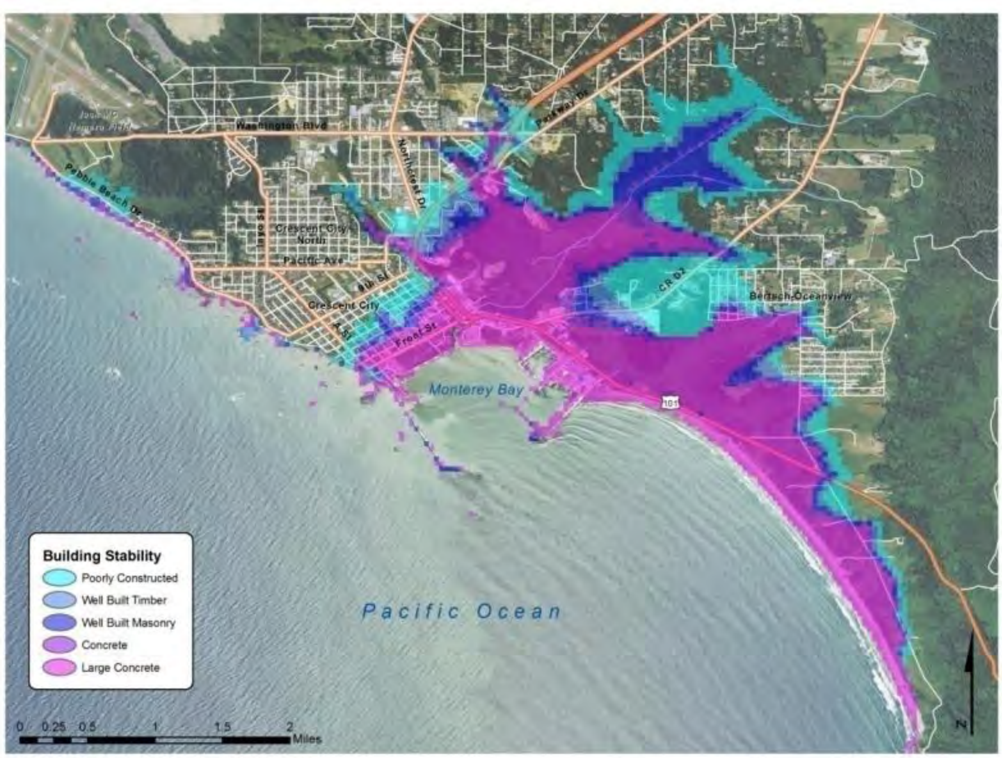

Figure D-22. Predicted building stability rating for Crescent City, CA

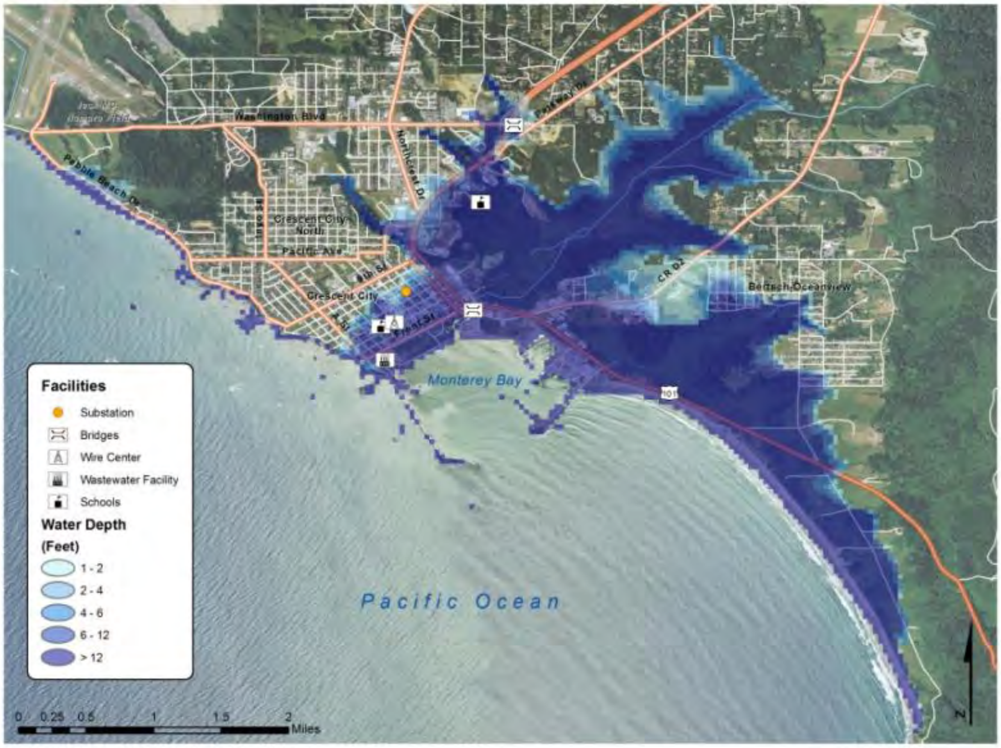

Figure D-23. Expected tsunami inundation depths and facility impacts for Crescent City, CA

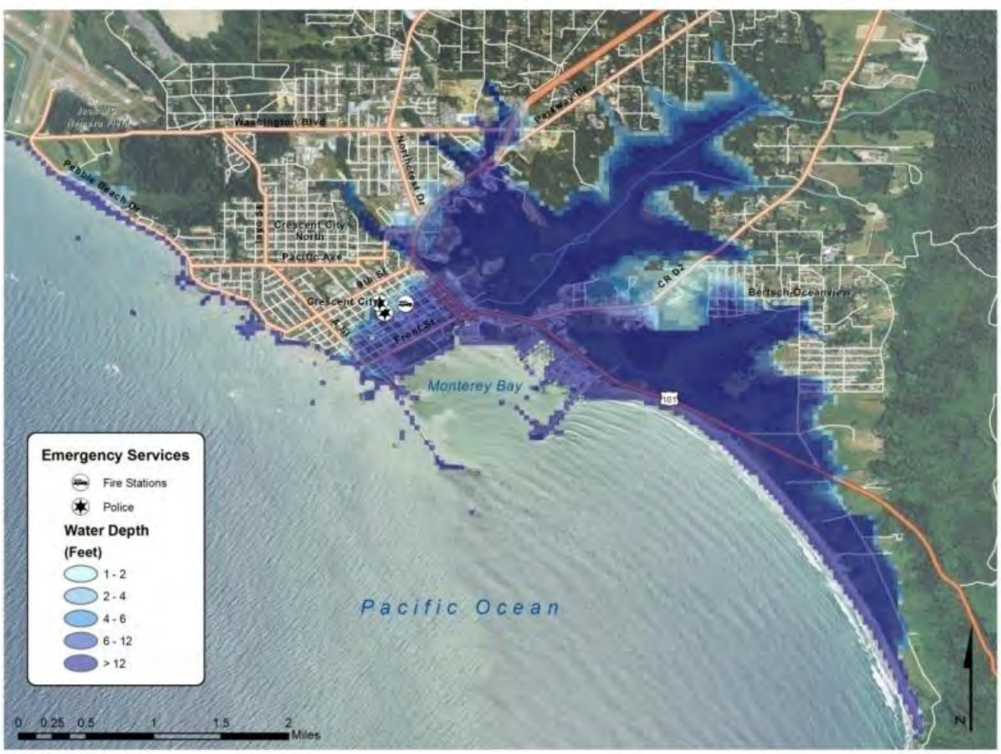

Figure D-24. Expected tsunami inundation and emergency service impacts for Crescent City, CA

Table D-1. Population at Risk in Crescent City, CA

Population Impacts	Number of Population at Risk (PAR)
Nighttime PAR	3,190
Daytime PAR	5,180
Injuries	780
Deaths	910

Table D-2. Impacted assets in Crescent City, CA

Sector	# Facilities
Water/Wastewater	1
Emergency Services	4
Transportation	8
Schools	3
Energy	1
Telecommunications	1

Table D-3. Impacted Schools in Crescent City, CA

Name	Address	Flood Depth (feet)	Building Stability Category
St. Joseph Elementary School	300 East Street	6 - 12	Well-built Timber
Elk Creek Elementary School	1115 Williams Drive	6 - 12	Well-built Masonry
McCarthy Community Center	1115 Williams Drive	6 - 12	Well-built Masonry

Table D-4. Impacted Emergency Services in Crescent City, CA

Name	Address	Flood Depth (feet)	Building Stability Category
Del Norte County Sheriff's Department	650 5th Street	6 - 12	Well-built Masonry
Crescent City Volunteer Fire Department	520 I Street	6 - 12	Well-built Timber
California Highway Patrol - Crescent City	1444 Parkway Drive	2 - 4	Poorly Constructed
Crescent City Police Department	686 G Street	2 - 4	Poorly Constructed

Table D-5. Impacted Water/Wastewater Services in Crescent City, CA

Name	Address	Flood Depth (feet)	Building Stability Category
Crescent City Water and Wastewater Treatment Plant	277 Battery Street	> 12	Large Concrete

Table D-6. Impacted Telecommunications in Crescent City, CA

Name	Flood Depth (feet)	Building Stability Category
Telecom #1	> 12	Concrete

Table D-7. Impacted Transportation Services in Crescent City, CA

Road Name	Bridge Name	Flood Depth (feet)	Building Stability Category
U.S. Hwy 101	n/a	> 12	Large Concrete
Front Street	n/a	> 12	Large Concrete
A Street	n/a	> 12	Large Concrete
Washington Boulevard	n/a	> 12	Large Concrete
Pacific Avenue	n/a	> 12	Large Concrete
Elk Valley Road	n/a	> 12	Large Concrete
U.S. Hwy 101	Washington Blvd Bridge	6 - 12	Poorly Constructed
U.S. Hwy 101	Elk Creek Bridge	> 12	Large Concrete

Table D-8. Impacted Energy Services in Crescent City, CA

Name	Flood Depth (feet)	Building Stability Category
Northcoast	6 - 12	Poorly Constructed

Eureka-Humboldt, CA

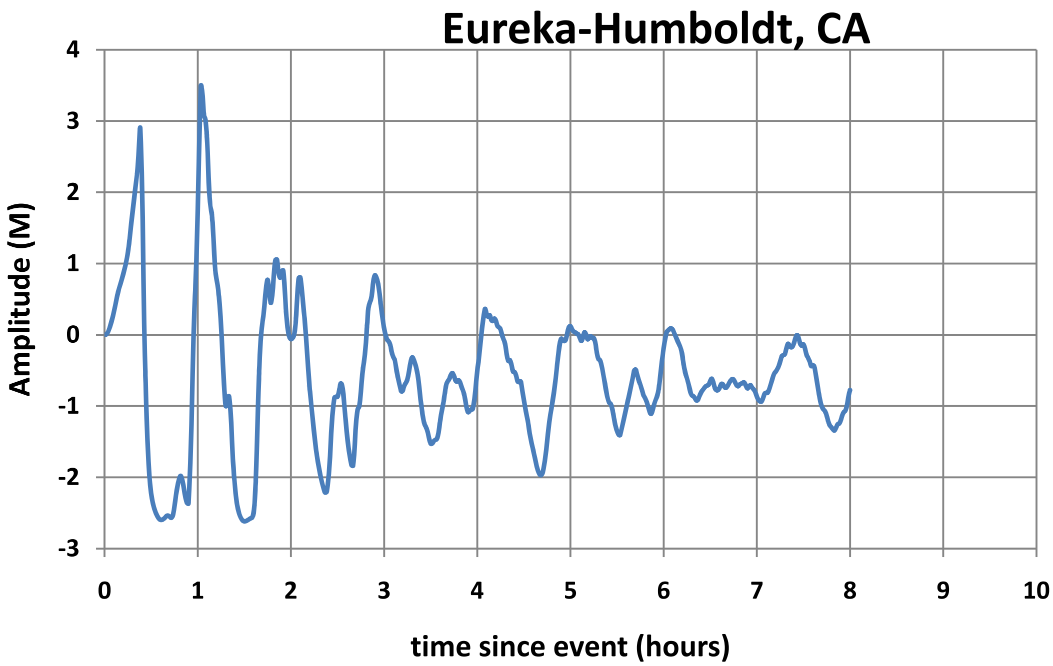

Figure D-25. Eureka-Humboldt, CA, seismic event marigram

Figure D-26. Predicted building stability rating for Eureka-Humboldt, CA

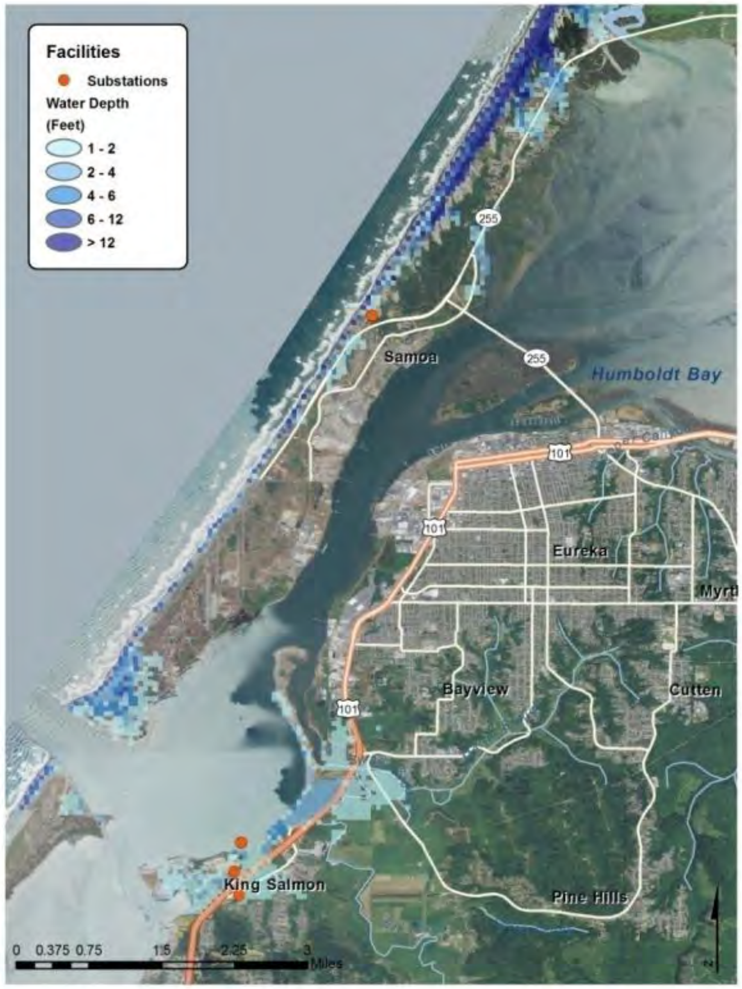

Figure D-27. Expected tsunami inundation depths and facility impacts for Eureka-Humboldt, CA

Table D-9. Population at Risk in Eureka-Humboldt, CA

Population Impacts	# People
Nighttime PAR	180
Daytime PAR	180
Injuries	20
Deaths	10

Table D-10. Impacted Assets in Eureka-Humboldt, CA

Sector	# Facilities
Energy	4
Transportation	2

Table D-11. Impacted Energy Service for Eureka-Humboldt, CA

Name	Flood Depth (Feet)	Building Stability Category
Humboldt	6 - 12	Well-built Timber
Humboldt-B	2 - 4	Poorly Constructed
Humboldt -By	0 - 1	Poorly Constructed
LP JCT	0 - 1	Poorly Constructed

Table D-12. Impacted Transportation Services in Eureka-Humboldt, CA

Road Name	Flood Depth (Feet)	Building Stability Category
U.S. Highway 101	2 - 4	Poorly Constructed
State Road 255	2 - 4	Poorly Constructed

Oregon
Cannon Beach, OR

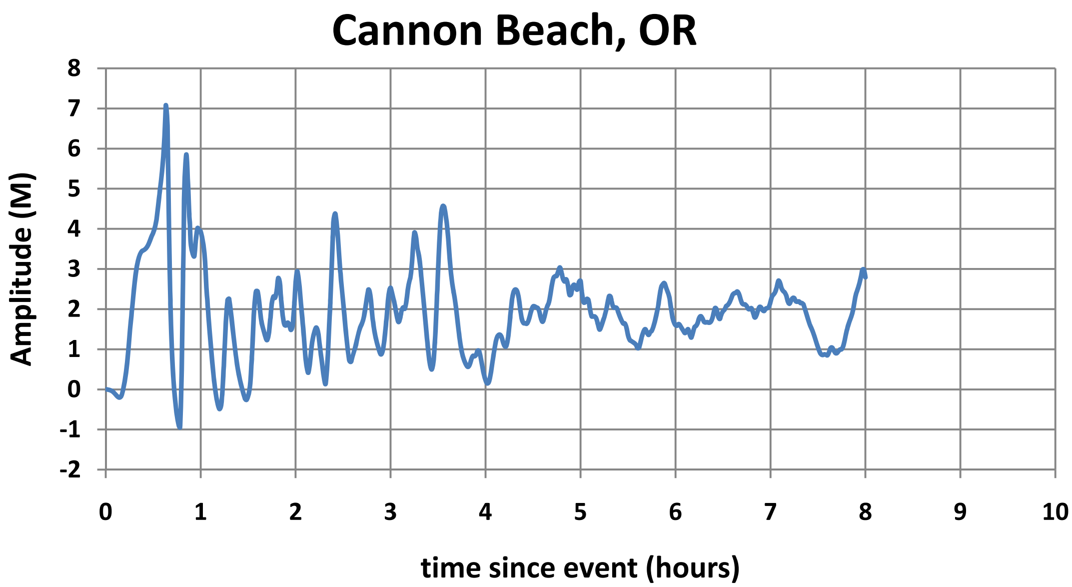

Figure D-28. Cannon Beach, OR, seismic event marigram

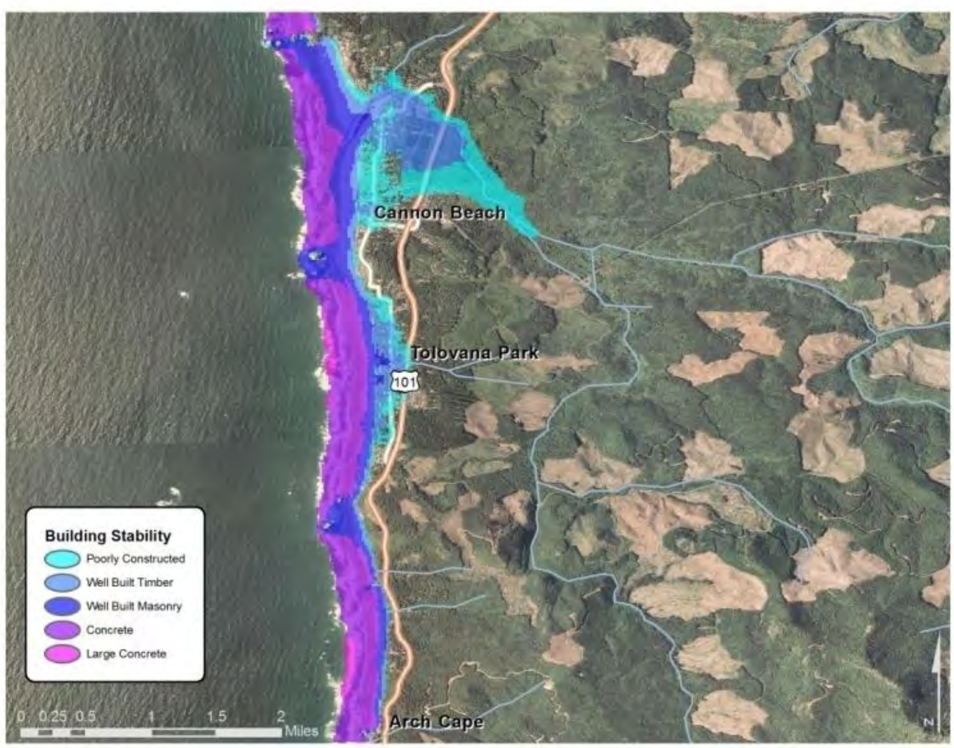

Figure D-29. Predicted building stability rating for Cannon Beach, OR

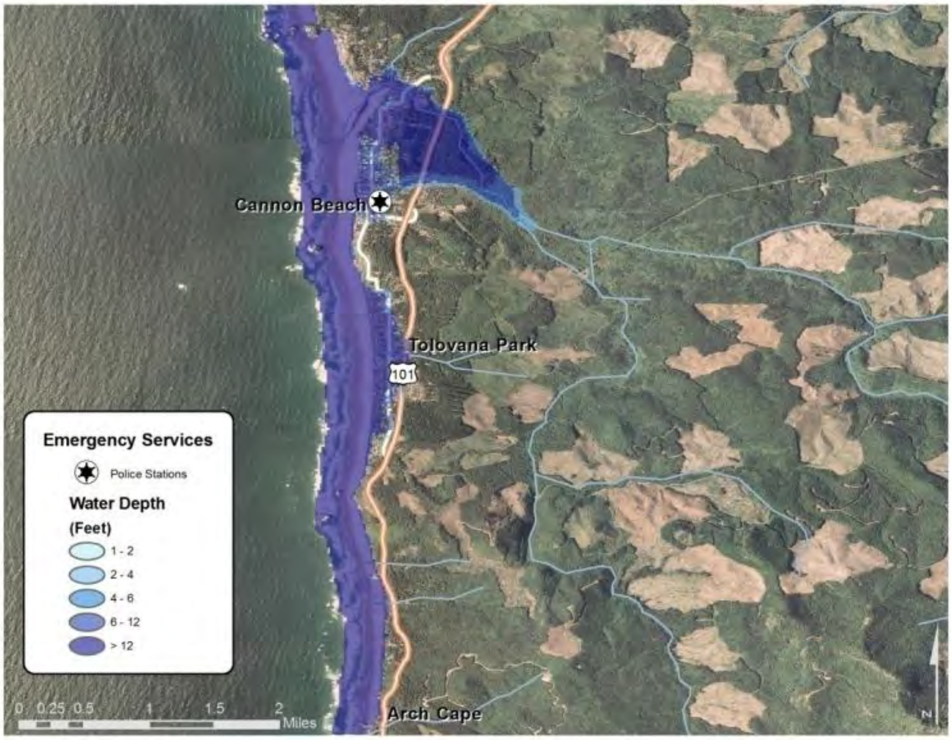

Figure D-30. Expected tsunami inundation depths and emergency service impacts for Cannon Beach, OR

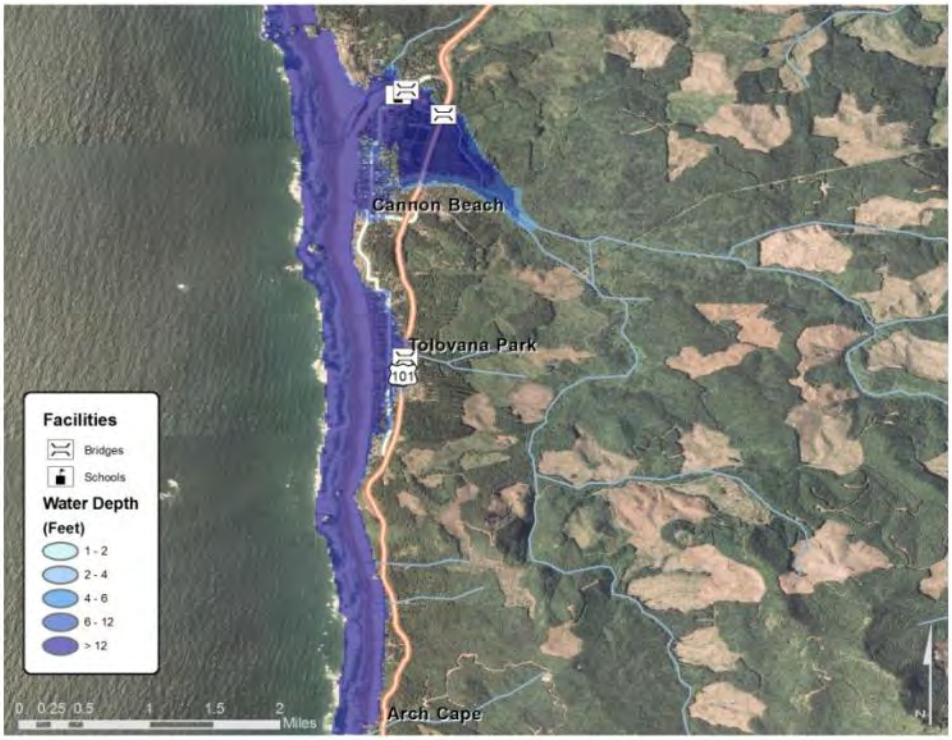

Figure D-31. Expected tsunami inundation depths and facility impacts for Cannon Beach, OR

Table D-13. Population at Risk in Cannon Beach, OR

Population Impacts	# People
Nighttime PAR	370
Daytime PAR	990
Injuries	110
Deaths	240

Table D-14. Impacted assets in Cannon Beach, OR

Asset	# Facilities
Emergency Services	1
Transportation	4
Schools	1

Table D-15. Impacted Schools in Cannon Beach, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Cannon Beach Elementary	268 Beaver Street	> 12	Well-built Timber

Table D-16. Impacted Emergency Services in Cannon Beach, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Cannon Beach Police Department	163 East Gower Street	0 - 1	Poorly Constructed

Table D-17. Impacted Transportation Services in Cannon Beach, OR

Road Name	Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. Hwy 101	n/a	> 12	Well-built Timber
U.S. Hwy 101	Warren Street Bridge	> 12	Poorly Constructed
U.S. Hwy 101	Ecola Creek Bridge	> 12	Well-built Timber
Alternate - U.S. Hwy 101	Ecola Creek Bridge #2	> 12	Well-built Timber

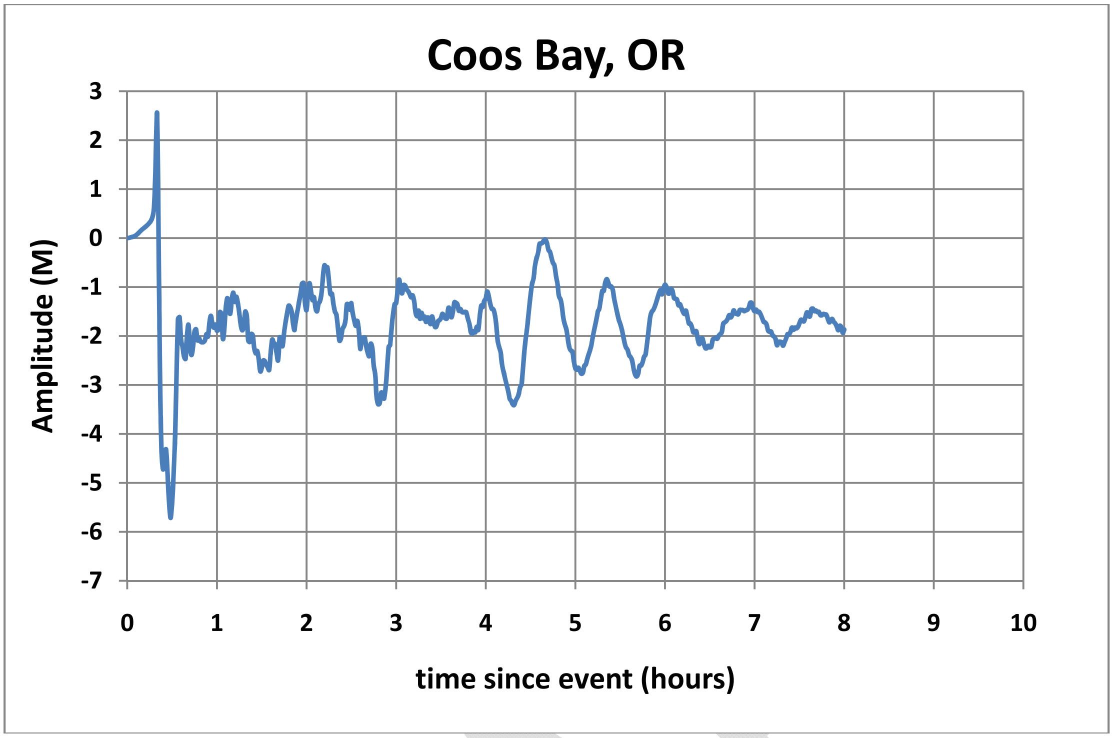

Figure D-32. Coos Bay, OR, seismic event marigram

Figure D-33. Predicted building stability rating for Coos Bay, OR

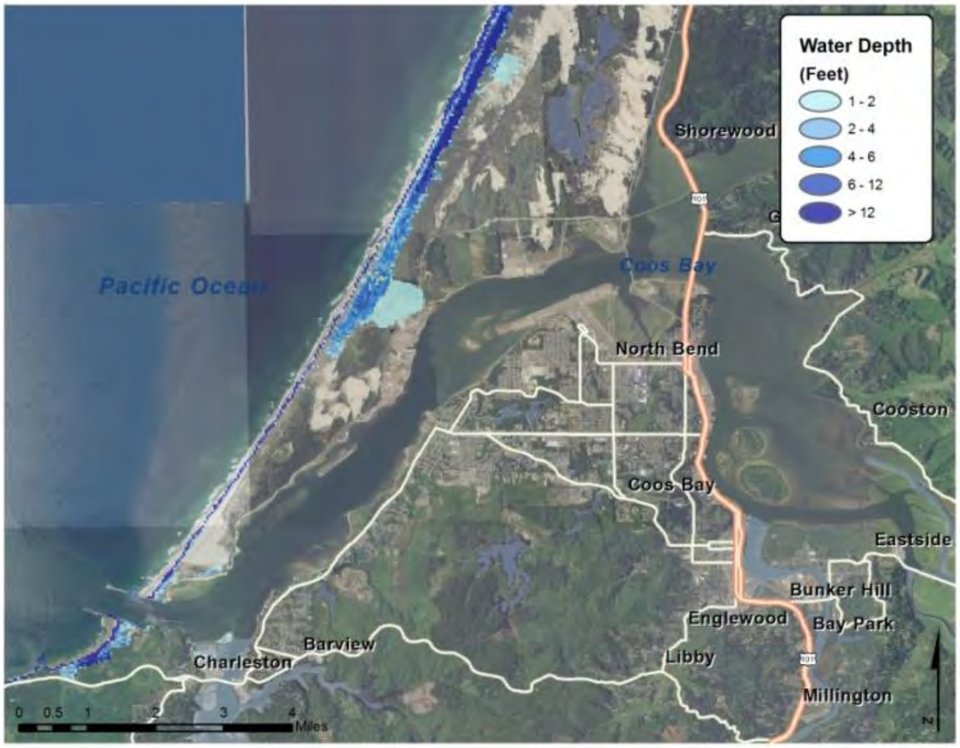

Figure D-34. Expected tsunami inundation depths for Coos Bay, OR

Table D-18. Population at Risk in Coos Bay, OR

Population Impacts	# People
Nighttime PAR	210
Daytime PAR	150
Injuries	30
Deaths	30

East Astoria, OR

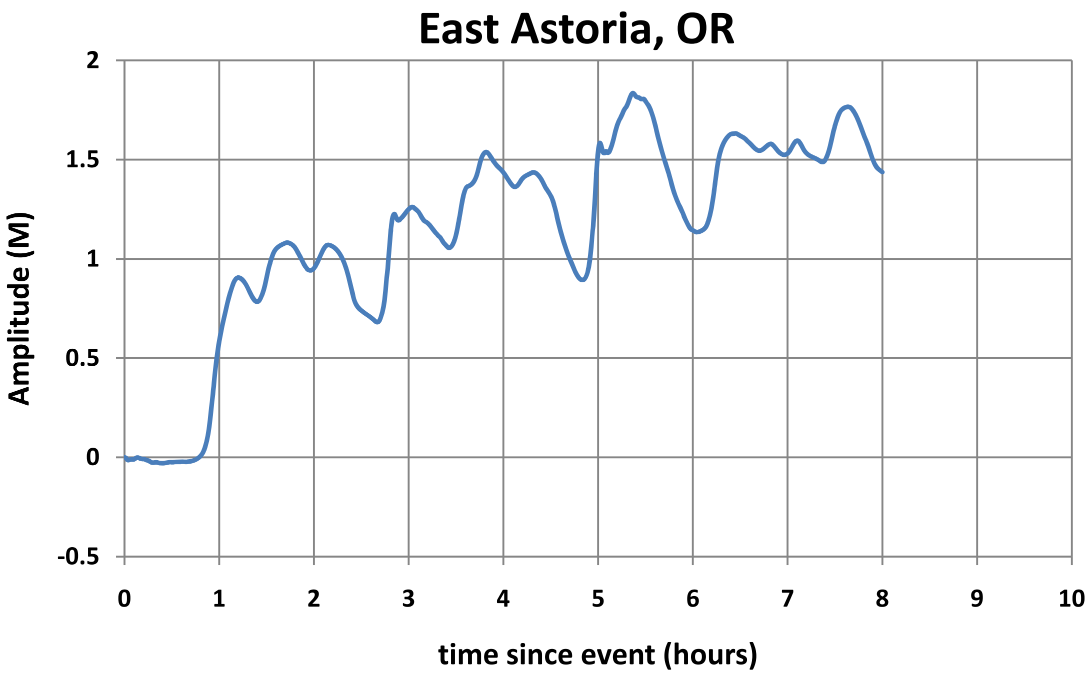

Figure D-35. East Astoria, OR, seismic event marigram

Figure D-36. Predicted building stability rating for East Astoria, OR

Figure D-37. Expected tsunami inundation depths and emergency service impacts for East Astoria, OR

Figure D-38. Expected tsunami inundation and facility impacts for East Astoria, OR

Table D-19. Population at Risk in East Astoria, OR

Population Impacts	# People
Nighttime PAR	820
Daytime PAR	960
Injuries	20
Deaths	10

Table D-20. Impacted assets in East Astoria, OR

Sector	# Facilities
Energy	1
Transportation	4
Emergency Services	4
Water/Wastewater	1

Table D-21. Impacted Energy Facilities for East Astoria, OR

Name	Flood Depth (Feet)	Building Stability Category
Yungsbay Substation	2 - 4	Poorly Constructed

Table D-22. Impacted Emergency Services in East Astoria, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Warrenton Police Department	225 South Main Avenue, Warrenton	0 - 1	Poorly Constructed
Warrenton Fire Department	225 South Main Avenue, Warrenton	0 - 1	Poorly Constructed
Lewis & Clark Rural Fire Dept.	34571 U.S. Highway 105	4 - 6	Poorly Constructed
Oregon State Police	413 Gateway Avenue, Astoria	0 - 1	Poorly Constructed

Table D-23. Impacted Transportation Services in East Astoria, OR

Road Name	Flood Depth (Feet)	Building Stability Category
U.S. Hwy 101	6 - 12	Well-built Timber
State Road 202	6 - 12	Well-built Timber
Warrenton Astoria Road	0 - 1	Poorly Constructed
Fort Stevens Road	0 - 1	Poorly Constructed

Table D-24. Impacted Water/Wastewater Services in East Astoria, OR

Name	Flood Depth (Feet)	Building Stability Category
City of Warrenton Public Water Supply	6 - 12	Poorly Constructed

Newport, OR

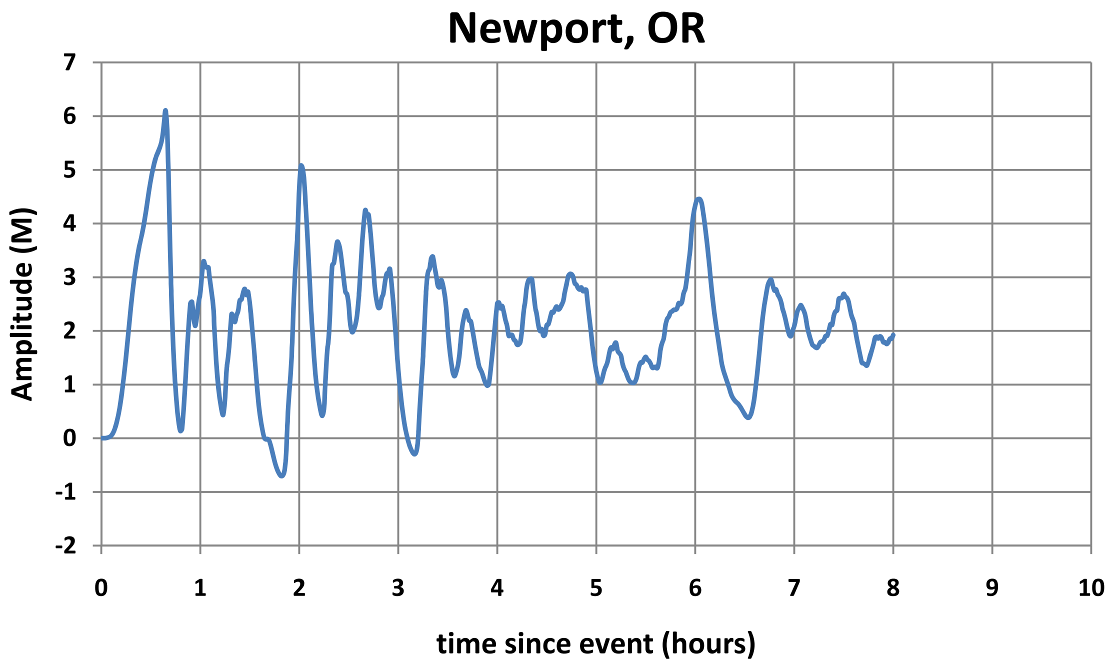

Figure D-39. Newport, OR, seismic event marigram

Figure D-40. Predicted building stability rating for Newport, OR

Figure D-41. Expected tsunami inundation and facility impacts for Newport, OR

Table D-25. Population at Risk in Newport, OR

Population Impacts	# People
Nighttime PAR	250
Daytime PAR	420
Injuries	50
Deaths	20

Table D-26. Impacted assets in Newport, OR

Sector	# Facilities
Transportation	1

Table D-27. Impacted Transportation Services in Newport, OR

Road Name	Bridge Name	Water Depth (feet)	Building Stability Category
U.S. Hwy 101	Yaquina Bay Bridge	6 - 12	Poorly Constructed

Port Orford, OR

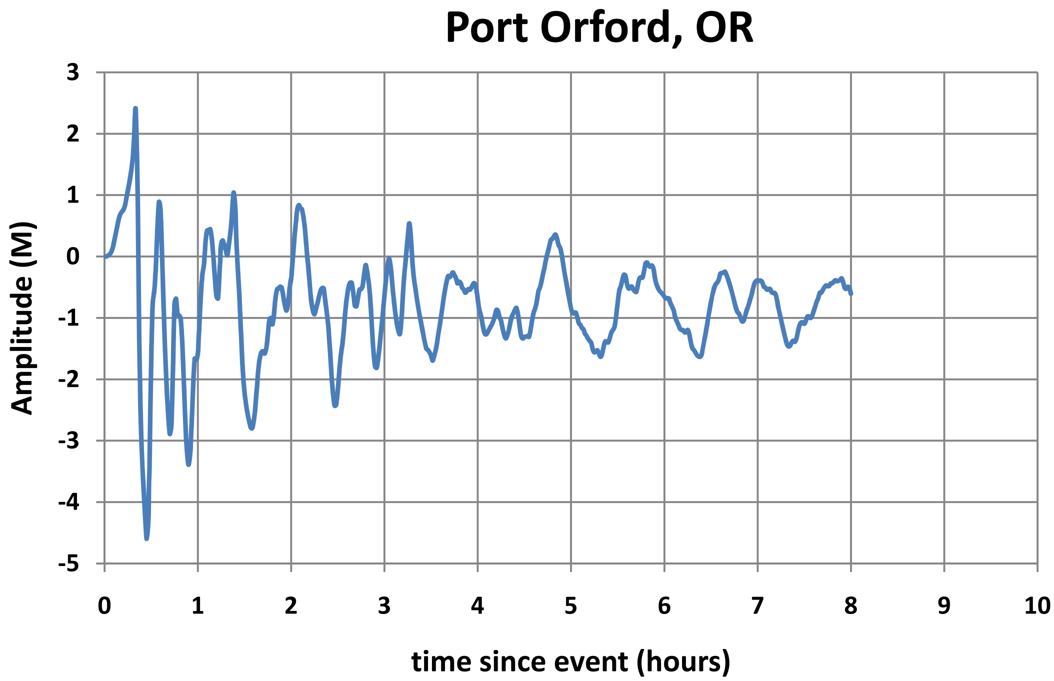

Figure D-42. Port Orford, OR, seismic event marigram

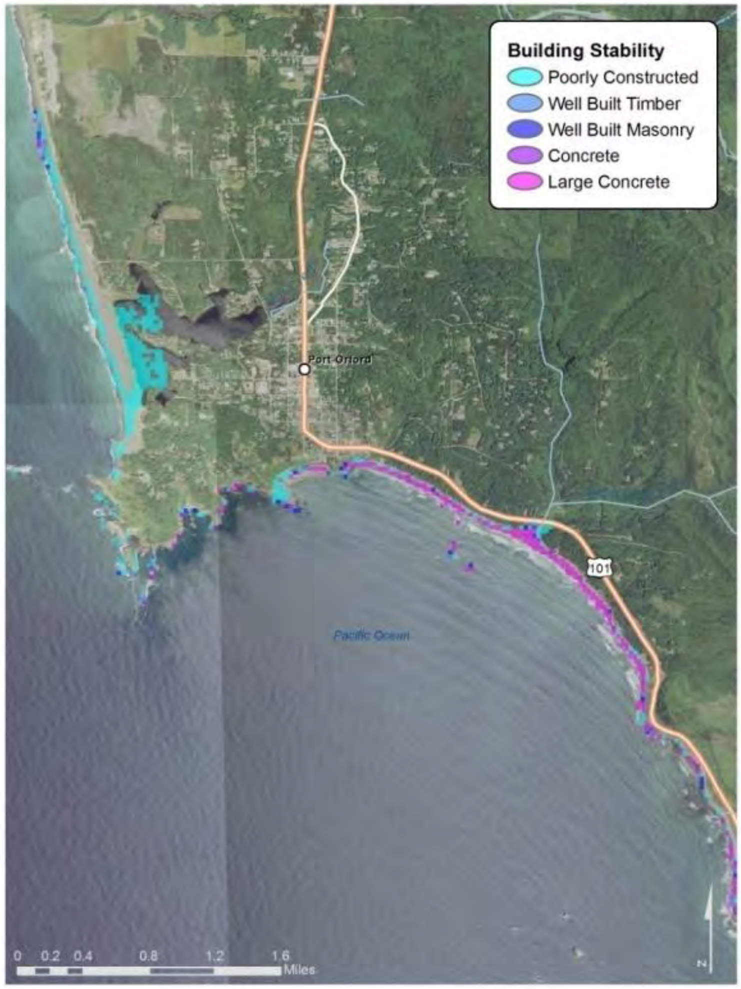

Figure D-43. Predicted building stability rating for Port Orford, OR

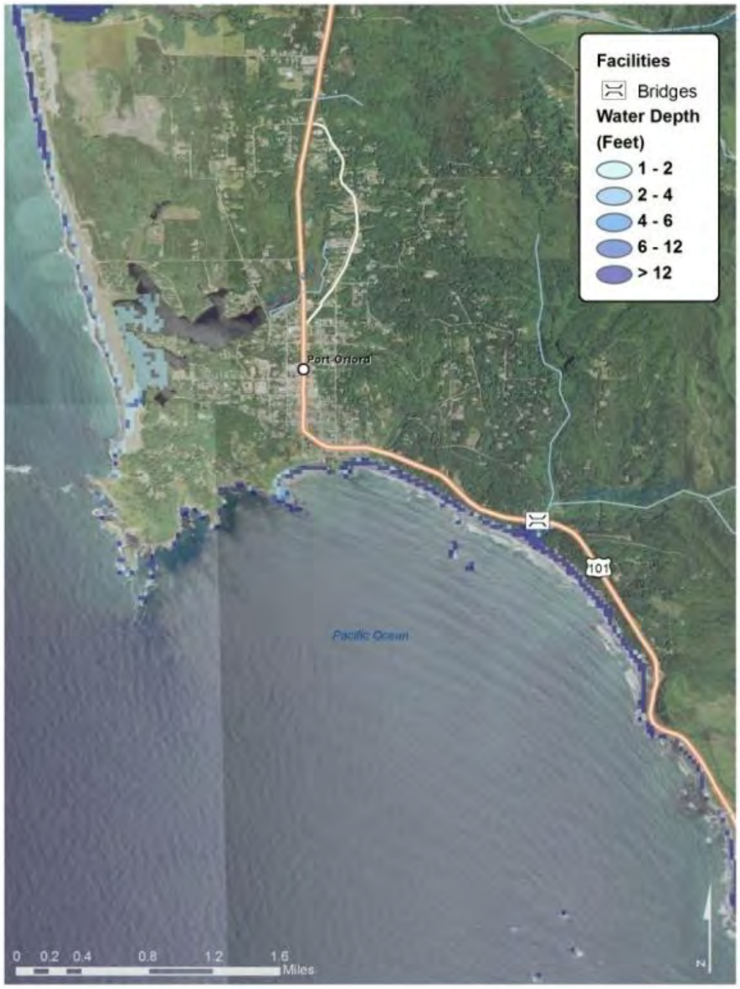

Figure D-44. Expected tsunami inundation and facility impacts for Port Orford, OR

Table D-28. Population at Risk in Port Orford, OR

Population Impacts	# People
Nighttime PAR	40
Daytime PAR	40
Injuries	10
Deaths	10

Table D-29. Impacted assets in Port Orford, OR

Sector	# Facilities
Transportation	1

Table D-30. Impacted Transportation Facilities in Port Orford, OR

Road Name	Bridge Name	Flood Depth (feet)
U.S. Hwy 101	Hubbard Creek Bridge	6 - 12

Gearhart/Seaside, OR

No directly associated marigram was available for this location.

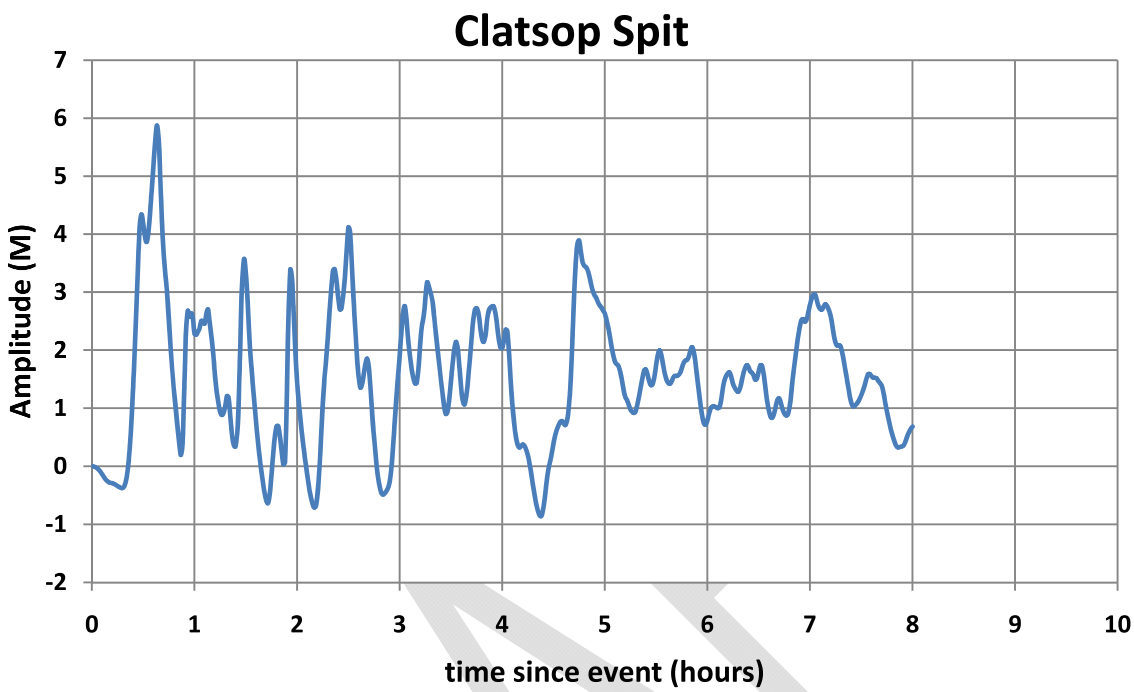

Figure D-45. Gearhart to Seaside, OR, seismic event marigram

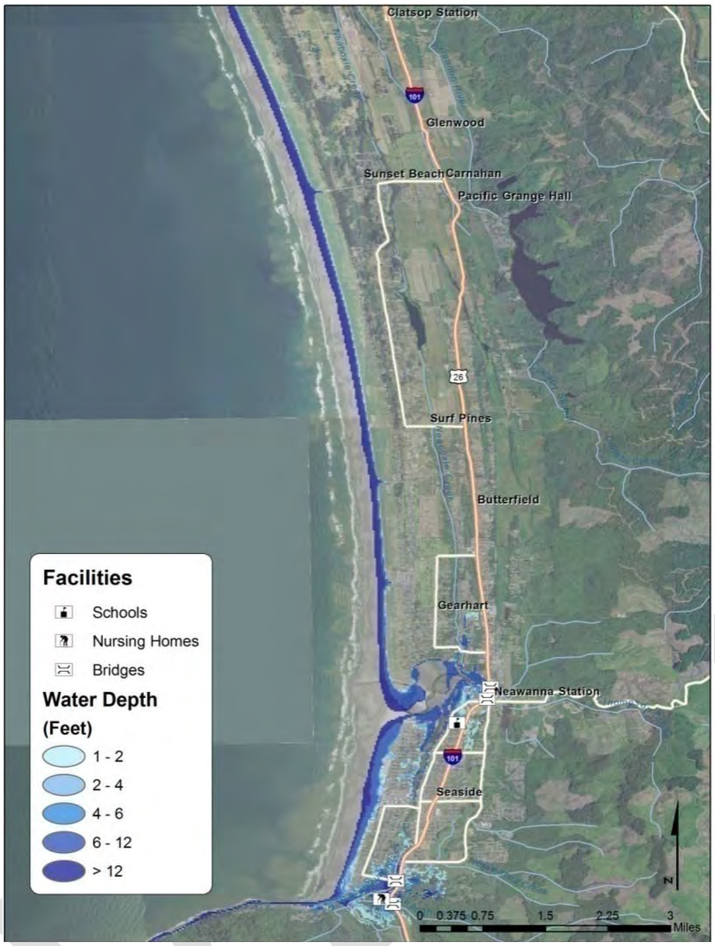

Figure D-46. Expected tsunami inundation and facility impacts for Gearhart to Seaside, OR

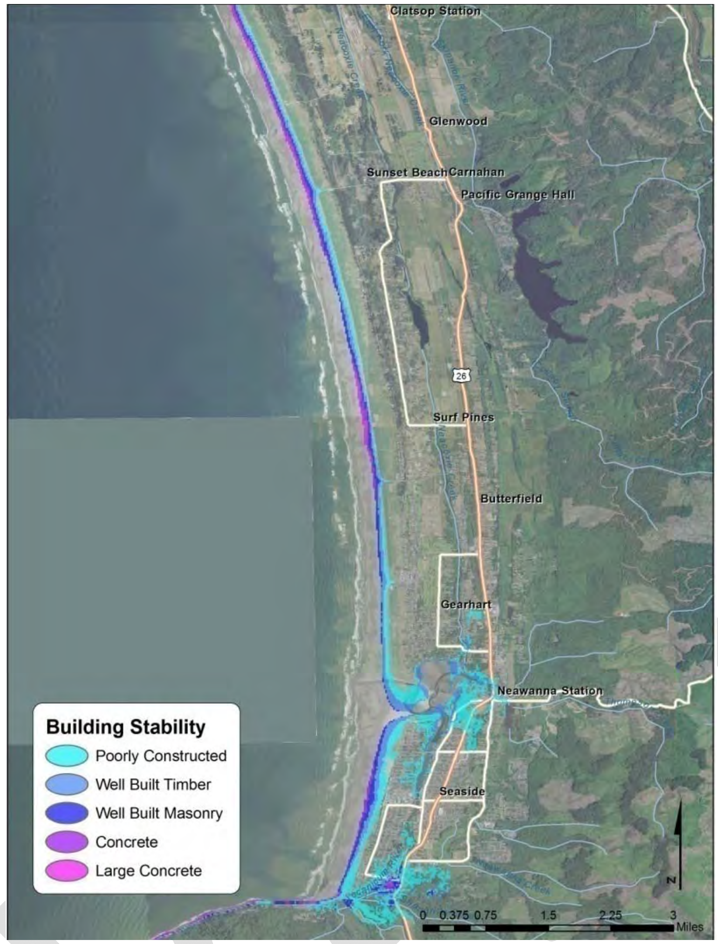

Figure D-47. Predicted building stability rating for Gearhart to Seaside, OR

Table D-31. Population at risk from Gearhart to Seaside, OR

Population Impacts	# People
Daytime PAR	730
Nighttime PAR	720
Injuries	50
Deaths	10

Table D-32. Impacted assets from Gearhart to Seaside, OR

Asset	# Impacted
Schools	1
Bridges	4
Major Roads	5
Nursing Homes	1

Table D-33. Impacted schools from Gearhart to Seaside, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Seaside High School	1901 North Holladay Drive	3	Poorly Constructed

Table D-34. Impacted nursing homes from Gearhart to Seaside, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Necanicum Village	2500 South Roosevelt Dr.	6 - 12	Well-built Timber

Table D-35. Impacted transportation facilities from Gearhart to Seaside, OR

Road Name	Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	n/a	6 - 12	Poorly Constructed
U.S. 101	Shangri La Creek Bridge	6 - 12	Poorly Constructed
U.S. 101	Mill Creek Bridge	0 - 2	Poorly Constructed
U.S. 101	Neawanna Creek Bridge	0 - 2	Poorly Constructed
Neacoxie Dr	n/a	2 - 4	Poorly Constructed
Lewis and Clark Road	n/a	0 - 2	Poorly Constructed
Avenue U	n/a	> 12	Well-built Timber
Avenue U	Necanicum River Bridge	> 12	Well-built Timber
North Wahanna Road	n/a	0 - 2	Poorly Constructed

Warrenton, OR

No directly associated marigram was available for this location.

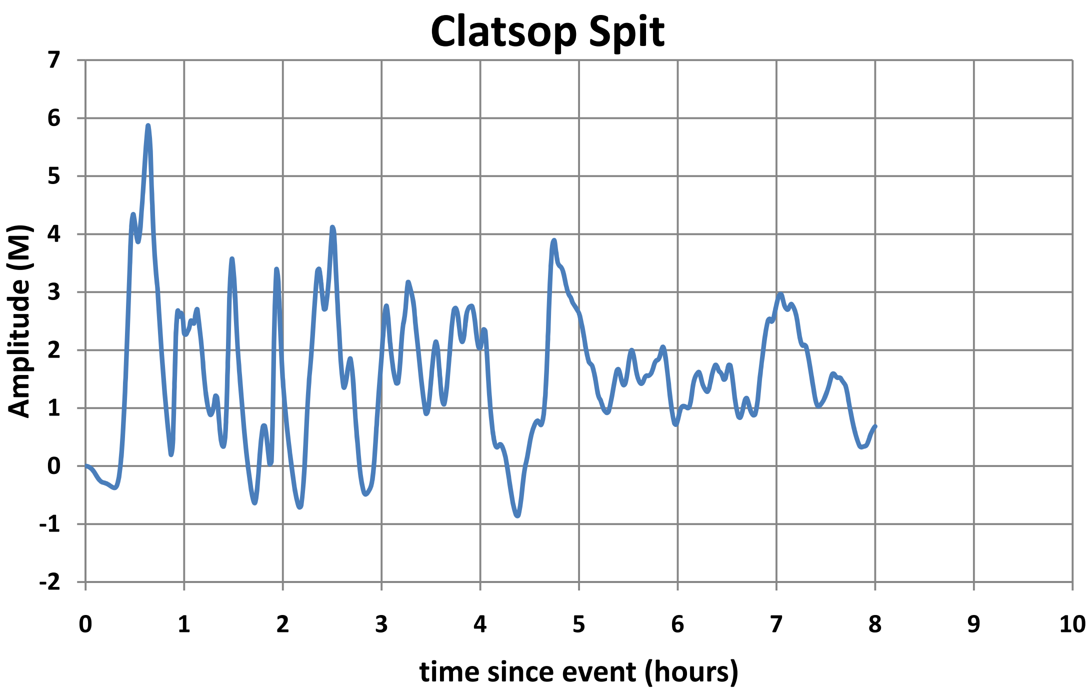

Figure D-48. Clatsop Spit, OR, seismic event marigram

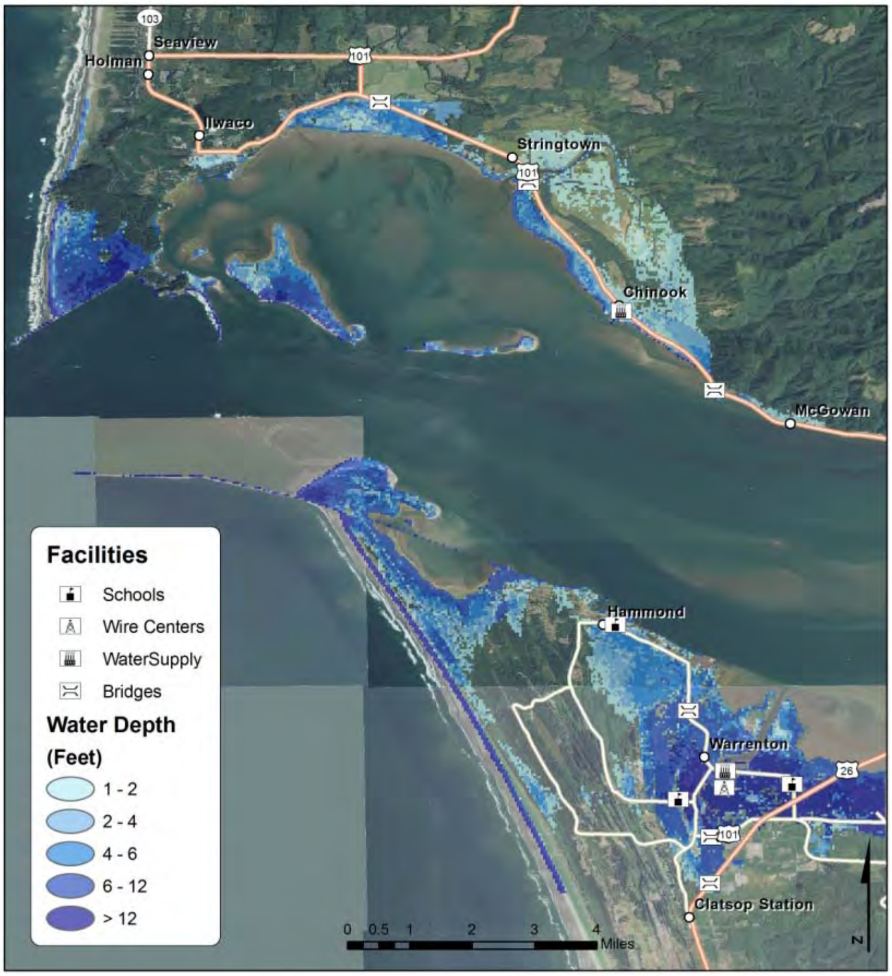

Figure D-49. Expected tsunami inundation and facility impacts for Warrenton, OR

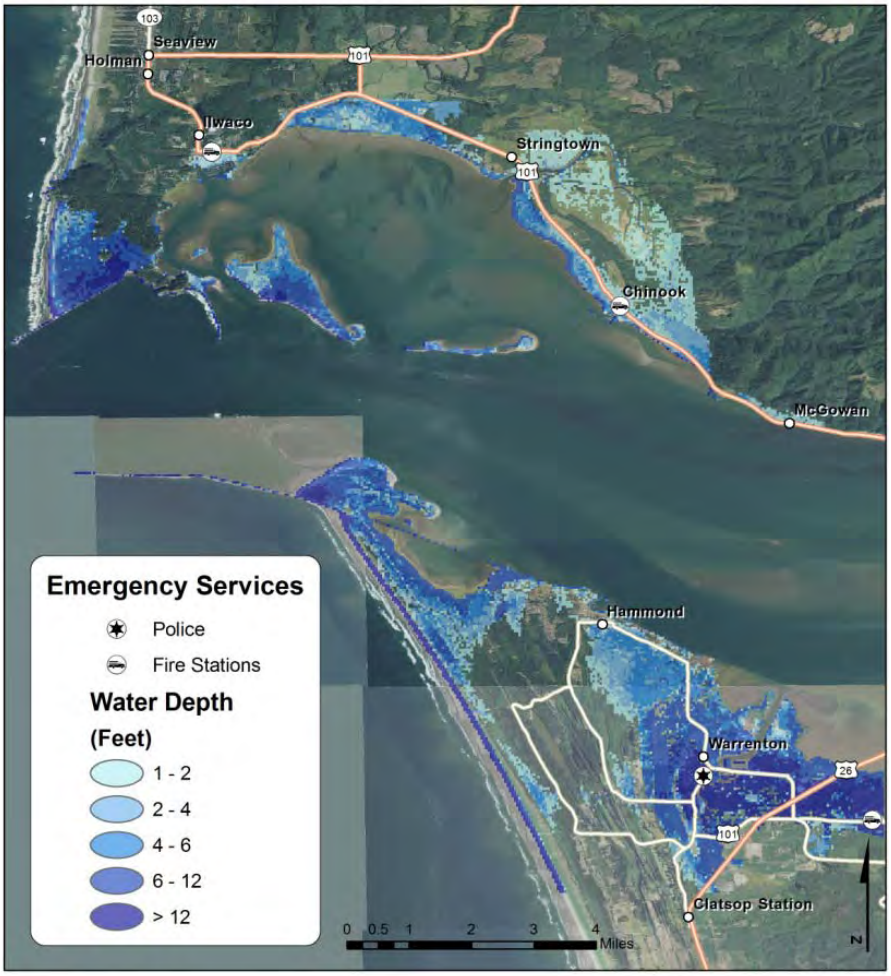

Figure D-50. Expected tsunami inundation and emergency services impacts for Warrenton, OR

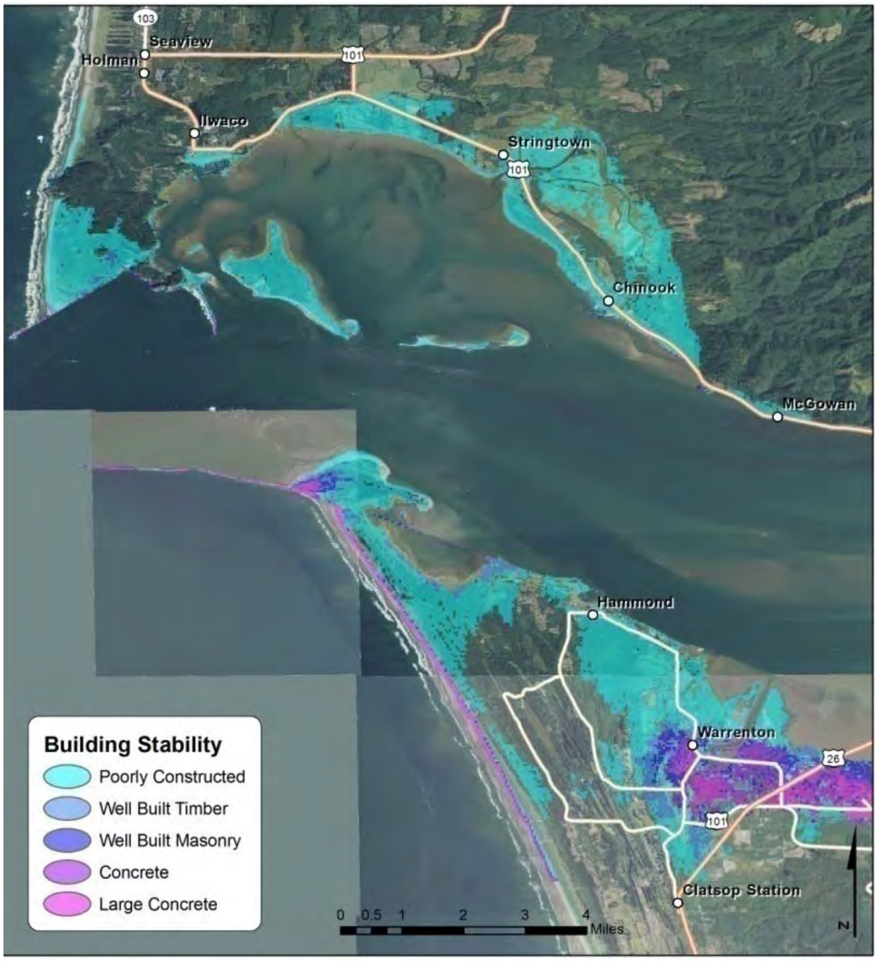

Figure D-51. Predicted building stability rating for Warrenton, OR

Table D-36. Population at risk in Warrenton, OR

Population Impacts	# People
Daytime PAR	3,840
Nighttime PAR	2,720
Injuries	550
Deaths	280

Table D-37. Impacted assets in Warrenton, OR

Asset	# Impacted
Bridges/Tunnels	7
Fire Stations	4
Major Roads	9
Police	1
Schools	3
Water Supply	2

Table D-38. Impacted transportation facilities in Warrenton, OR

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
Hwy 104	Skipanon River Bridge	6 - 12	Well-built Timber
Hwy 104	Power Slough Bridge	6 - 12	Poorly Constructed
Hwy 105	Skipanon River Bridge	> 12	Concrete
U.S. 101	Fort Columbia Tunnel	6 - 12	Poorly Constructed
U.S. 101	Skipanon River Bridge	6 - 12	Poorly Constructed
U.S. 101	Chinook River Bridge	2 - 4	Poorly Constructed
U.S. 101	Wallicut River Bridge	6 - 12	Poorly Constructed
U.S. 101	n/a	6 - 12	Poorly Constructed
Alt Hwy 101	n/a	> 12	Large Concrete
Southwest 18th Street	n/a	2 - 4	Poorly Constructed
East Harbor Drive	n/a	> 12	Large Concrete
South Main Avenue	n/a	4 - 6	Poorly Constructed
Southeast Marlin Avenue	n/a	> 12	Large Concrete
Pacific Drive	n/a	6 - 12	Poorly

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
			Constructed
North Main Avenue	n/a	> 12	Well-built Timber
Northwest Warrenton Drive	n/a	6 - 12	Poorly Constructed

Table D-39. Impacted fire stations in Warrenton, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Warrenton Fire Dept.	225 South Main Avenue	6 - 12	Well-built Timber
US Coast Guard - Air Station Astoria	2185 Southeast 12th Place	> 12	Concrete
Ilwaco Fire Dept.	301 Spruce Street East	0 - 2	Poorly Constructed
Pacific County Fire Protection District 2	764 U.S. Hwy 101	2 - 4	Poorly Constructed

Table D-40. Impacted police stations in Warrenton, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Warrenton Police Dept.	225 South Main Avenue	6 - 12	Well-built Timber

Table D-41. Impacted water supply facilities in Warrenton, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
City of Warrenton Water	n/a	> 12	Well-built Timber
Chinook Water District	n/a	2 - 4	Poorly Constructed

Table D-42. Impacted schools in Warrenton, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Warrenton Grade School	820 Cedar Street	4 - 6	Poorly Constructed
Coryell's Crossing, Inc.	n/a	> 12	Well-built Masonry
North Coast Christian School	796 Pacific Drive	2 - 4	Poorly Constructed

Rockaway Beach, OR

No directly associated marigram was available for this location.

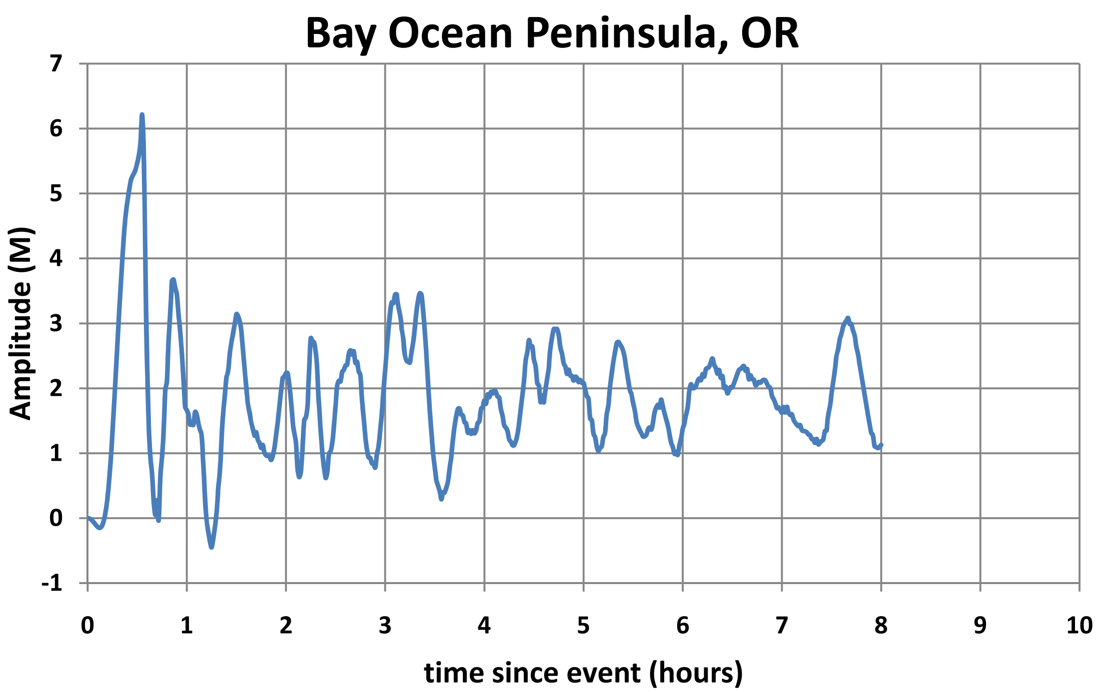

Figure D-52. Bay Ocean Peninsula, OR, seismic event marigram

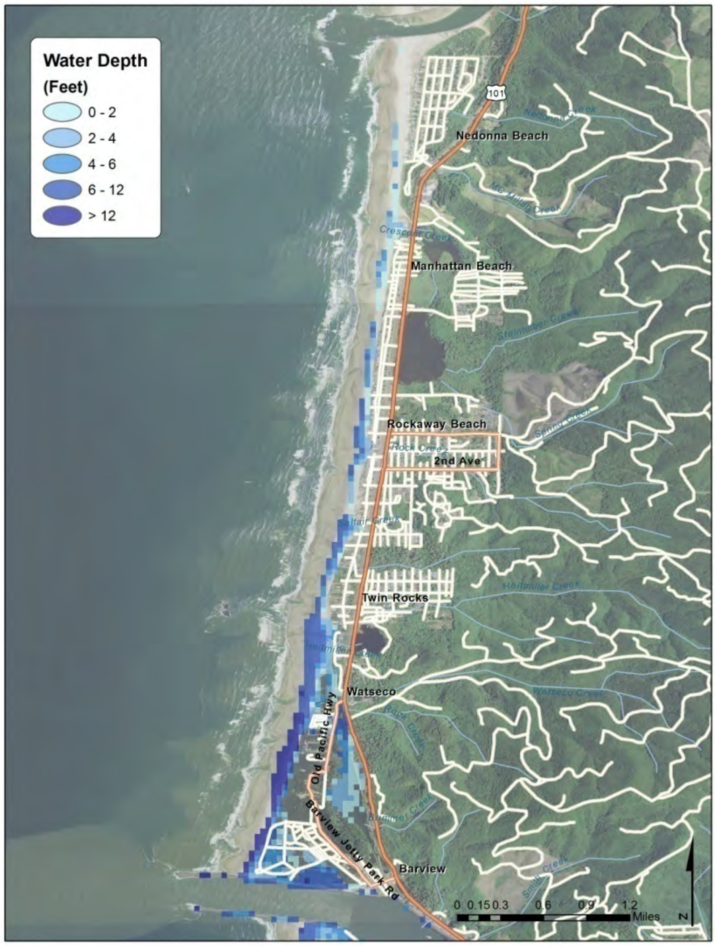

Figure D-53. Expected tsunami inundation in Rockaway Beach, OR

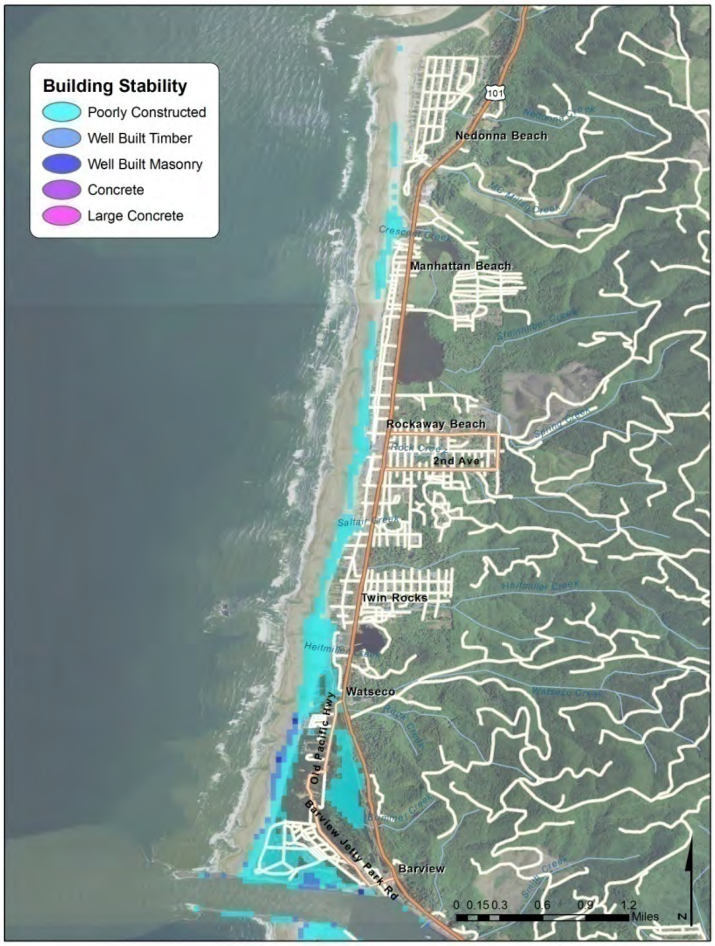

Figure D-54. Predicted building stability rating for Rockaway Beach, OR

Table D-43. Population at risk in Rockaway Beach, OR

Population Impacts	# People
Daytime PAR	70
Nighttime PAR	75
Injuries	4
Deaths	1

Table D-44. Impacted assets in Rockaway Beach, OR

Asset	# Impacted
Major Roads	3

Table D-45. Impacted transportation facilities in Rockaway Beach, OR

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	n/a	2 - 4	Poorly Constructed
Old Pacific Hwy	n/a	2 - 4	Poorly Constructed
Barview Jetty County Roads	n/a	6 - 12	Poorly Constructed

Lincoln City, OR

No directly associated marigram was available for this location.

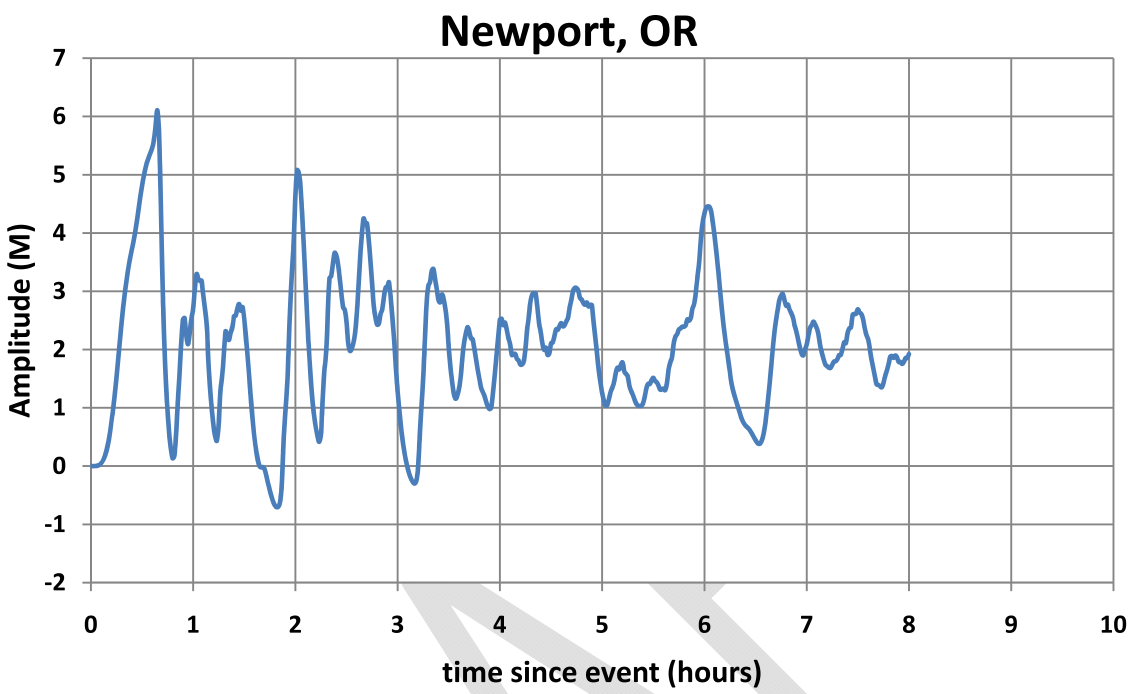

Figure D-55. Newport, OR, seismic event marigram

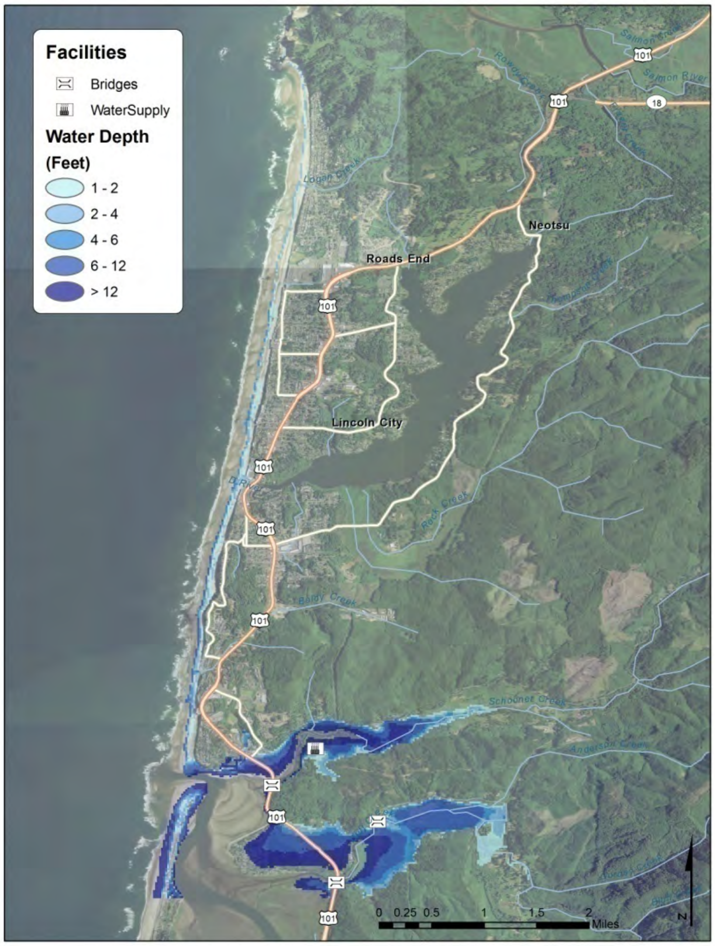

Figure D-56. Expected tsunami inundation and impacted facilities in Lincoln City, OR

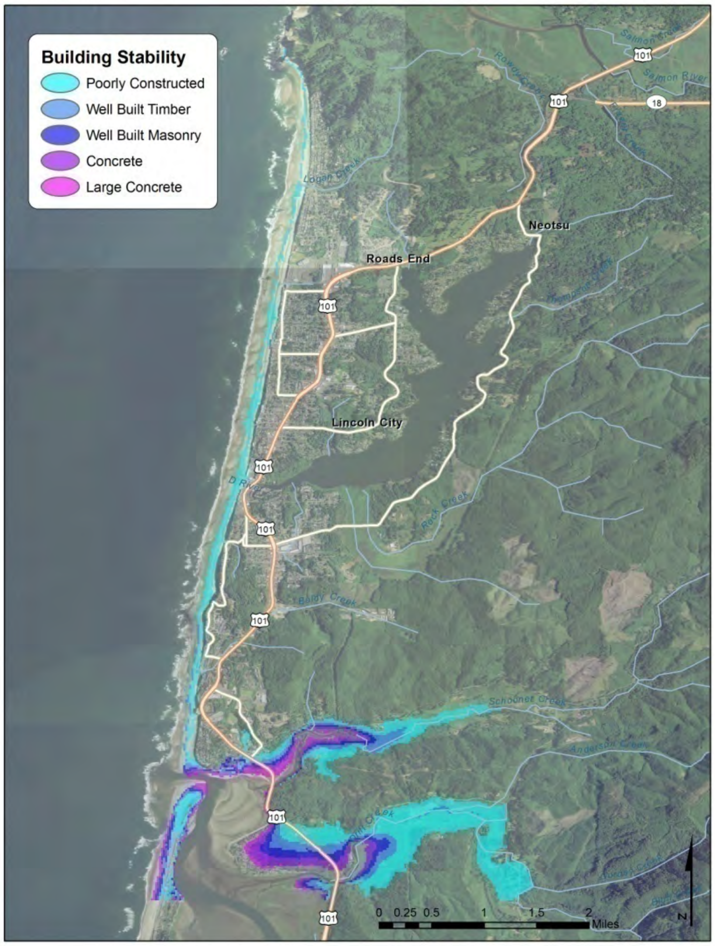

Figure D-57. Predicted building stability rating in Lincoln City, OR

Table D-46. Population at risk in Lincoln City, OR

Population Impacts	# People
Daytime PAR	420
Nighttime PAR	370
Injuries	70
Deaths	40

Table D-47. Impacted assets in Lincoln City, OR

Asset	# Impacted
Bridges	3
Major Roads	1
Water Supply	1

Table D-48. Impacted water supply facilities in Lincoln City, OR

Name	Address	Flood Depth (Feet)	Building Stability Category
Lincoln City Water District	n/a	6 - 12	Well-built Timber

Table D-49. Impacted transportation facilities in Lincoln City, OR

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	n/a	> 12	Well-built Masonry
U.S. 101	Drift Creek Bridge	0 - 2	Poorly Constructed
Gorton Road	Drift Creek Bridge	4 - 6	Poorly Constructed

Waldport-Yachats, OR

No directly associated marigram was available for this location.

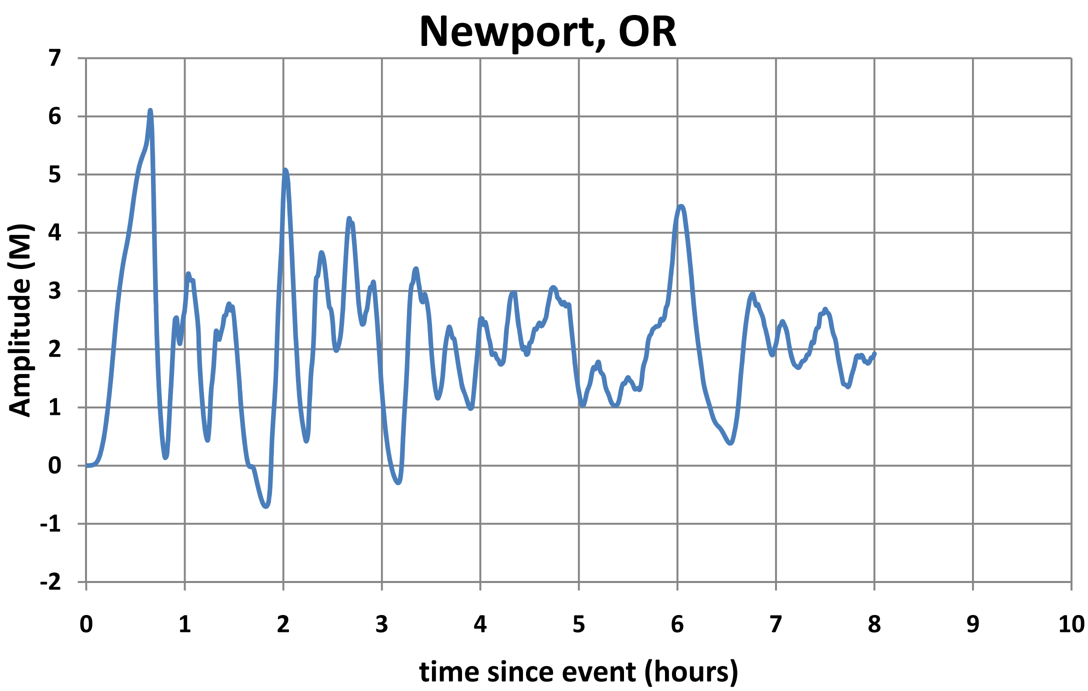

Figure D-58. Newport, OR, seismic event marigram

Figure D-59. Expected tsunami inundation in Waldport to Yachats, OR

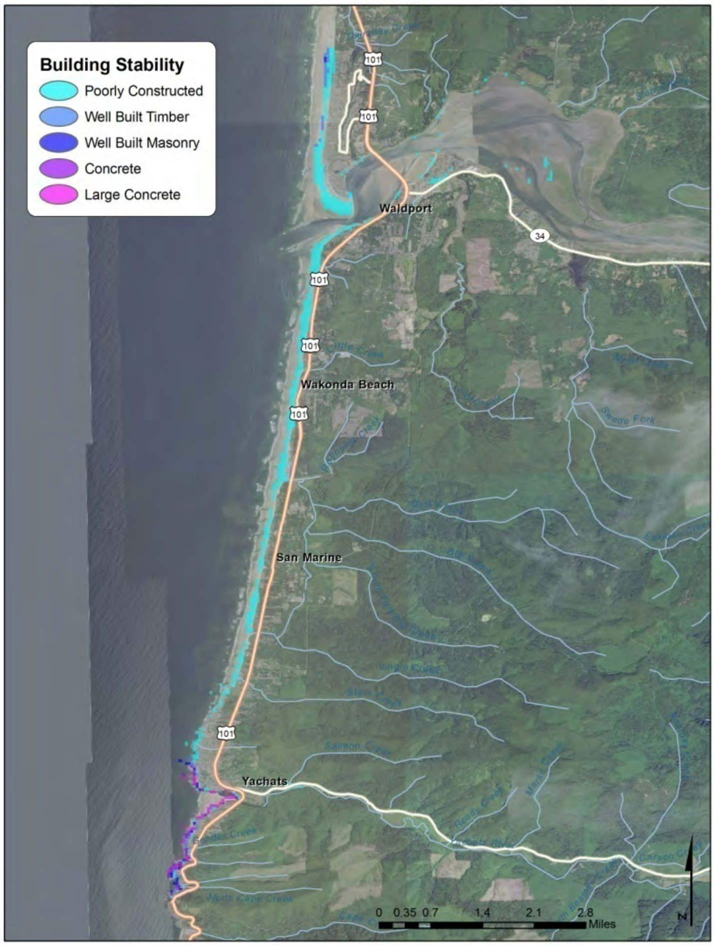

Figure D-60. Predicted building stability rating in Waldport to Yachats, OR

Table D-50. Population at risk in Waldport to Yachats, OR

Population Impacts	# People
Daytime PAR	90
Nighttime PAR	80
Injuries	3
Deaths	2

Table D-51. Impacted assets in Waldport to Yachats, OR

Asset	# Impacted
Major Roads	2

Table D-52. Impacted transportation facilities at Waldport to Yachats, OR

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
U.S. 101	n/a	6 - 12	Poorly Constructed
State Road 34	n/a	0 - 2	Poorly Constructed

Washington

Bellingham, WA

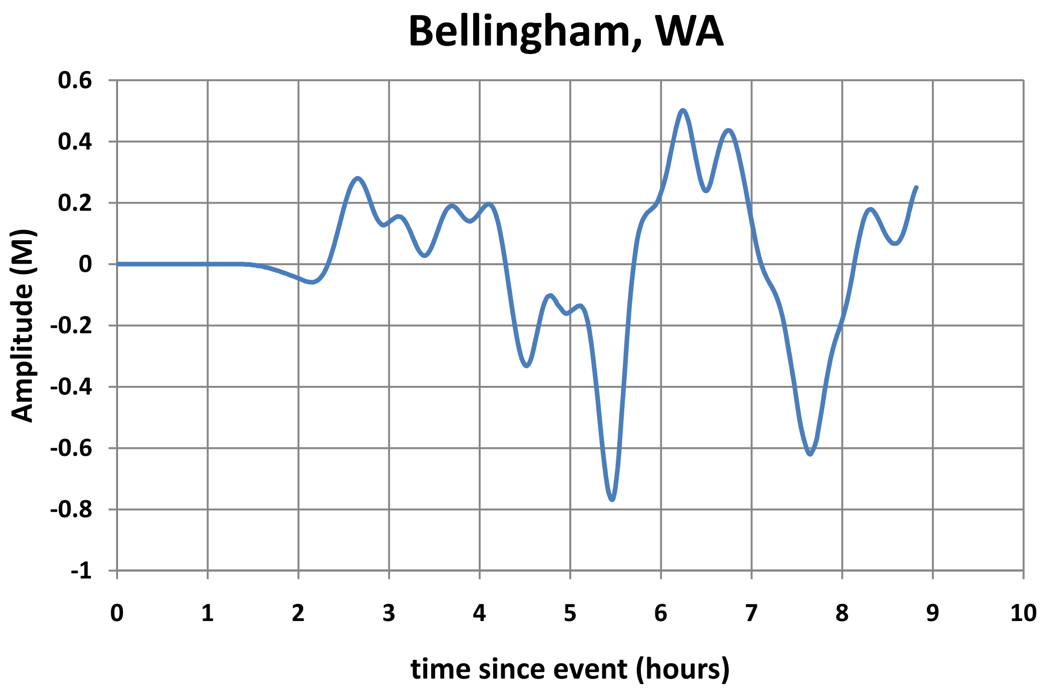

Figure D-61. Bellingham, WA, seismic event marigram

Figure D-62. Predicted building stability rating for Bellingham, WA

Figure D-63. Expected tsunami inundation depths for Bellingham, WA

Table D-53. Population at Risk in Bellingham, WA

Population Impacts	# People
Nighttime PAR	60
Daytime PAR	290
Injuries	10
Deaths	0

Moclips to Westport, WA

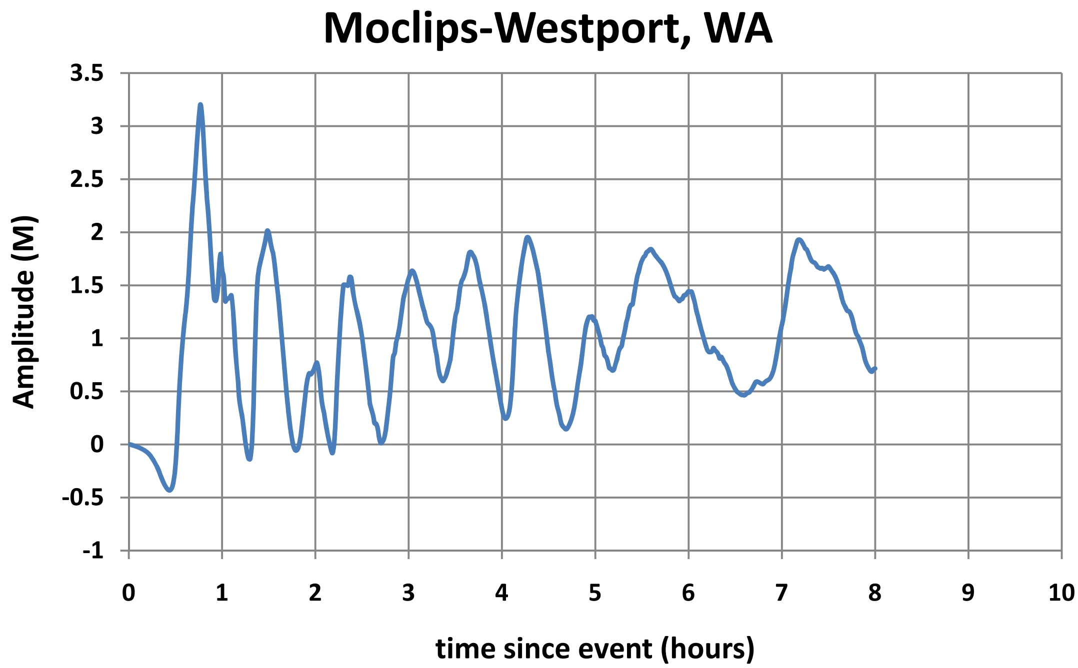

Figure D-64. Moclips-Westport, WA, seismic event marigram

Figure D-65. Predicted building stability rating for Moclips-Westport, WA

Figure D-66. Expected tsunami inundation and facility impacts for Moclips-Westport, WA

Table D-54. Population at Risk from Moclips to Westport, WA

Population Impacts	# People
Nighttime PAR	5,500
Daytime PAR	4,920
Injuries	430
Deaths	140

Table D-55. Impacted assets from Moclips to Westport, WA

Sector	# Facilities
Schools	1
Transportation	13
Water/Wastewater	1

Table D-56. Impacted Schools from Moclips to Westport, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Ocean Shores Elementary	300 Mt. Olympus Way, Ocean Shores	6 - 12	Well-built Timber

Table D-57. Impacted Water/Wastewater Services from Moclips to Westport, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Ocean Shores Sewer Treatment Plant	1440 E Ocean Shores Boulevard	6 - 12	Well-built Timber

Table D-58. Impacted Transportation Services from Moclips to Westport, WA

Road Name	Bridge Name	Flood Depth (Feet)	Building Stability Category
State Road 115	n/a	> 12	Concrete
State Road 105	n/a	2 - 4	Poorly Constructed
State Road 109	n/a	1 - 2	Poorly Constructed
Ocean City (2nd Avenue)	Connor Creek Bridge	0 - 1	Poorly Constructed
Overlake Drive	Overlake Duck Lake Bridge	1 - 2	Poorly Constructed
SR 109	Copalis River Bridge	2 - 4	Poorly Constructed
Albatross Street	Duck Lake Bridge	1 - 2	Poorly Constructed
Ocean Lake Way	Grand Canal Bridge	> 12	Concrete
Bass Avenue	Bass Avenue Canal Bridge	> 12	Concrete

Road Name	Bridge Name	Flood Depth (Feet)	Building Stability Category
Razor Clam Avenue	Lake Minard Bridge	6 - 12	Well-built Timber
Point Brown Avenue	Canal Bridge	6 - 12	Well-built Timber
Tonquin Avenue	Lake Minard Bridge	6 - 12	Well-built Timber
Mt. Olympus Avenue	Canal Bridge	6 - 12	Well-built Timber

Neah Bay, WA

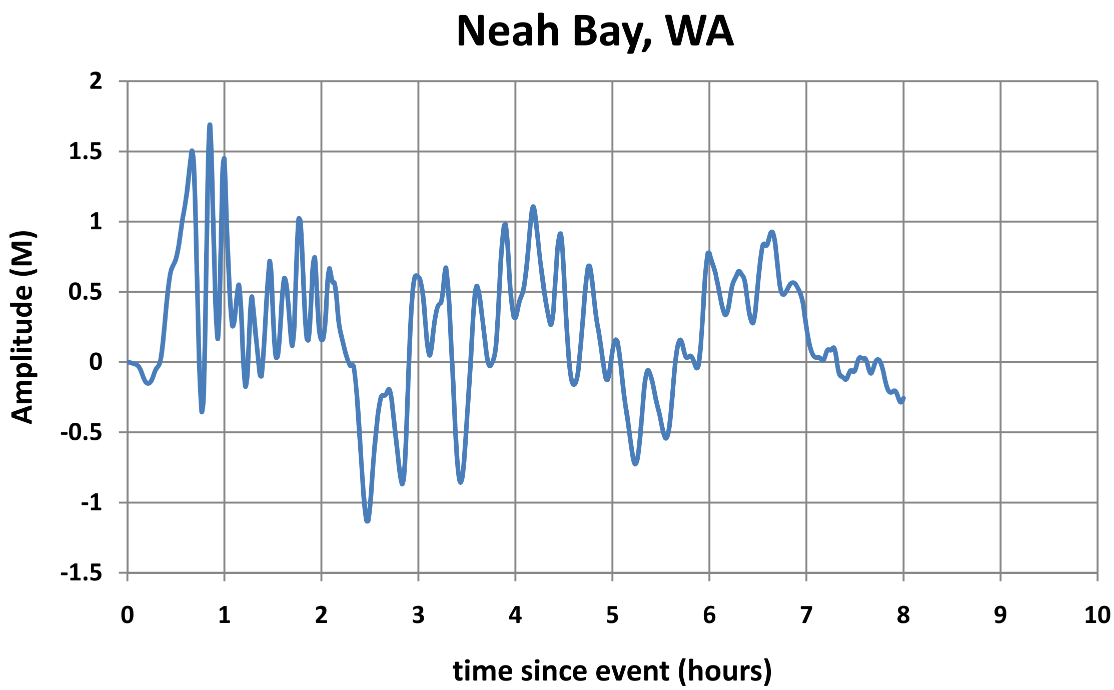

Figure D-67. Neah Bay, WA, seismic event marigram

Figure D-68. Predicted building stability rating for Neah Bay, WA

Figure D-69. Expected tsunami inundation depths for Neah Bay, WA

Table D-59. Population at Risk in Neah Bay, WA

Population Impacts	# People
Nighttime PAR	20
Daytime PAR	10
Injuries	0
Deaths	0

Port Angeles, WA

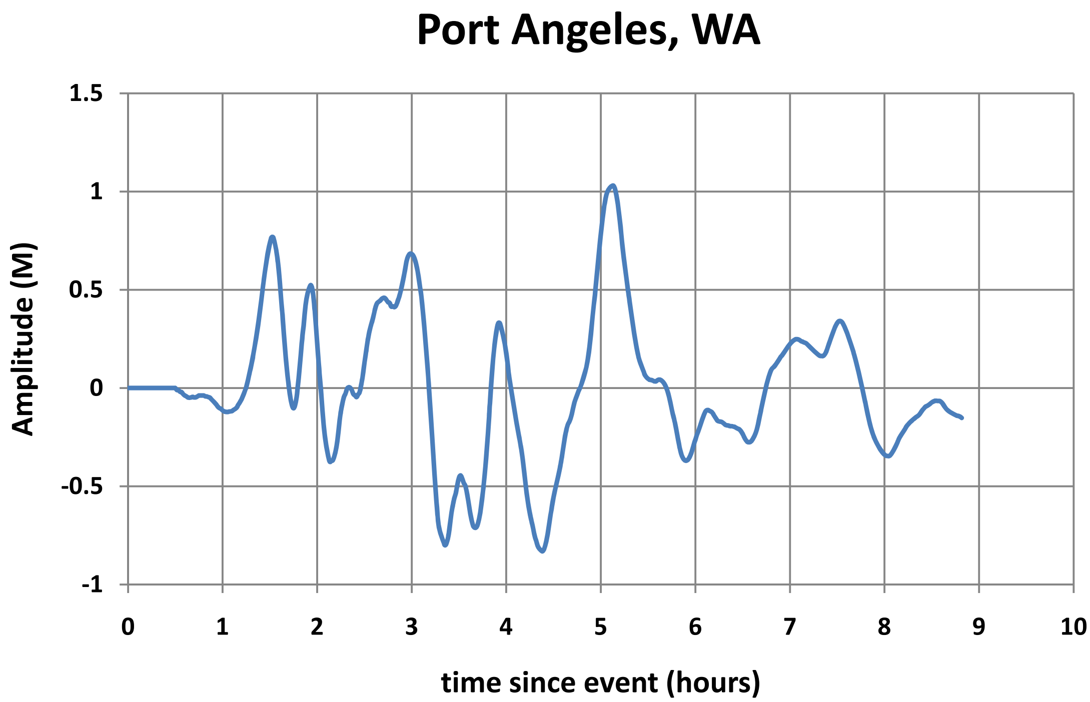

Figure D-70. Port Angeles, WA, Seismic Event Marigram

Figure D-71. Predicted building stability rating for Port Angeles, WA

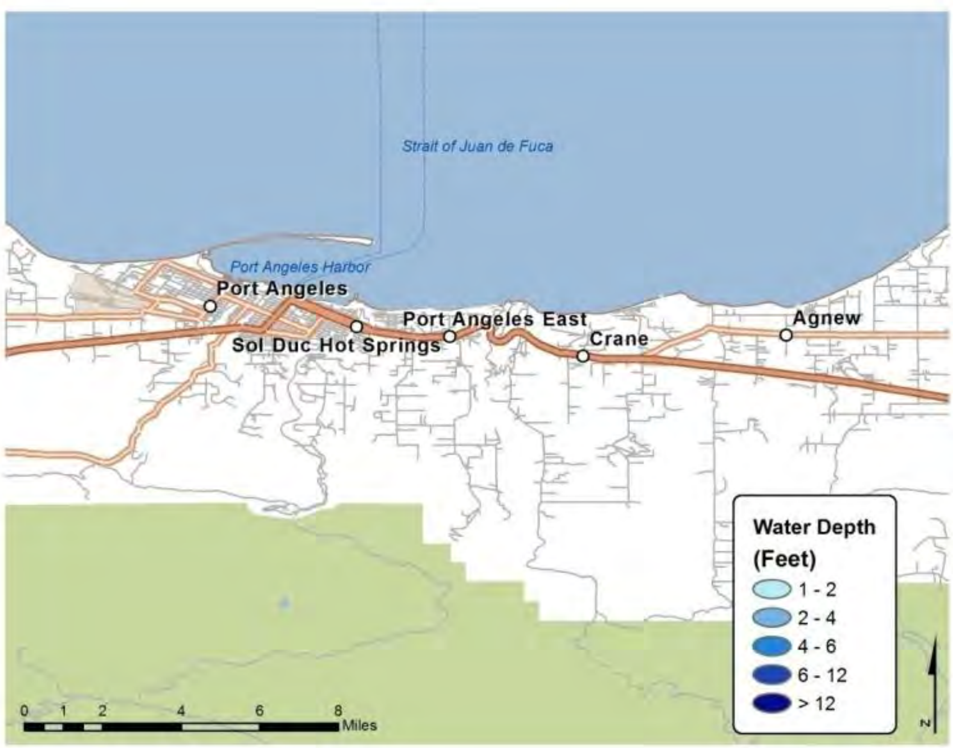

Figure D-72. Expected tsunami inundation depths for Port Angeles, WA

Table D-60. Population at Risk in Port Angeles, WA

Population Impacts	# People
Nighttime PAR	40
Daytime PAR	50
Injuries	10
Deaths	0

Seattle, WA

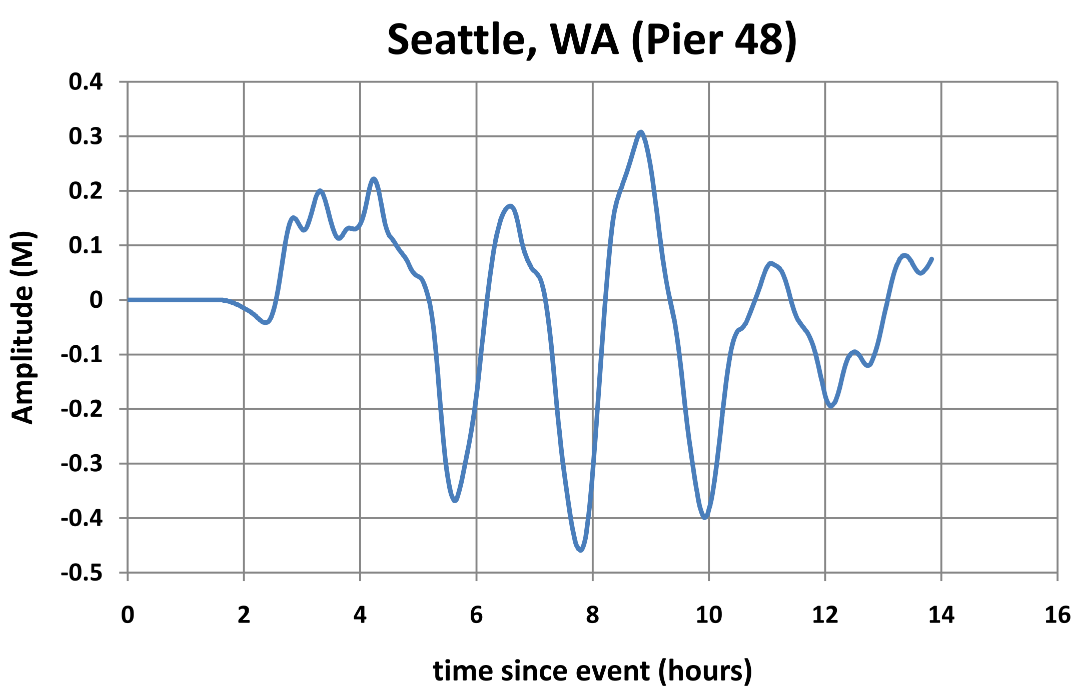

Figure D-73. Seattle, WA, seismic event marigram

Figure D-74. Predicted building stability rating for Seattle, WA

Figure D-75. Expected tsunami inundation depths, EMS, and facility impacts for Seattle, WA

Table D-61. Population at Risk in Seattle, WA

Population Impacts	# People
Nighttime PAR	2,110
Daytime PAR	7,100
Injuries	190
Deaths	50

Table D-62. Impacted assets in Seattle, WA

Sector	# Facilities
Emergency Services	1
Education	3

Table D-63. Impacted Education Facilities in Seattle, WA

Name	Address	Flood Depth (Feet)
Art Institute of Seattle	2323 Elliott Avenue	> 12
Argosy University-Seattle	2601-A Elliott Avenue	2 - 4
Mars Hill Graduate School	2501 Elliott Avenue	2 - 4

Table D-64. Impacted Emergency Services in Seattle, WA

Name	Address	Flood Depth (Feet)
Seattle Fire Department - Station 5	925 Alaskan Way	0 - 1

Grays Harbor, WA

No directly associated marigram was available for this location.

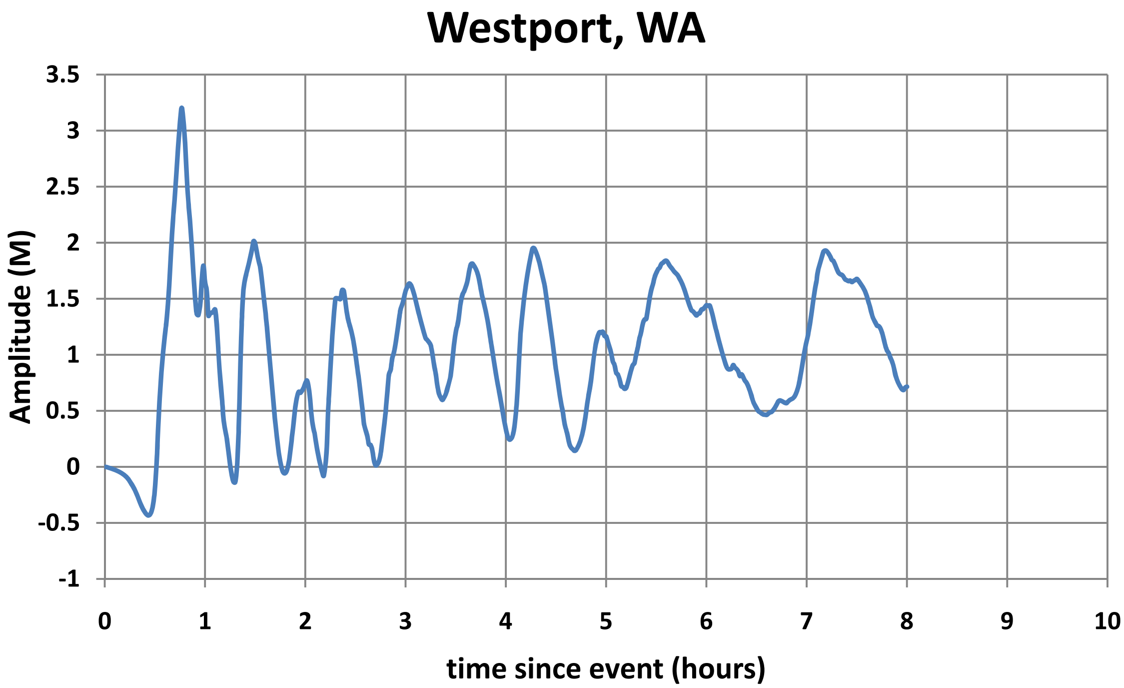

Figure D-76. Westport, WA, seismic event marigram

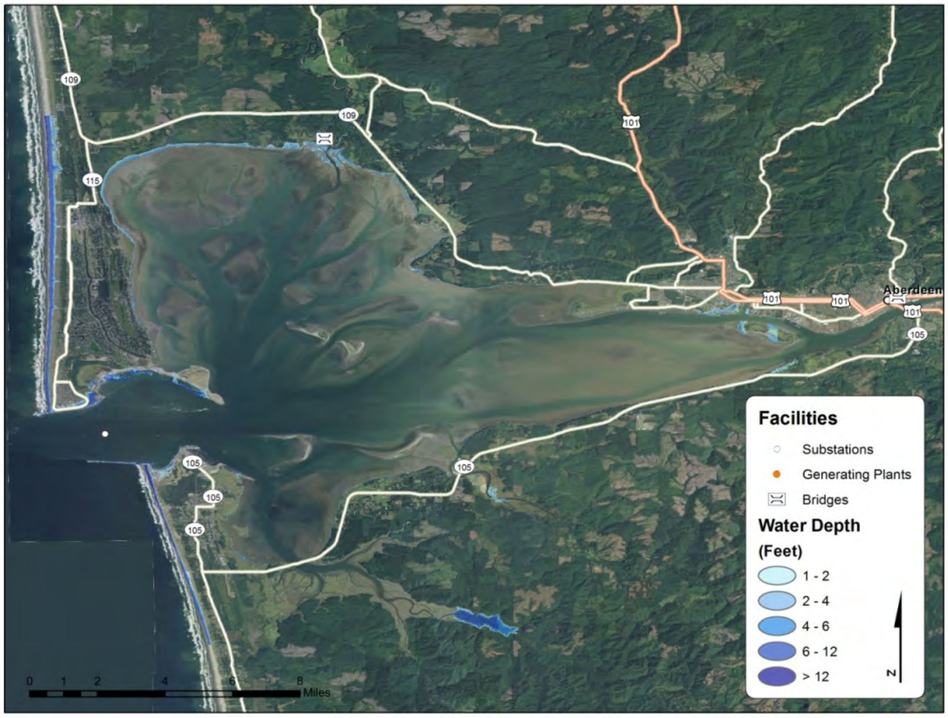

Figure D-77. Expected tsunami inundation and impacted facilities for Grays Harbor, WA

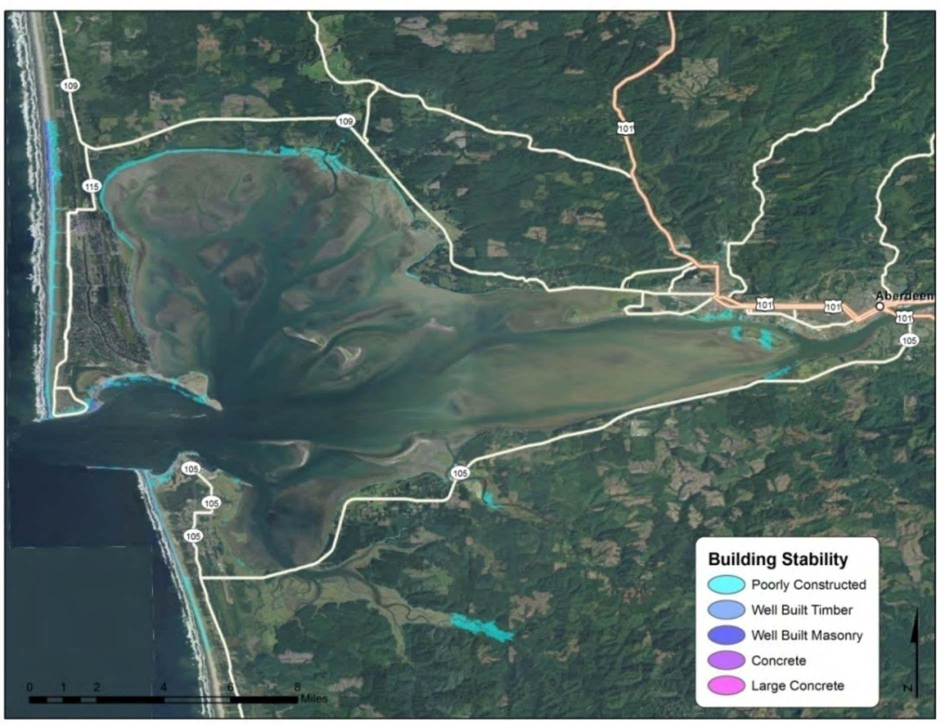

Figure D-78. Predicted building stability rating at Grays Harbor, WA

Table D-65. Population at risk in Grays Harbor, WA

Population Impacts	# People
Daytime PAR	780
Nighttime PAR	650
Injuries	12
Deaths	1

Table D-66. Impacted assets in Grays Harbor, WA

Asset	# Impacted
Major Roads	3
Bridges	2
Energy	2

Table D-67. Impacted energy facilities in Grays Harbor, WA

Name	Flood Depth (Feet)	Building Stability Category
Grays Harbor Ocean Energy Plant (Proposed)	> 12	Large Concrete
Grays Harbor Ocean Energy Substation (Proposed)	> 12	Large Concrete

Table D-68. Impacted transportation facilities at Grays Harbor, WA

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
Burrows Road	Jessie Slough Bridge	0 - 2	Poorly Constructed
U.S. Hwy 12	Wishkah River Bridge	0 - 2	Poorly Constructed
Ocean Shores Blvd	n/a	0 - 2	Poorly Constructed
State Road 109	n/a	0 - 2	Poorly Constructed
State Road 105	n/a	0 - 2	Poorly Constructed

South Bend – Raymond, WA

No directly associated marigram was available for this location.

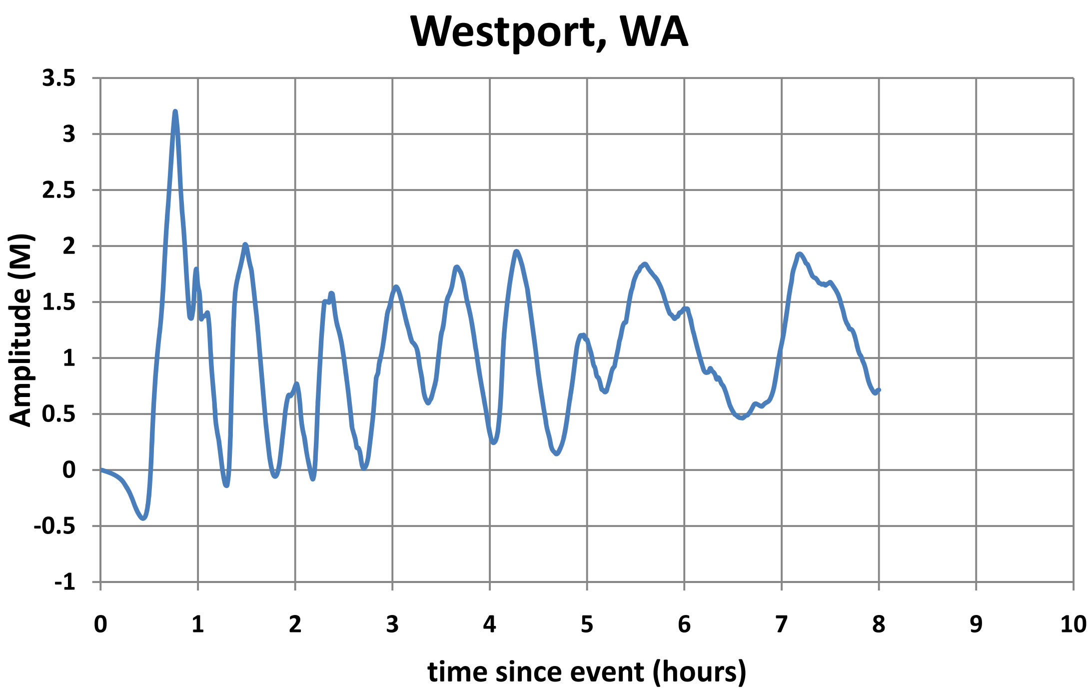

Figure D-79. Westport, WA, seismic event marigram

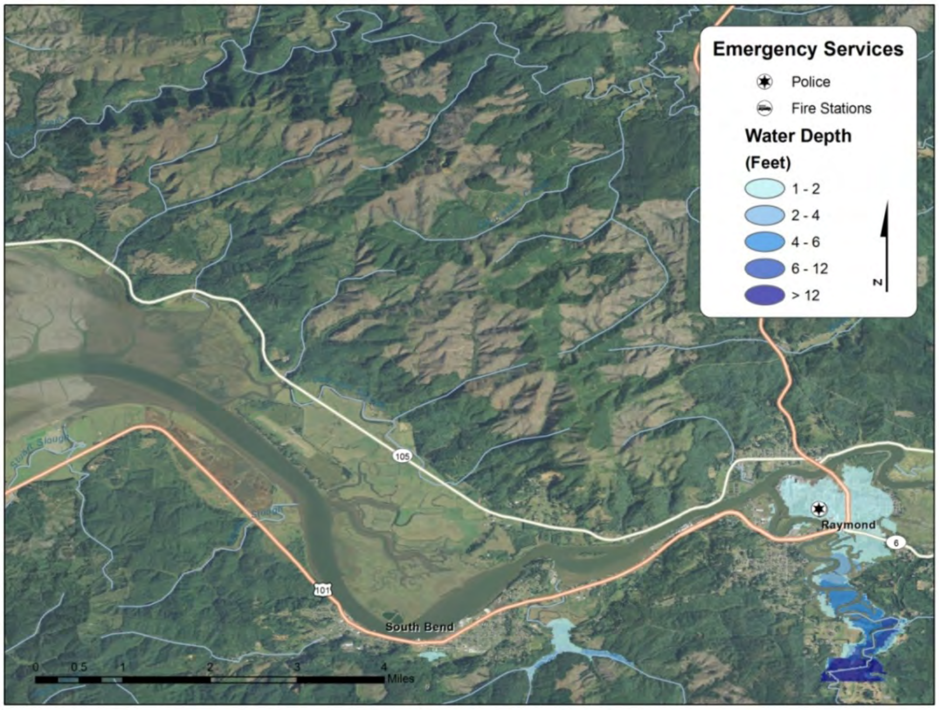

Figure D-80. Expected tsunami inundation and impacted emergency services in South Bend to Raymond, WA

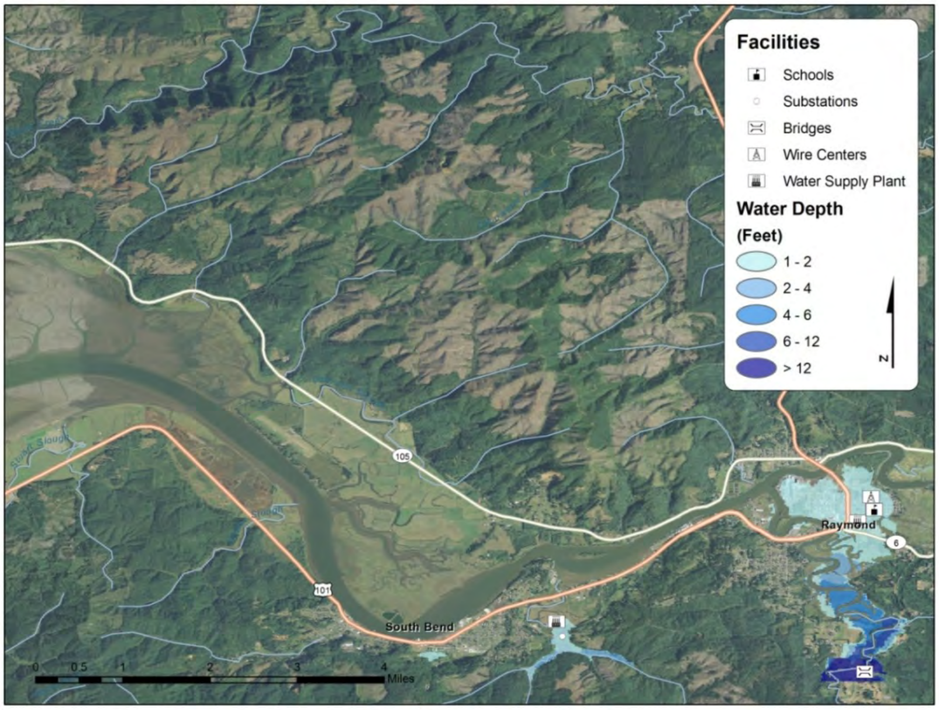

Figure D-81. Expected tsunami inundation and impacted facilities for South Bend to Raymond, WA

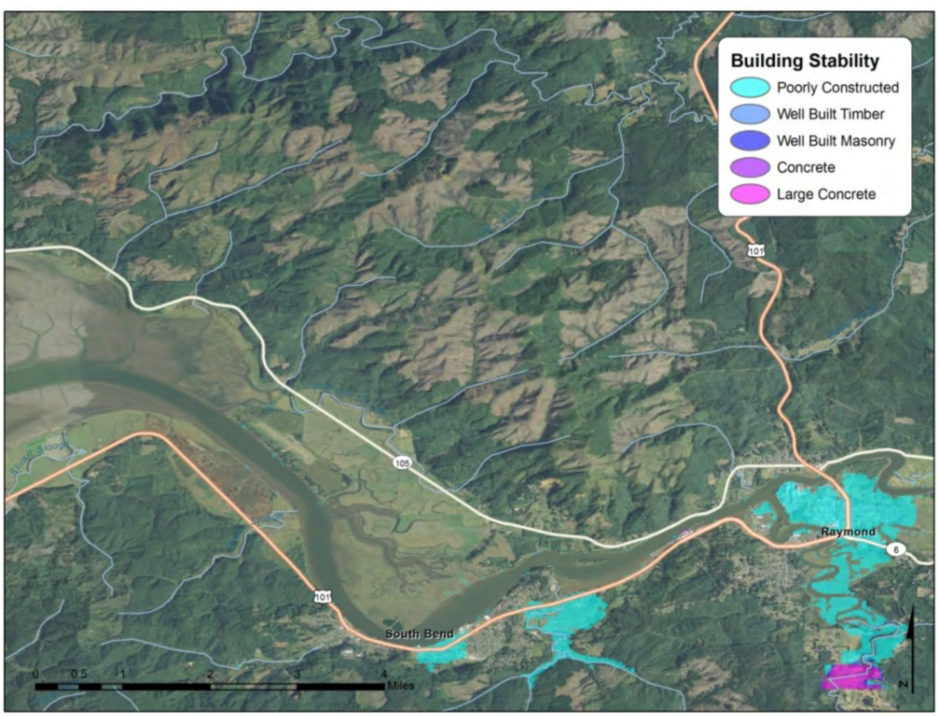

Figure D-82. Predicted building stability rating for South Bend to Raymond, WA

Table D-70. Population at risk in South Bend to Raymond, WA

Population Impacts	# People
Daytime PAR	2,500
Nighttime PAR	750
Injuries	7
Deaths	4

Table D-71. Impacted assets in South Bend to Raymond, WA

Asset	# Facilities
Bridges	1
Fire Stations	1
Police	1
Roads	2
Schools	3
Substations	1
Water Supply	2
Wire Centers	1

Table D-72. Impacted transportation facilities in South Bend to Raymond, WA

Road Name	Tunnel/Bridge Name	Flood Depth (Feet)	Building Stability Category
Fowler Road	South Fork Willapa River Bridge	> 12	Well-built Masonry
U.S. 101	n/a	0 - 2	Poorly Constructed
State Road 6	n/a	0 - 2	Poorly Constructed

Table D-73. Impacted fire stations in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Raymond Fire Dept.	**212 Commercial Street**	**0 - 2**	**Poorly Constructed**

Table D-74. Impacted police stations in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Raymond Police Dept.	**233 Second Street**	**0 - 2**	**Poorly Constructed**

Table D-75. Impacted education facilities in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Raymond Elementary School	1016 Commercial Street	0 - 2	Poorly Constructed
Raymond Jr./Sr. High School	1016 Commercial Street	0 - 2	Poorly Constructed
Developmental Preschool	1016 Commercial Street	0 - 2	Poorly Constructed

Table D-76. Impacted energy facilities in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
Willapa River Substation	n/a	0 - 2	Poorly Constructed

Table D-77. Impacted water supply facilities in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
South Bend Water Dept.	n/a	0 - 2	Poorly Constructed
Raymond Water Dept.	n/a	0 - 2	Poorly Constructed

Table D-78. Impacted wire centers in South Bend to Raymond, WA

Name	Address	Flood Depth (Feet)	Building Stability Category
RYMNWAXA	311 4th Street	0 - 2	Poorly Constructed

DHS Point of Contact

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