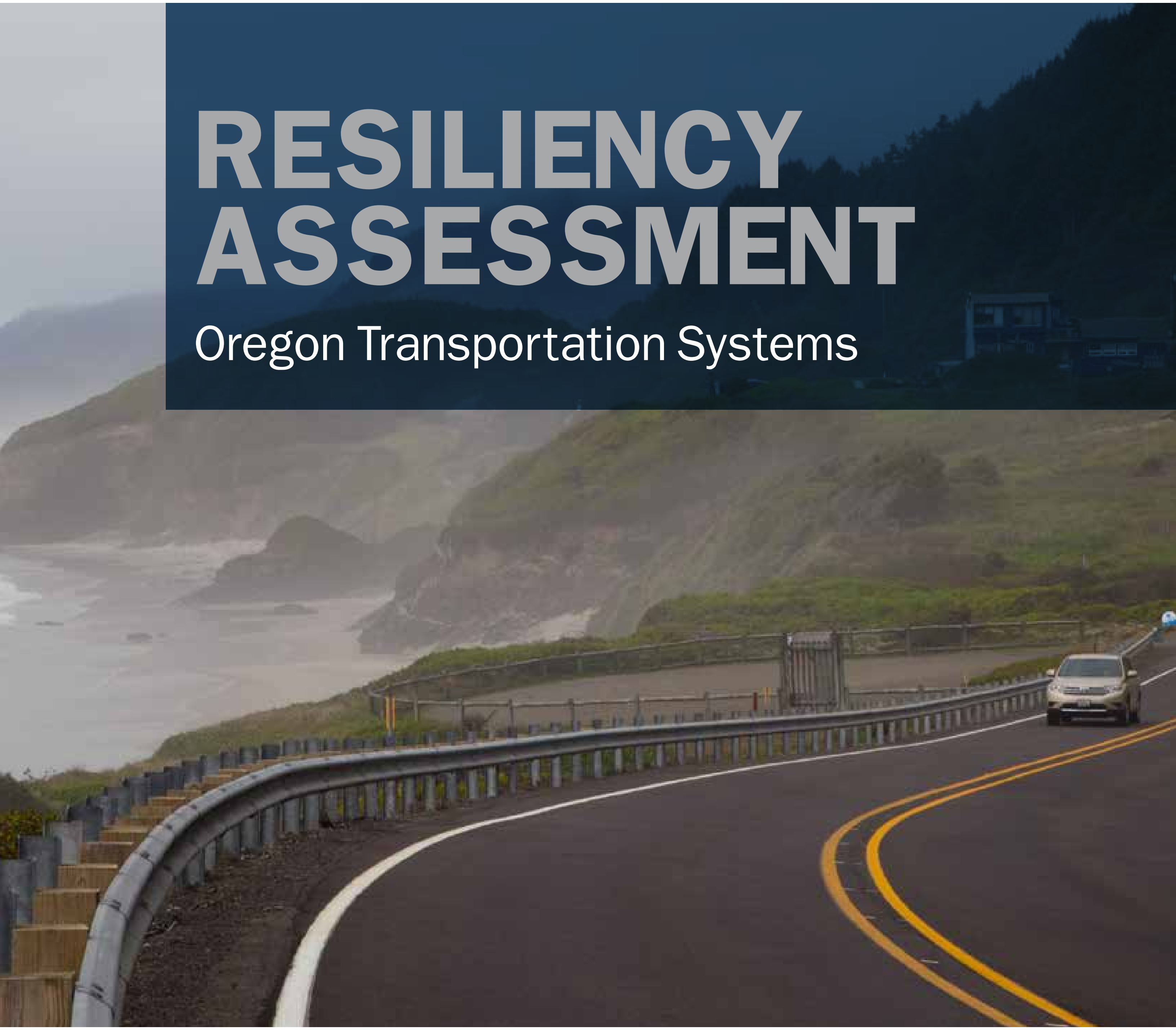
July 2021

RESILIENCY ASSESSMENT

Oregon Transportation Systems



"Infrastructure assessment, planning, and investment activities that improve the resilience of airport infrastructure systems and surface transportation lifelines are critical to meeting the post-earthquake public health and safety needs of affected populations."

Program Overview

The Regional Resiliency Assessment Program (RRAP) is a cooperative assessment of specific critical infrastructure within a designated geographic area and a regional analysis of the surrounding infrastructure that address a range of infrastructure resilience issues that could have regionally and nationally significant consequences. These voluntary, non-regulatory RRAP projects are led by the Cybersecurity and Infrastructure Security Agency (CISA) and are selected each year with input and guidance from federal, state, and local partners.

Program Goal and Participants

The goal of the RRAP is to generate greater understanding and action among public and private-sector partners to improve the resilience of a region's critical infrastructure. To accomplish this, the RRAP does the following:

- Resolves infrastructure security and resilience knowledge gaps;
- Informs risk management decisions;
- Identifies opportunities and strategies for to enhance infrastructure resilience; and
- Improves critical partnerships among the public and private sectors.

Strong partnerships with federal, state, local, tribal, and territorial government officials and private-sector organizations across multiple disciplines are essential to the RRAP process. These include private-sector facility owners and operators, industry organizations, emergency response and recovery organizations, utility providers, transportation agencies and authorities, planning commissions, law enforcement, academic institutions, and research centers.

RRAP Activities and Results

Each RRAP project typically involves a year-long process to collect and analyze data on the critical infrastructure within the designated area, followed by continued technical assistance to enhance the infrastructure's resilience. Individual projects can incorporate opportunities for valuable information and data exchanges, including voluntary facility security surveys, first responder capability assessments, targeted studies and modeling, and subject matter expert workshops. An RRAP project can usually be described as having three phases: a data collection phase, an assessment/analysis phase, and an implementation phase.

The culmination of RRAP activities, research, and analysis is presented in a Resiliency Assessment report documenting project results and findings, including key regional resilience gaps and options for addressing these shortfalls. Facility owners and operators, regional organizations, and government agencies can use the results to help guide strategic investments in equipment, planning, training, and infrastructure development to enhance the resilience and security of facilities, surrounding communities, and entire regions.

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Table of Contents

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Executive Summary

Executive Summary

The Oregon Transportation Systems project assessed the resilience of Oregon's roadway, airport, and maritime port transportation systems to a Cascadia Subduction Zone (CSZ) earthquake, and the ability of those systems to support post-disaster response and recovery activities. This project was conducted as part of the DHS Cybersecurity and Infrastructure Security Agency (CISA) Regional Resiliency Assessment Program (RRAP) and in close coordination with the project's local sponsor, the State Resilience Officer in the Office of the Governor, and other state, federal, regional, and local partners.

The primary purpose of this project was to identify priority roadway transportation routes that will be best able to reopen quickly following a CSZ earthquake to establish post-disaster emergency supply chains among state and federal staging areas for disaster logistics, and between these staging areas and surrounding communities. These staging areas, located primarily at airports across western and central Oregon, are critical locations in state and federal earthquake response plans for bringing life-saving and life-sustaining resources to affected communities. This RRAP project also assessed the hazard exposure and various resilience capabilities of the 12 airports currently designated as disaster logistics staging areas, as well as the hazard exposure of seven maritime ports located along the Columbia River and Oregon coast. The RRAP research team has synthesized findings from these analyses, assessments, and site visits and from extensive stakeholder engagement with transportation owners/operators, state/local emergency managers, and other state and local officials into key findings and related resilience enhancement options to address these findings.

A key outcome of this RRAP project was the identification of priority roadway routes across western Oregon with comparatively greater seismic resilience than similar routes. These newly identified routes will be better able to support post-disaster logistics supply chains originating from designated staging areas. A regional "islanding" analysis that was focused on the western half of Oregon drove this outcome; the analysis delineated communities and areas in the western half of Oregon that will become functionally disconnected or isolated from one another, or from the broader region, as a result of disruptions to the transportation system induced by a CSZ earthquake. This islanding analysis, using seismic screening tools developed in direct collaboration with the Oregon Department of Transportation (ODOT) and the Oregon Department of Geology and Mineral Industries (DOGAMI), then incorporated extensive network- and system-level assessments of roadway systems to identify priority roadway routes and facilities branching out from the staging areas that will be best able to reconnect communities efficiently to post-disaster response and recovery supply lines. This islanding analysis also approximated the populations and "service areas" that each of the disaster logistics staging areas will need to serve following the disaster, as well as how these service areas will expand and grow throughout post-disaster response and recovery phases as transportation routes are repaired and reopened over time. The intent is that the outcomes of this islanding analysis will directly inform emergency management and response planning activities.

A key finding of the airport analysis and stakeholder engagement is that few airports across Oregon have conducted seismic vulnerability analyses of their facilities and therefore do not have a good understanding of the capability of their facilities to serve in the capacity of a post-disaster logistics staging area. This gap forces emergency managers to perform emergency management and disaster response planning with an incomplete picture of supply chain capabilities; these professionals would need to address this gap through further study and site-specific assessments. Furthermore, as airports rely on critical infrastructure services to maintain operations, this study found that their greatest external dependencies are on critical infrastructure in the fuel and electricity sectors. However, persistent resilience gaps exist that airports could address to reduce the potential for disruptions to air operations following a CSZ earthquake.

Although maritime port systems will be particularly hard hit by CSZ earthquake impacts, they nonetheless have some potential to support disaster logistics supply chains on the Oregon coast. However, only one of the seven sea and river ports we visited—the Port of Portland—has conducted any seismic resilience analysis. Therefore, while a general expectation exists among port officials and emergency managers that ports will suffer significant disruptions during a CSZ earthquake, the extent and magnitude of such disruptions are largely unknown. Similarly, although officials noted that port operations rely on other critical infrastructure systems and services (in particular, fuel, electricity, and navigable waterways), this study found that port personnel and other regional and state officials do not have a good understanding of their resilience. Greater coordinated study of both site-specific and systems-level port vulnerabilities in Oregon would enable emergency managers and officials at the federal, state, and local levels to better incorporate Oregon ports as a component of post-disaster supply chains.

The following report first offers background information on the RRAP as a program, the Oregon Transportation Systems project in particular, and regional stakeholder engagement. It then discusses the analytical activities and outcomes that the RRAP research team undertook as part of this RRAP project. This report concludes with a series of Key Findings that synthesize the project's analytical outcomes and offers a series of Resilience Enhancement Options that state, federal, and regional partners could explore, pursue, and/or implement to increase the seismic resilience of Oregon's roadway, aviation, and maritime transportation systems. These actions could ultimately support more effective and efficient response and restoration activities following a major CSZ earthquake in the region.

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Project Overview

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Project Description

In recent years, state officials, emergency managers, and infrastructure owners and operators in Oregon, and across the Pacific Northwest, have become increasingly concerned about the impacts of a major Cascadia Subduction Zone (CSZ) earthquake, both to the safety of communities and to the viability of infrastructure across the state. *The Oregon Resilience Plan* (OSSPAC 2013) outlined the broad range of concerns associated with a CSZ earthquake in Oregon and laid out a roadmap for enhancing the resilience of community and infrastructure systems. In 2016, the Federal Emergency Management Agency (FEMA), in close coordination with states in the region, conducted a joint multi-state exercise, *Cascadia Rising*, which underscored the importance of transportation systems to post-disaster response, recovery, and mobility needs (FEMA 2016).

In their federal and state disaster response plans for a magnitude (M) 9.0 CSZ earthquake, FEMA and the Oregon Office of Emergency Management (OEM) call for a series of disaster logistics staging areas, designated at airports across the state, that will serve as central hubs to receive and organize disaster relief supplies and equipment from around the country for further distribution to local communities (FEMA 2013). Incident response partners will activate staging areas following a disaster based on numerous factors (e.g., actual damage impacts, local government and disaster survivors' needs, cooperation of facility owners and operators). However, FEMA and Oregon OEM have pre-identified potential locations in Oregon to serve as staging areas, shown in figure 1, which includes designating Redmond Airport-Roberts Field and Crater Lake-Klamath Regional Airport as incident support bases (ISBs). These airports are large staging areas located outside of the area primarily impacted by the earthquake that will receive resources from across the United States. Responders will then transport these resources to federal staging areas (FSAs) located within the impacted areas for distribution to surrounding communities. Although state and regional disaster response plans propose these specific locations, FEMA and Oregon OEM could use additional or different airports and locations as staging areas, as dictated by response needs immediately following the disaster, to best meet the needs of surrounding communities. It is important to note that ISB and FSA locations identified in this study are not inclusive of all of the sites that state and federal agencies may possibly use as post-disaster staging areas (which could include state staging areas, or other types of logistics hubs), nor are they definitive staging locations. That is, state and federal agencies will establish the post-disaster ISBs or FSAs based on actual damage impacts along with local government and disaster survivors' needs. The willingness of facility owners and operators to enter into a contract with the Federal Government after a disaster for the use of their facility as a staging area for an extended period will also influence designation of ISB and FSA locations.

The Oregon Transportation Systems Regional Resiliency Assessment Program (RRAP) project assessed the vulnerabilities and resilience of statewide transportation infrastructure systems to the anticipated impacts of a CSZ earthquake. The impacts assessed ranged from direct earthquake impacts (e.g., seismic forces/shaking) to secondary impacts (e.g., ground failure, tsunamis), with the overall goal to determine the relative viability of statewide surface transportation systems to facilitate the movement of resources from the ISBs to the FSAs as part of the state and federal response and recovery effort.

FIGURE 1.—Planned Locations of CSZ Earthquake Disaster Logistics Staging Areas in Oregon.

The two primary transportation systems assessed in this study are roadway and airport transportation systems. Regional response plans rely on air transportation, particularly for the initial stages of response, as Oregon planners expect that surface transportation systems will sustain substantial damage and require extensive repairs before they are able to reopen. Airports generally have dual roles: they are critical nodes for receiving goods and resources transported by aircraft; however, as indicated above, numerous airports across Oregon are also designated in federal and state response plans as disaster logistics staging areas (e.g., ISBs and FSAs) to serve in vital roles as hubs to receive, sort, store, and distribute critical resources to communities. The viability of an airport's infrastructure, particularly the airfield and other systems that directly support the movement of aircraft, is central to its ability to serve in this disaster logistics function. FEMA has undertaken a series of studies to assess the operational capabilities of airports across Oregon in order to develop a series of comprehensive airport-specific air operations plans. These reports focus on the capabilities of airports with respect to their ability to support various aircraft; provide onsite cargo-handling and other support equipment; and identify onsite logistics space planning, site access, and other activities that drive how responders can best use airports as logistics staging areas given their current configurations. A small number of airports in Oregon have conducted detailed, site-level assessments of their infrastructure's seismic vulnerability; however, no high-level, statewide assessment of airport capabilities from an infrastructure resilience perspective has taken place. This study has focused on screening airports on a statewide basis to determine the relative risk of their infrastructure systems to CSZ seismic hazards and to identify potential vulnerabilities related to the external lifeline infrastructure systems (e.g., fuel, water, electricity, telecommunications) upon which they depend to function. Its objective is to give state and federal planners a broader perspective on how these airports can function as a system to support post-disaster logistics operations.

Roadway systems are the second major transportation infrastructure system assessed in this study. Generally speaking, surface transportation modes (i.e., road, rail, maritime) are better able than air-based transportation to move the large volumes of goods and resources necessary for sustained response and recovery. Therefore, while roadways are important in the initial phases of post-disaster response for distributing to local communities the goods and resources brought in by air, roadways will become increasingly important critical lifelines for the state as response activities progress and as recovery and restoration phases commence. The Oregon Department of Transportation (ODOT) has undertaken numerous studies to better understand the seismic vulnerability of the statewide highway system (ODOT 2014b) and the impacts of specific CSZ-induced hazards and structure vulnerabilities (ODOT 2015b, 2014c, 2013), as well as activities to plan for and invest in seismic retrofits (ODOT 2015a,c; 2016, 2009), all of which will help enhance the resilience of those systems. This RRAP project builds upon these prior ODOT studies by assessing Oregon's statewide roadway transportation systems through the specific lens of post-disaster response and recovery logistics supply chains by identifying and assessing the resilience of those facilities best positioned to support such activities. This assessment includes a system-level vulnerability screening of state, county, and local bridges and roadways.

The RRAP team assessed sea and river ports in this study only insofar as their exposure to seismic hazards may provide some indication of their vulnerability, as well as general resilience considerations or activities undertaken to date that emergency planners should consider. In addition, rail systems were not assessed as part of this project given the focus of current federal and state disaster response plans on roadway and aviation systems. Nonetheless, the potential is great for rail transportation systems, which operate on separate and dedicated infrastructure systems, to support post-disaster response and recovery efforts; and rail transport should be considered for future, in-depth study and emergency response planning in the context of a CSZ earthquake disaster.

The Oregon Transportation Systems RRAP project was a 3-year effort that began in 2018. The primary analytical outcomes of this RRAP project prioritize statewide roadways that can act as transportation links to distribute post-disaster response and recovery resources to communities and among staging areas. A state-level screening of the seismic vulnerability of state, county, and local roadway bridges and pavements inform these results. Additional results include a system-level screening assessment of the hazard exposure, vulnerability, and resilience of airport infrastructure systems to a CSZ event. This Resiliency Assessment report is the main product of this study; however, all data generated during this project's analytical activities—such as geographic information system (GIS) data and modeling outcomes—will be provided to the state for continued use by state agencies and other stakeholders.

System Criticality

An M9.0 CSZ earthquake will have a broad, regional impact area that extends more than 700 miles from British Columbia to northern California. Such widespread impacts will disrupt regional transportation at a systemic level. Direct seismic forces, ground failure (e.g., liquefaction, landslides), and tsunami-related flooding and waterway impacts will cause extensive damage to much of the region's road and rail networks, as well as port and airport facilities. In many cases, such an earthquake will likely render these systems unusable immediately after the initial earthquake, and they could sustain additional damage from strong aftershocks, which are characteristic of subduction-zone-type earthquakes (CREW 2009). Such extensive damage to western Oregon's transportation system will disrupt regional mobility and normal supply-chain operations, placing significant demand on government and private-sector resources to respond by transporting large volumes of basic commodities and other relief supplies into the region to sustain disaster survivors.

Regional response plans place heavy reliance on air transportation for the initial stages of response, and therefore the resilience of airport facilities and airfield infrastructure is critical to these systems' ability to serve as logistics staging areas. In addition, surface transportation modes, which are better able to move the large volumes of goods and resources that will be necessary to sustain the affected population in the mid- to long-term, will become critical lifelines for impacted populations. As noted in the Oregon Resilience Plan,

> emergency response, access to critical buildings, the restoration of utilities, and the reopening of businesses all depend on the transportation network. The resilience of the transportation network is considered a key factor for re-establishing other lifelines after a major Cascadia subduction zone earthquake. (OSSPAC 2013)

Therefore, infrastructure assessment, planning, and investment activities that improve the resilience of airport infrastructure systems and surface transportation lifelines are critical to meeting the post-earthquake public health and safety needs of affected populations.

Oregon's aviation and surface transportation systems are essential components of the CSZ earthquake response and recovery plan and will serve as vital lifelines for the individuals, communities, and critical facilities located within the earthquake-affected area. Oregon's unique geography will likely isolate communities from one another and also from other regions of the state. Only a limited number of surface transportation routes exist crossing the Cascade Mountains to connect central Oregon with the Willamette Valley, and a similarly limited number of routes cross the Coastal Mountains to connect to the numerous coastal communities. The Oregon coast itself functions as a single transportation corridor based along U.S. Route 101, with little north–south redundancy. Oregon's geography and, in many instances, the limited redundancy in its surface transportation network underscore the importance of seismic resilience within the state's aviation and land surface transportation systems, as well as maritime systems particularly along the coast and Columbia River, to enable responders to reestablish these critical linkages in the shortest possible amount of time.

Stakeholders

The Oregon Transportation Systems RRAP project facilitated collaboration, dialog, and information sharing among regional stakeholders engaged in CSZ seismic resilience planning, and the project's intent is to provide greater awareness and understanding of related goals that would benefit a variety of state and local agencies, as well as the private sector. The Office of the Governor, under the oversight of the State Resilience Officer, has sponsored this project locally. In addition, eight organizations participated as core stakeholders, offering continued input on the project's scope, approach, methodologies, analytical outcomes, and key findings to help ensure that project outcomes align with regional needs. These core stakeholders included the following:

- Oregon Office of Emergency Management
- Oregon Department of Transportation
- Oregon Department of Geology and Mineral Industries (DOGAMI)
- U.S. Department of Transportation
- Federal Emergency Management Agency (FEMA)
- U.S. Coast Guard (USCG)
- U.S. Department of Defense
  - U.S. Army Corps of Engineers (USACE)
  - United States Transportation Command (USTRANSCOM)
  - United States Northern Command (USNORTHCOM)

In addition to these core stakeholders, the successful execution of the Oregon Transportation Systems RRAP project required the coordinated involvement of numerous partners from federal, state, county, and local government agencies and the private sector, listed below. The RRAP research team met with these stakeholders in person to better understand their infrastructure systems and local concerns, and visited numerous sites across the state, shown in figure 2.

FEDERAL GOVERNMENT

- **DHS**
  - FEMA Region 10
  - USCG Sector Columbia River
  - USCG Sector Coos Bay
- **U.S. Department of Defense**
  - USACE
  - USNORTHCOM
  - USTRANSCOM
- **U.S. Department of Transportation, Region 10**

STATE GOVERNMENT

- **Office of the Governor**
- **Oregon OEM**
- **DOGAMI**
- **ODOT**
  - Bridge Engineering
  - Emergency Operations
  - Engineering Geology
  - Multimodal Transportation
  - Pavement and Roadways
- **Oregon State University**
- **Portland State University**
- **University of Washington**

REGIONAL, COUNTY, AND CITY GOVERNMENT

- **Clackamas County**
- **Clatsop County**
- **Columbia County**
- **Coos County**
- **Curry County**
- **Deschutes County**
- **Jackson County**
- **Klamath County**
- **Lane County**
- **Lincoln County**
- **Linn County**
- **Marion County**
- **Multnomah County**
- **Tillamook County**
- **Washington County**
- **City of Astoria**
- **City of Bend**
- **City of Brookings**
- **City of Clatskanie**
- **City of Coos Bay**
- **City of Eugene**
- **City of Gold Beach**
- **City of Klamath Falls**
- **City of Medford**
- **City of Newport**
- **City of Portland**
- **City of Redmond**
- **City of Salem**
- **City of Tillamook**
- **City of Warrenton**

PRIVATE SECTOR

- **Airports**
  - Astoria Regional Airport
  - Aurora State Airport
  - Bandon State Airport
  - Cape Blanco State Airport
  - Crater Lake – Klamath Regional Airport
  - Eugene Airport – Mahlon Sweet Field
  - Hillsboro Airport
  - Newport Municipal Airport
  - Portland International Airport
  - Redmond Municipal Airport
  - Rogue Valley International – Medford Airport
  - Salem Municipal Airport – McNary Field
  - Tillamook Airport
- **Maritime Ports**
  - Port of Astoria
  - Port of Brookings Harbor
  - Port of Coos Bay
  - Coos Bay Rail
  - Port of Gold Beach
  - Port of Newport
  - Port of Port Orford
  - Port of Portland
  - Port of Westward
- **Private Sector**
  - BNSF Railway Company
  - Teevin Brothers Rainier

All participation in this RRAP project was voluntary. The type and degree of participation varied among organizations. Participation does not imply a formal role in the review or approval of this report.

FIGURE 2.—Infrastructure Sites or Stakeholders Visited by RRAP Research Team.

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Analytic Outcomes

Analytic Outcomes

The analyses undertaken in this RRAP project are intended to enhance Oregon's understanding of its transportation system's resilience to a CSZ earthquake, identify gaps or needs, and complement prior planning efforts. In 2011, the DHS Homeland Infrastructure Threat and Risk Analysis Center (HITRAC) and National Infrastructure Simulation and Analysis Center (NISAC) undertook a regional study, *Analytical Baseline Study for the Cascadia Earthquake and Tsunami*, which provides a broad foundation for how an M9.0 CSZ earthquake could impact multiple infrastructure systems and sectors (NISAC and HITRAC 2011). As discussed in the Project Description section, ODOT has also undertaken numerous studies over the past decade to assess the vulnerability of Oregon's bridges and roadways to a CSZ earthquake and better plan for the seismic resilience of their assets. In addition, ODOT's study, *Oregon Highways Seismic Plus Report*, identifies priority highway corridors across the state, and recommends both phased bridge retrofitting and landslide assessment and mitigation, to help ensure post-disaster mobility for a wide range of post-disaster functions (ODOT 2014b). This RRAP project complements these prior studies by assessing at a statewide and systems level the seismic vulnerability and resilience of Oregon airports and roadways (including county and local roadways), and it tailors outcomes to inform state and federal CSZ logistical response plans more directly. In addition, at the outset of this study, state and regional stakeholders stressed the need for transparency and the ability to share this project's findings broadly with the community to most effectively inform statewide planning.

The following sections provide a brief background of the CSZ, discuss the primary hazards associated with a CSZ earthquake, and summarize the three major areas of analysis conducted as part of this RRAP project. The hazards discussion identifies the data and information that supported the analyses, as well as the gaps within those data and information sources that, if strengthened, could better support future analytical efforts. The three analysis areas include (1) an evaluation of roadways within the western half of Oregon to seismic vulnerabilities and a regional study of how disruptions to these systems could isolate communities into "island" areas; (2) a screening-level assessment of the seismic resilience and capabilities of key airports across western and central Oregon currently designated as disaster logistics staging areas, as well as a summary of stakeholder-related engagement findings for airport infrastructure; and (3) a hazard exposure analysis and summary of findings for marine port infrastructure.

Background on the CSZ

The CSZ is a megathrust fault zone located off of the west coast of North America that stretches approximately 700 miles from northern Vancouver Island, Canada, to Cape Mendocino, Calif. (figure 3). Along this fault, three regional tectonic plates—the Explorer, Juan de Fuca, and Gorda plates—are pulling away from the larger Pacific plate and moving toward the North American plate. At the North American plate boundary, these three regional plates are descending—or subducting—underneath the North American plate (figure 4). As this subduction occurs, "a large portion of the boundary between the subducting and overriding plates resists the convergent motion, until this part of the boundary breaks in a great earthquake" (CREW 2013). Historic records suggest that the last such great earthquake along the CSZ boundary occurred in January 1700 with an estimated magnitude of 8.7–9.2 (Atwater et al. 2005). Furthermore, paleoseismology studies evaluating centuries' worth of seismic history in the region have identified numerous prior earthquakes that occurred as early as 1400 BC (Atwater et al. 2003). These studies place the likelihood of a major CSZ earthquake occurring in the next 50 years at approximately 10 percent (Goldfinger et al. 2012).[1]

[1] Goldfinger et al. (2012) note that "time-independent probabilities for segmented ruptures range from 7–12 percent in 50 years for full or nearly full margin ruptures to ˜21 percent in 50 years for a southern-margin rupture. Time-dependent probabilities are similar for northern margin events at ˜7–12 percent and 37–42 percent in 50 years for the southern margin."

Scientists project that a CSZ earthquake could occur with a magnitude of 9.0 and that the ground could shake for several minutes, releasing tremendous amounts of energy that could damage infrastructure and affect communities along the west coast of the United States and Canada. Since the mid-twentieth century, several other subduction zone earthquakes have occurred around the Pacific region that provide context for what the Pacific Northwest region could experience during a CSZ earthquake. These include an M9.2 earthquake in Prince William Sound, Alaska (1964); an M9.1 earthquake in Aceh-Andaman, Sumatra (2004); an M8.8 earthquake in Maule, Chile (2010); and an M9.0 earthquake in Tohoku, Japan (2011) (CREW 2013).

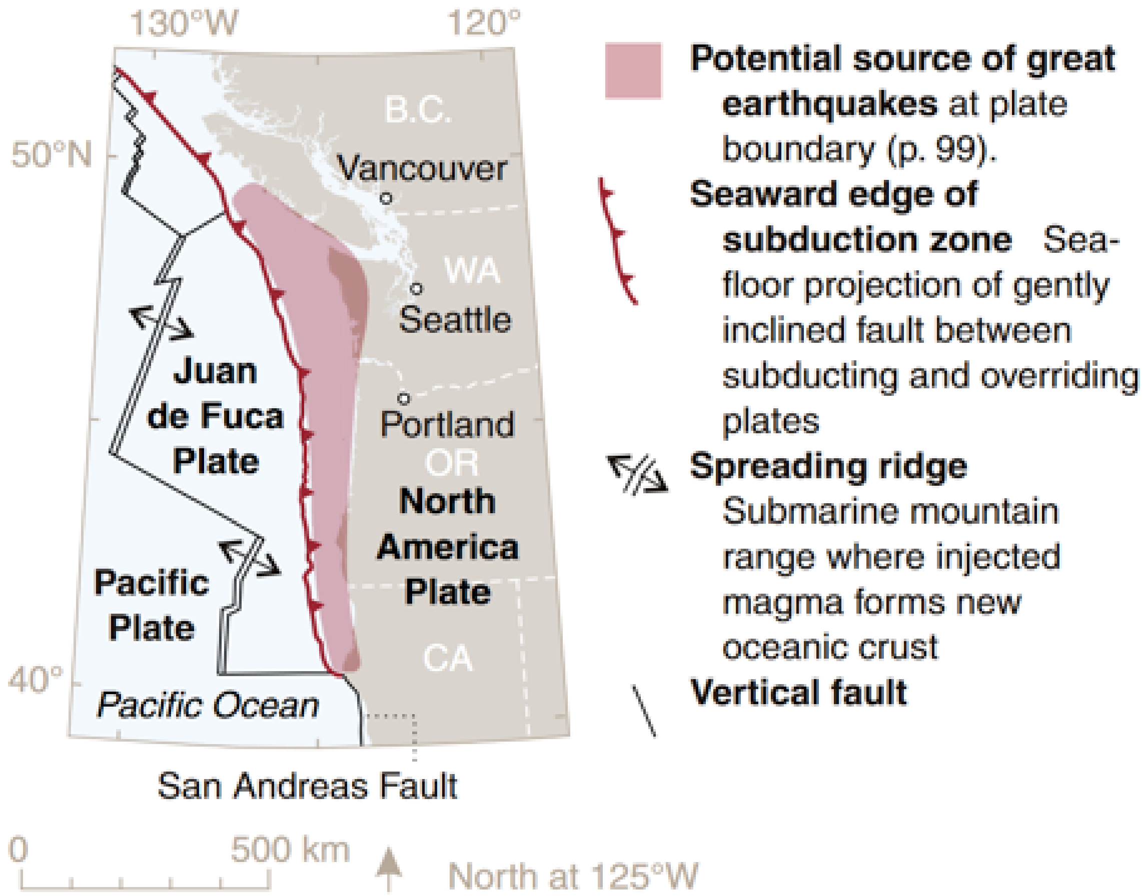


FIGURE 3.—CSZ Geographical Extent. (Source: Atwater et al. 2005)

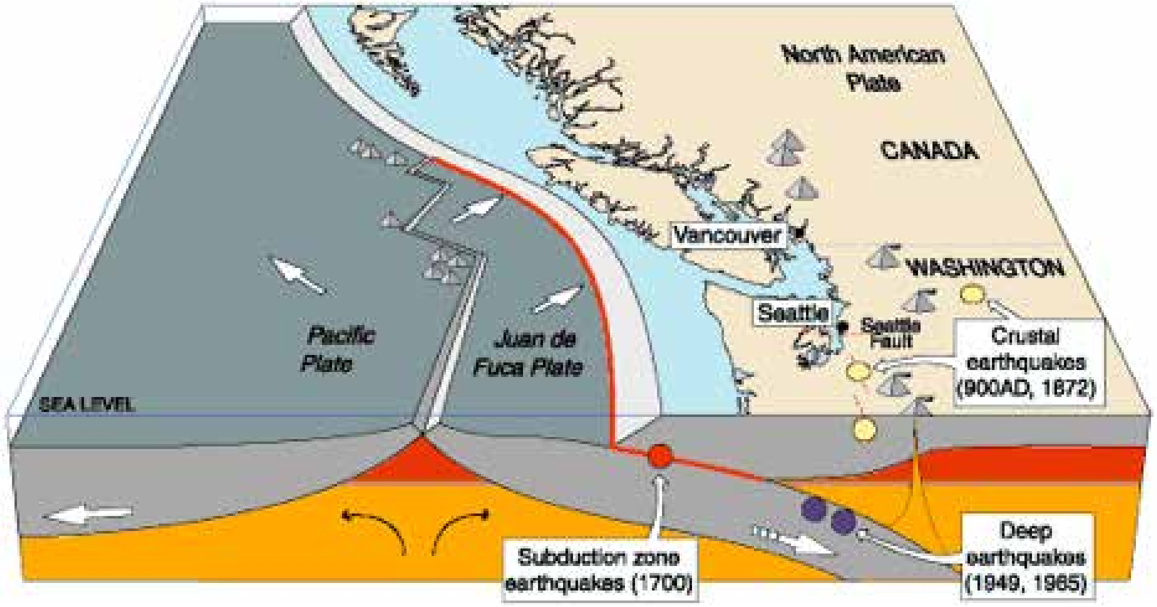


FIGURE 4.—Plate Tectonics in the CSZ. (Wells et al. 2016)

CSZ Seismic and Secondary Hazards

The primary hazard associated with a CSZ earthquake is strong and prolonged shaking, or ground motion, and the forces that such shaking can impart on infrastructure and the built environment. However, the primary earthquake can also trigger several secondary hazards associated with a CSZ earthquake. These include ground failure (e.g., landslides, liquefaction, ground displacement or deformation), tsunamis, and—particularly in winter months—avalanches. Both the primary and secondary hazards associated with a CSZ earthquake can cause significant damage to statewide transportation systems and can adversely affect their ability to facilitate response and recovery efforts. This section discusses the several hazards associated with a CSZ earthquake that this RRAP project considered, the supporting hazard data and information available that the RRAP team used to inform this study's analysis, and any gaps in the available data and information that should be addressed in future work.

While this report did not integrate all seismic and secondary hazards considered for this RRAP project into the ultimate analysis, it discusses them here to provide context for their exclusion and to identify actions that emergency planners could take to better integrate them into future analyses.

Ground Motion

Ground motion is the most apparent and direct hazard associated with an earthquake. The size of an earthquake is expressed most commonly (by U.S. Geological Survey [USGS] and others) using the Moment Magnitude Scale (MMS), which quantifies the amount of energy that an earthquake releases (USGS undated[a]). In this RRAP project, the core stakeholder group agreed that the "USGS M9.0 Scenario Earthquake – Cascadia M9.0 Scenario (mean value)" should form the basis for all analysis (USGS 2017). This USGS CSZ scenario is a 2017 update to an earlier 2011 USGS scenario that the Cascadia Region Earthquake Workgroup (CREW) identified for use in regional catastrophic planning (CREW 2013), and it was also the basis for analysis in the Washington State Transportation Systems RRAP project (CISA 2019). Earlier versions of this USGS CSZ scenario were also used in the NISAC/HITRAC study, the Cascadia Rising 2016 exercise, and FEMA's *CSZ Catastrophic Earthquake and Tsunami Response Plan* (Ver. 2.0) (FEMA 2013, 2016; NISAC and HITRAC 2011).[2]

Peak ground acceleration (PGA) is a quantitative measure of shaking intensity that is commonly used in infrastructure-related seismic design specifications and building codes. Whereas MMS is a measure of an earthquake's overall size, PGA is a location-specific measure of ground shaking intensity that can be used to approximate the seismic forces that a specific location or structure will experience during an earthquake.[3] PGA is the primary metric for earthquake intensity used in this study to assess the vulnerability of Oregon's surface transportation system to ground motion. Figure 5 shows the GIS data collected from the USGS for PGA projected across Oregon under the USGS M9.0 CSZ scenario. The USGS CSZ scenario projects that the strongest shaking will occur on the Oregon Coast and across the Coastal Mountains into the Willamette Valley and southwestern Oregon. However, it will generally diminish moving east across the state, particularly across the Cascade Mountains into central and eastern Oregon.

FIGURE 5.—Projected PGA for Oregon under the USGS M9.0 CSZ Scenario.

[2] The University of Washington and the USGS's current "M9 Project" (University of Washington 2021) offers improved characterization of a CSZ earthquake using dozens of scenarios; the RRAP research team, with the agreement of the core stakeholder group, decided to use the USGS M9.0 CSZ scenario to enable more consistent regional planning with the Washington State Transportation Systems RRAP project (CISA 2019).

[3] PGA is expressed as an acceleration in units of g; 1 g is the Earth's gravitational acceleration, or 9.81 m/s^2.

Subduction earthquakes, in general, typically experience a longer duration of shaking as compared with other types of earthquakes, which increases the potential for structures to sustain damage or to fail. The duration of shaking for a CSZ earthquake is projected to range from 2–6 minutes (CREW 2013). However, the effects of longer-duration shaking on structures have not been widely studied, and current seismic design specifications and codes do not explicitly consider shaking duration in structural design and assessment practices (Chandramohan 2016). The earlier Washington State Transportation RRAP project (CISA 2019) had incorporated some findings from this nascent field of research to account for the effects of longer-duration shaking on bridge structures, and the RRAP research team revised that methodology in this study in consultation with structural engineering experts from Portland State University and the University of Washington. (See the accompanying document, *Bridge Seismic Screening Tool [BSST] – Technical Report, Version 2.0*.) Additional research is necessary to better quantify the effects of long-duration shaking on structural systems and to characterize with greater certainty their potential impacts on bridge structures in Oregon.

Strong aftershocks commonly occur in the hours, days, weeks, and months following subduction earthquakes. It is likely that strong aftershocks following a CSZ earthquake will cause additional damage to structures in the region; however, the occurrence of aftershocks and their impacts on already degraded infrastructure are impossible to predict. For these reasons, the core stakeholder group agreed that this study would focus on assessing impacts and vulnerabilities associated with the primary M9.0 earthquake and would not attempt to address the impacts of aftershocks on Oregon's transportation system.

Ground Failure

Ground failure refers to a range of secondary hazards that an earthquake can trigger, in which ground and soils become unstable, shift, flow, or lose their load-bearing capacity and ability to support structures. This study considered two major types of ground failure: soil liquefaction and landslides.

Soil Liquefaction

Soil liquefaction (also referred to as liquefiable soils) refers to the phenomenon where certain types of soils that are saturated with water can behave like a liquid when they experience seismic shaking. Liquefaction can result in the loss of support for surface structures (e.g., buildings and bridges), in soil flows on even very gentle slopes, and in large differential settlements where areas of the ground surface sink in comparison to nearby or surrounding soils. Soil liquefaction occurs typically in alluvial soils—loose sand and silty soils that are characteristic of river valleys, river deltas, and other areas with flowing water (USGS 2006). DOGAMI maintains a statewide geospatial database (called Oregon HazVu: Statewide Geohazards Viewer) that characterizes soils susceptible to liquefaction across Oregon (DOGAMI 2020), assigning liquefaction-susceptible soils as having Low, Moderate, or High susceptibility (DOGAMI 2021). This dataset served as the primary basis for analyzing seismic-related ground failure impacts on the statewide surface transportation system in Oregon.

As figure 6 shows, soils with high and moderate liquefaction susceptibility in Oregon occur most frequently along river valleys. In particular, high liquefaction susceptibility exists throughout the Willamette Valley, along the lower reaches of the Columbia River from the Portland metropolitan area to the coast, and throughout much of the low-lying and riverine areas of the Oregon Coast. Using GIS software, the RRAP research team overlaid Oregon's roadway network (including state, county, and local roadways) with this liquefaction susceptibility dataset and found that 34 percent of Oregon roadways within the study area are constructed on soil with a liquefaction susceptibility of Moderate or High, which is sufficient to put them at greater risk of experiencing impacts from liquefaction-based ground failure.

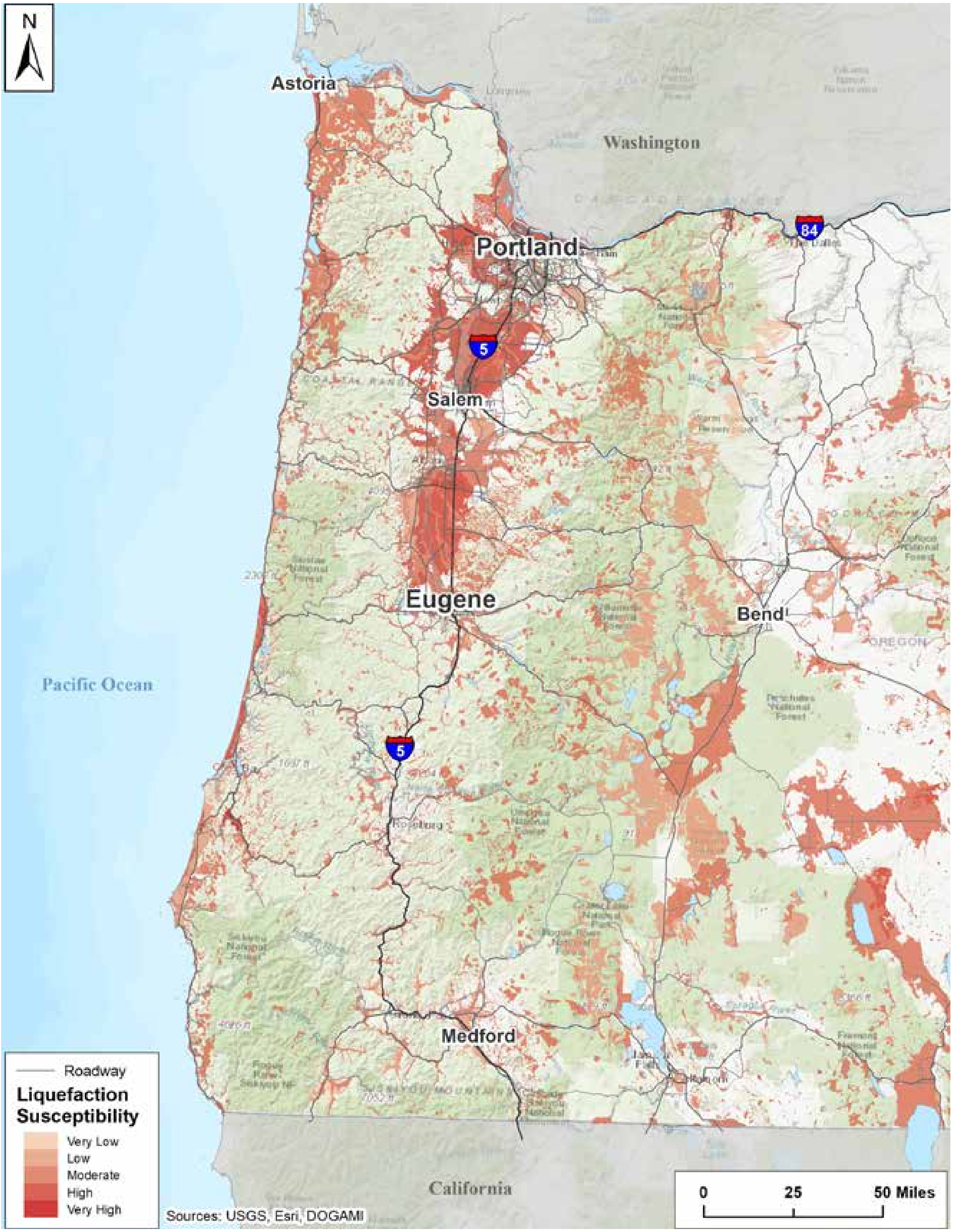


FIGURE 6.—Soil Liquefaction Susceptibility in Oregon.

The impacts of seismic-induced soil liquefaction to infrastructure is commonly quantified as permanent ground deformation (PGD), which refers to the vertical and lateral deformation of soil resulting from soil liquefaction, as measured in inches or feet of displacement. PGD can create significant disruptions to regional transportation systems. For highways, bridge foundations can fail, leading to bridge failure; roadbeds and pavements can sink or shift, creating significant cracking or discontinuities in the driving surface; and slopes or earth-retaining structures adjacent to highways can fail. For airports, runways, taxiways, and ramp areas can sink or shift, similar to roadways, creating significant discontinuities or cracking that could prevent aircraft from safely operating; critical structures such as air traffic control facilities, navigation systems, fuel storage facilities, and piping systems could experience foundation damage due to deformation or differential settlement. For rail infrastructure, rail lines can shift and buckle, rail yards can experience significant deformation or differential settlement, and rail bridges can experience impacts similar to highway bridges. Last, port and maritime infrastructure can experience differential settlement or liquefaction, resulting in submarine landslides that can affect navigation channels and also potentially lead to failure of seawalls supporting port infrastructure.

FEMA's Hazus natural disaster risk model uses PGD as the primary measure of seismic-induced ground failure to evaluate infrastructure impacts. Accordingly, this study uses PGD as the primary metric for ground failure to assess the statewide surface transportation system's vulnerability to seismically induced soil liquefaction. Numerous methods exist to calculate approximate PGD values given liquefaction susceptibility data such as that provided by DOGAMI. In consultation with geotechnical engineering experts at Portland State University and the University of Washington, the RRAP research team identified several options, including a method developed by Bardet, Mace, and Tobita (1999), which was used previously in the Washington State Transportation Systems RRAP (CISA 2019), and which the RRAP research team ultimately selected for this study, as well. The accompanying report, *Oregon Roadway CSZ Liquefaction and Landslide Impact Screening Analysis*, describes a comparison of PGD calculation methods evaluated for use in this project, as well as the application of the selected method for calculating CSZ-induced PGD values for Oregon roadways.

This study's PGD calculation method required the RRAP research team to make some analytical assumptions before we could apply it directly to the dataset maintained by DOGAMI; these assumptions introduce some uncertainty into the analysis. Two of the primary inputs to calculating PGD are the local ground slope and the thickness of saturated soils where PGD is being calculated. Use of GIS software and a USGS-published digital elevation model dataset (USGS undated[b]) enabled the research team to readily approximate ground slope across the state. This dataset expresses land surface elevations using a 10-meter grid, which is sufficient to calculate general slope trends. In some areas, however, slope calculations using this dataset may be underestimated where local embankments or slopes fall within the 10-meter grid. The second assumption—determining the thickness of saturated, liquefiable soils—is somewhat more difficult. While the DOGAMI dataset characterizes soils according to their liquefaction susceptibility, it does not quantify the thickness of liquefiable soils, and therefore the research team assumed the thickness of liquefiable soils throughout the state in order to approximate PGDs. The RRAP research team discussed and agreed upon these assumptions with the ODOT State Geotechnical Engineer, and the accompanying technical report noted above describes the assumptions in greater detail.

Landslides

Landslides are a type of ground failure that occurs where gravity acts on soils located on overly steep or unstable slopes to cause some movement (USGS 2020), including rock falls, deep failures of slopes, and shallow debris flows. Landslides can disrupt transportation systems by depositing soil and other debris on top of roadways and facilities, by causing the failure of the soils that support such facilities (frequently causing these facilities to slide down the slope), or by imposing direct force on transportation structures or facilities (e.g., bridge piers) by sliding or flowing soils and debris. These types of slope failures occur along state highways in Oregon even under normal conditions, and ODOT mitigates them as part of ongoing highway operations and maintenance. However, a major CSZ earthquake could cause significant additional landslides to occur, which could require significant additional time and resources before infrastructure owners can reopen roadways so that post-disaster emergency response and recovery activities can proceed.

DOGAMI has characterized the landslide potential of slopes across Oregon based on information it collects about historic landslides and through topographic surveys, LIDAR investigations, soil surveys, and knowledge of local conditions. These studies have enabled DOGAMI to develop the Statewide Landslide Information Database for Oregon (SLIDO), which the RRAP research team used as the basis for landslide analyses in this project (DOGAMI 2019a). The SLIDO dataset, shown in figure 7, characterizes landslide hazard potential across the state as low, moderate, high, and very high. No common metric exists to quantify landslide impacts (i.e., as with PGA for ground motion, or PGD for liquefaction); thus, the RRAP research team developed a landslide risk characterization methodology, in collaboration with ODOT's Unstable Slopes Program Manager, which the accompanying technical report, *Oregon Roadway CSZ Liquefaction and Landslide Impact Screening Analysis*, describes. This approach incorporates information from SLIDO, ODOT maintenance and landslide records, and other datasets to quantify landslide risks to roadways across Oregon.

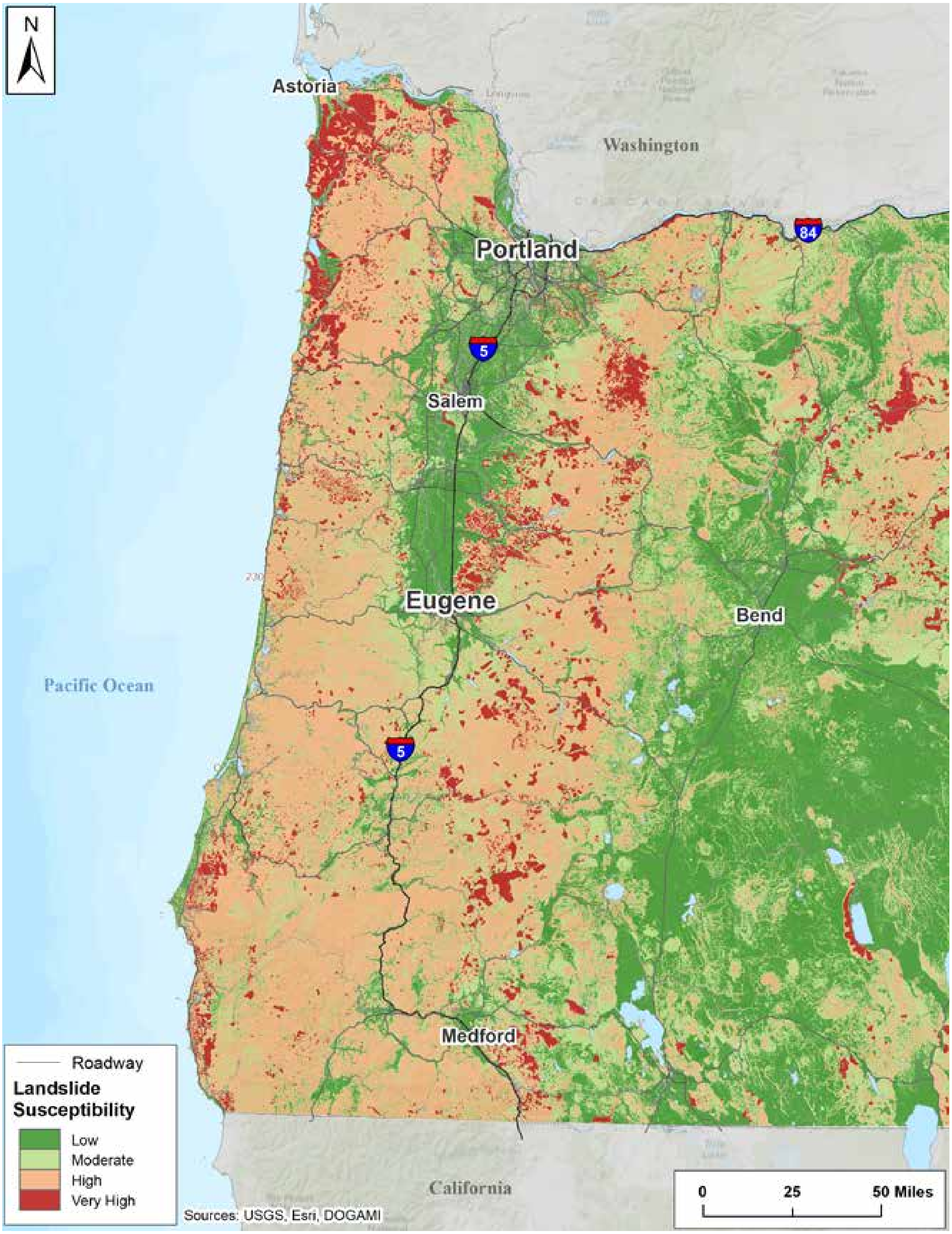


FIGURE 7.—Landslide Susceptibility in Oregon.

Tsunamis

A tsunami is a large ocean wave (or series of waves) that occurs when some incident or disruption displaces a large volume of water. In the context of a CSZ earthquake, the fault rupture causes the sudden movement of tectonic plates, displacing the ocean floor and propagating an ocean wave. The amplitude of the wave will increase as it travels out from the fault line and approaches shallower water near the coastline. The first CSZ tsunami wave is projected to reach the coastline within 10 to 30 minutes of the initial earthquake, with many communities fully inundated in approximately 35 minutes (Bauer et al. 2020; Gabel et al. 2020). Simulations indicate that average tsunami wave heights along the open coast could reach approximately 50 feet (depending on location, wave heights will range generally from 22 to 78 feet) (Allan 2021). Given experiences with similar coastal subduction zone earthquakes around the world, subsequent large waves could follow this initial tsunami wave in the hours following the earthquake (CREW 2013).

Tsunamis can affect coastal transportation infrastructure systems in a number of ways. The large volume of water moving inland can inundate infrastructure for hours or days until floodwaters drain and subside. Tsunami waves can impose tremendous lateral and uplift forces on structures, such as bridges, docks, or other marine structures, which can cause structural damage or failure. Similarly, the swift movement of tsunami inundation water around bridge columns or piers can rapidly deteriorate or remove the soils that support bridge pier foundations—a condition referred to as bridge scour—increasing the potential for structural failure. If flooding is prolonged, water infiltration into road subgrades and bridge abutments could lead to the accelerated deterioration of pavement structures.

Tsunamis also create strong currents and wave forces that can dislodge and carry large quantities of floating debris and suspended sediments. Debris can collect near structures, such as bridges and docks, and exert additional lateral forces on the supporting superstructure; or debris can block waterway access to coastal infrastructure, such as ferry terminals and commercial ports. Sediments can collect in shallower waterways and coastal areas, restricting the draft of vessels that can operate in those waterways and access nearby maritime facilities. Debris must be removed before marine vessels can resume operations, and waterways may require dredging to remove sediments and restore operating depths.

DOGAMI has undertaken numerous studies to model several tsunami scenarios along Oregon coastlines and has used the recurrence interval of increasingly strong earthquakes as measures of intensity. These scenario-based datasets characterize aspects such as inundation depth, inundation extent, and other attributes (Priest et al. 2013), and are available publicly via DOGAMI's Tsunami Inundation Map Series (DOGAMI 2019b). The modeling in the DOGAMI tsunami scenarios covers a range of CSZ earthquake sources, corresponding to different tsunami inundation extents: Small (SM), Medium (M), Large (L), Extra Large (XL), and Extra Extra Large (XXL). DOGAMI's Open-File Report O 13-19 recommends using the XXL tsunami scenario, which is associated with an approximately 1,200 year CSZ earthquake recurrence interval, for evacuation zone planning. Given this recommendation, and in consultation with DOGAMI's resilience engineer and other core stakeholders, the RRAP research team used the XXL tsunami scenario as the basis for analysis in this project. This selection also helps to maintain consistency with a recent DOGAMI pilot study analyzing the impacts of an XXL CSZ tsunami on people and structures in five Oregon coastal communities (Bauer et al. 2020), which was expanded to include countywide assessments of earthquake and tsunami damage (Allan et al, 2020a, 2020b; Allan and O'Brien 2021). DOGAMI's datasets project the inundation extent for these tsunami hazards with high local detail. Figure 8 shows the extent of tsunami hazard mapping (in this case, the XXL scenario), which covers Oregon's entire Pacific coastline, and the inset figure shows an example of the high-resolution detail in local inundation projections in the dataset.

FIGURE 8.—Tsunami Inundation Hazard Mapping in Oregon.

Analysis of Regional Islanding from Roadway Disruptions

One of the primary analytical objectives of this RRAP project was to assess the relative viability of statewide surface transportation systems to facilitate the movement of resources both among the ISBs and FSAs, as well as from these disaster logistics staging areas out to communities across the state as part of the state and federal response and recovery effort. In particular, Oregon OEM, ODOT, and FEMA Region 10 were interested in the ability of Oregon's extensive roadway network to facilitate these post-disaster logistics functions, and also of the airports themselves that will serve as many of the primary disaster logistics staging areas. To accomplish this objective, the RRAP research team conducted a regional "islanding" analysis focused on the western half of Oregon. The islanding analysis delineated communities and areas in the western half of Oregon that will become functionally disconnected or isolated from one another, or from the broader region, as a result of CSZ earthquake-induced disruptions to the transportation system. That is, as infrastructure is disrupted across an area, disruptions to transportation links will create functional boundaries that separate previously connected areas. For example, a community could become isolated either from adjacent communities, or the surrounding region, if service over a key bridge over a river is disrupted and no alternate routes exist (or if the alternate routes are similarly damaged/disrupted). A local-scale islanding study of the Oregon coast that Oregon OEM conducted (Songer 2016) and a county-level assessment that Clallam County, Washington, presented (Orr undated) inspired the concept of incorporating an islanding analysis.

This islanding analysis identified the priority roadway routes and facilities branching out from the staging areas that are best able to reconnect communities efficiently to post-disaster response and recovery supply lines. The analysis also approximated the populations and "service areas" that each of the disaster logistics staging areas will need to serve following the disaster, as well as how these service areas will expand and grow throughout post-disaster response and recovery phases as transportation routes are repaired and reopened over time. The islanding analysis first determined island boundaries by identifying how each of the hazards presented earlier (i.e., liquefaction, landslides, tsunamis) disrupted roadway transportation systems. It then determined the approximate reopening times for each asset and facility based on the extent of damage, facility characteristics, and other factors. Working outward from each of the staging areas shown in figure 1, an optimization model identified the roadways and routes that can reopen most quickly to reach the largest population(s) in surrounding communities most efficiently. Those primary roadway routes that are able to reopen most quickly, reestablishing connections from the staging areas to communities across the state, constitute the priority routes for disaster logistics supply chains.

The RRAP research team intends for the outcomes of this islanding analysis to directly inform emergency management and response planning in two ways. First, the set of priority routes enables infrastructure owners and operators and emergency managers to prioritize both the pre-disaster response planning and resilience investment and also the post-disaster inspection, repair, and reopening activities along those routes. In addition, the islanding analysis identifies the approximate service areas, as a function of time (i.e., as roadways are progressively reopened), for each disaster logistics staging area with their associated populations; emergency planners can use this information to specify the operational requirements of staging areas during pre-disaster planning activities.

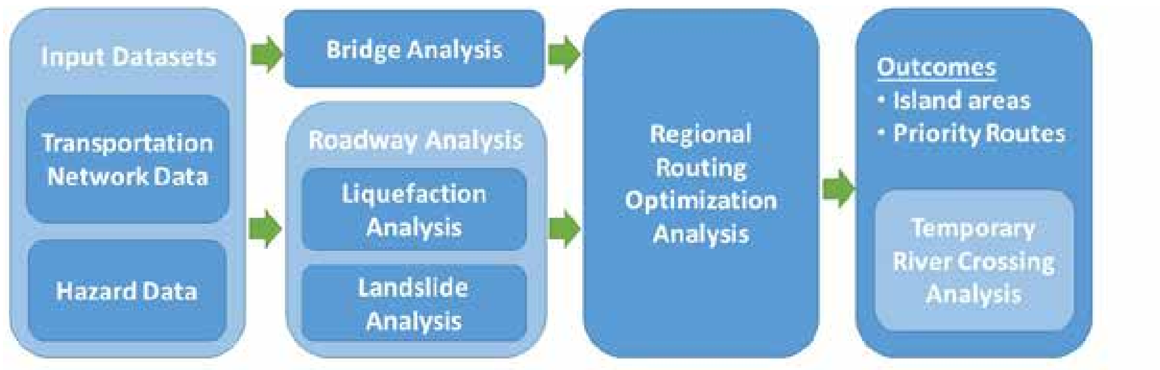


FIGURE 9.—Islanding Analysis Methodology.

To determine the priority routes and islanded areas, the RRAP research team undertook a systems-level analysis of Oregon's roadway and bridge network for the western half of the state. Figure 9 shows the steps in this islanding analysis of the roadway network. First, the RRAP research team developed a network model of Oregon roadways using available transportation data. The roadway network model is comprised of GIS data of roadway links and nodes based on data from OpenStreetMap (OSM)—a community-driven, open-source dataset detailing roadways across the globe (OpenStreetMap contributors 2018). Roadway segments in this dataset vary in length from several feet to a mile or more. The research team then incorporated bridge data provided by ODOT for state, county, and local bridges into the roadway network model, resulting in a network with 426,498 discrete roadway segments and 5,646 bridges in the study region. This model excluded some minor roadways, including service roads (e.g., alleyways), local/neighborhood streets, and forest service roads. Service and local/neighborhood streets are not likely to be able to accommodate the volume of traffic required for CSZ disaster response, and were thus excluded. Forest service roads were excluded because the research team determined that some of these roads in the OSM dataset were no longer maintained, and therefore unfit for immediate use in post-disaster response without necessary repairs and maintenance being made first. In addition, without engineering improvements, such roads are unlikely to accommodate the large traffic volumes required in a post-CSZ earthquake response and recovery effort.

In the next stage of this methodology, the RRAP research team conducted a system-level assessment of bridge and roadway/pavement infrastructure to assess its seismic resilience. This assessment determined the approximate reopening times for bridges and roadway segments based on their projected levels of damage as a result of CSZ seismic hazards, resulting in a roadway network model with post-disaster reopening times for all 426,498 segments.

These segment-based reopening times were input into a network optimization model that computed the optimal roadway network pathways (i.e., lowest aggregate reopening time) connecting each of the staging areas shown in figure 1 to communities in western and central Oregon. Last, the RRAP research team evaluated Oregon's

In a post-disaster emergency environment, restoration time refers to the amount of time needed to return an asset or facility to its pre-disaster condition. For example, infrastructure owners would replace or return highway bridges to a condition sufficient to allow the traveling public to use that bridge safely, and without any temporary restrictions on weight or other operating factors.

In contrast, reopening time, as it is used in the context of post-disaster activities in this study, refers simply to the time required to repair an asset or facility to a minimum safe condition that would enable emergency responders to use the facility, but not sufficient for broader or unrestricted use by the general traveling public.

river system to identify locations where the emergency response effort could use temporary river crossings (e.g., temporary bridge structures) to facilitate nearer-term emergency and disaster response transportation needs while making longer-term bridge repairs. The following sections describe the methodology and results for the bridge and roadway assessments that fed into the regional network optimization model and the network optimization model itself, as well as the results of both of these intermediate analyses and the overall islanding analysis.

This study focused on *reopening* times instead of restoration times. While restoration time generally refers to the amount of time required to restore facilities to a fully operable, pre-disaster state of repair, reopening time simply refers here to the amount of time required to bring transportation infrastructure and facilities back to a minimally acceptable state of repair. That minimally acceptable state of repair must be sufficient to enable the initial movement of emergency response vehicles and resources into the affected region, but does not have to support broader inter- and intra-regional mobility. The RRAP sponsor and core stakeholders recommended this use of reopening times given this study's focus on the immediate response to a CSZ earthquake and the reestablishment of emergency supply lines, as well as to maintain consistency with the related Washington State Transportation Systems RRAP project.

Bridge Seismic Screening Analysis

Bridges are critical links within roadway networks across otherwise impassable rivers, terrain, intersecting roadways, or other obstacles. When damaged, bridges can require substantial amounts of time and resources to reopen and reestablish these connections.

In fact, the Washington State Transportation Systems RRAP project completed in 2019 found that along the 1,305 miles of state owned highways in Washington projected to have a reopening times of 2 weeks per mile or greater, it was the bridge reopening times on all but 71 miles of these roadways that accounted for more than 90 percent of their per-mile reopening times (CISA 2019).

To assess the seismic vulnerability of roadway bridges in western and central Oregon to a CSZ earthquake, the RRAP research team used a tool developed previously in the Washington project called the BSST (Bergerson et al. 2019). These researchers created the BSST in close collaboration with the Washington State Department of Transportation's (WSDOT's) Bridge and Structures Office, and the RRAP research team updated the BSST methodology for this project through close collaboration with ODOT's Bridge Office and with extensive input from structural engineering experts at Portland State University and the University of Washington. The accompanying document, *Bridge Seismic Screening Tool (BSST)* – Technical Report, Version 2.0, provides a more detailed discussion of the development, implementation, supporting data, and updates to the BSST methodology for Oregon.

The BSST is a seismic risk *screening* tool that conducts a system-level assessment of the seismic resilience of state- and locally owned Oregon bridges to a CSZ earthquake. While it provides bridge-specific outcomes that are intended to inform corridor- and system-level analyses, the BSST does not enable researchers to conduct a detailed, asset-level engineering analysis of individual structures. And although its outcomes may be useful in high-level infrastructure investment or emergency response planning activities such as this RRAP project, its use cannot replace more detailed, asset-level engineering assessments of direct seismic and seismic-related impacts on individual bridges.

The BSST analysis focused on a seismic screening analysis of 5,646 state, county, and local bridges located in the western half of Oregon using asset management data that ODOT collected and provided. Figure 10 presents the BSST methodology and begins by evaluating each bridge's structural configuration, first separating out those "special bridges" with non-standard design configurations.

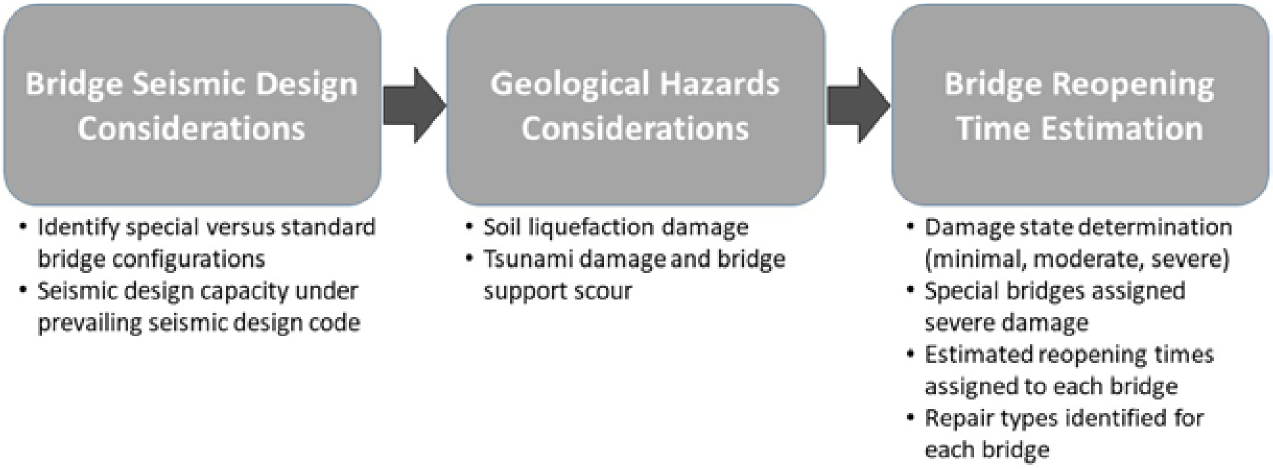


FIGURE 10.—Bridge Seismic Screening Tool (BSST) Methodology.

The BSST evaluates these 23 special bridges, which include, for example, moveable bridges, vertical lift bridges, or suspension bridges, separately. The analysis then evaluated the remaining 5,623 bridges with respect to the seismic design of their superstructure, which first considers whether owners and/or operators built a bridge originally or retrofitted it subsequently using design standards that incorporate seismic design considerations. If a bridge was built using seismic design standards, the BSST then evaluated whether the PGA projected for the bridge to experience during a CSZ earthquake will exceed the PGA specified by the prevailing design standard in use when the bridge was either built or retrofitted.

The BSST then evaluated the vulnerability of bridges to two primary geological hazards associated with a CSZ earthquake—soil liquefaction and tsunami inundation. The RRAP research team evaluated soil liquefaction by calculating approximate PGD values at each bridge location using the method described in the accompanying report, *Oregon Roadway CSZ Liquefaction and Landslide Impact Screening Analysis*. The team then assigned ranges to these PGD values that corresponded with one of three bridge damage levels—minimal, moderate, or severe. They evaluated tsunami vulnerability by considering bridge overtopping by a tsunami wave or related flooding, and the potential for scour damage to occur along foundations, piers, or other supporting substructure.

Finally, the BSST assigned approximate reopening times to bridges using damage levels and types determined during the seismic design analysis, liquefaction, and scour analysis, and also using additional information on bridge characteristics, such as bridge length and configuration, or the obstacle that the bridge traverses (e.g., river, ravine, surface roadway). The RRAP research team made several assumptions in determining approximate reopening times for bridges that should be taken into consideration by emergency response planners. Predicting several factors that influence bridge construction and reopening time is challenging, including the availability of bridge inspectors; site accessibility; availability of construction materials, equipment, and personnel; and the number of bridge reopening projects that will compete for these limited resources. These constraints are effectively unknowable for a post-CSZ earthquake environment, and therefore the RRAP research team did not consider these constraints in determining bridge reopening times. All bridge reopening times reflect the amount of time needed to reopen a crossing absent any such constraints. As a result, the actual bridge reopening times could be longer depending on post-disaster conditions.

Table 1 contains damage levels, damage types, and associated approximate reopening times for bridges, as determined by the RRAP research team in close collaboration with ODOT's Bridge Office, and based on values previously developed with WSDOT's Bridge and Structures Office under the prior RRAP project. The BSST also provides some broad information about repair types—that is, the types of actions that may be needed to reopen bridges or reestablish connections, as shown in table 1. These include, for example, the possibility of constructing temporary local bypass roads around collapsed bridges or overpasses, or whether soil liquefaction may contribute to bridge damage and thus require subsurface strengthening prior to reconstruction or reopening.

TABLE 1.—Bridge Reopening Times and Repair Types Criteria.

Damage Level	Damage Severity	Consideration	Bridge Length (ft)	Reopening Time	Repair Type
Minimal	None	None	N/A	0 days	None
Moderate	Moderate	None	N/A	4 days	Bridge inspection and minor or no repairs
Severe	Severe damage without soil liquefaction	Bridge not over waterway or impassable topography	> 2610	2 years	Temporary road
			≤ 2610, > 50	2 weeks per 50 ft of bridge length	
			≤ 50	2 weeks	
		Bridge over waterway or impassable topography	> 150	2 years	Major bridge rehabilitation or replacement
			≤ 150, > 50	14 months	
			≤ 50	7 months	
	Severe damage with soil liquefaction	Bridge not over waterway or impassable topography	> 3260	2.5 years	Temporary road
			≤ 3260, > 50	2 weeks per 50 ft of bridge length	
			≤ 50	2 weeks	
		Bridge over waterway or impassable topography	> 150	2.5 years	Major bridge rehabilitation or replacement and subsurface strengthening

Bridge Seismic Screening Results

This section provides the BSST results, projecting damage types, repair types, and reopening times. Results project bridge damage types as a function of damage severity (i.e., minimal, moderate, or severe) and each bridge's characteristics and configuration (e.g., special bridge, pier wall supports), as well as the types of impacts that the bridge will experience. Appendix A contains a table summarizing the damage results for the CSZ earthquake scenario; however, notably, while the results project that 1,335 of the bridges evaluated will experience no damage, 76 percent (4,288 bridges) will experience some level of damage. Among those bridges projected to experience some level of damage, 35.6 percent (2,012 bridges) will experience moderate damage, while the results project that 40.3 percent (2,276 bridges) will experience severe damage.

Ground motion is the largest driver of moderate or severe damage among bridges in Oregon, causing (either exclusively or as a contributing hazard) moderate damage to 35.3 percent of the bridges evaluated (1,991 bridges), and severe damage to 30 percent (1,692 bridges). Liquefaction will be the second-greatest contributor to bridge damage in Oregon under the scenario, either as the main driver of bridge damage or as a contributing factor to moderate damage in 3.4 percent of cases (190 bridges), and to severe damage in 17.5 percent of cases (989 bridges). Tsunami impacts on bridges, including significant scour or overtopping, are somewhat limited among the bridges evaluated. The BSST projects that tsunamis will be a driving or contributing factor to severe damage among 51 bridges due to significant tsunami-related substructure scour, and among 4 bridges due to wave overtopping.

Figure 11 shows the geographical distribution of projected damage severity for state-owned and non state-owned bridges throughout Oregon. In both cases, the greatest damage to bridges is evident among bridges situated along the Interstate 5 (I-5) corridor and to the west toward the coast. The BSST projects that moderate damage among state-owned bridges will occur primarily between the I-5 corridor and the Cascade Mountains range; however, among non-state-owned bridges, moderate damage is more widely distributed across western Oregon. The analysis projects that nearly all of the bridges located within or east of the Cascade Mountains range, with only a few exceptions, will experience minimal damage.

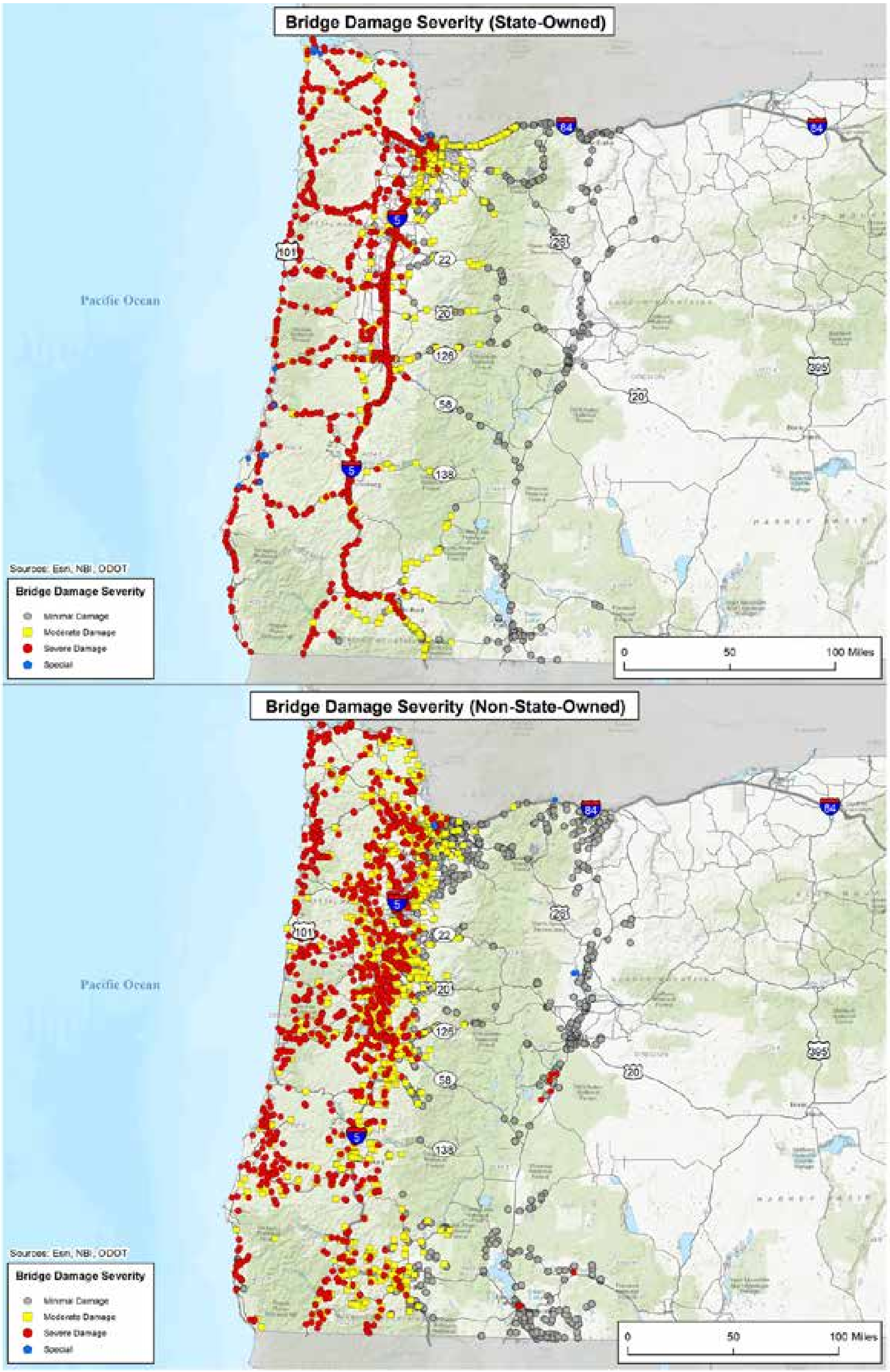


FIGURE 11.—BSST Projected Damage Severity for State- and Non-state-owned Bridges.

The RRAP research team calculated the projected repair types and reopening times necessary to bring bridges back to a minimum level of functionality that enables their use for emergency response by using the methodology specified in table 1. Table 2 summarizes projected repair types, where 35.6 percent of the bridges evaluated (2,012 bridges) will experience moderate damage during the CSZ scenario earthquake and may require inspection and potential minor repair prior to reopening. Of the bridges that require some level of intervention greater than inspection and minor repair, the majority (1,839 bridges, or 32.6 percent of the assessed bridges) are crossings over water that could require the building of an entirely new bridge. Liquefiable soils are present at 909 of these crossings, which could require subsurface stabilization or strengthening prior to the construction of a new bridge. Infrastructure owners may potentially reopen some of the bridges projected to experience significant damage (422, or 7.5 percent of the assessed bridges) by implementing a temporary roadway that bypasses the damaged bridge, at locations where no geographic obstacles (e.g., rivers, ravines) exist. An example of this would be a collapsed bridge that functions as an overpass for an intersecting roadway on level terrain. In this instance, a temporary roadway featuring a surface intersection between the two previously separated roadways could function in place of an overpass. Finally, 15 bridges (0.3 percent of the assessed bridges) are crossings over steep terrain that could require the building of an entirely new bridge; one of these crossings is also in proximity to projected liquefaction that could require subsurface stabilization or strengthening prior to the construction of a new bridge.

Figures 12 and 13 show the geographical distribution of bridge repair types for both state and non-state-owned bridges, respectively, in Oregon, and according to repair types requiring new bridges or other types of repairs. Nearly all of the bridge locations requiring a new bridge and subsurface strengthening are located west of the I-5 corridor. This distribution is consistent with the alignment of many roadways through the Coastal range on the Oregon coast along river valleys, where liquefiable soils are generally more prevalent. These results project that a temporary roadway (whereby the construction efforts clear debris of a damaged overpassing bridge from the roadway and build a temporary surface intersection) is not a viable solution for many non-state-owned bridges. Conversely, the majority of state-owned bridges, particularly along the I-5 corridor, that will experience significant damage could be bypassed by a temporary surface roadway configuration. Despite this finding, the effects on the comparatively smaller number of bridges with longer projected reopening times are important considerations for emergency managers and planners, as these locations could have an outsized impact on the ability of I-5 to resume functioning as a corridor.

TABLE 2.—Summary of Projected Bridge Repair Types.

Repair Type	Number of Bridges	% of Total
None	1,335	23.6
Bridge Inspection with Potential Minor Repairs	2,012	35.6
Temporary Road to Bypass Bridge	422	7.5
New Bridge over Water	930	16.5
New Bridge over Impassable Topography	14	0.2
New Bridge over Water with Subsurface Strengthening	909	16.1
New Bridge over Impassable Topography with Subsurface Strengthening	1	0.0
New Special Bridge	23	0.4

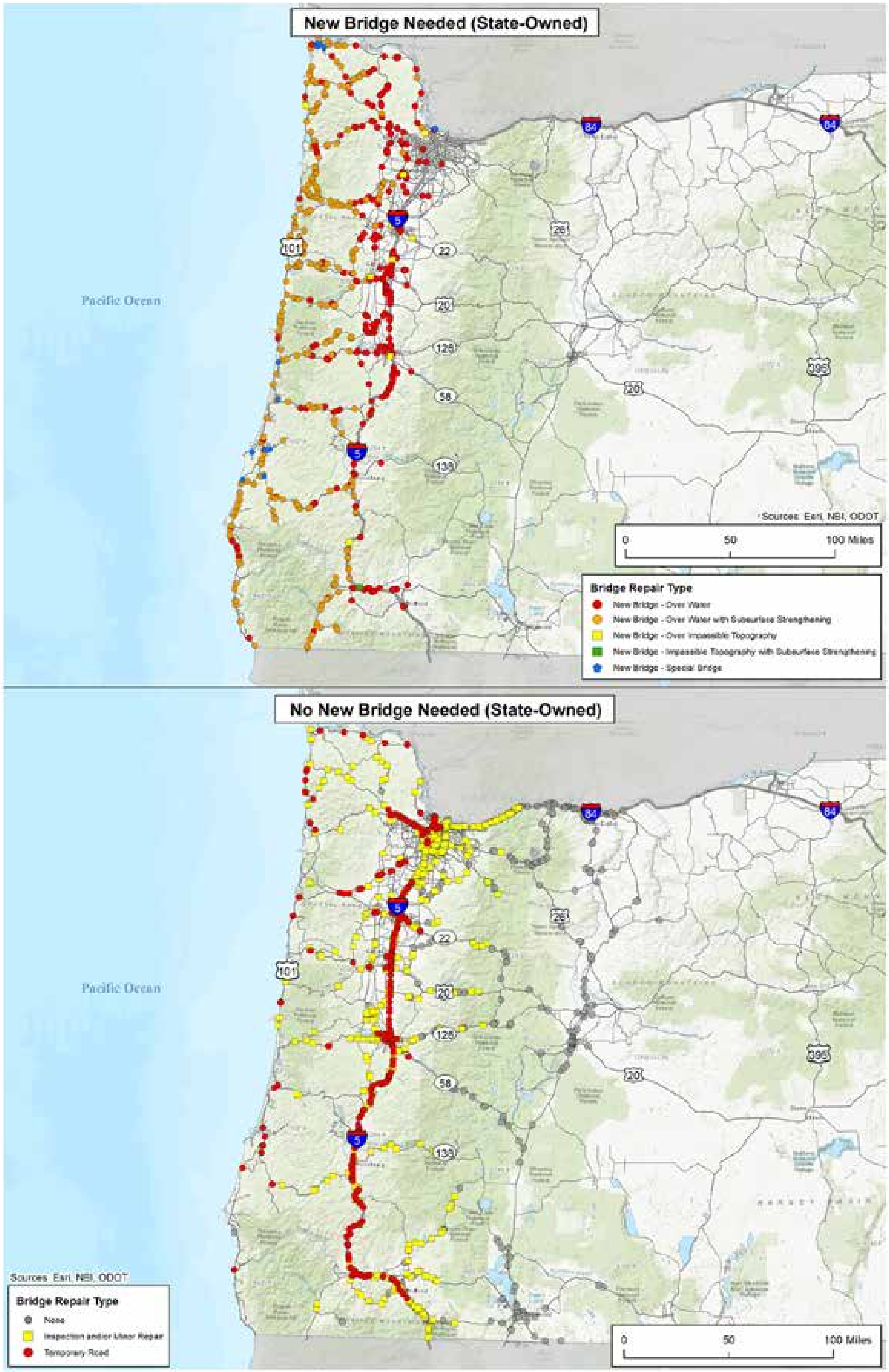


FIGURE 12.—Bridge Repair Types for State-owned Bridges, New Bridges, and Other Repair Types.

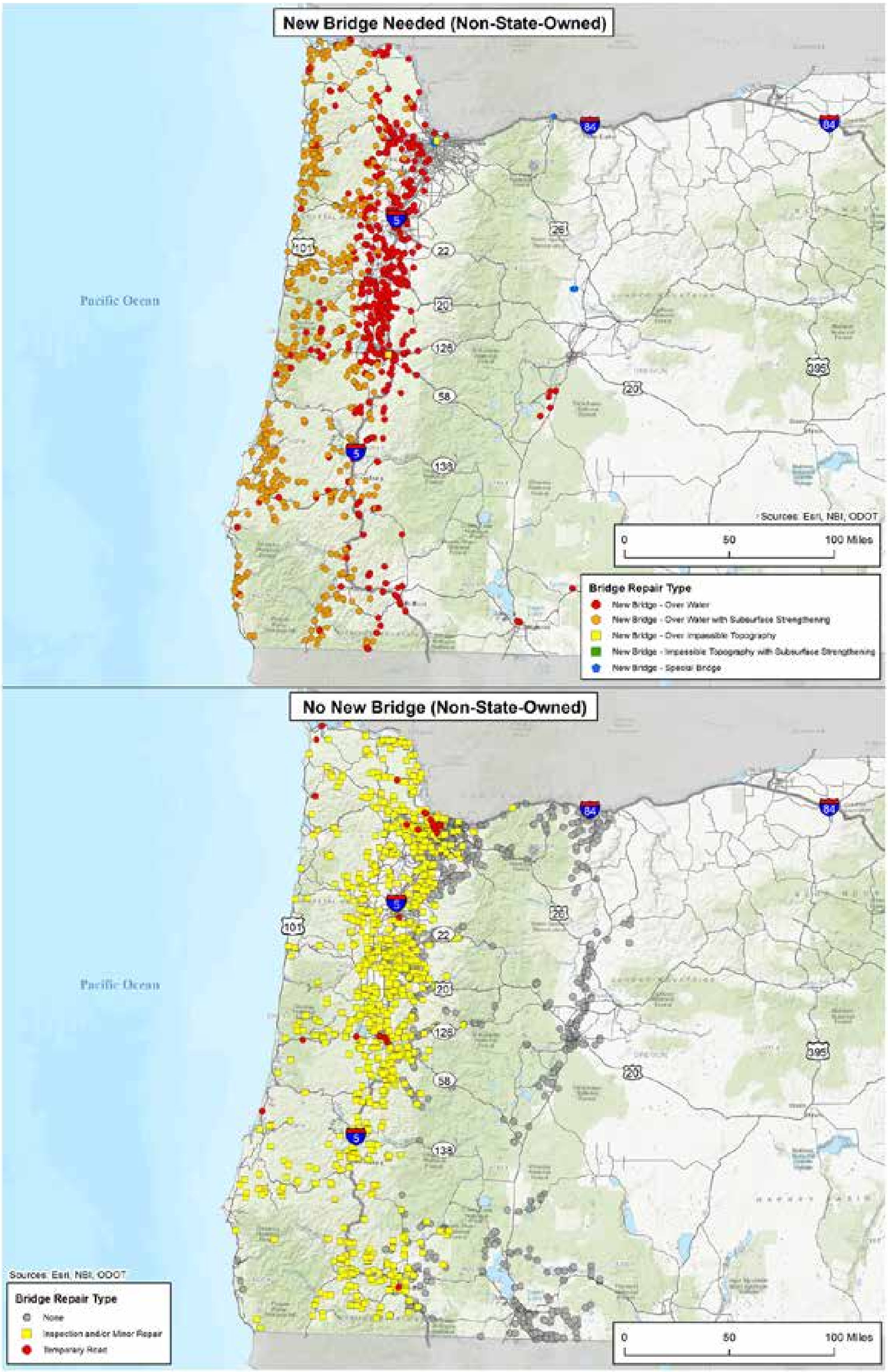


FIGURE 13.—Bridge Repair Types for Non-state-owned Bridges, New Bridges, and Other Repair Types.

Table 3 summarizes the approximate reopening times projected by the BSST for the bridges evaluated. Of the bridges evaluated, the results project that 1,335 bridges, or 23.6 percent—of which 522, or 21.1 percent are state owned and 813, or 25.6 percent are non-state-owned—sustain no damage, and therefore have no projected delay in reopening from a structural repair perspective. However, it is important to note that ODOT may still choose to conduct inspections on some structures, which could cause minor reopening delays of days or weeks depending on the availability of bridge inspectors. Nonetheless, infrastructure owners could reopen 2,066 bridges (36.6 percent) within the first month after the earthquake occurs after the completion of inspections and minor repairs or the building of temporary roads to bypass significantly damaged bridges. Of these bridges, 859 bridges are state owned (34.8 percent of assessed state-owned bridges) and 1,207 are non-state owned (38 percent of assessed non-state-owned bridges). Conversely, 1,530 bridges, or nearly 27 percent of the bridges evaluated—of which 682 are state owned and 848 are non-state owned)—would require more than 1 year to reopen.

TABLE 3.—Projected Bridge Reopening Times.

Reopening Time	Number of Bridges	% of Total
None	1,335	23.6
1–30 days	2,066	36.6
1–3 months	297	5.3
3–6 months	51	0.9
6–12 months	367	6.5
1–2 years	1,231	21.8
> 2 years	299	5.3

Figure 14 shows the geographical distribution of state and non-state-owned bridges in Oregon, respectively, according to their reopening times. Reopening times are greatest along and west of the I-5 corridor, moderate between the I-5 corridor and the Cascade Mountains range, and minimal east of the Cascade Mountains range.

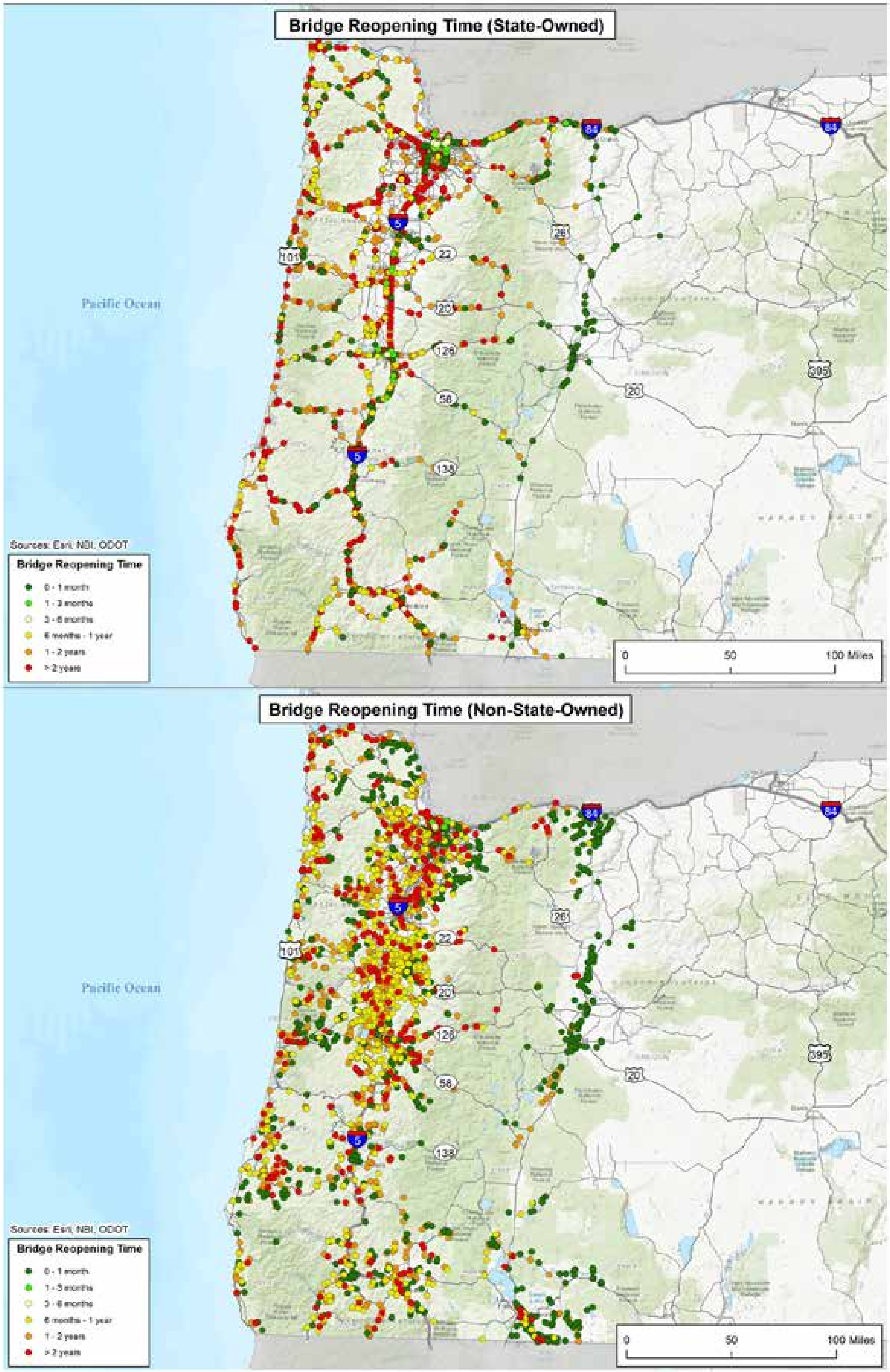


FIGURE 14.—BSST Projected Reopening Times for State- and Non-state-owned Bridges.

Roadway Seismic Screening Analysis and Results

Earthquake-induced ground failures, such as liquefaction and landslides, have the potential to disrupt roadway connectivity. Liquefaction can create major discontinuities or displacements in pavement surfaces that become impassable to vehicles, and landslides can block roadways by either covering them with debris or by removing or shifting the soils that support roadways. Within the transportation network model of Oregon, the RRAP research team evaluated 426,498 segments of roadways comprising more than 45,891 miles of state, county, and local roadways with respect to their vulnerability to CSZ earthquake-induced liquefaction and landslide impacts, The researchers then determined approximate per-mile reopening times for impacted roadway segments. The sections that follow discuss the methodological approaches and results for both the liquefaction screening analysis and the landslide screening analysis.

Roadway Liquefaction Screening Analysis

To assess the damage to roadway pavements in Oregon resulting from CSZ earthquake-induced liquefaction in the underlying soils, the RRAP research team used a method to calculate approximate PGD developed by Bardet, Mace, and Tobita (1999). The Washington Transportation Systems RRAP used this same methodology to evaluate liquefaction impacts on Washington State's highway network (Wilkey et al. 2019).

This approach calculates PGD on an individualized basis for each roadway segment in the roadway transportation network, and then determines approximate per-mile reopening times for Oregon roadways based on multiple factors, including the magnitude of displacement, pavement type affected, and temporary pavement construction times. The accompanying technical report, *Oregon Roadway CSZ Liquefaction and Landslide Impact Screening Analysis*, provides a more detailed discussion of the development, implementation, and data supporting this liquefaction analysis in Oregon, including a detailed discussion of PGD calculations and assumptions. This report also benchmarks PGD calculations developed using this approach against the Portland Water Bureau's more detailed geotechnical engineering-based study of PGD (InfraTerra Inc. and Cascade GIS & Consulting LLC 2016).

Figure 15 shows an overview of the roadway liquefaction screening analysis methodology that begins in GIS software with overlaying the roadway transportation network dataset with the liquefaction hazard data that DOGAMI has provided. The RRAP research team then characterized each segment in the roadway network according to four factors: segment soil liquefaction potential, distance from the CSZ fault, relative ground slope, and segment pavement type. The assigned pavement type was either flexible/asphalt or rigid/concrete based on data that ODOT provided for state-owned roadways (Coplantz 2020), and the RRAP research team assumed that non-state-owned roadways are constructed of flexible/asphalt pavement. Using these four factors, the RRAP research team then calculated PGD values for each segment and estimated segment repair and reopening times. The RRAP research team initially based reopening times on metrics developed originally in collaboration with WSDOT's Maintenance Office as part of the Washington Transportation Systems RRAP project but discussed them with ODOT for concurrence. As with bridges, an important underlying assumption in these repair and reopening times was that they specify the amount of time necessary to repair pavements to a minimum acceptable state of repair to facilitate the movement of emergency response and supply vehicles, and not to restore them to a pre-disaster state of repair. To that end, this RRAP report bases reopening times on the construction time associated with installing a temporary wearing surface composed of compacted crushed gravel, which would provide a sufficient surface for emergency response and supply activities. This report also assumes that a single lane of travel would be sufficient for initial response operations, and ODOT could expand to more lanes later during the ongoing response.

The analysis found that 34 percent of the roadway miles evaluated (16,127 centerline miles) are built on soils with sufficient liquefaction potential to create measurable PGDs during a CSZ earthquake (i.e., a liquefaction susceptibility level of 3 or greater, based on the DOGAMI dataset). Figure 16 shows the geographic results of the PGD calculations. The highest PGD estimates are concentrated on the Oregon Coast and in the Coastal Mountain range, where they are predominantly located in the valleys leading down the mountain range's western slope to the Pacific Ocean. The Willamette Valley and locations east are projected to experience some permanent ground deformation, but at the lower range of projected values.

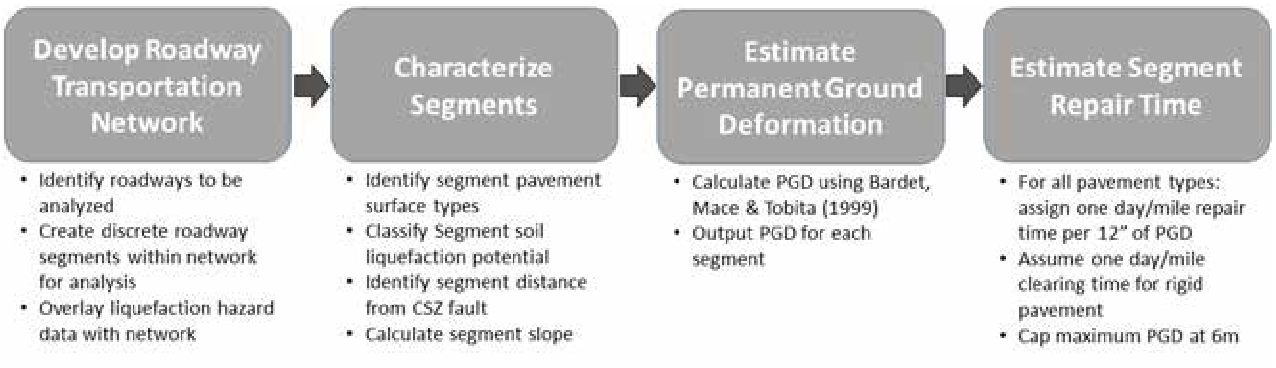


FIGURE 15.—Roadway Liquefaction Screening Analysis Methodology.

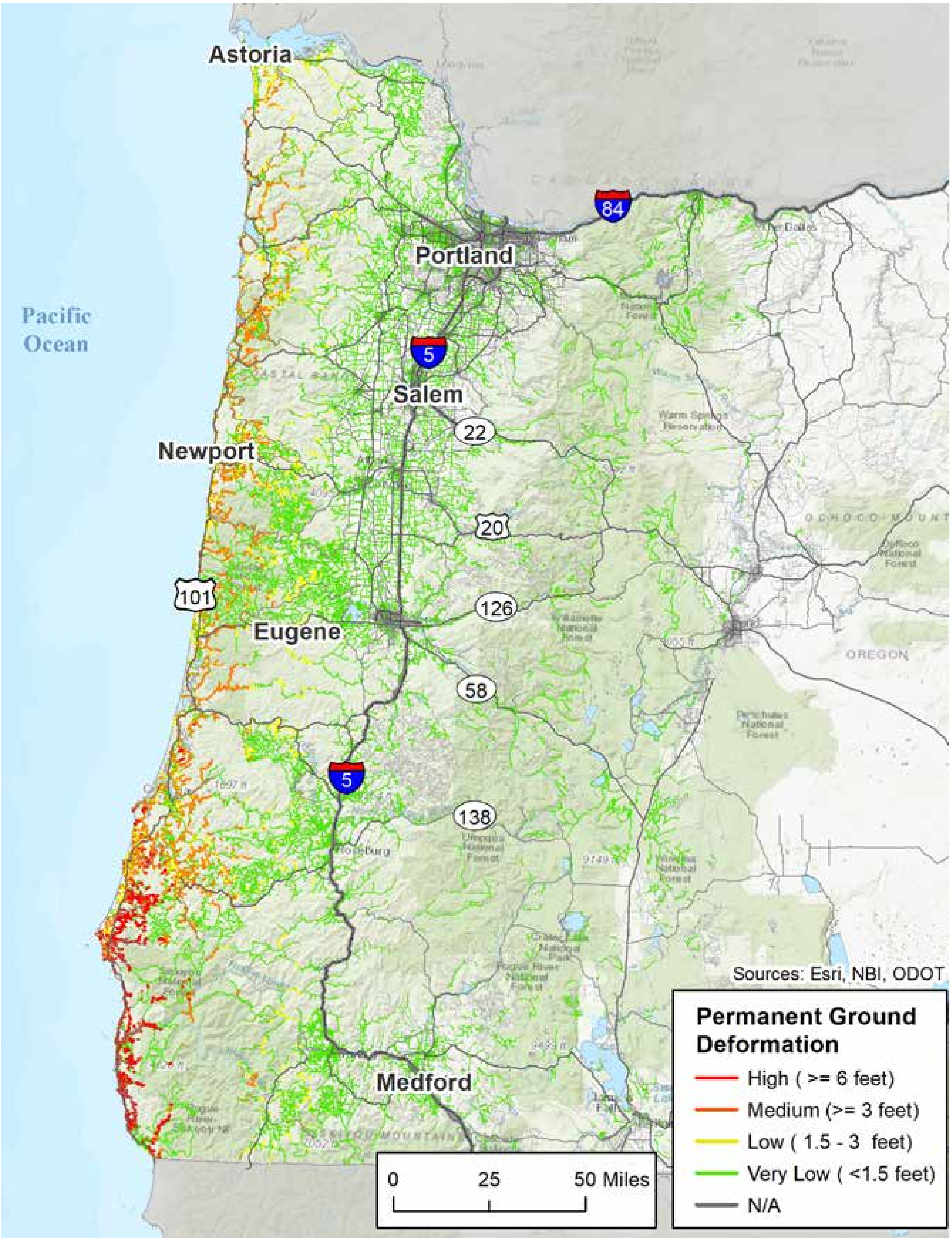


FIGURE 16.—Estimated Roadway PGD due to Soil Liquefaction.

The roadway repair and reopening times for pavements damaged by liquefaction largely mirror the results of the projected PGD magnitudes. Variability between the two outcomes is largely attributable to differences in repair times associated with different pavement types and thicknesses. As figure 17 shows, the roadways with the highest average per-mile repair and reopening times are located along the I-5 corridor and heading west through the Coastal Mountain range to the Oregon Coast. The per-mile repair times for locations east of the I-5 corridor are generally lower with a few higher repair and reopening times occurring in the alluvial valleys and fills along the major east–west routes into the Cascade Mountains.

Table 4 shows the overall distribution of mileage associated with each repair time range. The majority of mileage of roadway segments have an average per-mile repair time of less than half a day. The results project that only 5 percent of total roadway mileage located on liquefiable soils will require more than 1 day per mile to repair. Rigid/concrete pavements require longer amounts of time for repair and reopening owing to the need to remove rigid pavement debris before placement of crushed rock fill for the temporary roadway; however, rigid pavements represent less than 1 percent of the roadways analyzed for this RRAP project.

TABLE 4.—Distribution of Liquefaction Repair and Reopening Days per Mile for Roadway Pavements.

Repair Days/Mile	Miles	% of Total	Cummulative %
0 days	974.92	6.05	6.1
>0 to 0.5 day	13286.03	82.39	88.4
>0.5 to 1 day	1064.99	6.60	95.0
>1 to 2 days	523.76	3.25	98.3
>2 to 4 days	207.49	1.29	99.6
>4 to 7 days	39.11	0.24	99.8
>7 to 14 days	26.15	0.16	100.0
>14 days	4.25	0.03	100.0

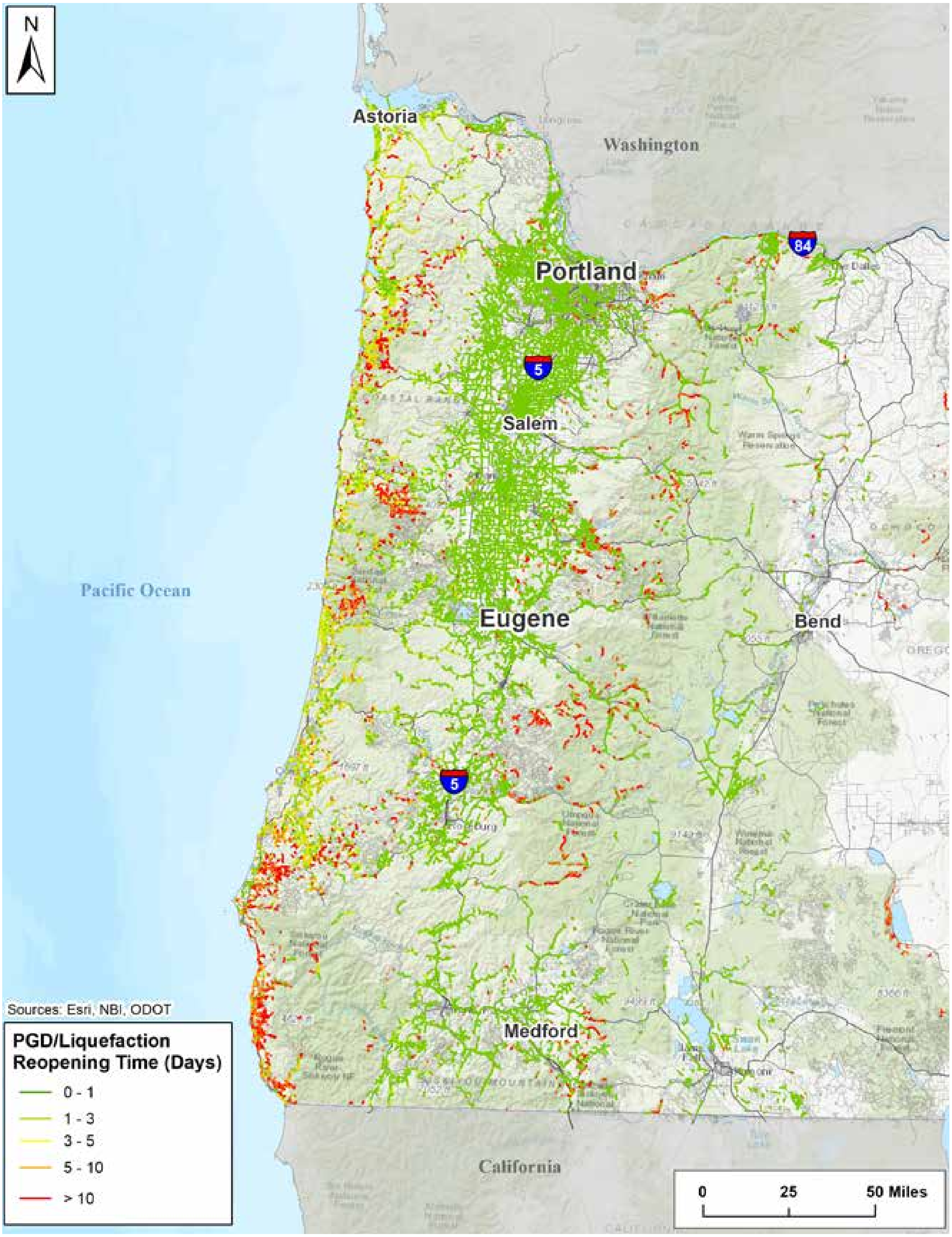


FIGURE 17.—Roadway Liquefaction Per-Mile Reopening Times.

Roadway Landslide Screening Analysis

To assess the damage to roadway pavements in Oregon resulting from CSZ earthquake-induced landslides, the RRAP research team developed an analytical methodology in consultation with engineering geologists and geotechnical engineers at both DOGAMI and ODOT, focusing on major landslides as identified in the SLIDO dataset.

Using GIS analysis and landslide risk matrices developed in coordination with ODOT, the research team characterized all major landslides in the western half of Oregon that pose some earthquake-induced risk to roadways, as well as the type, extent, and magnitude of such impacts. The research team then worked with ODOT to develop a set of roadway reopening times based upon these seismic hazard characteristics, as well as historic landslide reopening costs and timelines provided by ODOT. The accompanying technical report, *Oregon Roadway CSZ Liquefaction and Landslide Impact Screening Analysis*, provides a more detailed discussion of the development, implementation, and data supporting this landslides analysis in Oregon.

The overall steps in the landslide analytical methodology are similar to those for the liquefaction analysis shown in figure 15, as follows:

- Develop a roadway transportation network.
- Characterize the segments in the network.
- Estimate a landslide risk for each segment prone to landslide.
- Estimate a repair time for segments with high risk.

Based upon discussions with DOGAMI, the RRAP research team used only landslides in the SLIDO dataset characterized as “High-Landslide Likely,” or “Very High-Existing Landslide” in this analysis, as significant uncertainty exists concerning whether a CSZ earthquake would activate landslide areas in lower risk categories. Furthermore, even if smaller, lower-risk landslides were activated, the severity of their impact may be more consistent with nuisance landslides (e.g., minor debris that could be cleared from a roadway with relative ease) rather than substantial impacts requiring longer reopening times. The RRAP research team overlaid these higher-risk landslide areas with the roadway network using GIS software and then further evaluated those landslides overlapping or falling within 250 feet of roadway centerlines. In total, the analysis projected that 38,323 roadway segments covering 6,427 centerline miles of roadway would experience some landslide risk.

The RRAP research team characterized each at-risk segment in the roadway network according to multiple landslide risk factors, including: the size of the landslide area, average slope, aspect of the landslide (i.e., direction of the slope in relation to the roadway centerline), proximity to the roadway, elevation relative to the roadway (i.e., above, below), and whether or not the landslide area overlapped the roadway. The team then combined these factors in a risk matrix to determine the relative risk (i.e., high, medium, low) of the landslides and evaluated them for their nearby roadways. Next, the team developed estimated per-mile roadway reopening times with extensive support of ODOT using historic landslide data and associated recovery times. ODOT staff conducted an analysis of landslides and recovery times along three major routes (US 101, US 26, and OR 140), and identified that only 5 percent of landslide-impacted miles experienced impacts greater than nuisance levels and thus required significant amounts of time before reopening. Based upon this study data, the RRAP research team, in collaboration with ODOT, developed per-mile reopening times associated with the greatest risk categories in the landslide risk matrix (i.e., greater-than-nuisance-level impacts) and applied those metrics to the roadway segments they evaluated.

The results of the roadway landslide risk analysis indicate that of the total roadway miles identified as being at some risk to landslides, 44.5 percent (2,861 miles) have a high landslide risk (i.e., impacts greater than nuisance levels). Figure 18 shows the geographical distribution of the landslide risk ratings across western Oregon, where roadways with risk ratings of high are present along much if not most of the Oregon Coast, as well as in valleys throughout the Coastal and Cascade Mountain ranges.

The results project average per-mile repair and reopening times for 2,861 miles of roadways significantly impacted by landslides to be 13.9 days per mile; however, the lengths of most roadway segments impacted by landslides are far shorter than 1 mile. Approximately 920 miles of roadway will experience landslide impacts requiring up to 10 days per mile to reopen, whereas 110 miles of roadway may experience more severe landslides requiring 10 days or more per mile to reopen.

As figure 19 shows, the greatest impacts from landslides generally occur along roadways in the Coastal and Cascade Mountain ranges, although the duration of most of the repairs at each landslide are two days or less. However, some corridors exist in the Portland area, along the Oregon coast and east of the I 5 corridor between OR 126 and US 20, that exhibit concentrations of greater landslide impacts, which could have greater aggregate impacts on corridor reopening times. That is, while the projected reopening times for individual landslides in these areas may be comparatively short, the concentration of multiple sequential projected landslides along these corridors may aggregate to create corridor reopening times that are considerably longer.

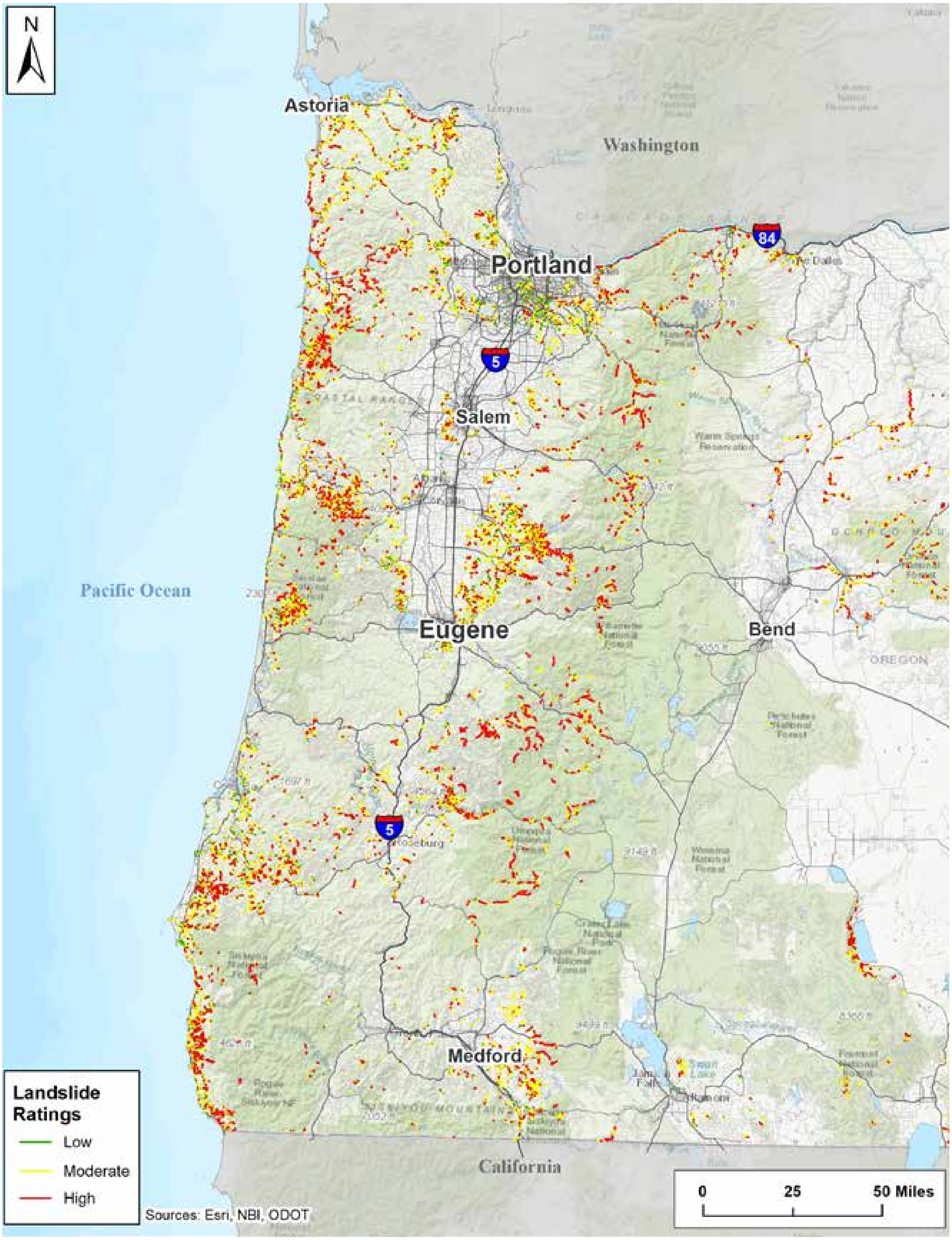


FIGURE 18.—Oregon Roadway Landslide Risk Ratings.

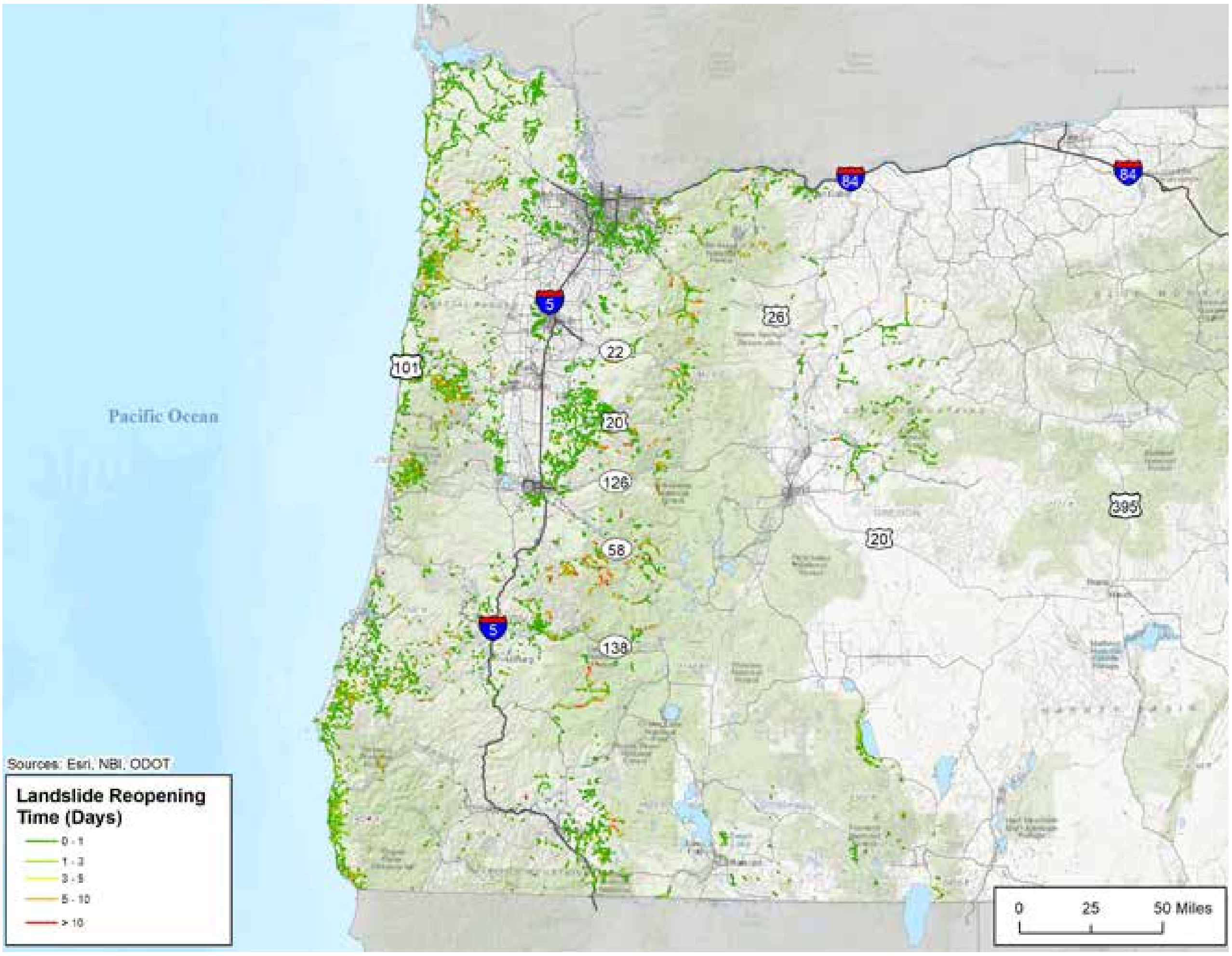


FIGURE 19.—Oregon Roadway Landslide Impact Reopening Times.

Islanding Analysis Network Optimization Model

The goal of the regional islanding analysis was to identify islanded communities and the roadway infrastructure systems that can efficiently reconnect them to regional staging areas following a CSZ earthquake disaster.

By identifying the islanded populations and regions surrounding staging areas, as well as the priority routes to reach those populations and regions, state officials can begin to better integrate transportation system capabilities into post-disaster logistics supply chains and other planning activities. For example, this information could enable planners to assess staging area throughput and capacity requirements by quantifying the populations that they will need to serve in surrounding islanded areas. This analysis could also help officials identify and prioritize pre-disaster roadway investments that infrastructure owners could make along those routes to harden or increase roadway and bridge resilience, effectively buying down reopening time. In addition, they could use this information to emphasize post-disaster assessment, inspection, and reopening to establish disaster logistics supply chains more quickly.

To identify the islanded populations and regions surrounding each staging area, as well as the priority roadway routes to reach those populations, the network optimization model combined the outputs of the bridge seismic screening analysis and roadway seismic screening analysis (i.e., liquefaction and landslide analyses) to define combined link-based reopening times for the 426,498 links and 5,646 bridges assessed. The model then used a forward-in-time simulation to implement a variant of Dijkstra's algorithm that simultaneously determined which population centers are served by each of the 12 statewide staging areas (i.e., ISBs and FSAs), and also which network links are used to serve these population centers. In effect, this model identifies a series of successive roadway segments and bridges that form pathways branching out from the staging areas to surrounding communities, and does so by optimizing for connectivity to the largest population using roadways with the shortest post-disaster reopening times. The Washington State Transportation RRAP project applied a variant of this network optimization algorithm to similarly evaluate post-CSZ earthquake transportation network capabilities (CISA 2019); however, broader critical infrastructure studies have also applied the algorithm to assess electric grids and other networked energy infrastructure (Verner, Kim, and Petit 2017).

Census block group data from the 2010 U.S. Census provide the size and location of populations in this study, as obtained through the Oregon Spatial Data Library (U.S. Census Bureau 2010). Oregon's 2,634 block groups provide sufficient spatial resolution for population size and location, while still enabling adequate computational efficiency for the optimization model. The optimization analysis made several underlying assumptions in determining which block group-based population centers are served by which staging area, and also in identifying the transportation network links able to connect to these block groups most quickly. First, the analysis assumed that communities will have some capacity to self-mobilize following a CSZ earthquake, independent of coordinated disaster response efforts, and even before connections to disaster logistics staging areas are established. That is, this study assumes that communities have some innate capacity, using local resources, to remove or relocate minor debris blocking roadways, or to conduct other activities to reopen roadways suffering minor impacts. The RRAP research team used this assumption in the model to define "initial mobility areas" (IMAs) for each of the census block groups. Specifically, the IMA of a census block group g is the set of those census block groups that can access starting from the geographic center of g within a (post-disaster) time of less than 14 days. A block group is fully accessed if more than 75 percent of its total roadway network links are reachable within the 14 day timeline. This 75 percent assumption reflects the additional assumption that roadway density is a reasonable proxy for population density. Functionally, this IMA approach means that as the algorithm works out from a staging area, if it reaches a block group g, it assumes that all of the additional block groups that are part of block group g's IMA are accessible immediately without any further roadway reopening times.

The 14-day cutoff reflects the assumption that minor impacts on roadways could be addressed locally within this timeframe by using either community or local-agency resources (e.g., a local public works department's heavy equipment, local construction equipment/supplies)—consistent with Oregon OEM's "2 Weeks Ready" preparedness campaign (OEM 2021)—but also that communities will not self-mobilize indefinitely into the future. This approach implies that any impacts requiring 14 days or greater to resolve are likely of sufficient scale or complexity as to require outside disaster response assistance and resources to overcome.

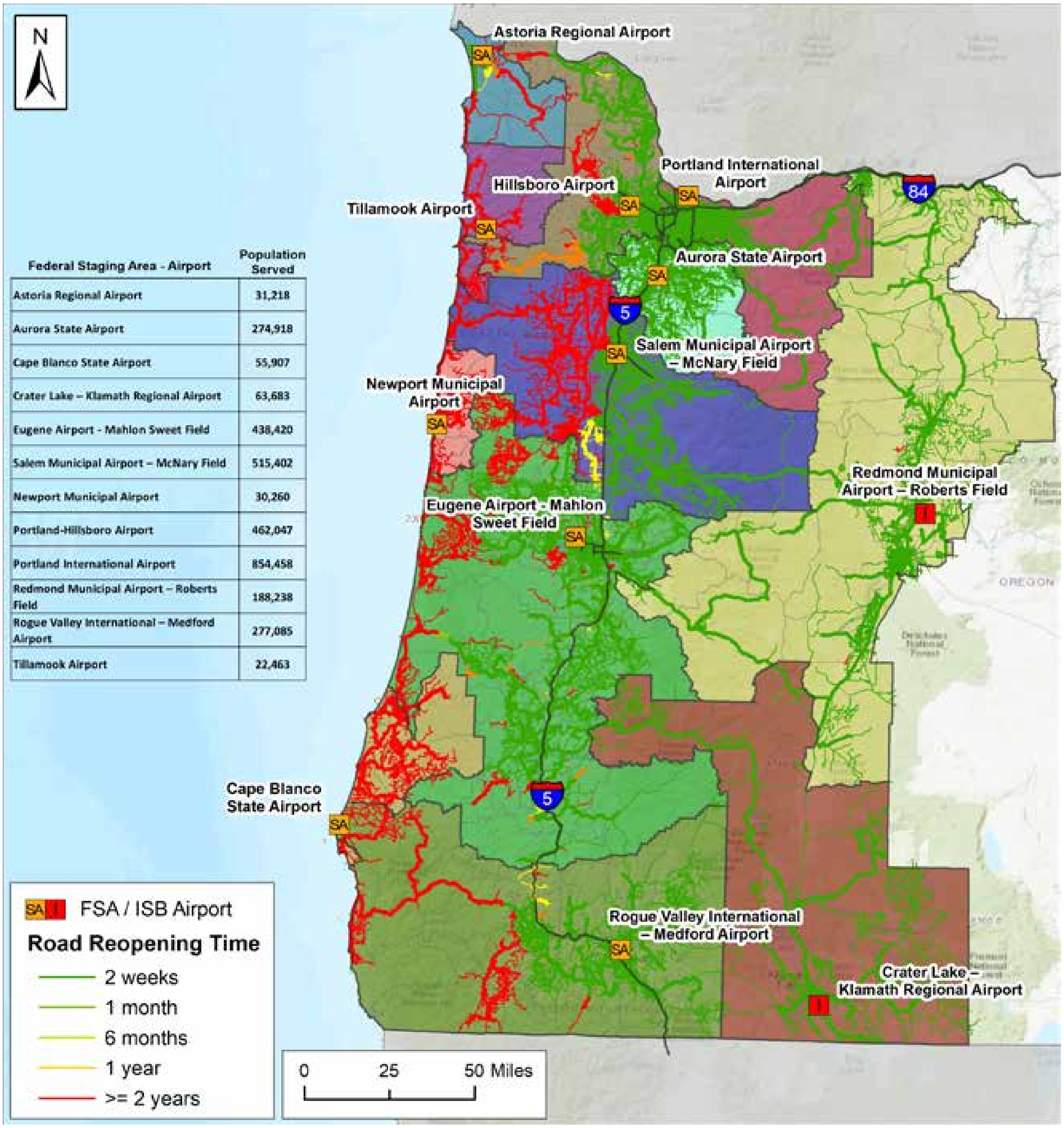
The optimization model also assumes that once a network link is re-opened (irrespectively as part of an IMA's 14-day self-mobilization timeline, or as part of a route from an ISB/FSA reopened as part of state or federal disaster response), its effective traversal time decreases from its reopening time (i.e., as a function of bridge, liquefaction, and landslide impacts) to an unimpeded travel time based simply on distance and an assumed travel speed. The model did, however, assume that emergency responders and infrastructure owners will reopen roadway segments successively, meaning that a roadway segment (and the affected bridges and pavements located on that segment) must be reopened first before repairing and reopening roadway segments lying beyond. This assumption could lead to the model projecting reopening timelines for reaching population centers that are unrealistically long.

Islanding Analysis Uncertainty

Several assumptions made by the RRAP research team in projecting bridge and roadway reopening times are important for emergency managers, planners, infrastructure managers, and other officials to understand and consider because they affect the degree of uncertainty in the analytic results. As noted earlier with respect to bridges, predicting the numerous factors that affect bridge and roadway reopening is challenging—for example, the availability of bridge inspectors; site accessibility; availability of construction materials, equipment, and personnel; and the number of transportation and other infrastructure projects statewide that will compete for limited resources. All of these constraints are effectively unknowable for a post-CSZ earthquake environment, as they will be affected by both the characteristics of the earthquake, as well as numerous external factors. The RRAP research team did not consider these constraints in determining bridge and roadway reopening times, which in turn inform the islanding analysis. All bridge, roadway, and island reopening times reflect the amount of time needed to restore connectivity absent any such constraints. As a result, the actual reopening and reconnection times could be longer depending on post-disaster conditions, resource availability, or other factors.

Islanding Analysis Results and Conclusions

Figure 20 shows the results of the islanding analysis across the western portion of Oregon, and Figure 21 shows the same results locally in the Portland metropolitan area. The shaded areas represent the regions (i.e., service areas) served by each of the staging areas once enough roadways are reopened to ensure connectivity to all block groups within the central and western Oregon study area. Figure 20 also shows the population sizes residing within each service area. The roadways shown are all of the roadways in Oregon that the RRAP research team evaluated in this project, not just the priority routes. They are color coded to represent when the post-disaster timeline projects them to reopen, providing an indication of when various regions across the state may reconnect to post-disaster supply lines. A subset of these roadways shown in bold are the priority routes, which represent those Oregon roadways that can reopen most quickly to serve as the backbone of supply chains connecting disaster logistics staging areas to all of the block group-based population centers across the study region.



Federal Staging Area - Airport	Population Served
Astoria Regional Airport	31,218
Aurora State Airport	274,918
Cape Blanco State Airport	55,907
Crater Lake – Klamath Regional Airport	63,683
Eugene Airport - Mahlon Sweet Field	438,420
Salem Municipal Airport – McNary Field	515,402
Newport Municipal Airport	30,260
Portland-Hillsboro Airport	462,047
Portland International Airport	854,458
Redmond Municipal Airport – Roberts Field	188,238
Rogue Valley International – Medford Airport	277,085
Tillamook Airport	22,463

FIGURE 20.—Oregon CSZ Earthquake Islanding Analysis Results – Service Areas Based on Staging Area Locations.

One of the most immediate conclusions from these results is that proximity to a staging area is not always the best indicator for which staging area will serve a community. Instead, disruptions projected to occur within the state's roadway transportation system may connect communities more immediately with post-disaster supply chains based at staging areas that are not geographically closest to their location. For example, the figure shows that Hillsboro Airport will serve a region from the west side of Portland that extends northwest along the Columbia River toward Astoria, and also southwest toward, and nearly including, Tillamook. This result is attributable to major bridge and roadway disruptions in the vicinity of Tillamook Airport. In this instance, the timeline projected to connect these coastal communities to Hillsboro is shorter than that for connecting to Tillamook Airport despite their proximity to Tillamook. In a similar example, projected disruptions along the I-5 corridor in the Siskiyou Mountains of southwest Oregon will mean that the response effort will more quickly connect some regions closer to Medford–Rogue Valley Airport to Eugene Airport–Mahlon Sweet Field, despite the greater distance.

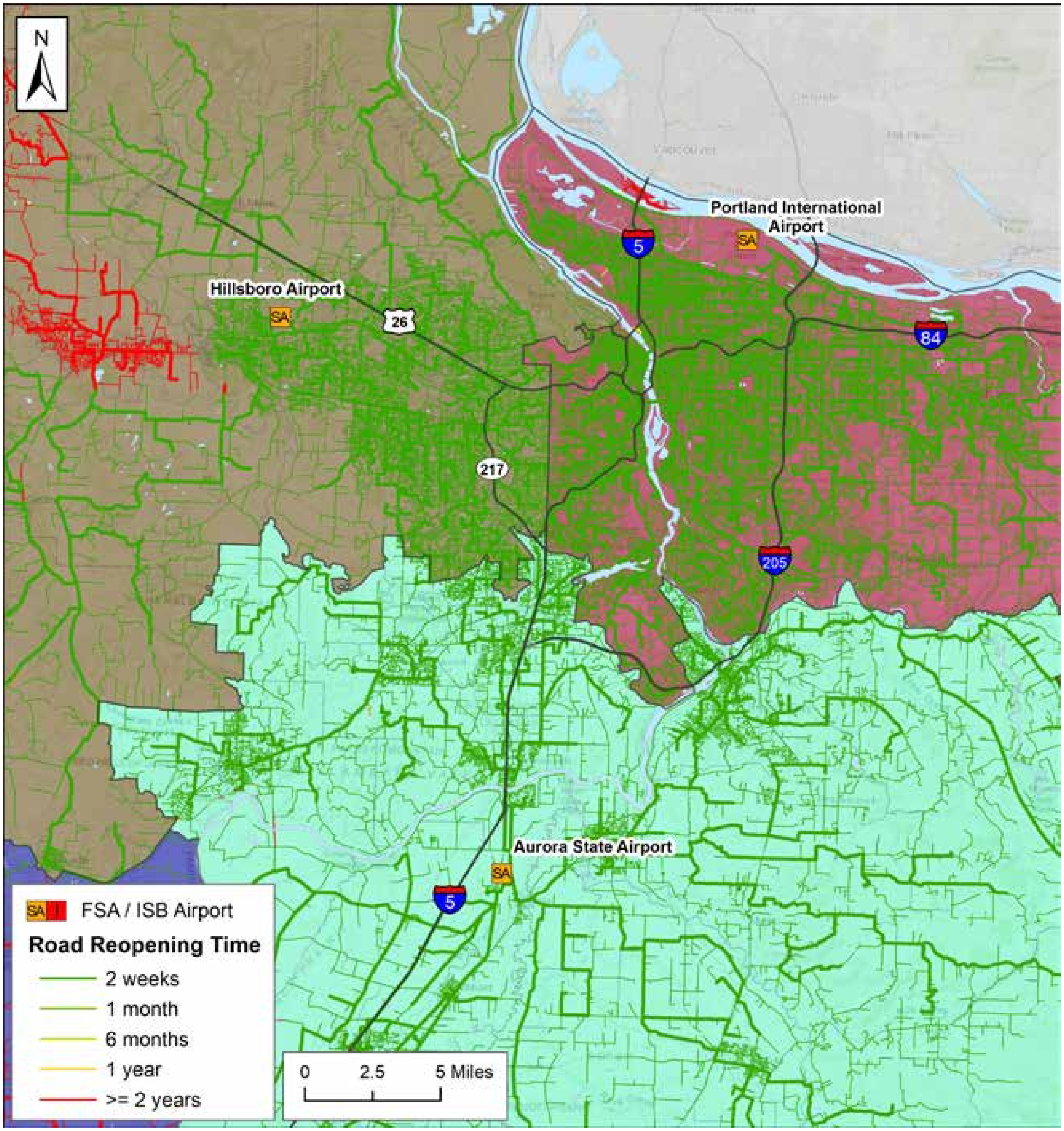


FIGURE 21.—Oregon CSZ Earthquake Islanding Analysis Results – Portland Metropolitan Area Detail.

An encouraging conclusion from these results is that much of Oregon east of I-5 will be accessible within 14 days of the earthquake, as figure 22 shows (note that in this instance, only priority routes are shown, and they are color-coded according to the staging area from which they originate). This result is attributable in large part to a combination of generally less severe impacts to infrastructure east of the I-5 corridor and also to the availability of alternate routes that allow for detouring around more severely impacted or disrupted infrastructure. The implication of this conclusion is that after 14 days, the model results indicate that post-disaster resources could flow somewhat more freely among many of the staging areas shown in the 14-day service area, provided that connectivity exists across service area boundaries between staging areas. That is, for example, although both sides of the Willamette River in metropolitan Portland are accessible within 14 days from a combination of Hillsboro and Portland International Airports, the transit of resources between these airports within 14 days requires that at least one bridge crossing the Willamette reopens in that timeframe (in fact, the analysis projects that several bridges will remain useable).

This service area in figure 22 is important as it indicates that responders from multiple staging areas could access and serve populations located within the 14-day accessibility region. This finding could give emergency management officials greater flexibility in planning disaster logistics supply chains across the region, particularly during the initial phases of response. For example, if disaster logistics supply chains based at Portland International Airport and Salem Airport-McNary Field can adequately serve the population surrounding Aurora State Airport, then officials could potentially repurpose Aurora State for other disaster response functions, or use it to supplement resource inflows to one or both of these other service regions.

In addition to projecting the 14-day, post-earthquake islanded region that will occur throughout western Oregon, the time-based nature of roadways reopening in the optimization analysis allows the model to project how these islands will expand over time as additional roadways reopen to re-establish connectivity. Appendix B presents the full set of post-disaster, time-based islands as a series of maps with the additional census block groups accessible within each successive time step highlighted in yellow. These figures show that, based upon this RRAP project's analysis, the optimization model indicates that reconnection to staging area-based, post-disaster logistics supply chains may not occur for some regions for months or even several years. However, it is important to recall that a foundational assumption in the optimization model is that the response effort will reopen roadway segments sequentially working outward from the staging areas. As noted earlier, this approach will lead to model results that project reopening times that will potentially be unrealistically long, when in fact roadway segment reopening activities could occur in parallel, or could occur more quickly than projected in the analysis, depending on construction resource availability and other factors. For example, the establishment of maritime-based disaster response supply chains along the coast that rely less heavily on roadway transportation could accelerate post-disaster connectivity along the coast. Nonetheless, these reopening timelines are generally consistent with the Oregon Resilience Plan, which stated that Oregonians "can expect some interruptions to last...in some cases from 18 to 36 months or more" (OSSPAC 2013).

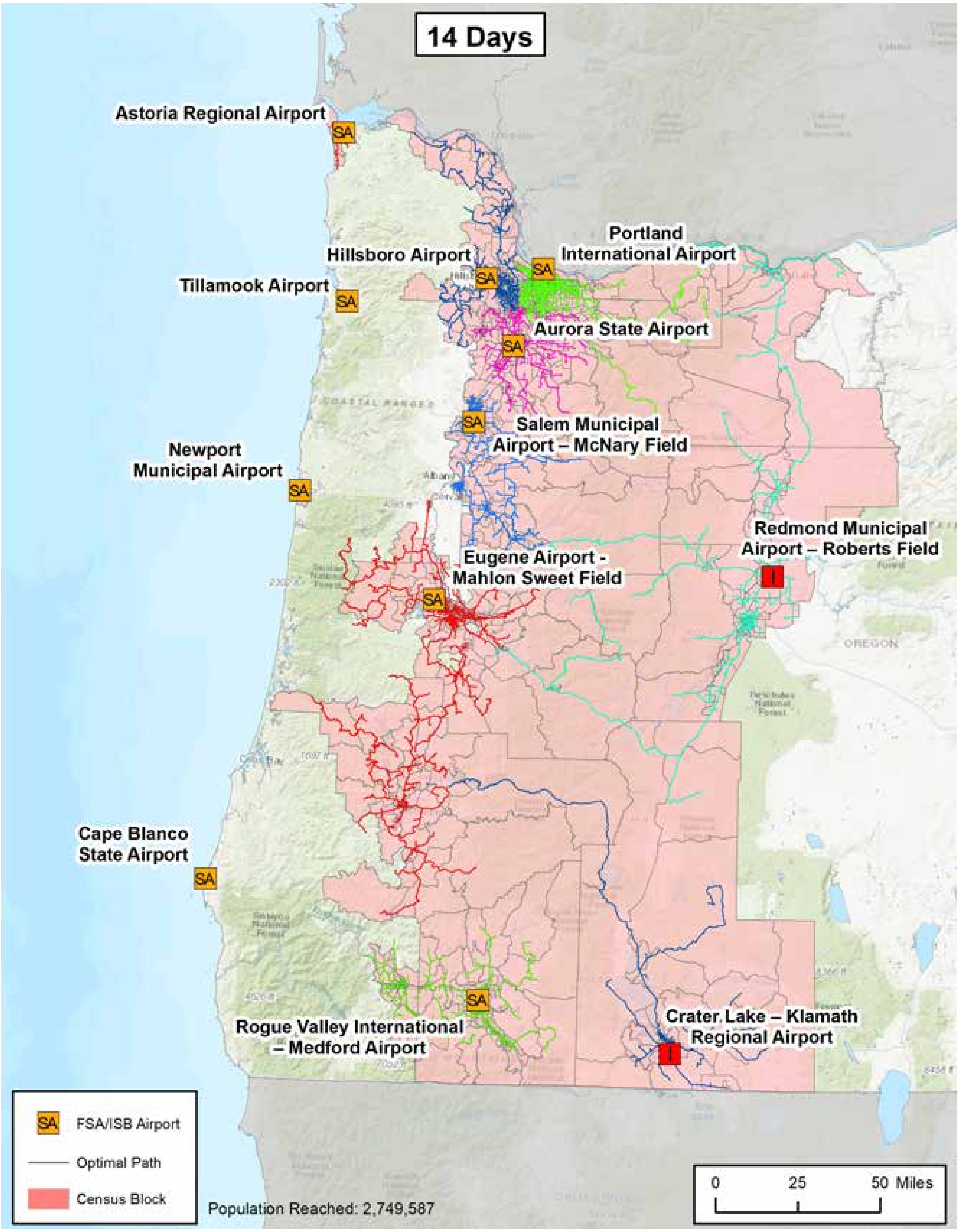


FIGURE 22.—Oregon CSZ Earthquake Islanding Analysis Results – 14-Day Post-Disaster Service Area.

Several unique aspects to these results exist that emergency planners should consider when interpreting the results of this islanding analysis. First, the shape and configuration of census block groups, while capturing regional connectivity, may misrepresent connectivity to communities at very local levels, and particularly among block groups with larger land areas typically found in more rural locations.[4] For example, local communities located in the northern-most portion of the Klamath service area that extends toward Roberts Field may have quicker or more immediate access to Roberts Field. However, because the census block group is large, and the population accesses the majority of that block group's roadways more readily from Klamath Falls, those local communities along the northern edge of the boundary become associated in the model with the Klamath Falls service area. This outcome is less of a concern where block groups are smaller in more densely populated areas.

Figures 20—22 (and those presented in Appendix B) provide a system-wide, state-level overview of the regional islanding analysis results. However, federal, state, and local officials should scrutinize these results and datasets[5] to better understand their implications for disaster planning at local scales, starting in the immediate vicinity of the staging areas. For example, figure 23 shows the roadway reopening times surrounding Cape Blanco State Airport, a planned disaster logistics staging area along the southern Oregon coast. The census block containing Cape Blanco State Airport extends far to the east, and the optimization model indicates that Rogue Valley–Medford Airport primarily serves it. Meanwhile, smaller block groups immediately north and south of Cape Blanco are shaded to indicate that Cape Blanco State Airport would primarily serve them. This outcome results from the way the model assigns block groups to staging areas according to whichever staging area provides primary access to the majority of an individual block group's priority roadways. Because the census block group containing Cape Blanco is very large, the majority of the priority routes it contains (shown in bold in figure 23) are in the east, and associated with Rogue Valley-Medford Airport (bold lines shown in red), whereas Cape Blanco State Airport (bold lines shown in blue) has comparatively fewer miles of priority routes associated with it. In reality, the communities situated in the western portion of this block group would likely be served more immediately by Cape Blanco State Airport. This illustrates one of the limitations of conducting optimizations using census block-group-based population areas based on uniformity in population, as opposed to optimizing smaller spatial areas based on uniformity in land area. These limitations are a greater issue for large block groups and of less concern for smaller block groups. When viewed independent of the block-group-based results, the priority roadway data provides the most direct indication of which staging area would most likely serve local communities in these instances, as figure 23 shows.

[4] U.S. Census Bureau block groups tend to seek uniformity in population (generally between 600 and 3,000 people) as opposed to uniformity in land area. In rural or more sparsely populated areas, this approach can lead to comparatively larger block groups than are found in more urban and densely populated areas. Furthermore, their boundaries are based on a combination of permanent visible features (e.g., rivers) and political or administrative boundaries, such as county and state borders.

[5] The RRAP research team delivered all model results and underling data in this study to state partners for their continued use in CSZ earthquake planning.

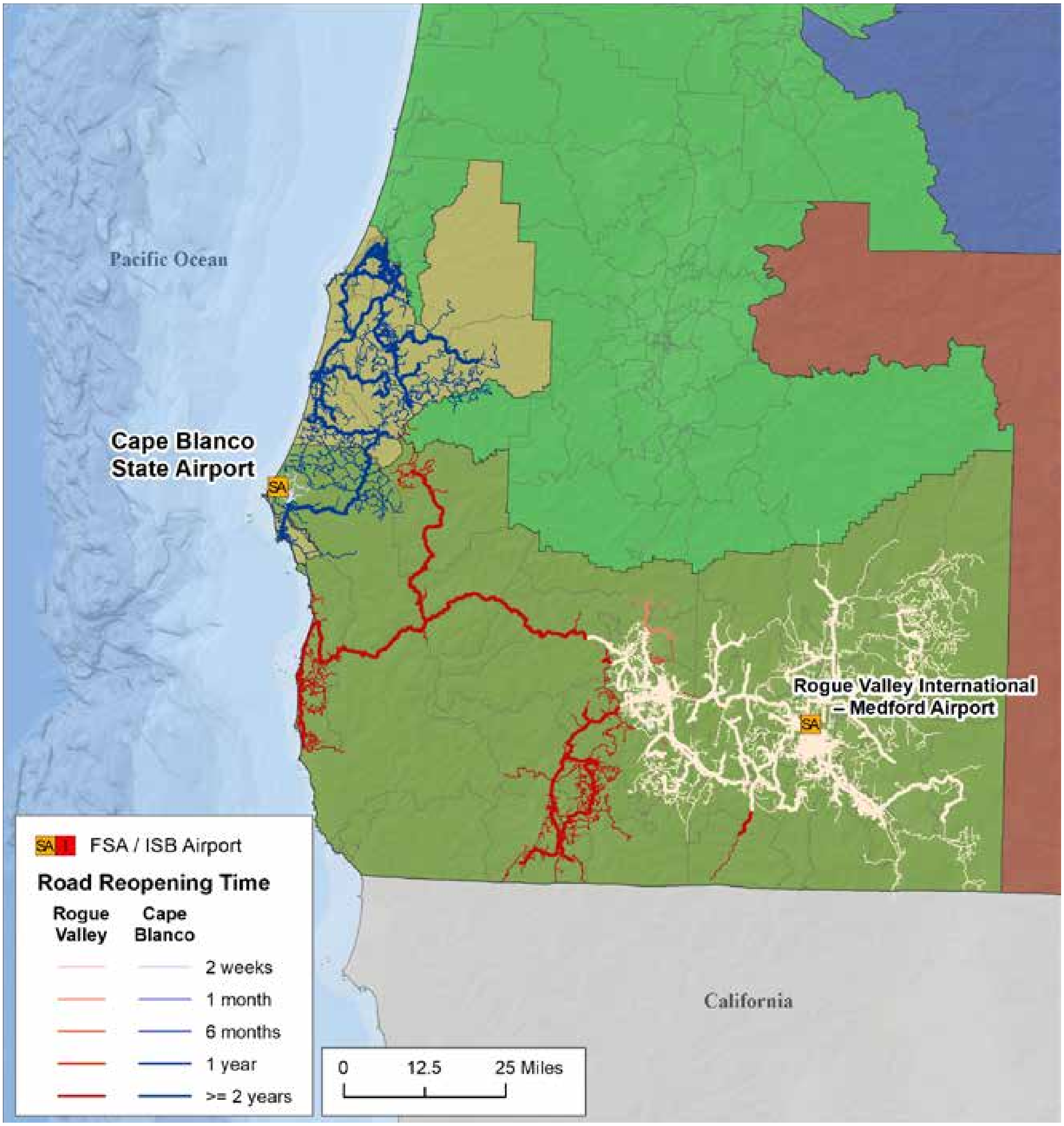


FIGURE 23.—Island Analysis Results at Cape Blanco Airport with Roadway Reopening Times.

Figure 24 compares the priority routes identified in this islanding analysis with roadways that ODOT designated as Oregon Seismic Lifeline Routes (OSLRs) in the *Oregon Highways Seismic Plus Report* (ODOT 2014b). ODOT identified and prioritized OSLR roadways according to three primary goals, each of which has numerous associated criteria that ODOT evaluated in the context of post-CSZ earthquake response and recovery. These goals were as follows:

1. Support survivability immediately following the event (short-term).
2. Provide transportation facilities critical to life support for an interim period following the event (mid-term).
3. Support statewide economic recovery (long-term).

These goals are oriented toward providing broad transportation access to different facilities (e.g., hospitals, fire stations, ports/airports) and communities, as well as maintaining statewide connectivity for response and recovery activities following a CSZ earthquake. This focus is much broader than this RRAP project's islanding analysis and route prioritization, which align more directly with FEMA and Oregon OEM's post-disaster logistics response plan. Nonetheless, as figure 24 shows, the two sets of priority roadways across Oregon have notable similarities, particularly when viewed at a corridor level instead of at an individual facility level.

Disparities between the two sets of priority roadways are largely attributable to three factors. First, the RRAP priority routes are focused on connecting communities to one of the 12 staging areas, not necessarily establishing broad statewide connectivity. For example, US 97 in central Oregon is emphasized in both analyses, particularly as part of the supply chain originating at Redmond Municipal Airport. While the OSLR dataset prioritized the entirety of US 97, the RRAP islanding analysis prioritized those sections in closer proximity to the staging areas as part of the regional islands. The second key difference is that while the OSLR analysis focused on highways across Oregon, the RRAP islanding analysis evaluated county and local roadways in addition to highways. Therefore, in many instances, local roadways that the RRAP islanding analysis identified as having comparatively shorter reopening times than parallel highways were identified as priority roadways. Lastly, the extent of the priority roadway network is much greater in the RRAP islanding analysis outcomes than in the OSLR dataset due to the different objectives of each analysis. Whereas the OSLR analysis focused on broad connectivity across the state, the RRAP analysis focused on connecting block-group-level communities to staging areas, which required a much more extensive network of roadways to ensure this community connectivity.

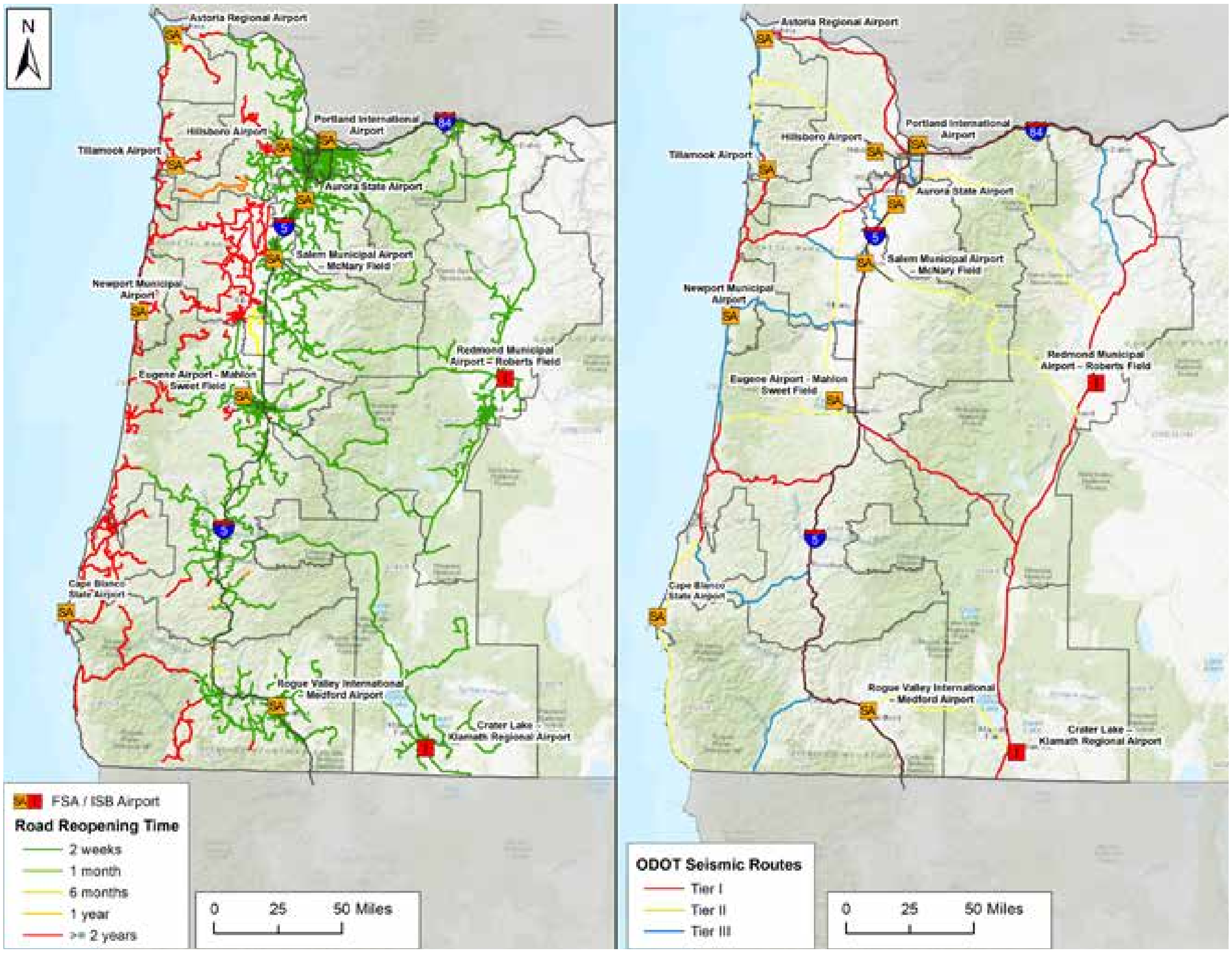


FIGURE 24.—Comparison of Islanding Analysis Priority Routes (left) with ODOT Seismic Lifeline Routes (right).

Temporary River Crossing Analysis

When bridges crossing rivers are disrupted, infrastructure owners and operators can address this lost connectivity by repairing/rebuilding the bridge, by establishing detours to a nearby crossing, or by constructing/locating an acceptable temporary crossing (e.g., river ford, temporary structure). As part of the transportation network islanding analysis, the RRAP research team assessed potential temporary river crossing locations along the priority routes identified.

The initial challenge in conducting this river analysis was that no statewide database exists that characterizes the width, depth, and flow characteristics of all major rivers in Oregon with adequate spatial accuracy. Yet, this information is essential to conducting a systems-level assessment of potential crossing viability, as different crossing strategies are better suited to different river characteristics. To address this lack of more comprehensive river network data, the research team used machine learning techniques in conjunction with various satellite imagery and other datasets to characterize, at high spatial resolution, the location and width of major Oregon rivers under both peak and low flow conditions. Beyond seasonal differences in flows, the RRAP research team did not consider other factors affecting flow rates, for example, scheduled releases from upstream dams or potential dam failures across the state that could occur as a result of a major CSZ earthquake—although a concern about potential dam failure was raised by numerous county/local emergency managers and infrastructure owners and operators across the state.

A more complete discussion of how the RRAP research team generated this dataset is presented in the accompanying technical report, *Oregon River Characterization Tool* (Yan, Feinstein, and Wall 2021), which presents a more complete discussion of how the RRAP research team generated this dataset. Although this river characterization method does not comprehensively characterize every reach along all of Oregon's rivers and streams, it was able to characterize river width, depth, and flow characteristics along major rivers (~10 m in width or greater), which is more comprehensive than what is available currently among DOGAMI and USGS datasets.

The RRAP research team then determined several possible temporary river-crossing strategies, many of which were identified in consultation with county and local emergency management, transportation, and public works officials through discussion at facilitated discussions across the state. Table 5 lists the temporary river crossing strategies identified initially in this study, as well as the river characteristics that would be needed for their successful implementation. Other viable river crossing strategies may exist, and emergency planners should consider them in future studies as allowed by supporting data.

TABLE 5.—Temporary River Crossing Strategies with Required River Characteristics and Implementation Times.

Strategy	River Characteristics						Time to Implement
	Minimum Width	Maximum Width	Minimum Depth	Maximum Depth	Maximum Velocity, feet per second (fps)	Maximum Flow, cubic feet per second (cfs)	
Ford	-	150 ft	-	39 in.	5 fps	-	14 days
Single 4' Culvert	-	20 ft	-	-	-	150 cfs	21 days
Double 4' Culvert	-	30 ft	-	-	-	300 cfs	24 days
Flat Rail Car	-	50 ft	-	-	-	-	44 days
Bailey Bridge	30 ft	210 ft	-	-	-	-	28 days
Improved Ribbon Bridge	67 ft	500 ft	24 in.	-	10 fps	-	21 days

The RRAP research team identified river characteristics criteria for each temporary crossing strategy, as well as the time required to implement those strategies, using several source documents. Guidance provided in the U.S. Army manual, *Military Float Bridging Equipment* (U.S. Department of the Army 1988), served as the basis for river ford and improved ribbon bridge characteristics. The RRAP research team specified single and double culverts in this study with an assumed diameter of 4 feet, based on input from multiple county and local public works department officials, who noted that they generally maintain a stock of corrugated metal culvert pipes with at least 48 inch diameters (some noted that they also frequently had 72-inch-diameter or greater corrugated metal pipes in stock); the RRAP research team also determined a generalized approximation for maximum allowable flow rates at culverts using the *ODOT Hydraulics Design Manual* (ODOT 2014a). Several marine ports noted that due to onsite railroad operations, large numbers of flat-type railroad cars were frequently near their facilities. Departments of transportation throughout the United States have used flat railroad cars as temporary or permanent bridge structures for low-volume roadway applications (Wipf et al. 1999). Numerous studies of railroad flat cars for roadway bridging applications identified possible spans ranging generally from 51 feet to 89 feet (Wipf et al. 1999; Washeleski, Connor and Lloyd 2013). The RRAP research team selected flat cars with a length of 55 feet for consideration in this analysis, allowing for a 50 foot free-span and 2.5 feet for bearing on each side. Bailey bridges are pre-fabricated temporary roadway bridges originally developed for military use during World War II; while their availability is limited, some Oregon sites have used them (Winston and Gehring 2019), and thus the RRAP research team considered them in this analysis. Implementation times for all strategies assume that it will take 14 days to construct temporary, crushed-rock and gravel roadways connecting the riverbank crossing location with existing roadways, in addition to the time required to implement each crossing based on the strategy-specific implementation times identified in the source material specified above.

The RRAP research team evaluated the 5,646 bridges located along the priority roadway routes to screen for potential temporary river crossing locations within the vicinity of disrupted bridges. This screening analysis started with identifying whether the machine learning analysis had characterized rivers within 150 feet upstream or downstream of the bridge. If river characteristics data existed within the dataset, the research team checked those characteristics against the temporary crossing criteria shown in table 5. To be considered a viable option, the comparison of river characteristics with the criteria in table 5 had to identify the same river-crossing strategy under both winter peak-flow conditions and summer low-flow conditions based on the assumption that a temporary crossing will have to remain viable for at least one calendar year given the relatively long projected bridge and roadway reopening times from the islanding analysis. In total, the analysis identified 52 potential temporary crossing locations and selected only the river ford and improved ribbon bridge options (24 ford locations, 28 ribbon bridge locations). An examination of the input data found that seasonal differences in flow affected the outcomes, limiting the number of potential temporary crossing locations. For example, the analysis may have identified a culvert or a ford at a location as possible during summer low-flow conditions, but no crossing strategy would be sufficient at that same location during high-flow conditions earlier in the year.

The 52 potential temporary river crossing locations are, with few exceptions, located primarily on low-volume roadways and not in populated areas. It is likely that these 52 bridges constitute only a small subset of the locations statewide where emergency responders could actually implement temporary river crossings following a CSZ earthquake disaster. This result is due, in part, to limitations in the ability of the machine learning tool to characterize comprehensively the geometric river characteristics of Oregon's rivers and stream networks. In addition, it is possible that responders could implement other crossing strategies beyond the options identified in table 5. The RRAP research team made some preliminary investigations to see whether incorporating these temporary river-crossing results back into the islanding analysis' network optimization model would produce significantly different results, finding that any changes were, in most instances, very minor. The majority of the 52 temporary river crossings identified were located away from communities, so their effect on results was minimal and did not alter the configuration or timeline of the islanding results as shown earlier in figure 20. Given these factors, the RRAP research team conducted no further analysis of the temporary river crossings but is providing data associated with the 52 potential crossing locations to Oregon OEM and ODOT for their evaluation. With a more comprehensive river characteristics dataset, or through coordination with local/county emergency management and transportation officials who have greater local knowledge of their river and roadway systems, planners could identify and consider a greater number of temporary river crossings for future studies and planning efforts.

Airport Assessments

The disaster logistics staging areas identified in the federal and state CSZ response plans are located at airports across Oregon, as the initial phases of response and recovery will likely occur via airlift. Most airports also have full perimeter fencing, which helps ensure the secure storage of disaster response resources, as well as extensive paved areas, which better enable the storage, sorting, and distribution of bulk post-disaster response resources. To understand the ability of airports to perform this critical disaster response role, the RRAP team visited the 12 airports designated by state officials as staging areas to assess their capabilities and resilience to a CSZ earthquake, shown in figure 25. The intention of these visits was not to conduct an in-depth planning assessment, as FEMA and others are currently undertaking such activities within Washington and Oregon. Instead, the purpose of these site assessments was to gather information about any CSZ-related planning activities undertaken to date; gain a baseline understanding of each airport's infrastructure systems and resilience; and assess the dependency of airports on external lifeline infrastructure systems, which could limit their capacity to serve in a post-disaster response and recovery role. These site visits included a site tour of the airport facility, as well as a facilitated discussion with key airport stakeholders, including airport managers and tenants, and frequently with county and city emergency managers, public works departments, utility providers, and other local agencies or organizations. The outcomes of these site visits included an assessment of each airport's exposure to tsunami and liquefaction hazards (i.e., the greatest seismic concerns that could affect airfields themselves), as well as a synthesis of any airport seismic studies conducted to date, the capabilities and resilience capacities of greatest concern among airports, and their dependencies on external lifeline infrastructure. The RRAP research team intended that these outcomes provide additional screening-level details that may be useful to state and regional planners and that may motivate more detailed or in-depth engineering or facility-level analyses of specific airports or assets.

FIGURE 25.—Oregon Airports Visited and Assessed.

Airport Soil Liquefaction, Tsunami Inundation, and Landslide Hazard Exposure Analysis

The most important feature of an airport is the airfield itself—the runways, taxiways, aprons, and ramp areas that facilitate the arrival, departure, and ground movement of aircraft. As one official at Portland International Airport stated, “If you don’t have a runway, you don’t have an airport” (Portland International Airport 2018). For such pavement-based assets, the greatest concern in a seismic disaster is ground failure, whether it occurs through liquefaction and vertical displacements of soils, lateral shifting, or slope failures within the vicinity of pavements. Any of these ground failure modes can cause discontinuities or failures in pavements sufficient to prevent the movement of aircraft. In fact, staff at more than half of the airports visited explicitly stated that liquefiable soils or other types of ground failure (e.g., local slope failures, ground sinking) were of immediate and ongoing concern for their facilities in the context of a CSZ earthquake.

Therefore, the research team first assessed the exposure of the 12 airfields evaluated to liquefiable soils using the DOGAMI dataset discussed earlier. Appendix C contains the full set of maps showing airport facility exposure to potential soil liquefaction. The RRAP research team did not calculate PGD resulting from soil liquefaction at the airports visited, as the methods used in the roadway analysis are better suited for systems-level screening analyses, not site-specific or engineering-level analyses. Determining PGDs at each airport requires geotechnical engineering studies that consider the unique and location-specific soil conditions at each site. However, three such studies have been conducted at Oregon airports, finding that PGDs of up to 7 inches could occur at Hillsboro Airport (Pyrch, Marsters, and Nafie 2019), 12 inches or more at Portland International Airport (HNTB Corporation 2015), and up to 12 inches at Newport Municipal Airport (McFarland, Pyrch, and Marsters 2018).

Four of the airports visited and evaluated—Astoria Regional, Cape Blanco State, Tillamook, and Newport Municipal—are situated on the Oregon coast. Given its elevation above sea level, Cape Blanco State Airport is above and outside of the projected XXL tsunami inundation zone. However, tsunami inundation is still a significant concern for Astoria Regional, Newport Municipal, and Tillamook airports. Tsunami wave forces could damage or destroy airport structures and damage equipment, and the scouring action of tsunami waves could damage or remove pavements, as well as the soils that support airfield pavements. In addition, if inundation is prolonged, tsunami floodwaters could infiltrate the supporting soils for airport pavements, which could cause additional damage or accelerated degradation of the subbase soils that support pavements in the mid to longer term. Although officials at Astoria Regional, Newport Municipal, and Tillamook airports, and other officials within the surrounding communities, are well aware of the local hazards posed by tsunamis, the RRAP research team mapped tsunami inundation extents at these three airports for broader situational awareness among state and federal planners. Appendix C contains these maps, which show that an XXL tsunami is projected to completely inundate Astoria Regional Airport but does not encroach onto either Newport Municipal or Tillamook airports. However, in the case of these two latter airports, an XXL tsunami does approach areas immediately outside both airports' boundaries and could affect site access.

The airports that the RRAP research team visited are all located generally on flat and level terrain, and therefore landslide hazards are not of general concern. However, the research team overlaid the DOGAMI landslide dataset with each of the airports' boundaries for confirmation. The DOGAMI dataset projected landslide hazards at airports to be low at all airports with the exception of Newport Municipal Airport, and accordingly Appendix C provides a landslide hazard map for that airport only. Landslides are of greater risk around much of Newport Municipal's perimeter, as well as an area of increased risk that bisects the two runways. Airport officials indicated that the U.S. military originally constructed Newport Municipal Airport in the 1940s by infilling the valley between two adjacent hillsides, covering a stream that is now routed deep underneath the airport via culvert pipe. This bisecting landslide risk follows the alignment of this stream and infilled area, and emergency planners should confirm its potential for soil or slope failure through a more detailed, site-specific geotechnical assessment.

Synthesis of Facilitated Discussions with Airport Stakeholders

Members of the RRAP research team visited the 12 airports in Oregon currently designated to serve as CSZ disaster logistics staging areas to engage with airport managers; operations and engineering personnel; and regional emergency managers and infrastructure owners and operators from city, county, and state agencies. The purpose of these facilitated discussions was to obtain information based on local experiences, knowledge, and opinions of the experts gathered by seeking:

1. To discover any prior or planned efforts undertaken by airports to plan for or understand their vulnerabilities to a CSZ earthquake.

2. To gather information about the overall capabilities and resilience of airport and airfield infrastructure, and potential impacts to each airport from a projected CSZ earthquake.
3. To assess the reliance or dependency of airports on external lifeline infrastructure systems (namely, fuel, natural gas, electricity, water/wastewater, telecommunications, and surface transportation)

Airport CSZ Earthquake Planning or Vulnerability Studies

Three of the 12 airports that the RRAP research team visited have completed either a general airport resiliency assessment or an earthquake-specific seismic resiliency assessment. Portland International Airport and Hillsboro Airport, both part of the Port of Portland, were part of an organization-wide seismic resiliency study of the Port, which also included marine facilities (HNTB Corporation 2015). In 2019, Hillsboro Airport completed a more focused resilience inventory and assessment of its facilities and assets (Pyrch, Marsters, and Nafie 2019). In 2018, Newport Municipal Airport completed a similar, focused resilience inventory and assessment of its facilities and assets, with a strong focus on seismic resilience (McFarland, Pyrch, and Marsters 2018). These three assessments provide an excellent inventory of onsite assets, facilities, and resources (e.g., onsite structures, fuel capacities, pavement geometry and capacities) that could usefully inform statewide CSZ disaster response efforts. Furthermore, these studies also conducted more detailed, site-specific geotechnical assessments of potential seismic-induced ground failures that could occur during a CSZ earthquake. These assessments provide an excellent model for how other airports across the state could assess the seismic resilience of their infrastructure.

None of the nine other airports that the RRAP research team visited had completed any general or seismic-specific resilience assessments of their facilities beyond cursory inclusions of seismic concerns in agency business continuity or airport continuity of operations plans. The most common reason the airports gave for this absence was simply the lack of available funding to support such a more detailed or in-depth seismic resilience study. Airports noted that, in their experience, the Federal Aviation Administration (FAA), which commonly provides federal funding for airport capital improvements, will not fund seismic resiliency studies (Astoria Regional Airport 2019), nor would the FAA fund airport improvements intended specifically to enhance airport resilience to a potential seismic hazard, such as a CSZ earthquake, noting that these projects fall outside of the traditional set of capital funding justifications (Hillsboro Airport 2018). The three resilience studies conducted at Oregon airports were either self-funded (e.g., Port of Portland) or funded by the Oregon Department of Aviation's (ODA) Critical Oregon Airport Relief Program.

Airport Resilience Capabilities and Dependencies on External Lifeline Infrastructure

The RRAP research team discussed airport resilience capabilities with airport managers and staff, regional emergency management, and infrastructure owners and operators, in the specific context of each airport's ability to support the air operations component of a post-disaster logistics supply chain following a CSZ earthquake. Capabilities to resume commercial or general aviation were beyond the scope of these facilitated discussions and site visit assessments. Appendix D summarizes numerous airport and airfield metrics (e.g., runway geometry and weight capacities, onsite fuel storage), which provide a general overview of the relative capabilities and capacities of the Oregon airports visited.

Among the 12 airports evaluated, officials indicated unanimously that electricity and fuel were the two most critical resources for an airport to operate in a post-disaster logistics function. Electricity enables numerous critical functions at an airport: it is essential to powering navigational aids (NAVAIDS) and airfield lighting, pumping fuel, maintaining wireless communications between aircraft and ground staff (and for broader post-disaster coordination), and providing site access via automated security gates. With some exceptions (namely larger airports), most of the evaluated airports rely on single electrical substations or distribution feeder lines from utility providers to power the airport. Multiple connections may exist to these single feeders serving individual airport functions (e.g., lighting vaults, NAVAIDS) or site tenants, but these feeders nonetheless constitute a potential single point of failure for site power. In some instances, airport personnel were aware of the location of the local power utility substation serving their facility; however, in most cases, airport personnel were unaware of power system configurations beyond their property boundaries. The RRAP research team was unable to coordinate more broadly with regional power utilities to assess the vulnerability of these local or regional power systems, the disruption of which could cascade to adversely impact airports. However, such coordination and broader study of airport/electrical system interdependencies should be the focus of future studies to ensure greater resilience.

The RRAP research team widely discussed backup power generation with airport officials with respect to onsite capabilities should external electricity service become disrupted. Appendix D contains a table summarizing backup power generation capabilities at the airports visited. In general, most airports have backup generation for airfield lighting, which is frequently co-located at their airfield's lighting vault. In most instances, these backup lighting generators are diesel-operated, but in some instances—such as Newport Municipal Airport—they are propane-operated (Newport Municipal Airport 2018). Importantly, none of the airport officials indicated that navigational aids at their airports were connected to backup generation, as the FAA owns, operates, and maintains NAVAIDS as separate and autonomous systems. The one exception is Newport Municipal Airport (Newport Municipal Airport 2018), whose personnel were aware that the VHF Omnidirectional Beacon (VOR) located at its airport was connected to backup generation. In all other instances, airport officials reported that NAVAIDS would most frequently have only dedicated backup batteries to enable ongoing operations ranging from only 6 hours to a few days, depending on the application and utilization. In addition, airport control towers are also typically owned and operated by the FAA (either directly, or via subcontract), and therefore while some have backup generation capabilities, these systems are owned and operated by the FAA, so detailed knowledge of their capabilities was limited among airport officials.

At most airports, officials reported that a disruption to power would limit airport operations to limited instrument flight rules (IFR) operations (i.e., enabling operations during inclement weather or other conditions with restricted visibility), or potentially to visual flight rules (VFR) operations only. As NAVAIDS were most frequently found to be connected only to short-term backup batteries, IFR operations, which enable pilots to take off and land during limited visibility conditions, would likely be able to continue only for the hours or days immediately following a CSZ earthquake disaster if it disrupts utility power. Airfield lighting was the most commonly found airfield system connected to backup generation. At these airports, daytime and nighttime VFR operations would be able to continue if a disruption to utility power occurred, so long as backup generation for airfield lighting has sufficient fuel. Airport officials' estimations on how long the backup generation for airfield lighting could run using fuel-on hand varied widely depending on usage, but their estimates were generally within the range of 1–3 days before refueling is required. If both utility power and backup generation power were disrupted, airport officials indicated that their airports would revert to daytime VFR operations only, which would limit the flexibility and capacity volume of inbound airborne supply lines for emergency response purposes.

As mentioned, airports are advantageous to designate to serve in disaster logistics functions given that most have a fenced, secured perimeter. However, numerous airport personnel indicated that electric gate systems with security credential card readers facilitated site-access and security. With the exception of Redmond Municipal Airport, none of the airports' access control systems were connected with backup generation, as that would therefore require the manning of gates and manual operation by security or emergency response personnel during any post-disaster logistics activities, either indefinitely or until restoration of utility service power.

Aircraft fuel and, to a lesser extent, vehicle fuel were the second-most critical resources indicated by airport officials for their facilities to succeed in serving in a post-disaster logistics supply chain function. USTRANSCOM indicated that it would conduct any military-based operations such that aircraft would not have to rely on refueling services at the disaster logistics staging areas (USTRANSCOM 2018); however, other disaster response aviation operations would require functional ground refueling capabilities at the disaster logistics staging areas. Appendix D provides the airports' onsite fuel storage capacities; however, most airport officials indicated that storage was generally kept between 30–80 percent full, depending greatly on seasonal demand. Furthermore, airport officials and fixed-base operators (the organizations frequently maintaining or operating onsite fuel storage facilities) indicated that when ordering fuel to replenish supplies, it was not economically advantageous to order small quantities to simply "top-off" tanks, but rather to maximize orders due to delivery charges. Following this approach means that although airports have large onsite fuel storage capacities, the quantity of available fuel on-hand at any given time could be far less than capacity. Therefore, predicting the quantity of fuel that may be located at each airport at any given point in time is difficult. Nonetheless, their knowledge of onsite storage capacities should enable emergency managers to understand and plan for fuel shipments during post-disaster response and recovery activities, and better plan around the capability of airports to support ongoing aircraft refueling when re-establishing post-disaster fuel supply lines.

Given their configuration, fuel storage facilities require electricity to pump fuel (i.e., they cannot be gravity operated). However, with the exception of Tillamook Airport, none of the airports has backup power generation at their onsite fuel storage facilities, which significantly limits their utility in a post-disaster logistics capacity. Further, only Rogue Valley International—Medford Airport indicated that their onsite fuel storage tanks had permanent connection points for portable generators, although several indicated that ad-hoc connections could be implemented in order to pump fuel if portable generators were available. Only Aurora State and Eugene Airports indicated that they had manual pumps that would allow for some limited capacity of aircraft refueling (Aurora State Airport 2018, Eugene Airport–Mahlon Sweet Field 2018). Last, with respect to fuel, the RRAP research team observed that none of the airport fuel storage facilities incorporated any seismic anchoring or restraints beyond simple bolted attachments to concrete foundation pads (i.e., in the case of above-ground fuel storage tanks), which would likely shear during a CSZ earthquake event. This condition greatly increases the likelihood that CSZ-earthquake ground motions could damage fuel storage facilities and either limit their utility to post-disaster response and recovery activities or otherwise render them entirely unusable.

Among the other critical resources and supporting lifeline infrastructure discussed (water/wastewater, telecommunication, natural gas, and surface transportation), airport officials indicated that these resources are critical to normal airport operations, but may have limited or little impact to their airports' immediate ability to serve as disaster logistics staging areas. For example, water and wastewater services are essential for building occupancy (e.g., bathrooms, fire suppression), as is natural gas (used at airports for heating purposes only). A functional supply of water was only critical to airfield operations at airports with onsite airport rescue and firefighting (ARFF), and even then, only where commercial passenger operations are occurring. Even in the instance of ARFF, airports indicated that emergency airfield use could still continue without these functions, and that they could seek waivers from the FAA to enable this operation. Most airport officials indicated that telecommunications were essential for communicating airport operations information to the FAA and to pilots (e.g., automated weather observation information, notices to airmen), but that rechargeable hand-held radios could enable ground-to-air communications, which would be sufficient for post-disaster emergency operations. Surface transportation linkages are, of course, critical to the broader function of airports as disaster logistics staging areas, as emergency officials must be able to move goods and resources from airports to surrounding communities. In general, the RRAP research team discussed transportation topics with local officials, and considered or assessed any relevant findings as part of the islanding analysis discussed in the Analysis of Regional Islanding from Roadway Disruptions section.

Maritime Port Assessments

A significant proportion of Oregon's population lives along the Pacific coastline and Columbia River, and therefore the project's stakeholders showed great interest in better understanding the potential for maritime ports in these locations to aid in disaster response and recovery activities. In particular, as results of the regional islanding analysis described in the Analysis of Regional Islanding from Roadway Disruptions section indicate, a CSZ earthquake event will largely cut off the majority of coastal communities in Oregon from staging-areas-based disaster logistics supply chains—even those originating from airports along the Oregon Coast—during the initial phases of post-disaster response and recovery. To provide some baseline characterization of ports' seismic vulnerabilities and capabilities, the RRAP research team first visited seven of the major maritime ports in Oregon, as figure 26 shows, and we conducted facilities discussions of seismic considerations with port personnel. Staff from ODOT regional offices, county/city emergency managers, and county/city transportation and public works staff also frequently attended these meetings to provide broader perspectives of community capabilities, resources, and considerations. These maritime port assessments also focused on an analysis of the exposure of maritime port infrastructure to seismic hazards to serve as a common point of departure for future analysis and planning.

Maritime Port Tsunami Inundation and Soil Liquefaction Hazard Exposure Analysis

The majority of ports visited by the RRAP research team are located along Oregon's Pacific coastline, which makes them especially vulnerable to CSZ earthquake-related tsunami inundation and wave forces; and also substantially increases the likelihood that they are built on liquefiable soils, which are most prevalent in coastal and riverine environments. In addition, some ports within the region are built on imported fill materials that have been placed in previously open waterways to expand buildable land, or have been used to build-up or level existing land to better accommodate port activities. These fill materials are also frequently highly susceptible to liquefaction.

FIGURE 26.—Oregon Maritime Ports Visited and Assessed.

The RRAP research team first mapped approximate port facility boundaries and then overlaid those boundaries with tsunami hazard and liquefaction susceptibility datasets that DOGAMI provided (DOGAMI 2013, 2019a). Appendix E contains the full set of maps showing port facility exposure to potential soil liquefaction and tsunami inundation hazards, which table 6 also summarizes. The analysis projects that all coastal ports will experience complete inundation across their entire terminal facilities as a result of an XXL tsunami. In fact, as the figures in Appendix E show, the analysis projects that coastal ports will experience complete inundation under the more moderate L and XL tsunami scenarios. The DOGAMI tsunami datasets do not project that the two riverine ports assessed—Port Westward–St. Helens and the Port of Portland—will experience tsunami inundation. Although these datasets do not model inundation in the Columbia River beyond river reaches in the immediate vicinity of its confluence with the Pacific Ocean, DOGAMI staff indicated that tsunami inundation is not a significant concern at these two riverine ports, but that the potential exists for some minor flooding should coastal tsunami flooding cause shorter-term backups in Columbia River flows.

TABLE 6.—Summary of Maritime Port Exposure – Soil Liquefaction Susceptibility and Tsunami Inundation.

Maritime Port Facility	XXL Tsunami Inundation	Soil Liquefaction Susceptibility
Port of Astoria	Complete	Level 4, All of Port
Port of Brookings	Complete	Level 2, All of Port
Port of Coos Bay - Charleston	Complete	Level 4-5, All of Port
Port of Coos Bay - North Spit	Complete	Level 3, Along Spit
		Level 4, Inland
		Level 5, Along Shoreline
Port of Coos Bay - Upper Bay	Complete	Level 3, Waterway
		Level 5, Along Shoreline
Port of Gold Beach	Complete	Level 3, All of Port
Port of Port Newport	Complete	Level 4, South Marina
		Level 2-3, North Marina
		Level 2-3, Northwest Marina
Port of Port Orford	Complete	Level 1, Main Port
		Level 2, Port Access
Port of Portland - Terminal 2	None	Level 5, All of Terminal
Port of Portland - Terminal 4	None	Level 3, Inland Edges of Terminal
		Level 5, Majority of Terminal
Port of Portland - Terminal 5	None	Level 5, All of Terminal
Port of Portland - Terminal 6	None	Level 5, All of Terminal[1]
Port Westward - St. Helens	None	Level 3, All of Port

[1] Berths 604 and 605 have been hardened through soil improvement projects to withstand seismic activity.

In addition to tsunami exposure, most coastal and riverine ports have significant exposure to soils with medium to high liquefaction susceptibility. The RRAP research team did not model liquefaction-related PGDs at port facilities. However, ground-shaking intensity is a key factor in ground deformation and failure, and the location of coastal ports in particular places them nearest to the CSZ fault, likely exposing them to some of the greatest projected shaking intensities across Oregon (as figure 5 shows). Given this reality, even moderate soil liquefaction susceptibility could pose significant risks to coastal port infrastructure. In addition, soil liquefaction could possibly exacerbate the local impacts of tsunami inundation depths. As soils liquefy, they can flow down even gentle grades. This liquefaction subsidence can lower the overall land elevation in these areas such that the effective depth of tsunami inundation could increase. DOGAMI tsunami inundation modeling and mapping efforts do account for the effects of tectonic, or coseismic, subsidence (where rapid shifts in the underlying tectonic plates during an earthquake can cause ground elevations to change rapidly—dropping by as much as 4–10 feet along the coast) (DOGAMI 2013). However, the effects of soil liquefaction could cause similar localized changes in elevation, which could cause local effective inundation depths and extents at port facilities to occur in excess of those shown in Appendix E.

Synthesis of Facilitated Discussions with Port Stakeholders

Members of the RRAP research team visited the seven maritime ports in Oregon to engage with port managers, operations and engineering personnel, and both port and regional emergency managers and infrastructure owners and operators. The purpose of these discussions was twofold:

1. To discover any prior or planned efforts by maritime ports to plan for, or understand their vulnerabilities to, a CSZ earthquake; and
2. To solicit expert opinion of port facility personnel or additional information on the impacts to ports from a projected CSZ earthquake.

Port CSZ Earthquake Planning or Vulnerability Studies

None of the seven ports visited have undertaken any general or seismic-specific resiliency studies,[6] with the exception of the Port of Portland, which completed a corporate seismic risk assessment study in 2015 (HNTB Corporation 2015) that assessed the seismic risk of their marine terminals. Most ports indicated that a lack of funding to support such focused studies, alongside competing day-to-day operations, maintenance, and planning activities, was the primary reason that they had not been able to pursue such studies. Some ports also indicated that they were hesitant to make significant investments in either seismic vulnerability studies, or seismic retrofit activities, without greater state-level planning or guidance on how their facilities would support the broader maritime transportation system in Oregon as part of the coordinated CSZ earthquake response. At the same time, this lack of study by major ports of their respective CSZ earthquake vulnerabilities is a significant blind spot for maritime transportation with respect to CSZ response planning, and may be preventing state, federal, or other regional partners from more fully integrating the commercial maritime transportation system into the broader CSZ post-disaster supply chain.

Port Impacts from a CSZ Earthquake

Despite limited local study of CSZ earthquake seismic resilience, most ports had a strong general awareness of their exposure to CSZ earthquake hazards, and also of their ports' potential physical vulnerabilities. All ports were aware that their facilities are constructed on liquefiable soils and that the impacts of liquefaction-related ground failure could significantly disrupt their infrastructure and operations. While much of the port infrastructure in Oregon was built prior to the advent of seismic design, and therefore the seismic performance of that infrastructure is uncertain, some facilities have undertaken newer construction activities that incorporate some seismic resilience to liquefiable soils. For example, Port Westward–St. Helens noted that the majority

[6] This lack of plans includes among lease tenants, as none of the port authorities were aware of any seismic vulnerability assessments undertaken by their tenants of leased facilities.

of its inland facilities (many tenant-owned and -operated) were constructed on stone columns, which is a soil improvement method that can reduce the risks associated with liquefaction in saturated soils. Similarly, the Port of Portland made soil improvements (jet-grouted columns and stone columns) in sections of Terminal 6 (berths 604 and 605) in 2011 and 2012, as the port's Seismic Resilience Plan identifies Terminal 6 as a potential post-CSZ staging area.

Many of the dock and waterfront structures among ports in Oregon, particularly on the coast and at smaller ports, are constructed on wood piles that are subject to deterioration, thereby reducing their seismic resilience. Nonetheless, several ports noted that as they had made some capital improvements to these waterfront structures, and that most recent improvements used more modern materials that offer greater seismic resilience. For example, the Port of Astoria rebuilt portions of Pier 2 using reinforced concrete, and Port Westward improved its steel dockside mooring structures in 2016 to withstand an approximate 7.0M earthquake. As with seismic resilience studies, most ports cited a lack of funding as the primary reason that seismic improvements were not being pursued more broadly at their ports. In fact in one instance, personnel at the Port of Newport noted that they had to eliminate seismic tie-backs from improvements to their International Terminal in 2015 due to lack of funding.

In addition to landside impacts, port staff frequently expressed concern about navigational impacts to the coastal and river waterways that serve marine ports, which most noted as a key dependency for port operations. For example, most ports indicated that ongoing waterway maintenance and dredging were both essential activities to maintaining navigable waterways at their facilities. However, as most ports in Oregon are either built on rivers or are located at the mouth of rivers, officials expressed concern that earthquake ground motions could loosen upstream sediments, which could infill port berths and waterways, requiring significant dredging before reopening. In addition, the Port of Astoria noted that up to 7 feet of sediments can be deposited annually, resulting in annual dredging costs between $800,000 to $1M; the Port of Brookings Harbor noted that dredging is also an annual requirement at their port, while dredging is required approximately every three years at the Port of Gold Beach. Finally, numerous ports expressed concern about local slope failures along port berths, basins, jetties, or other waterside areas that could affect navigation. Submarine landslides along underwater slopes, or by the failure of seawall and other earth retention structures, could cause similar impacts or cause liquefiable soils or port fill materials to spill into the waterway, reducing water depth and affecting or limiting navigability.

Several ports and other agencies also expressed concern about waterway impacts resulting from either floating or sunken debris in the waterways. USCG, DOGAMI, and several of the ports indicated that tsunami currents would likely dislodge or carry floating debris into waterways, and that debris could both damage port infrastructure, or would otherwise have to be removed before the reopening of waterways. The Ports of Gold Beach and Brooking both indicated that they had experienced this locally as a result of the 2011 Tohoku Earthquake in Japan, which propagated a tsunami wave across the Pacific with arrival heights along the Oregon coast ranging from 0.6 ft to 6.0 ft (DOGAMI 2012). In addition to waterway impacts from floating debris, several ports, as well as county and local emergency managers, expressed concern that collapsed structures or dockside equipment could block waterways, requiring extensive salvage operations before waterways could be reopened. For example, local transportation and emergency management officials in Newport indicated that a collapse of the Yaquina Bay Bridge on US 101 could completely cut off the Port of Newport from the Pacific. Similarly, the Port of Coos Bay indicated that terminals in the eastern half of Coos Bay would be inaccessible if either the McCullough Memorial Bridge on US 101 or the Coos Bay Rail Line Bridge affected the waterway following a CSZ earthquake. Last, both the Port of Portland and Port Westward–St. Helens indicated that a failure of either the Astoria–Megler Bridge at the mouth of the Columbia River or the Lewis and Clark Bridge near Rainier, Oregon, could significantly affect waterway navigability, but that due to the depth of the Columbia River's navigation channel, shallow-draft barge operations may still be viable until salvage operations were able to remove collapsed structures and reopen the waterway.

All of the ports indicated their awareness of the threats that tsunamis pose, frequently citing the maps and studies published by DOGAMI. However, none of the ports had undertaken any studies to assess or quantify the impacts of tsunami wave forces or inundation to their facilities. In most cases, among the coastal ports, port staff indicated that the magnitude of tsunami impacts were perceived to be so great that no planning or capital improvements could adequately mitigate potential impacts, and thus any such investments were difficult to justify. In addition, most ports noted that fuel and electricity would be key resource dependencies required to reopen any facilities that were not severely damaged, or to resume operations as possible.

Several ports indicated that although their marine structures and facilities may be unusable following a CSZ tsunami, some landside infrastructure (e.g., concrete laydown areas, armored embankments) could be useful assets for post-disaster resource and materials staging, as construction of many landside lay-down areas feature reinforced concrete with high load capacities. Furthermore, staff frequently noted that these paved facilities could be advantageous if the military brings in post-disaster temporary harbor structures or joint logistics over-the-shore (JLOTS) operations, which are common among U.S. military supply-chain operations (e.g., USTRANSCOM, USNORTHCOM), to the region following a CSZ earthquake to support coastal response supply chains. Ports and local emergency managers noted that US NORTHCOM and Oregon National Guard have demonstrated such operations locally. For example, the USNORTHCOM Defense Support of Civil Authorities (DSCA) demonstrated a Navy landing craft, air cushion (LCAC) at Sunset Beach, Oregon, on June 3, 2019. The LCAC launched from a naval vessel and simulated the delivery of public works and engineering equipment for clearing roads after a catastrophic event.

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Key Findings

Key Findings

The remainder of this report focuses on documenting the Key Findings for the Oregon Transportation Systems RRAP project. The Key Findings are a result of the information-gathering and analytic activities for this assessment. Each of the Key Findings is supported by an explanation of the significance of the finding, options that could improve resilience in the focus area, and suggested players for implementing these options.

Key Finding #1: Oregon's statewide transportation system is vulnerable to a CSZ earthquake, the impacts of which will significantly disrupt the movement and distribution of post-disaster emergency supplies to communities throughout the affected regions—in particular, the Oregon coast and other regions within western Oregon.

During a CSZ earthquake, Oregon's statewide transportation system will experience both the direct seismic impacts associated with ground motion and seismic forces, as well as secondary seismic impacts in some areas, including the potential for widespread ground failure through landslides and soil liquefaction, and tsunami inundation and impacts along its coastlines. The vulnerability of statewide transportation systems will lead to widespread disruptions, impeding efforts to quickly establish the post-disaster supply chains via surface transportation that will be necessary to provide life-saving and life-sustaining resources to Oregon communities—particularly those on the Oregon coast and in other regions of western Oregon closest to the CSZ fault line where impacts are expected to be greatest.

While these hazards are unavoidable, the vulnerability of transportation systems can be better managed by increasing the amount of information available ahead of time to plan for and mitigate potential consequence. Studies in Oregon that DOGAMI and ODOT conducted to date of seismic-related natural hazards and impacts to bridges and roadways are a tremendous resource for infrastructure-focused analyses of statewide and community impacts, and sets Oregon up well for future studies of CSZ impacts in other infrastructure sectors. However, addressing some minor data gaps could strengthen Oregon's understanding of natural systems in the context of a CSZ earthquake, and enable emergency planners to gain a more complete understanding of both their impacts on infrastructure and on response and recovery.

Resilience Enhancement Options

Oregon OEM and DOGAMI should quantify more comprehensively the width, depth, and flow of Oregon's system of rivers and major streams in order to more directly inform planning activities focused on identifying potential temporary river crossing locations, both in general but also in proximity to existing river crossings that may be impacted or disrupted. Numerous county/city emergency managers and county/regional transportation officials expressed that temporary crossings could be constructed using materials on-hand, but that better information about both river characteristics and statewide post-disaster transportation planning would help to identify appropriate crossing locations, and although the machine-learning-based approach used in this study can provide high-level information, data collected through local site surveys will be better able to inform more tactical decision making.

ODOT and DOGAMI should develop an expanded searchable database of historic subsurface boring and other subsurface exploration reports in a GIS database, and update that database continually as new information is generated, particularly as related to transportation systems and assets. This database would provide additional detail beyond DOGAMI's current statewide liquefiable soils database and enable planners and engineers to more easily conduct site vulnerability assessments at critical infrastructure locations across the state. For example, such a dataset could minimize the need for additional sub-surface exploration during future studies of port and airport seismic vulnerability.

Oregon OEM should work with county/local emergency managers, the U.S. Forest Service, and the Oregon Department of Forestry to catalog the network and condition of forest service and fire roads, in particular throughout the Coastal Mountains. Numerous county managers throughout the Oregon coast noted that low-volume forest roads could become vital connections to islanded communities on the coast, where the timelines to reestablish surface transportation connections are months if not years. However, due to a lack of centralized information or data about the usability and location of forest service roads, the RRAP research team could not incorporate that material into this study. Such a dataset could form the basis of future transportation emergency planning and contingency studies, particularly at county and local levels.

Key Finding #2: Seismic impacts will create islanded communities that are functionally disconnected from one another, and also from the planned disaster logistics supply chains intended to support them.

The results of the islanding analysis confirm that communities across Oregon will functionally fragment and become disconnected from one another as the interconnecting transportation networks are disrupted by the seismic event. Similarly, preliminary results from the optimization analysis indicate that certain roadways and routes with comparatively shorter reopening timelines will enable post-disaster supply chains to reopen as efficiently as possible. This information could inform activities that will accelerate the post-disaster distribution of resources to communities in need, such as prioritizing more focused emergency planning; engineering analysis; infrastructure analysis and retrofitting; or post-disaster inspection, repair, and reopening activities along the priority routes identified.

Encouragingly, the islanding analysis shows that much of the Willamette Valley and communities along and east of the I-5 corridor may be able to reconnect to post-disaster supply lines within a few weeks of a CSZ earthquake. However, these results also show that within that region, some communities will remain cut-off for much longer, and also that communities along the Oregon coast will be disconnected from roadway-based supply chains both from staging areas located inland, as well as those identified along the coast. Although landslides and liquefaction are significant concerns for transportation system disruption, damage to bridges along major routes, particularly east–west routes connecting the coast with inland systems, have the greatest impact on roadway transportation system viability. Proactive actions to plan for, retrofit, or replace high-risk bridges will have a tremendous impact on reducing reconnection times throughout western Oregon, but especially to communities on the Oregon coast.

Resilience Enhancement Options

ODOT and county or local departments of transportation should prioritize investments along the priority roadway corridors identified in the islanding analysis, particularly those connections between the Oregon coast and inland locations. These investments should focus on retrofitting high-vulnerability bridges and mitigating major or high-risk landslide areas (either large single landslides, or multiple smaller high-risk landslides along landslide-prone corridors), as the analysis results show that these two seismic effects cause among the greatest reopening times.

Oregon OEM should work with ODOT and with county and local emergency managers to assess and identify potential locations for temporary river crossings, especially along the priority roadways identified in the islanding analysis, to reconnect communities served by roadways with particularly long reopening times. This analysis should start by evaluating the potential for temporary crossings at locations immediately adjacent to bridges with long projected reopening times located on the priority roadways, and may consider evaluating temporary river crossing strategies in addition to those identified in this study. Given the proposed use of military ribbon bridges, coordination with USNORTHCOM and USTRANSCOM (potentially via

Oregon National Guard) will be essential to better understanding their resources (e.g., deployment timelines, asset availability).

Oregon OEM, county emergency managers, and ODOT should investigate actions that could accelerate response and reopening along priority roadways and corridors, particularly those leading to and located on the Oregon coast. This effort should include relocating maintenance yards (i.e., construction equipment and materials storage) outside of tsunami inundation zones and away from high-risk landslides. This could also include pre-identifying in emergency plans the location of construction resource and material locations (e.g., such as gravel pits or quarries) throughout the impacted regions, or alternate suppliers (e.g., pre-cast or pre-stressed concrete suppliers) outside of the impacted regions, so that emergency planners can access and utilize these vendors more immediately after the disaster.

Oregon OEM should continue to engage with, or expand its outreach to, county/local emergency managers and communities in regions shown to be particularly isolated in the islanding analysis, and for which reconnection to post-disaster transportation supply chains will be prolonged. Oregon OEM's recommendation that communities should plan to be without services for up to two weeks following a CSZ earthquake is valid for some regions of the state, but other regions—particularly in the Coastal Mountain range and on the Oregon Coast—could be without services for considerably longer based on the islanding analysis in this study.

ODOT and DOGAMI should conduct or support ongoing research in the state to better understand the consequences of long-duration shaking on bridges and other transportation assets, as well as to begin to quantify the potential effects of aftershocks on damaged structures. Although the field of research studying the impacts of long-duration shaking to structures is nascent, obtaining a deeper understanding of these effects could enable engineers and emergency managers to better anticipate the viability of transportation infrastructure. In addition, while aftershocks will certainly exacerbate damage to structures and systems from the primary or initial ground motions, the extent of these impacts is extremely difficult to predict, limiting knowledge of the viability of infrastructure throughout early disaster response phases.

Key Finding #3: Airports and airfields in Oregon are critical to early disaster response efforts, serving as staging and distribution points for an anticipated national influx of critical supplies and resources into the region; however, significant planning and analysis are necessary to better understand and enhance the resilience of these facilities in order to more efficiently and effectively support incident response.

Although airports and airfields form the basis of federal and state CSZ response plans, the full seismic resilience of airports to a CSZ-type earthquake—and therefore their viability to serve as disaster logistics staging areas—is not well-understood. Of the 12 airports that the RRAP research team visited across Oregon, only three airports had conducted a detailed engineering- and planning-level assessment of their own infrastructure's seismic resilience; and only Portland International Airport has pursued design solutions to upgrade its airfield (a project to seismically upgrade 6,000 feet of the south runway is at 30 percent design). Therefore, the majority of airports do not fully understand the impacts that seismic forces, ground failure, or a tsunami may have on their facilities and airfield infrastructure, nor have they pursued seismic resilience projects. While the high-level seismic screening information collected at airports through this RRAP project may motivate further study of airfield resilience, these efforts are not sufficiently detailed to comprehensively evaluate an airport's viability to serve as a staging area. Nonetheless, the seismic resilience studies conducted at three Oregon airports underscore the tremendous value that such studies can provide, and also provide actionable outcomes that can directly inform planning and investment decisions for projects that will enhance the seismic resilience of airport infrastructure.

Airports noted that among the critical infrastructure systems on which they depend for operations, electrical power and fuel supply were most critical to ensuring their ability to support post-disaster response and recovery operations. Most airports had undertaken little to no joint planning, analysis, or engagement with external fuel and power providers to assess or understand the resilience of these services that support airports. However, to mitigate the risks of disruptions to these services, many airports had made efforts to install backup generation to key airport facilities. For example, airports most commonly had installed backup generators to provide power to airfield lighting systems, which could sustain or enable daytime/nighttime VFR operations. Backup power generation was broadly lacking among the airports visited to support NAVAIDS and pumping at fuel storage facilities.

Resilience Enhancement Options

ODA should conduct focused seismic resiliency assessments at state-owned airports, and support such assessments at non-state-owned airports which are designated in the state and federal CSZ response plans as disaster logistics staging areas. This funding and support should start at smaller, less well-resourced airports, or at those airports shown in the islanding analysis to be able to reach a broader population earlier in the post-disaster response timeline, as the need for the large-volume movement of goods through these facilities will be more immediate. Furthermore, ODA should work with the FAA and the Oregon state government to identify funding that can more directly support seismic resilience investments at airports. Airport officials identified that current FAA funding mechanisms do not support such investments, and that funding to date was either through ODA or through local investments and revenue.

Oregon airports should take actions to ensure that airfield and fuel systems vital to unrestricted air operations (i.e., IFR and VFR) will have a reliable source of backup power following a CSZ earthquake. This effort could include installing new backup generation, expanding connections to existing backup generation to support broader array of airfield systems, or otherwise hardening existing backup systems to seismic impacts. These systems should support, at a minimum, airfield lighting, fuel storage and pumping, site access control, and where possible, NAVAIDS. For non-airport-owned NAVAIDS or other systems, ODA should lead engagement with the FAA and among Oregon airports to ensure that these FAA-owned/operated systems also have backup generation capabilities beyond short-term battery backup. Airports and the FAA should also considerer coordinating with USACE to perform emergency prime-power analyses at each of these airfields to assist the USACE in providing emergency generators to airfield NAVAIDS post-disaster.

Oregon airports should make investments to enhance the resilience of their onsite fuel storage facilities. This should include, at a minimum, assessing the seismic integrity of storage tanks and supporting infrastructure (e.g., foundations, piping systems), making necessary seismic retrofits (e.g., seismic anchoring), and ensuring the ability to pump fuel during a loss of utility service power (e.g., backup generators, manual pumps, gravity-based operations).

ODA and Oregon airports should work with the electric power utilities and fuel providers serving airports to assess the resilience of these supporting systems and identify contingency plans. For example, aviation fuel deliveries currently originate from bulk storage facilities located in Portland and other locations in western Oregon, but contingency agreements with fuel providers could seek to source emergency fuel supplies from outside of this region. Similarly, cooperation with utilities could seek to ensure the continuity of services through investments in redundant or more resilient systems, such as the ability for multiple substations to serve airport facilities instead of single substations, reducing the potential for a single point of failure during a CSZ earthquake.

Key Finding #4: The ability of maritime transportation systems to support sustained incident response and recovery efforts is not well understood due to a lack of available information about the seismic resilience of these systems.

Maritime ports in Oregon along the Pacific coast and Columbia River may have the potential to support post-disaster response and recovery activities, but ports have generally not undertaken adequate studies to understand the seismic resilience of their maritime facilities. To date, none of the maritime ports that the RRAP research team visited had conducted or engaged in any seismic resilience studies or planning, with the notable exception of the Port of Portland, which had not only assessed the seismic resilience of its marine terminals, but had also made substantial seismic resilience upgrades to harden Terminal 6 to allow it to serve as a potential staging area. In order for emergency planners to more fully consider the role that maritime transportation may play in post-CSZ earthquake response activities, the seismic resilience of maritime ports, their facilities, and their infrastructure must be better understood through detailed, site-specific engineering and planning analyses and greater stakeholder engagement. At the same time, feedback from state officials to port officials about the potential role that maritime ports could play during a post-CSZ earthquake disaster response is essential to helping motivate additional studies and investment at marine port facilities.

The islanding analysis indicated that airports alone will not be able to meet all anticipated supply chain needs on the Oregon coast due to projected disruptions in the surface roadways that connect them to surrounding communities. Therefore, a maritime capability along the Oregon coast is essential to supplement air-based response in the near-to- mid-term as roadway connections to inland regions are reestablished. If ports cannot support these activities directly due to damaged infrastructure, then they may need these alternative maritime supply chain resources (e.g., JLOTS, temporary harbors).

Resilience Enhancement Options

Oregon ports should coordinate with the USCG (e.g., through USCG's Port Coordination Team), the U.S. Maritime Administration, USACE, and Oregon OEM to explore options for completing focused seismic resilience studies at individual ports in order to gain a greater understanding of potential CSZ earthquake impacts to their facilities and related infrastructure systems, as well as relevant mitigation measures for consideration. These studies could begin with higher-level screening assessments that incorporate some site-specific engineering investigations (the Port of Portland's corporate seismic risk assessment study provides a template for these activities, as do the airport resilience studies discussed earlier), and then focus on more in-depth engineering assessments of specific assets or facilities, as warranted.

Oregon OEM and USCG should conduct a high-level, statewide port systems planning assessment to set priorities for how to incorporate maritime ports into post-CSZ earthquake disaster response. Numerous ports indicated that greater state guidance on their port's potential role in disaster response was needed to justify further study and investment at the local level. This type of state-level assessment/planning effort uses as its basis any screening-level port vulnerability assessments to develop a broader state-level plan, which could then motivate greater local-level planning, study, and capital investment at those ports best positioned to support post-disaster response and recovery.

Oregon OEM should work with USNORTHCOM/USTRANSCOM, county emergency managers, and maritime ports to identify and assess potential sites for temporary port facilities or over-the-shore logistics operations, and identify the availability of resources and assets on the West Coast that could support such operations.

Ports should work with the USCG to prioritize capital investment in new or planned projects that enhance the disaster response capabilities of ports, and potentially in ways that can more directly support over-the-shore logistics operations instead of more traditional port operations. Although the magnitude of ground motion, ground failure, and tsunami hazards on the Oregon coast could destroy or extensively damage ports' marine and immediate landside infrastructure, some systems that could support over-the-shore operations may be less vulnerable to these impacts and could accelerate maritime response timelines. For example, several ports noted that many landside cargo lay-down areas were constructed of heavily reinforced concrete that could support heavy loading. Even if port maritime infrastructure was damaged or unusable, such facilities would be potentially less vulnerable to projected seismic impacts along the coast and could be extremely useful to over-the-shore logistics operations or for emergency management stockpiling, warehousing, and distribution.

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Conclusion

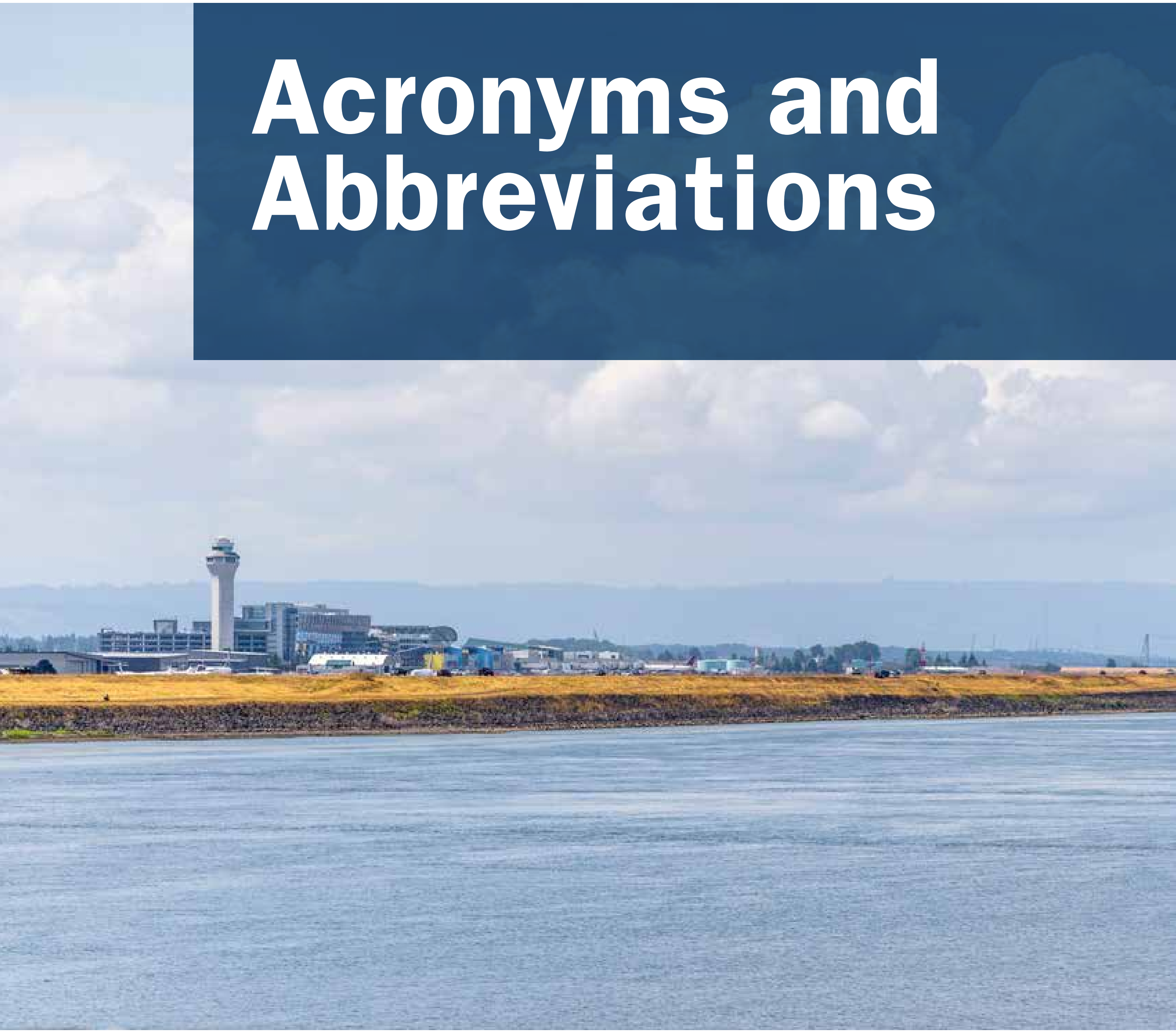
Conclusion

The Oregon Transportation Systems RRAP project integrated the expertise and knowledge of participants in the region into an assessment of statewide transportation infrastructure systems' abilities to support post CSZ earthquake response and recovery activities. The project revealed that Oregon's roadway network will generally be able to support post-disaster logistics supply chain activities within approximately two weeks of a CSZ earthquake, and particularly east of the I-5 corridor. However, a CSZ earthquake will cut off communities west of the I-5 corridor, and particularly along the Oregon coast, from inland supply routes, as well as other communities within their own regions, forming so-called islands that will be isolated from outside supplies until transportation systems reopen. This islanding analysis proposed a series of priority roadways that state officials could prioritize for investments that enhance their resilience to a CSZ earthquake, and could effectively "buy down" the reopening time of roadways to access isolated or islanded communities. In addition, this islanding analysis identified the approximate service areas for each of the currently identified disaster logistics staging areas, as well as the populations of those service areas and approximate timelines for how these service areas could expand and grow during post-disaster response and recovery as transportation systems reopen and as the emergency response effort restore connections.

In addition, this RRAP project assessed the resilience and post-disaster response capabilities of airports across Oregon that are currently designated as disaster logistics staging areas, as well as several maritime ports along the Oregon coast and Columbia River. The RRAP research team synthesized findings from a series of facilitated discussions and site visits at these facilities, finding that researchers have conducted only limited study and analysis to date to better understand the seismic vulnerability of airports and maritime ports. Airports consistently indicated their dependence on electric power and fuel to support ongoing operations, and the RRAP research team identified some clear actions to enhance the resilience of airports related to these interdependencies. The findings for maritime ports indicate a general need for greater study of facility vulnerability and planning among state officials and local port management to ensure coordination in maritime-based post-disaster response and recovery.

CISA, the State of Oregon, and the public and private partners involved in this RRAP project intend for this Resiliency Assessment and all associated documents and data to provide guidance to state, county, and local officials. In particular, this project offers guidance to the core stakeholders that participated in this project as to key challenges facing Oregon transportation systems and its ability to support post-CSZ response and recovery activities, but also actions that can help to address these gaps and ultimately inform greater emergency management planning and infrastructure investments that will collectively enhance the resilience of Oregon. For more information about this RRAP project, please contact CISA Region 10 at CISARegion10@hq.dhs.gov and/or CISA Headquarters at Resilience@hq.dhs.gov.

Acronyms and Abbreviations



Acronyms and Abbreviations

ARFF	Airport Rescue and Firefighting
BSST	Bridge Seismic Screening Tool
CFS	Cubic feet per second
CISA	Cybersecurity and Infrastructure Security Agency
CREW	Cascadia Region Earthquake Workgroup
CSZ	Cascadia Subduction Zone
DHS	U.S. Department of Homeland Security
DOGAMI	Oregon Department of Geology and Mineral Industries
DSCA	Defense Support for Civil Authorities
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FPS	Feet per second
FSA	Federal Staging Area
GIS	Geographic Information System
HITRAC	Homeland Infrastructure Threat and Risk Analysis Center
I	Interstate
IFR	Instrument Flight Rules
IMA	Initial Mobility Area
ISB	Incident Support Base
JLOTS	Joint Logistics Over-the-Shore
LCAC	Landing Craft, Air Cushion
M	Magnitude
MMS	Moment Magnitude Scale
NAVAIDS	Navigational Aids
NISAC	National Infrastructure Simulation and Analysis Center
ODA	Oregon Department of Aviation
ODOT	Oregon Department of Transportation
OEM	Oregon Office of Emergency Management
OSM	OpenStreetMap
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
RRAP	Regional Resiliency Assessment Program
SLIDO	Statewide Landslide Information Database for Oregon
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
USNORTHCOM	U.S. Northern Command
USTRANSCOM	U.S. Transportation Command
VFR	Visual Flight Rules
WSDOT	Washington State Department of Transportation

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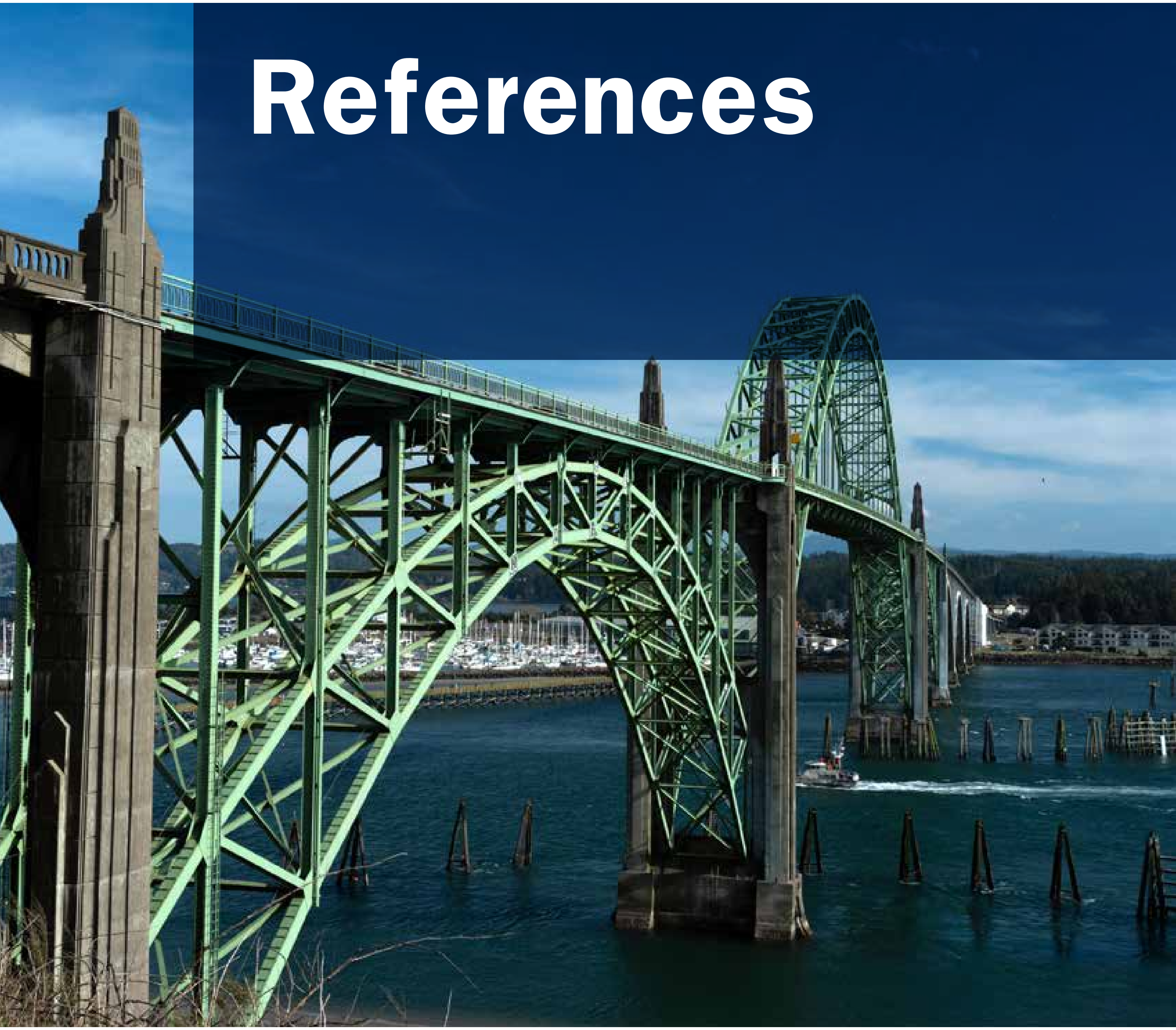

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Appendix A

Appendix A: Summary of Bridge Damage Types

Damage Level	Shaking	Liquefication	Tsunami	Number of Bridges
None	None			740
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage due to expected higher capacity due to existence of pier walls.	None		59
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage due to expected higher capacity because bridge is a single span bridge.	None		521
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage due to expected higher capacity because bridge is a single span bridge and has pier walls.	None		15
Moderate	Moderate: Seismic demand exceeds bridge's operational seismic design capacity.	None		706
	Moderate: Seismic demand exceeds bridge's operational seismic design capacity.	Moderate: Minor soil liquefaction occurs at bridge location.	None	5
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity due to existence of pier walls.	None		110
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity due to existence of pier walls.	Moderate: Minor soil liquefaction occurs at bridge location.	None	13
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	None		994
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	Moderate: Minor soil liquefaction occurs at bridge location.	None	149

Damage Level	Shaking	Liquefaction	Tsunami	Number of Bridges
Moderate	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge and has pier walls.	None		12
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge and has pier walls.	Moderate: Minor soil liquefaction occurs at bridge location.	None	2
	None	Moderate: Minor soil liquefaction occurs at bridge location.	None	4
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage from shaking due to expected higher capacity due to existence of pier walls.	Moderate: Minor soil liquefaction occurs at bridge location.	None	2
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage from shaking due to expected higher capacity because bridge is a single span bridge.	Moderate: Minor soil liquefaction occurs at bridge location.	None	15
Significant	Significant: Seismic demand exceeds bridge's reduced seismic capacity (reduced due to bridge having precast concrete piles).	None		127
	Significant: Seismic demand exceeds bridge's reduced seismic capacity (reduced due to bridge having precast concrete piles).	Significant: Major soil liquefaction occurs at bridge location.	None	21
	Significant: Seismic demand exceeds bridge's reduced seismic capacity (reduced due to bridge having precast concrete piles).	Significant: Major soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	1

Damage Level	Shaking	Liquefaction	Tsunami	Number of Bridges
	Significant: Seismic demand exceeds bridge's reduced seismic capacity (reduced due to bridge having precast concrete piles).	Moderate: Minor soil liquefaction occurs at bridge location.	None	10
	Significant: Seismic demand exceeds bridge's reduced seismic capacity (reduced due to bridge having precast concrete piles).	Moderate: Minor soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	1
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	None		990
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	Significant: Major soil liquefaction occurs at bridge location.	None	353
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	Significant: Major soil liquefaction occurs at bridge location.	Significant: Bridge is overtopped by tsunami waves.	2
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	Significant: Major soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	23
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	None	Significant: Tsunami waves at bridge location cause significant scour damage.	4

Damage Level	Shaking	Liquefication	Tsunami	Number of Bridges
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	Moderate: Minor soil liquefaction occurs at bridge location.	None	158
	Significant: Seismic demand exceeds bridge's life safety seismic design capacity.	Moderate: Minor soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	2
	None	Significant: Major soil liquefaction occurs at bridge location.	None	12
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	Significant: Major soil liquefaction occurs at bridge location.	Significant: Bridge is overtopped by tsunami waves.	2
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity due to existence of pier walls.	Significant: Major soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	3
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	Significant: Major soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	14
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity due to existence of pier walls.	Significant: Major soil liquefaction occurs at bridge location.	None	47

Damage Level	Shaking	Liquefication	Tsunami	Number of Bridges
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	Significant: Major soil liquefaction occurs at bridge location.	None	483
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge and has pier walls.	Significant: Major soil liquefaction occurs at bridge location.	None	13
	None: Seismic demand exceeds bridge's operational seismic design capacity, but bridge is expected to suffer no damage from shaking due to expected higher capacity because bridge is a single span bridge.	Significant: Major soil liquefaction occurs at bridge location.	None	7
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	None	Significant: Tsunami waves at bridge location cause significant scour damage.	2
	Moderate: Seismic demand exceeds bridge's life safety seismic design capacity, but bridge is expected to suffer moderate damage due to expected higher capacity because bridge is a single span bridge.	Moderate: Minor soil liquefaction occurs at bridge location.	Significant: Tsunami waves at bridge location cause significant scour damage.	1
Special	Special: Seismic performance of special bridges not assessed.	None		14
	Special: Seismic performance of special bridges not assessed.	Significant: Major soil liquefaction occurs at bridge location.	None	8
	Special: Seismic performance of special bridges not assessed.	Moderate: Minor soil liquefaction occurs at bridge location.	None	1

Appendix B

Appendix B: Post-Earthquake Islanded Areas as a Function of Time

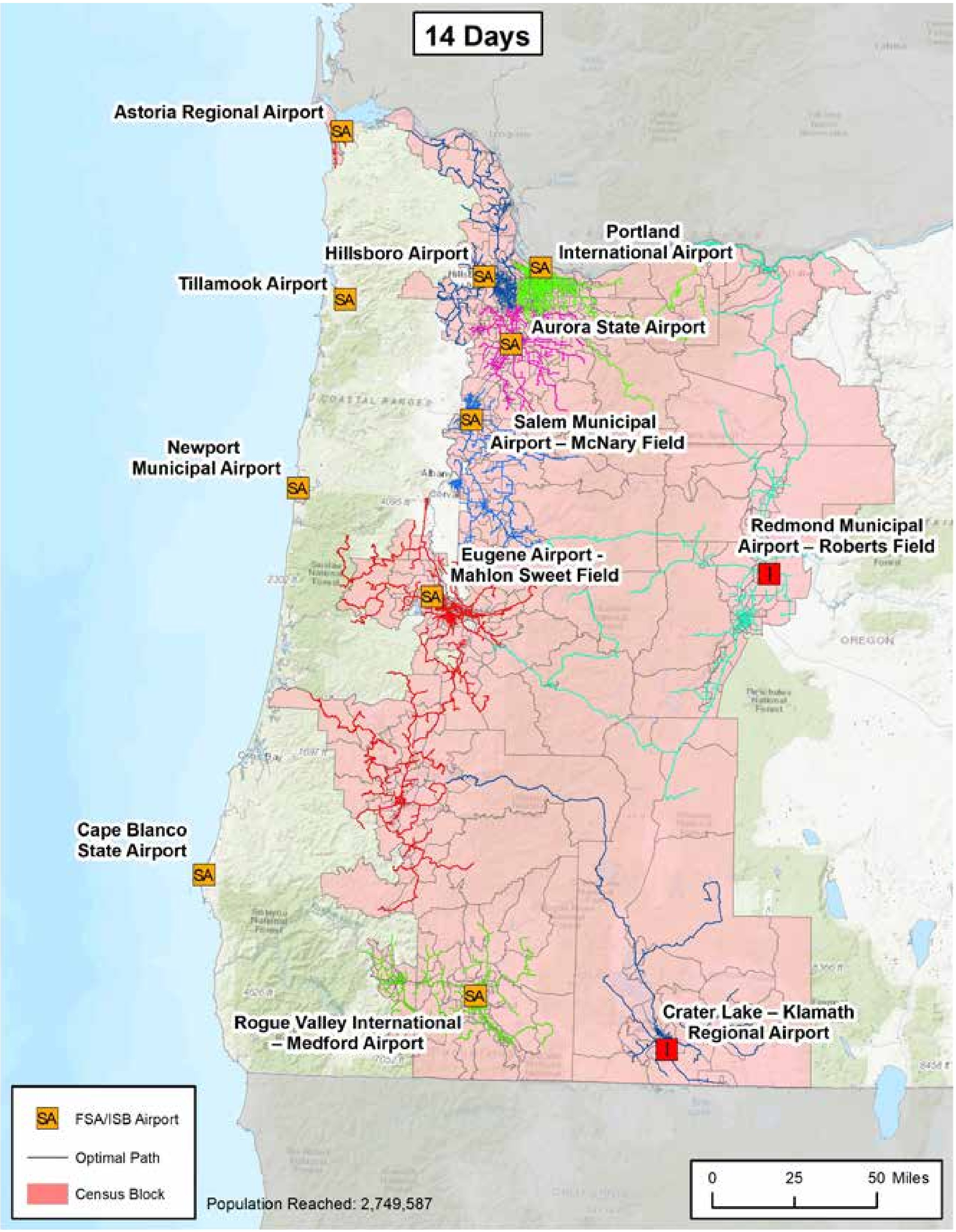

FIGURE B-1.—Islanded Areas 14 Days after the Cascadia Subduction Zone (CSZ) Earthquake.

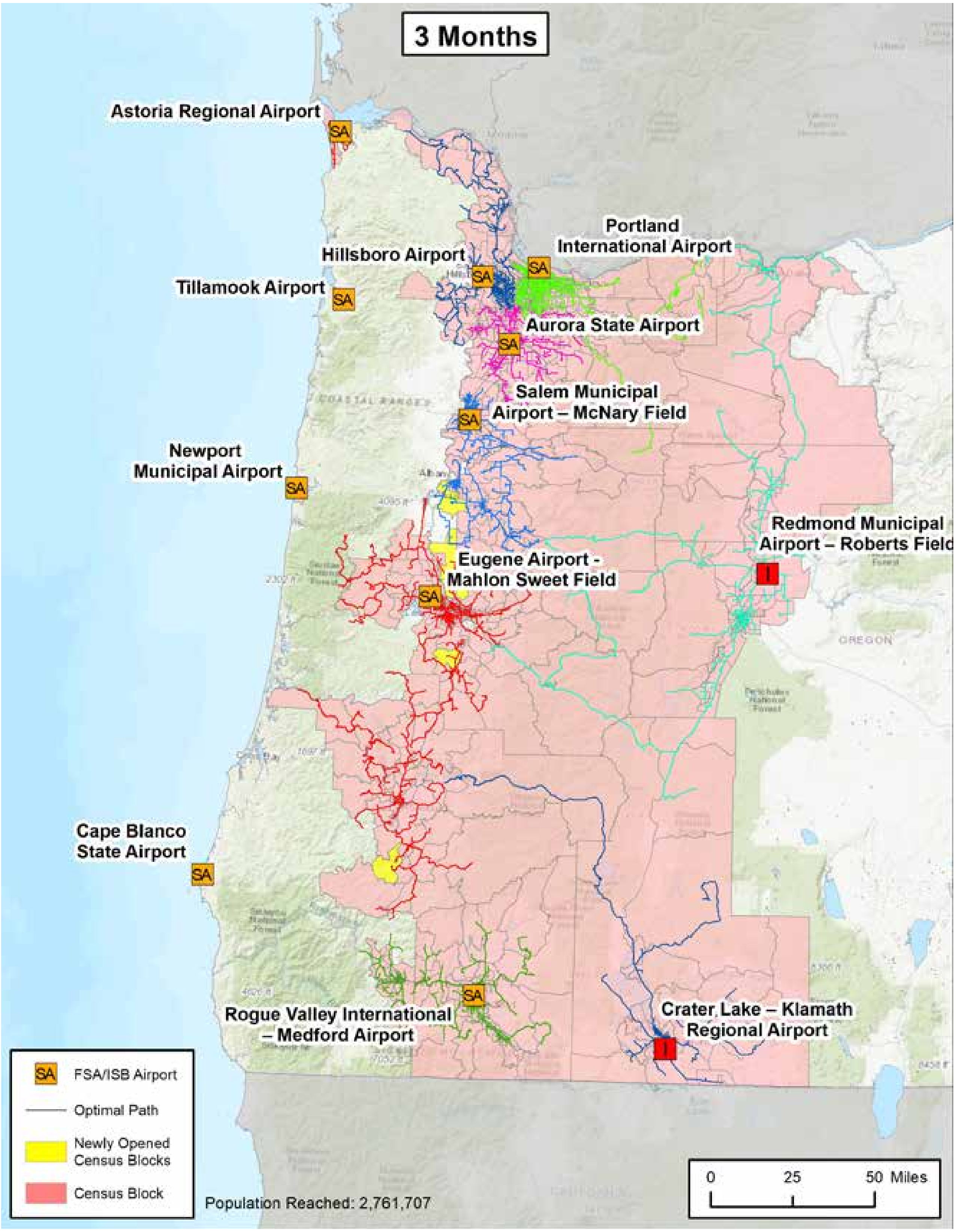

FIGURE B-2.—Islanded Areas 3 Months after the CSZ Earthquake.

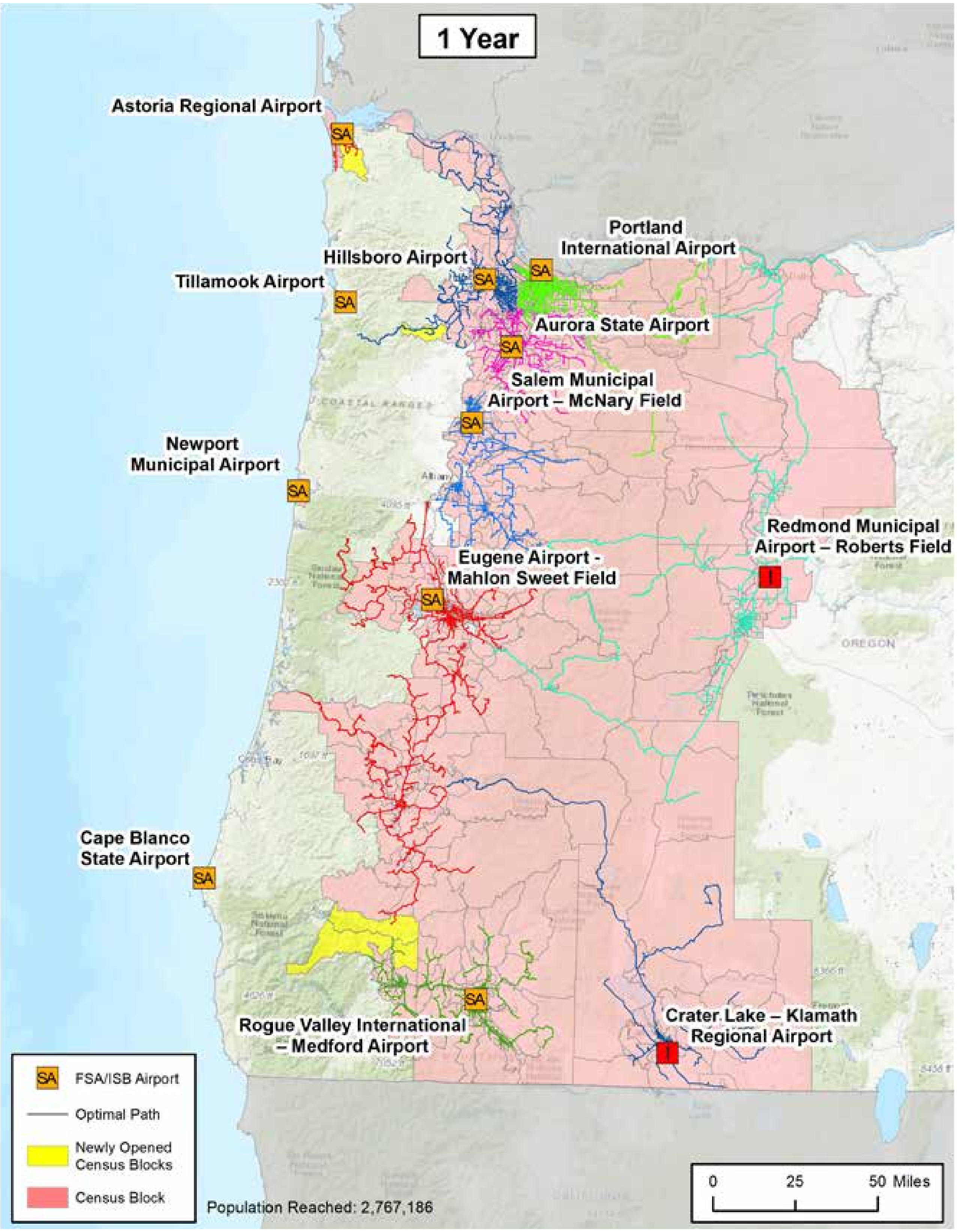

FIGURE B-3.—Islanded Areas 1 Year after the CSZ Earthquake.

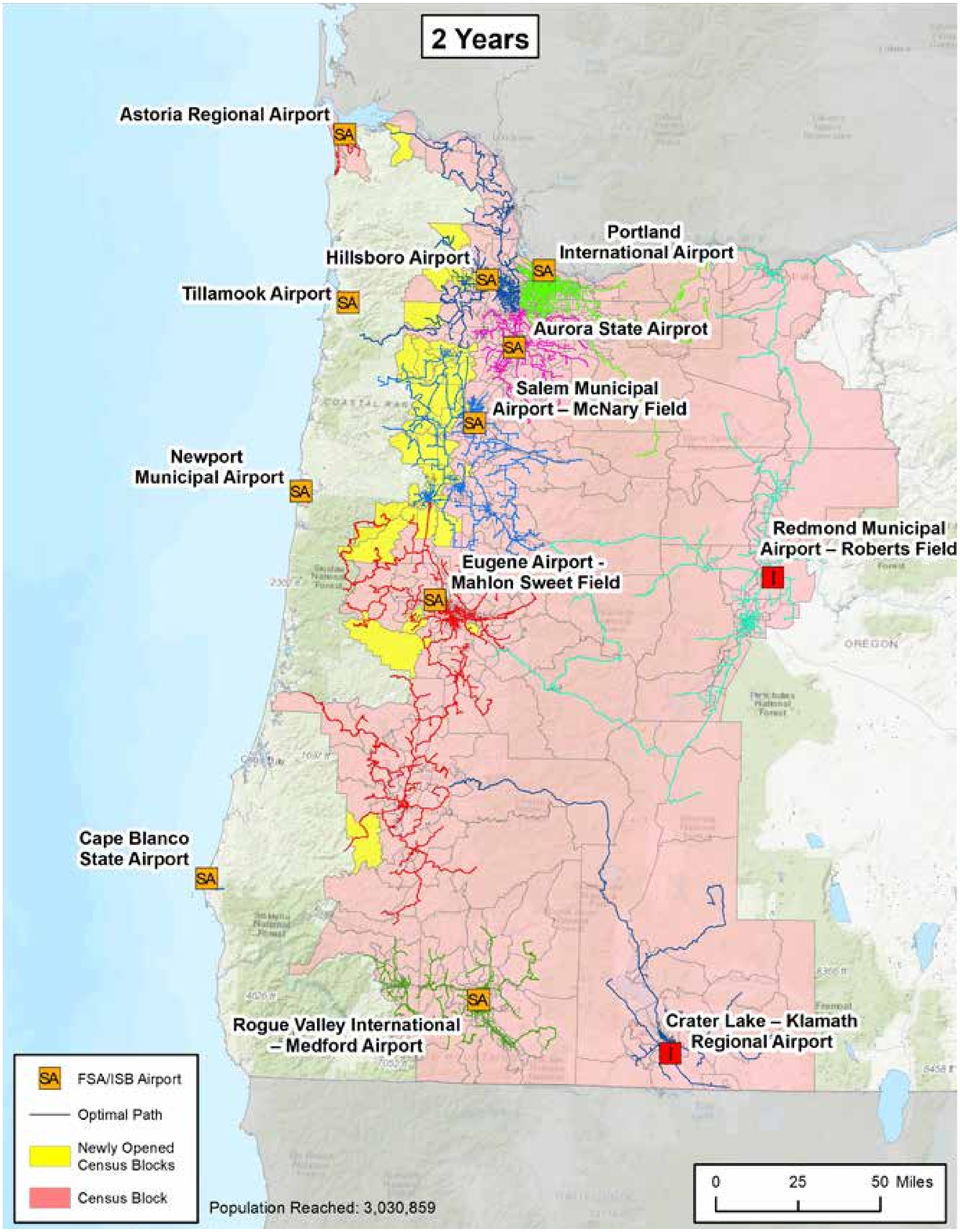

FIGURE B-4.—Islanded Areas 2 Years after the CSZ Earthquake.

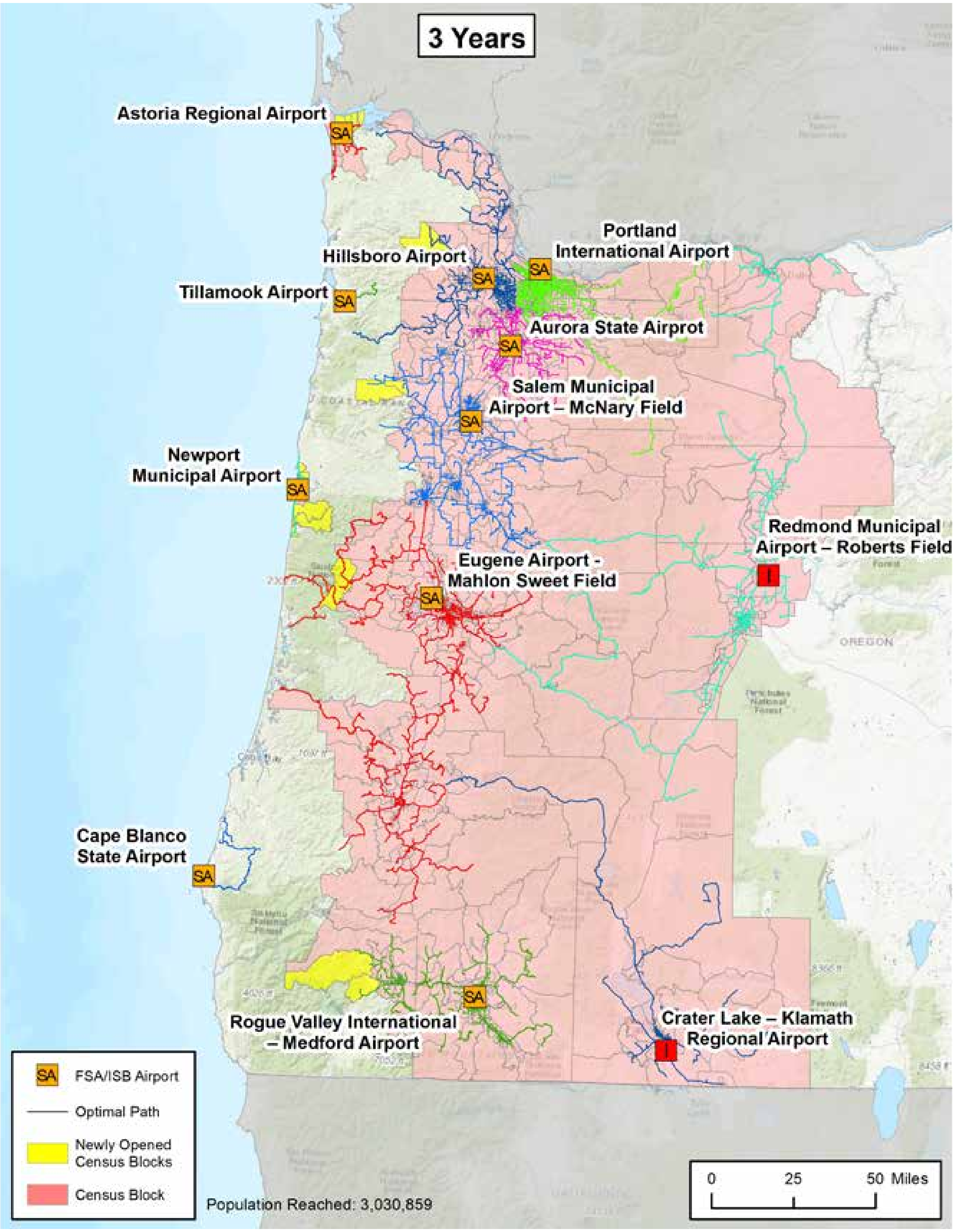

FIGURE B-5.—Islanded Areas 3 Years after the CSZ Earthquake.

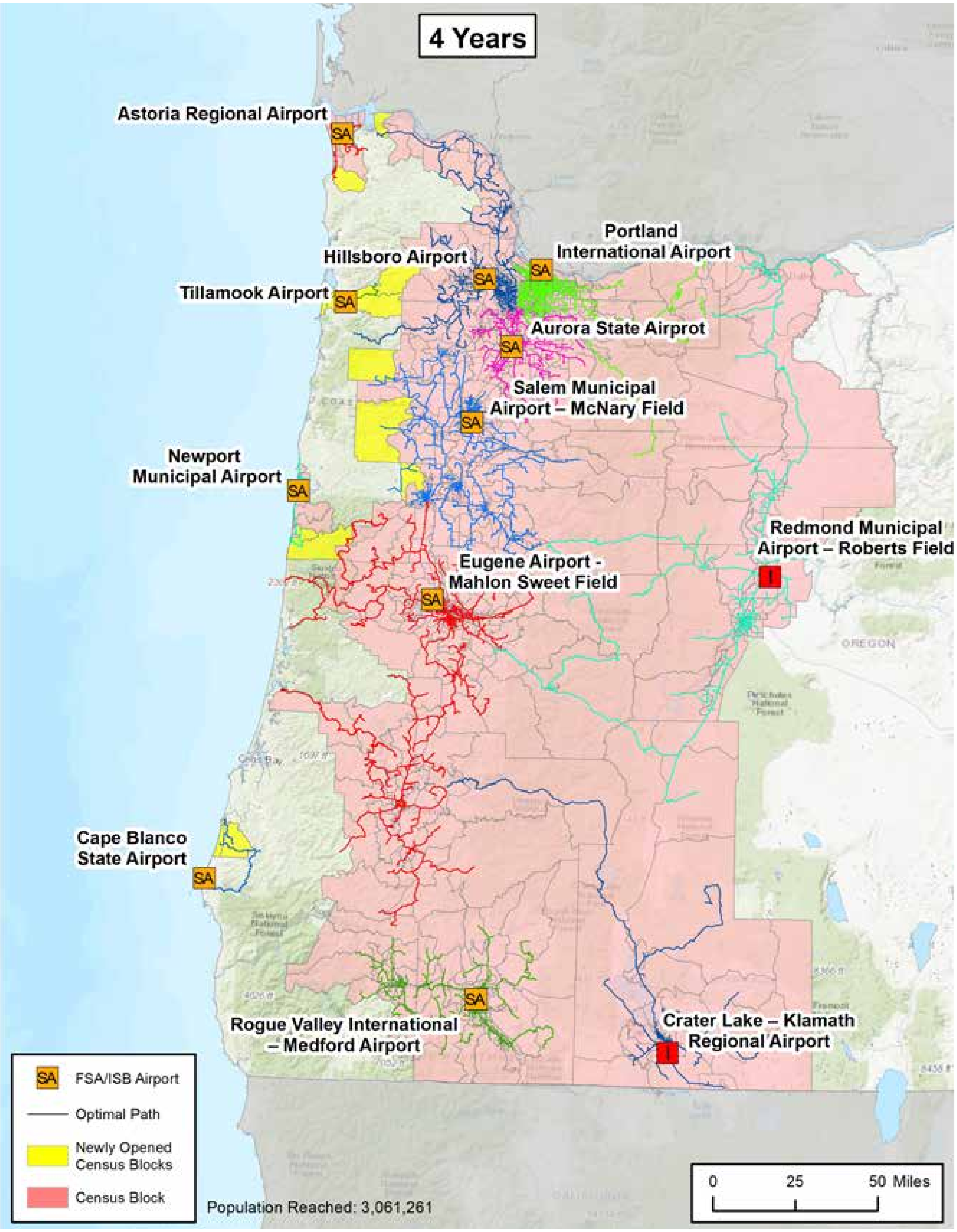

FIGURE B-6.—Islanded Areas 4 Years after the CSZ Earthquake.

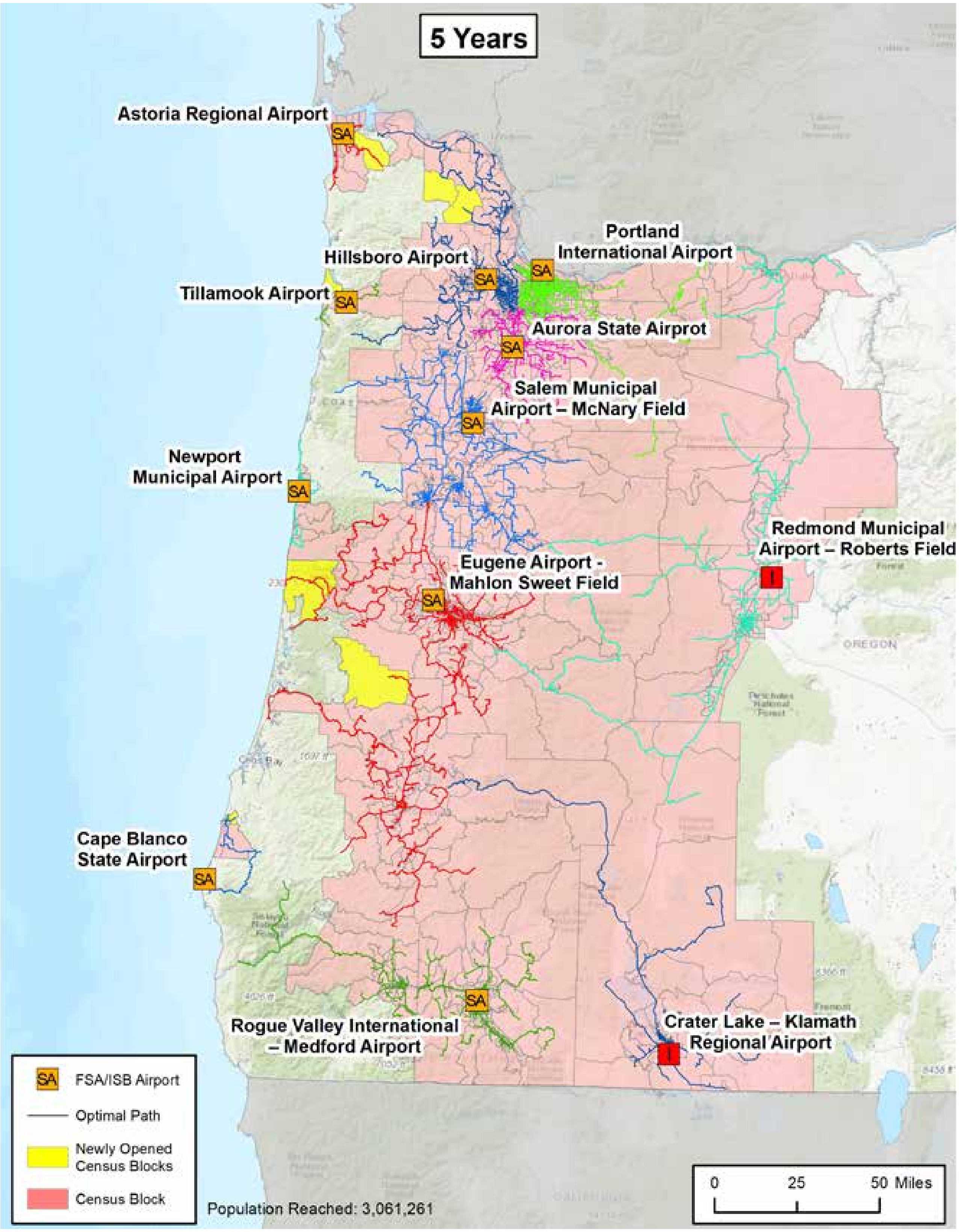

FIGURE B-7.—Islanded Areas 5 Years after the CSZ Earthquake.

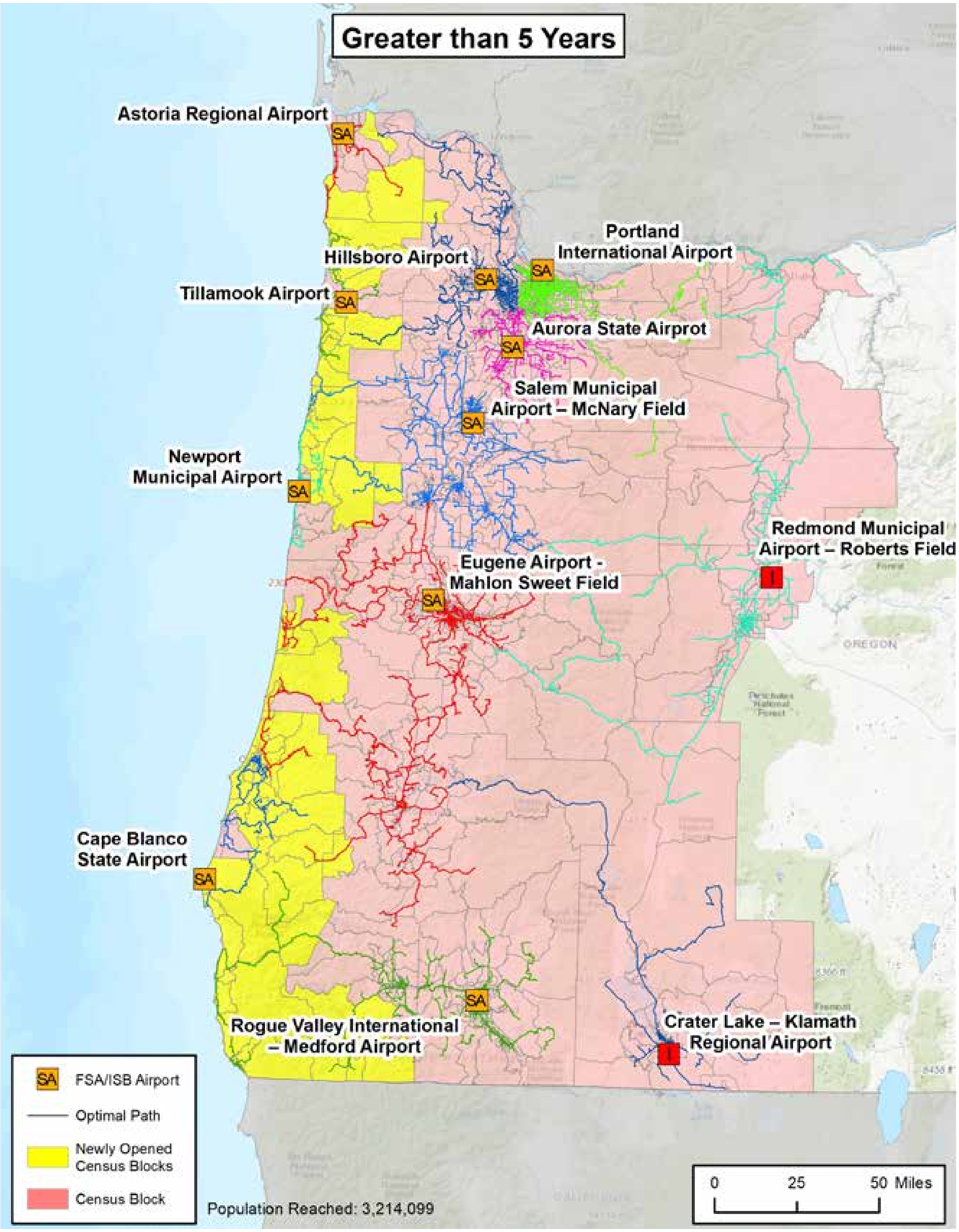

FIGURE B-8.—Islanded Areas Greater than 5 Years after the CSZ Earthquake.

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Appendix C

Appendix C: Airport Soil Liquefaction Susceptibility and Tsunami Inundation

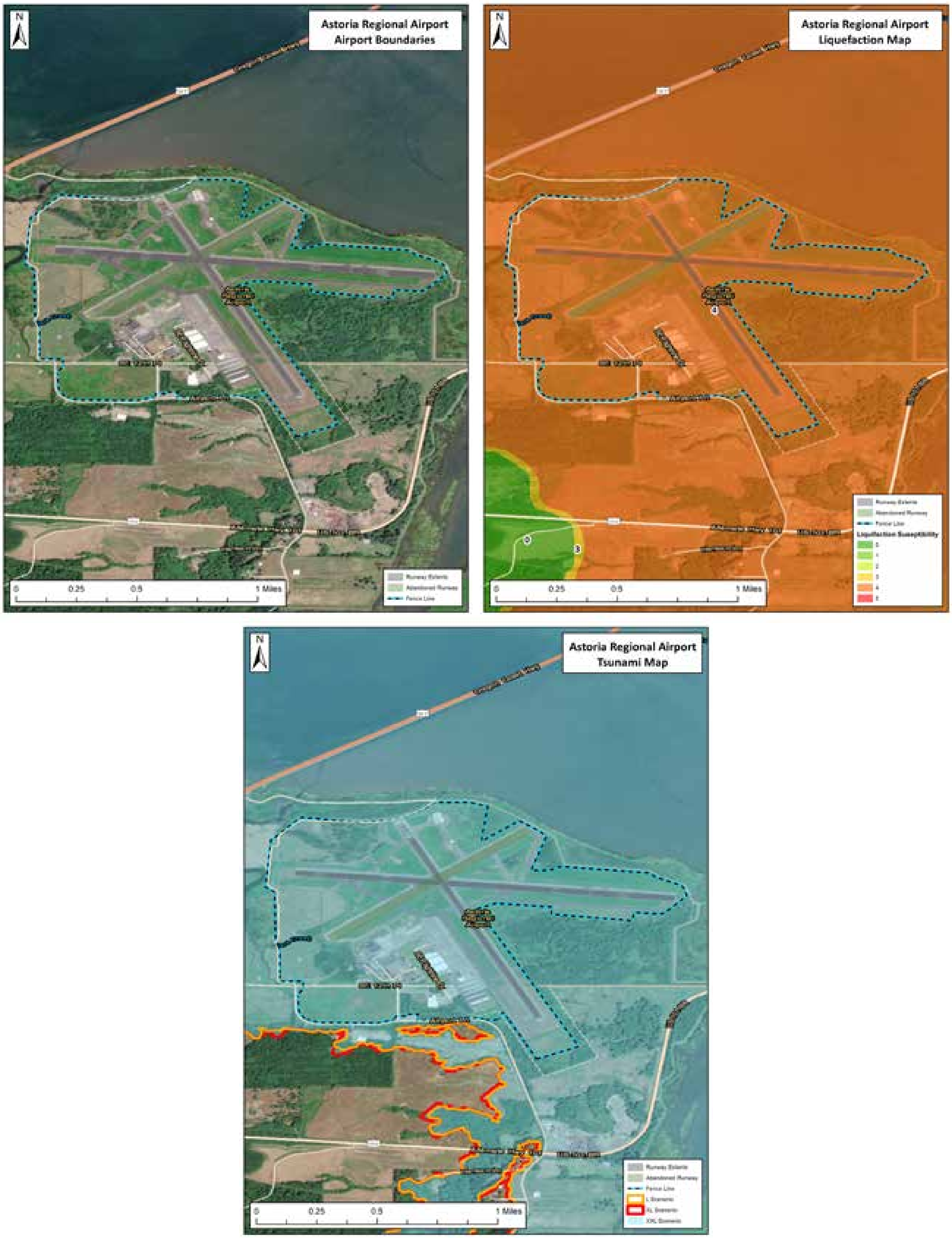

FIGURE C-1.—Airport Boundaries, Soil Liquefaction Susceptibility, and Tsunami Inundation for Astoria Regional Airport.

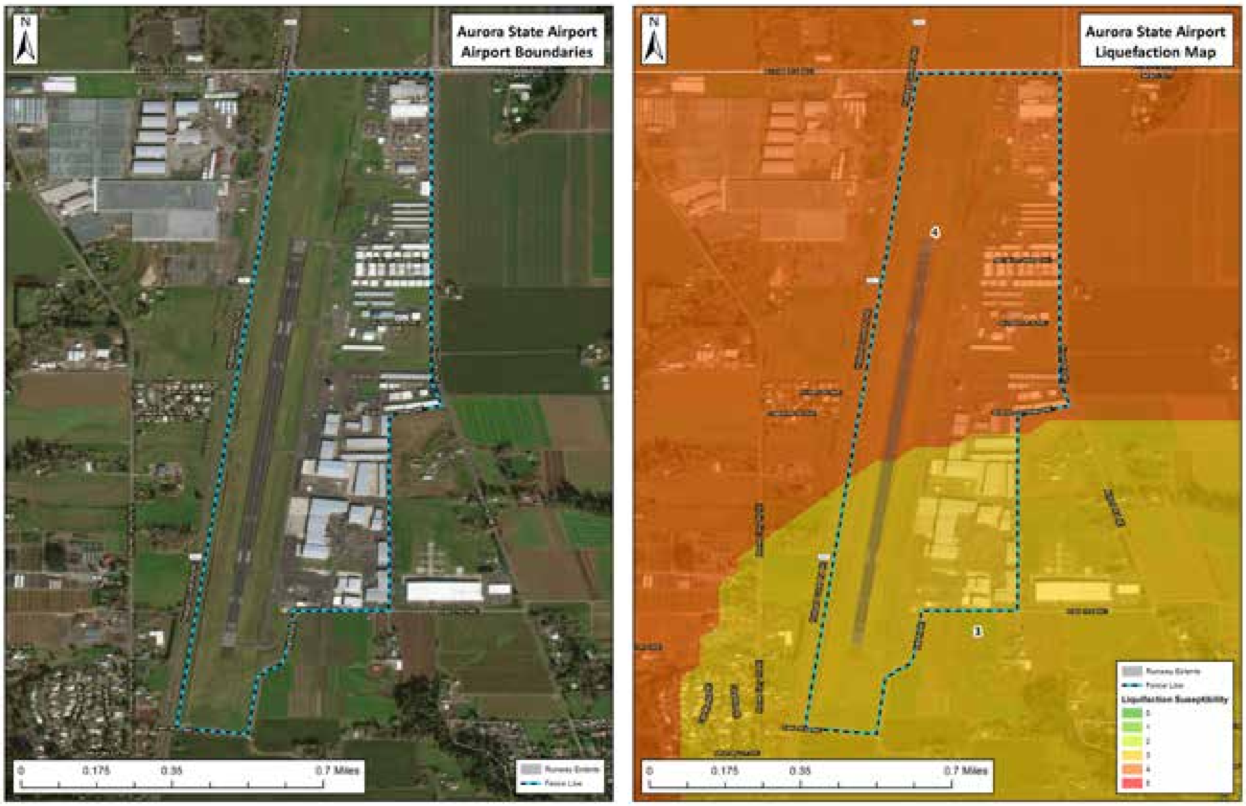

FIGURE C-2.— Airport Boundaries and Soil Liquefaction Susceptibility for Aurora State Airport.

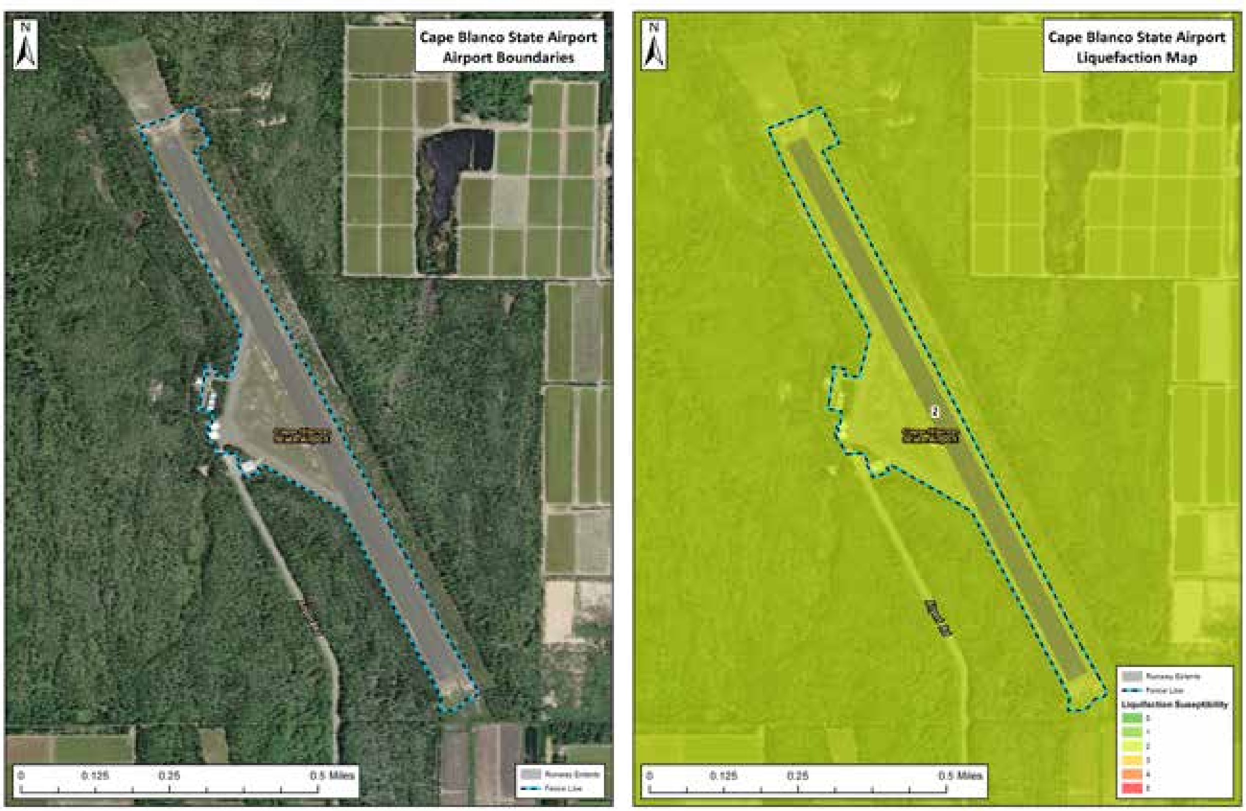

FIGURE C-3.—Airport Boundaries and Soil Liquefaction Susceptibility for Cape Blanco State Airport.

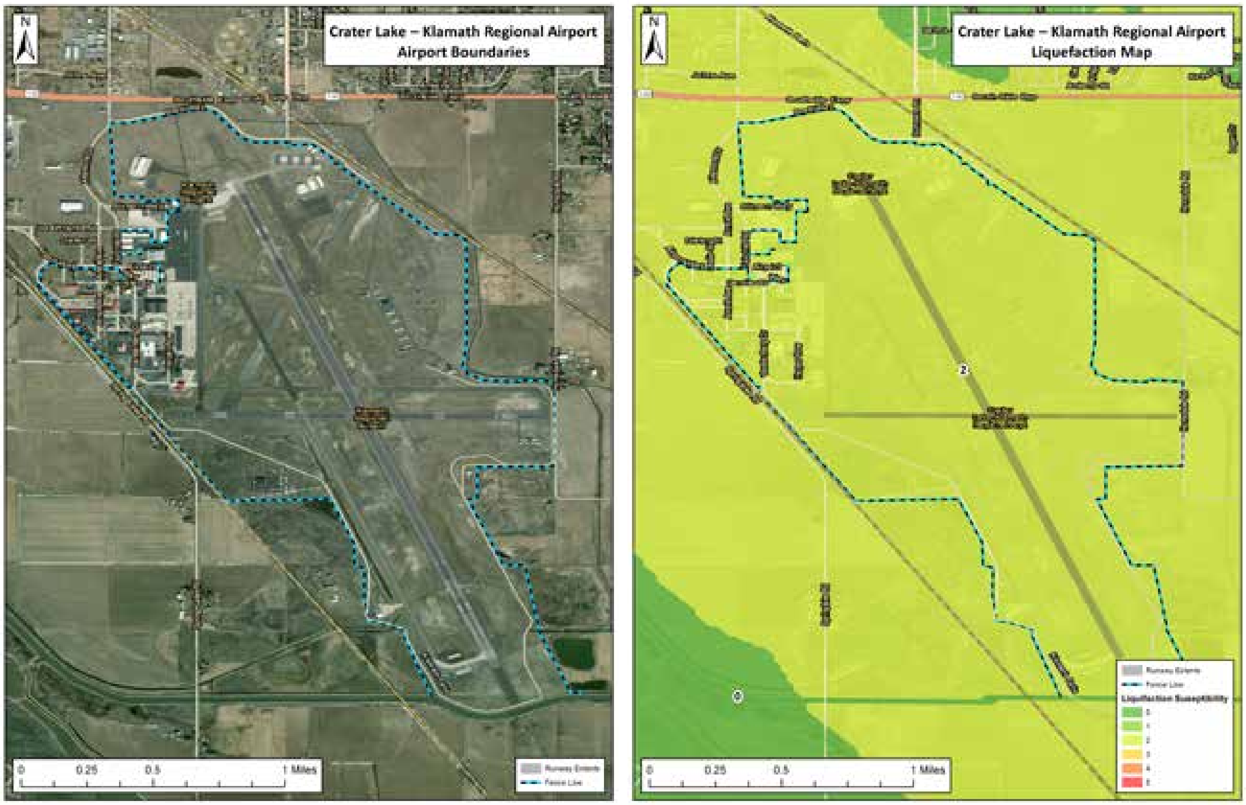

FIGURE C-4.—Airport Boundaries and Soil Liquefaction Susceptibility for Crater Lake–Klamath Regional Airport.

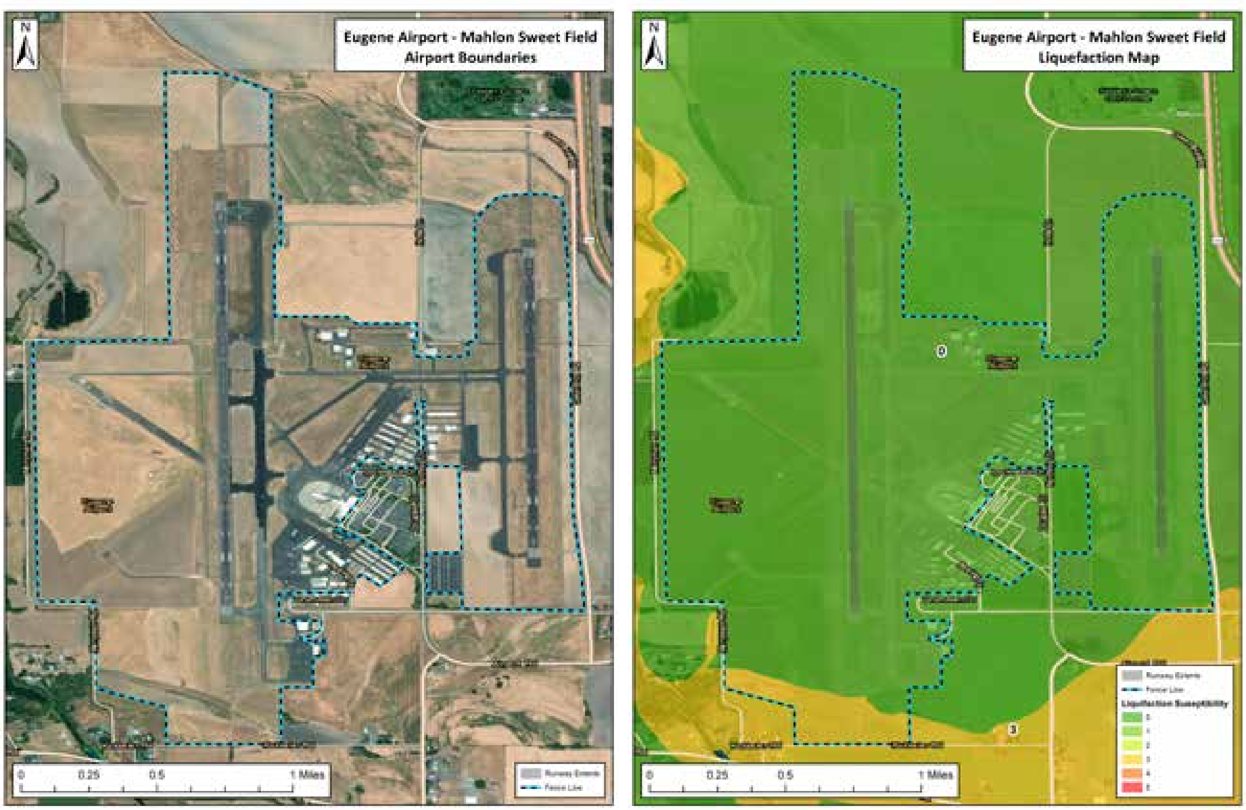

FIGURE C-5.—Airport Boundaries and Soil Liquefaction Susceptibility for Eugene Airport–Mahlon Sweet Field.

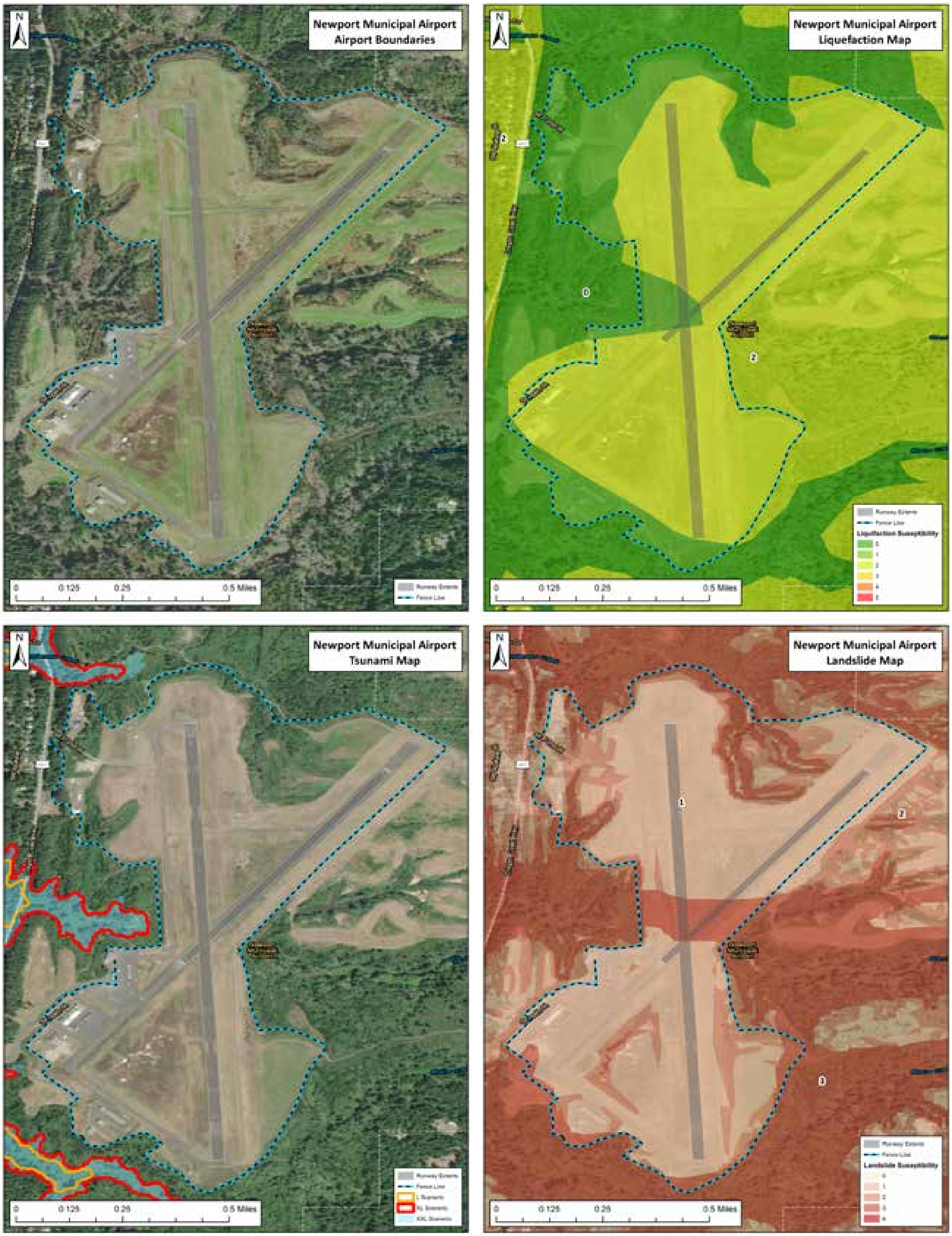

FIGURE C-6.—Airport Boundaries, Soil Liquefaction Susceptibility, Tsunami Inundation, and Landslide Risk for Newport Municipal Airport.

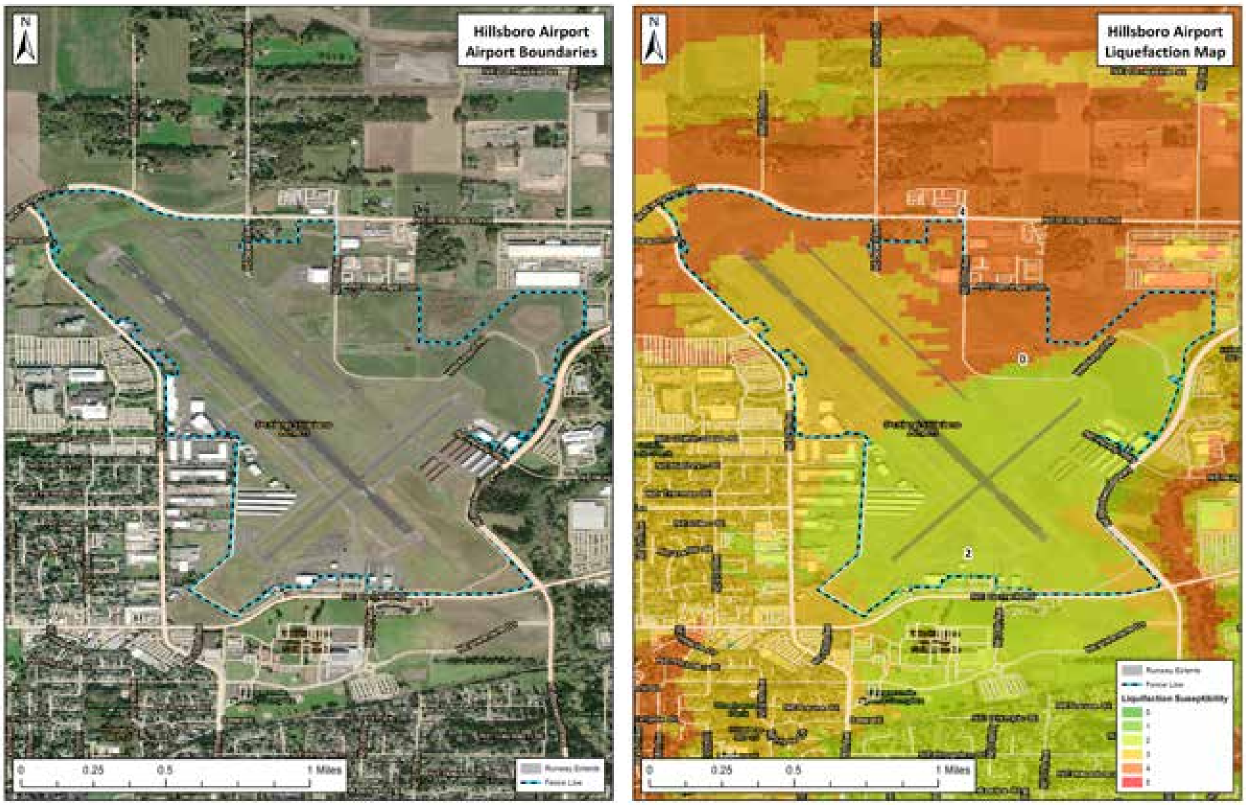

FIGURE C-7.—Airport Boundaries and Soil Liquefaction Susceptibility for Hillsboro Airport.

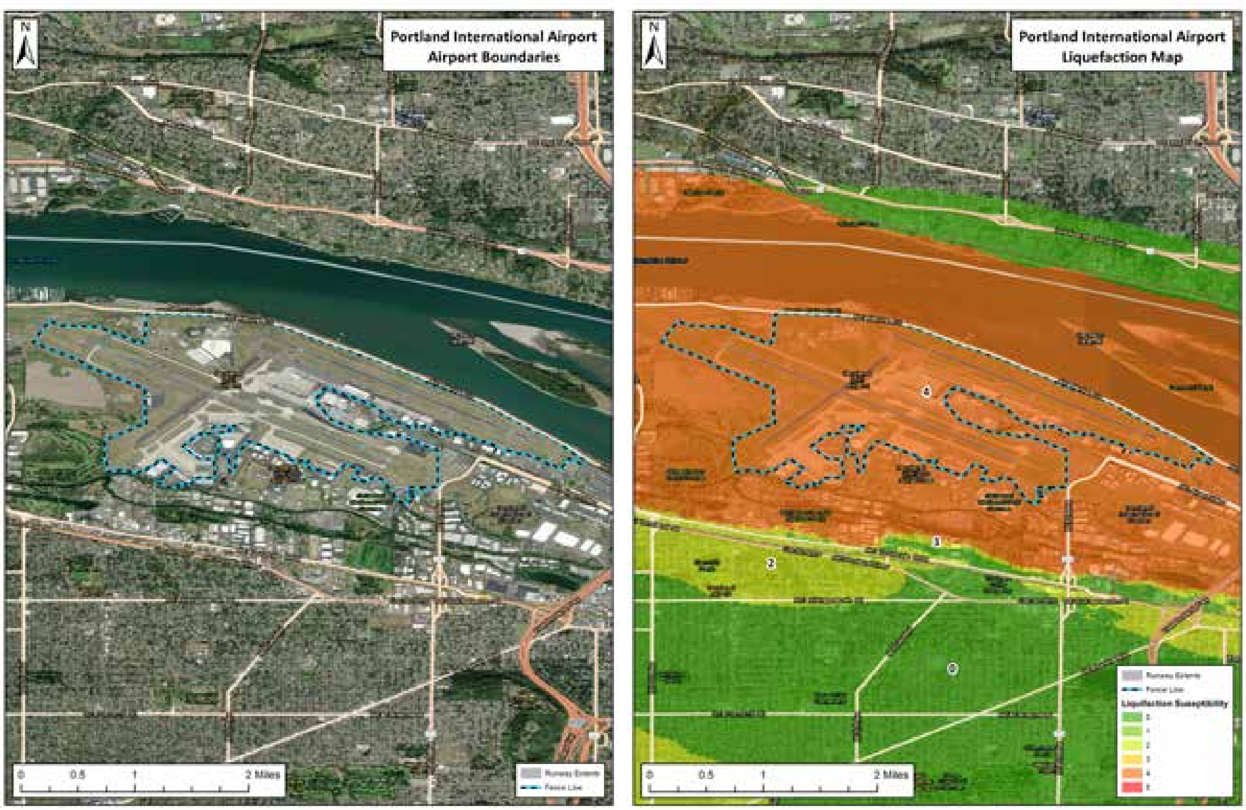

FIGURE C-8.—Airport Boundaries and Soil Liquefaction Susceptibility for Portland International Airport.

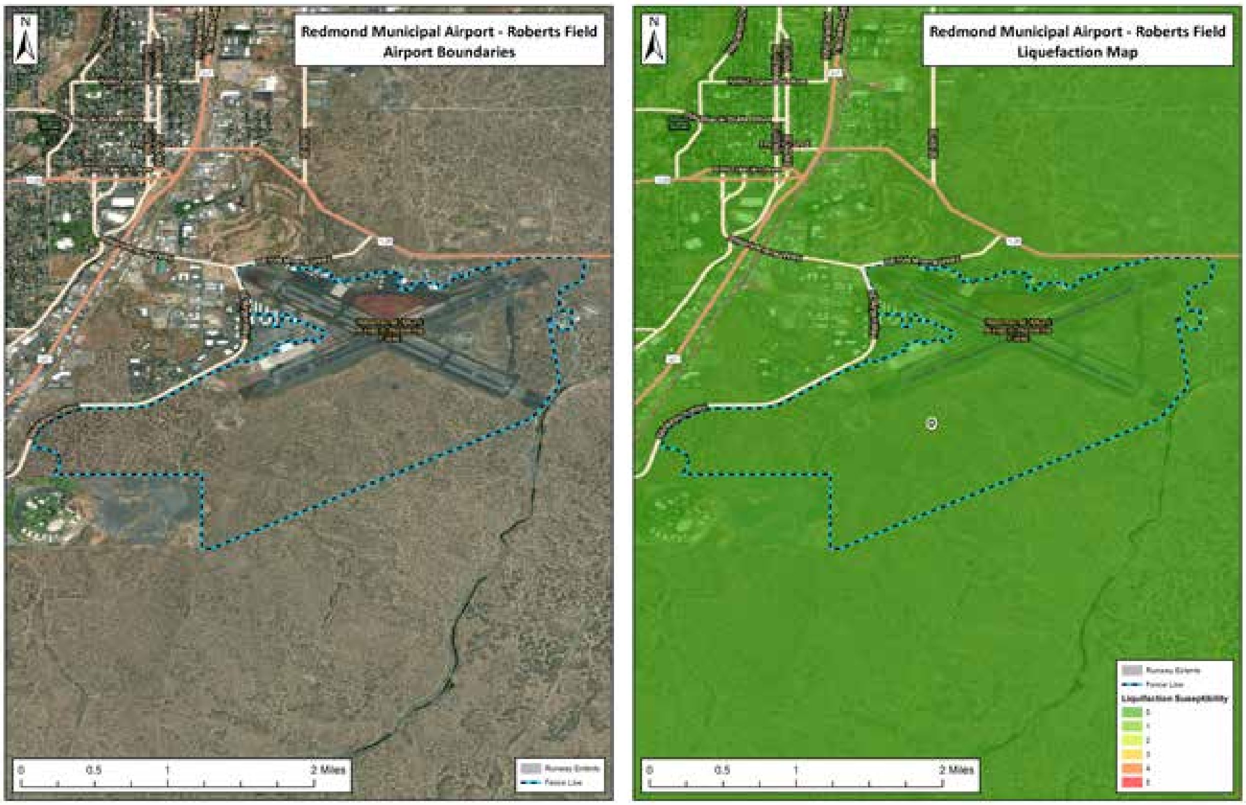

FIGURE C-9.—Airport Boundaries and Soil Liquefaction Susceptibility for Redmond Municipal Airport–Roberts Field.

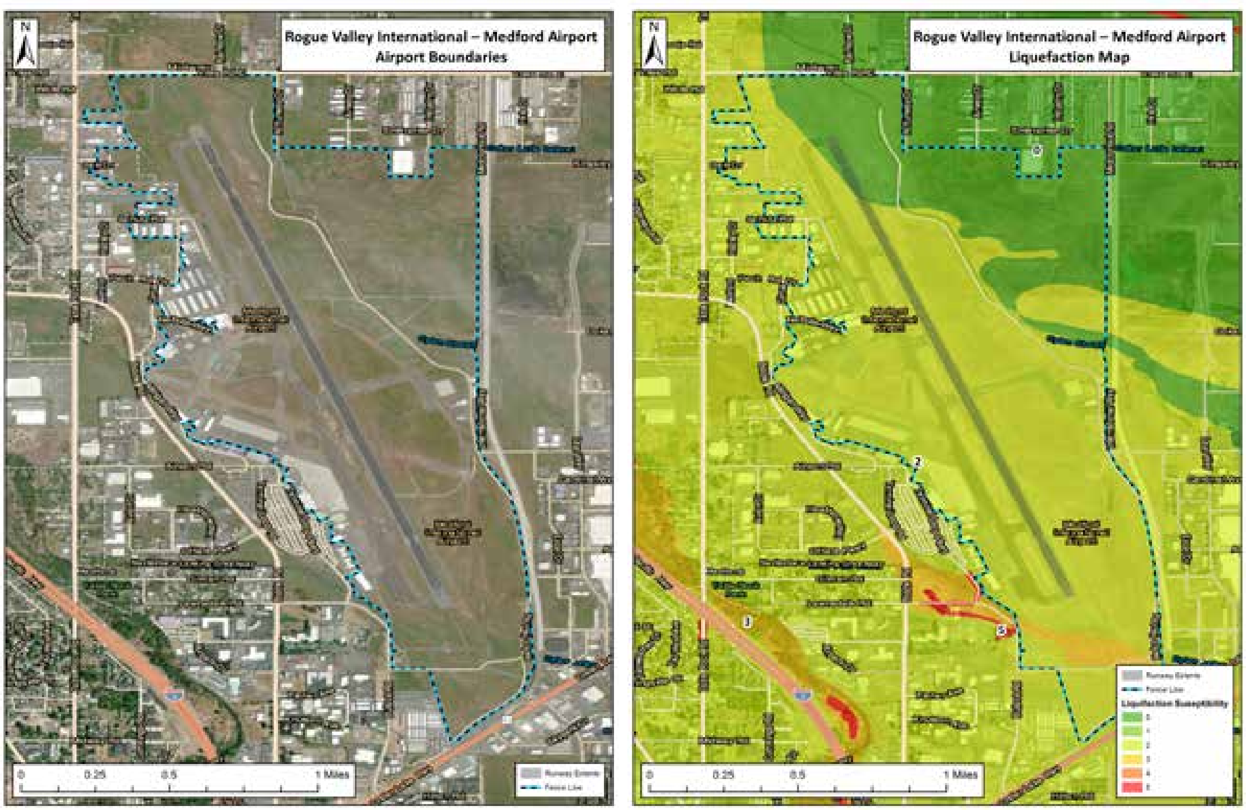

FIGURE C-10.—Airport Boundaries and Soil Liquefaction Susceptibility for Rogue Valley International–Medford Airport.

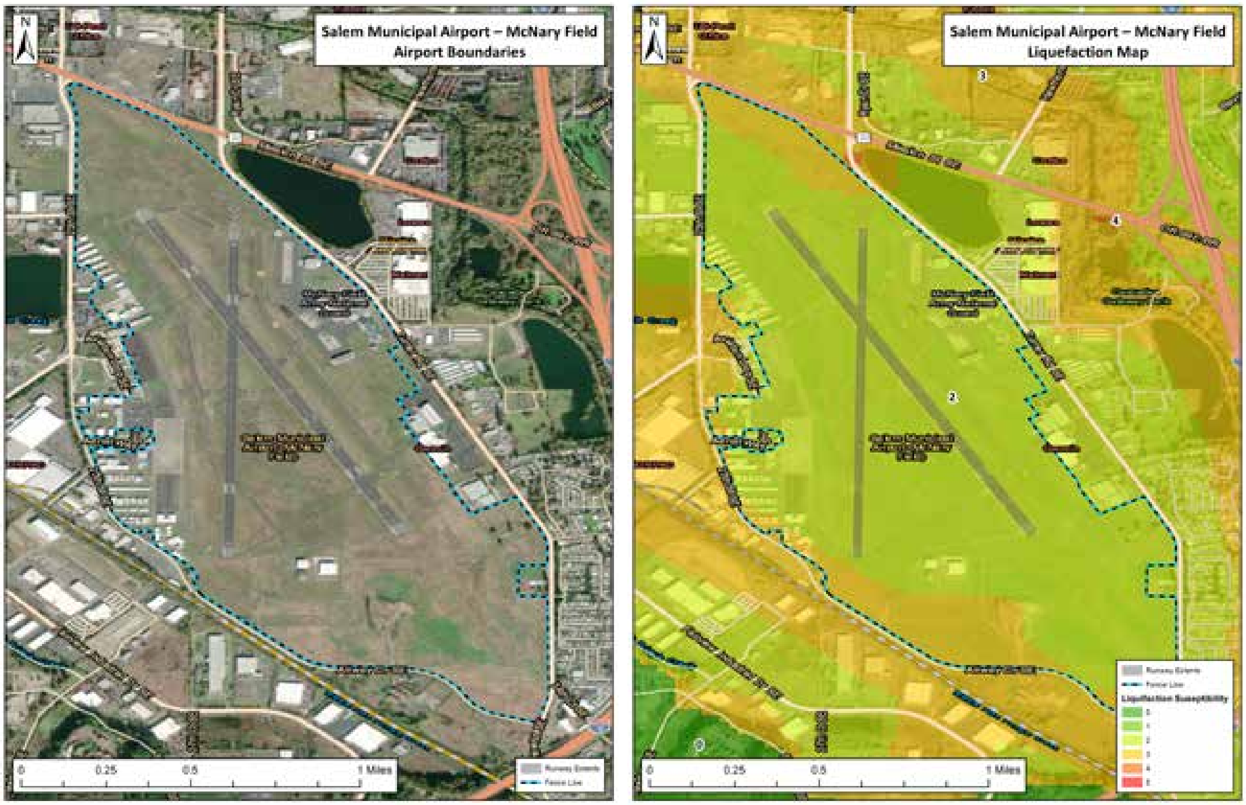

FIGURE C-11.—Airport Boundaries and Soil Liquefaction Susceptibility for Salem Municipal Airport–McNary Field.

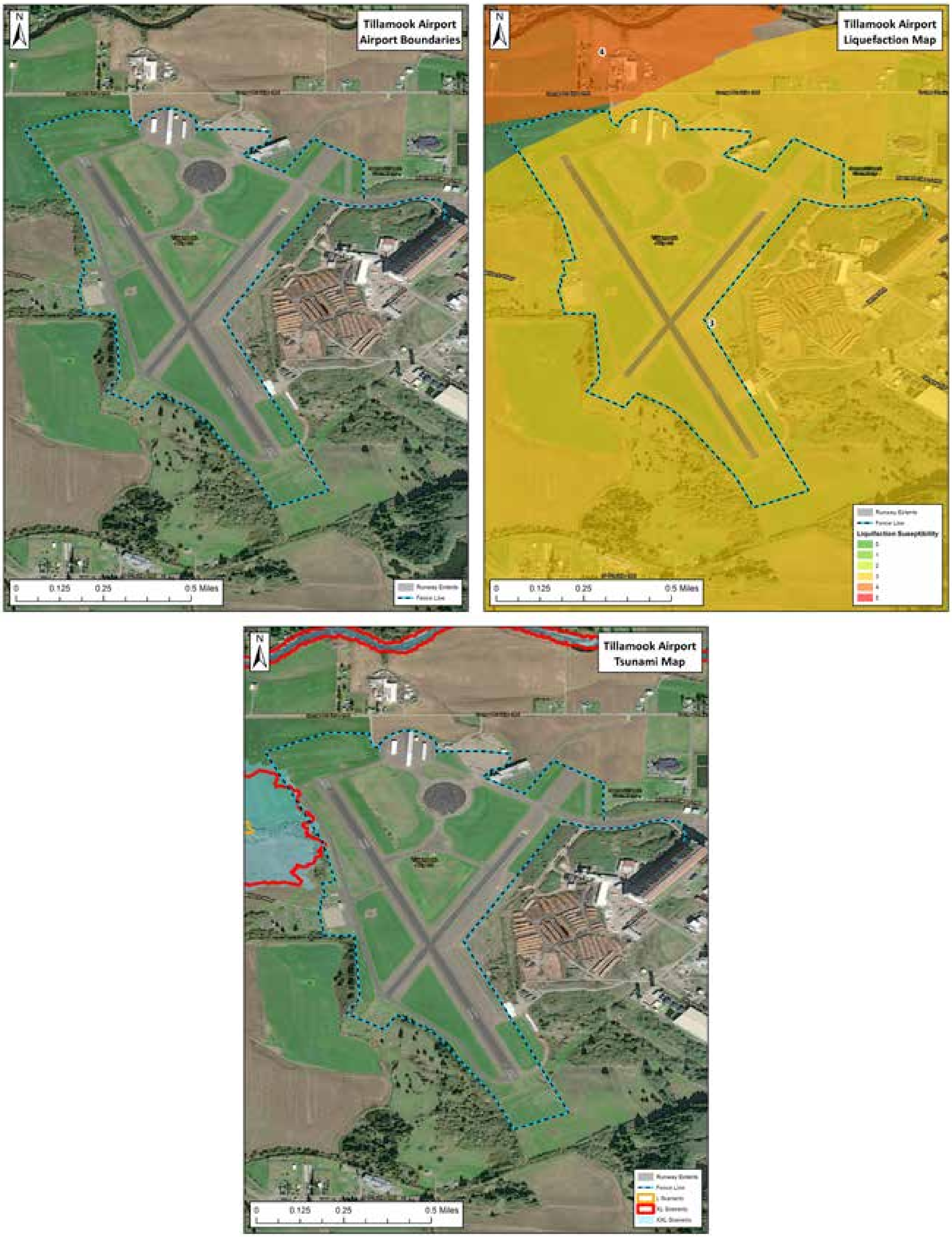

FIGURE C-12.—Airport Boundaries, Soil Liquefaction Susceptibility, and Tsunami Inundation for Tillamook Airport.

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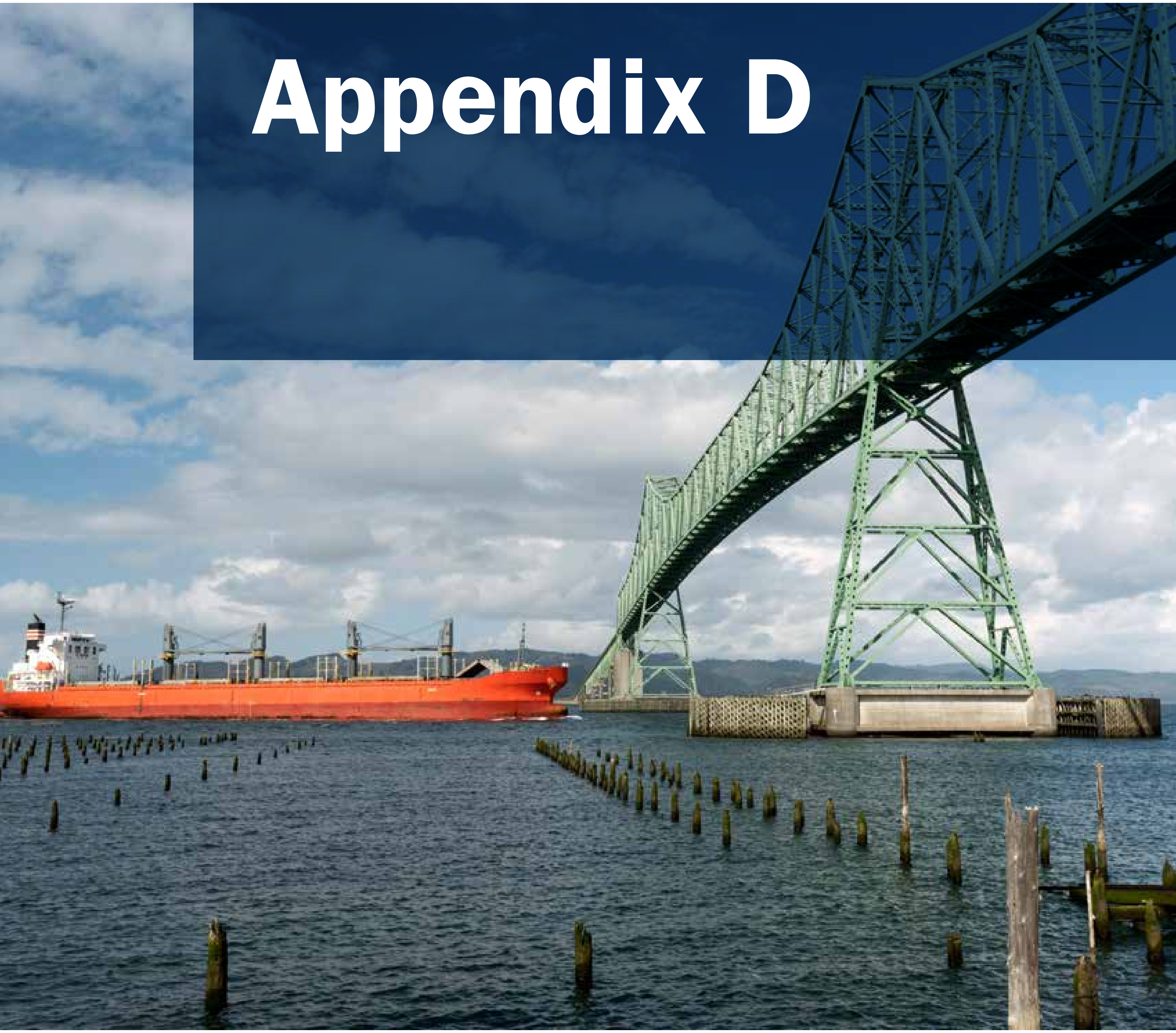
Appendix D



Appendix D: Summary of Airport/Airfield Facilities and Critical Resilience Capabilities

Airport Name	Code	City	Runways							Fuel			Other Facilities with Backup Generation
			Runway	Length	Width	Pavement	Runway Pavement Capacity (1000 lbs.)			Fuel Capacity Onsite		Backup Gen	
							Single Wheel	Double Wheel	Double-Tandem	AVGas/100LL	Jet A		
Astoria Regional Airport	AST	Atoria, OR	14/32	4,467	100	Asph-E	60,000	76,000	119,000	36,000	None	None	None
			08/26	5,794	100	Asph-	60,000	76,000	119,000				
Aurora State Airport	UAO	Aurora, OR	17/35	5,003	100	Asph-G	30,000	45,000	NA	22,000	31,000	None, but hand pumps	Control tower only
Cape Blanco State Airport	5S6	Sixes, OR	14/32	5,100	150	Asph-F	115,000	185,000	340,000	None	None	NA	None
Crater Lake - Klamath Regional Airport	LMT	Klamath Falls, OR	07/25	5,258	100	Asph-G	53,000	77,000	NA	12,000	36,000	None	Airfield Lighting Control tower
			14/32	10,302	150	Asph-Conc-G	107,000	175,000	315,000				
Eugene Airport - Mahlon Sweet Field	EUG	Eugene, OR	16R/34L	8,009	150	Asph-G	120,000	207,000-250,000[a]	335,000-550,000[a]	14,000	75,000	None, but hand pumps	Airfield Lighting Passenger terminal Airport rescue and fire
			16L/34R	6,000	150	Asph-G	117,000-120,000[a]	167,000-184,000[a]	273,000-300,000[a]				
Hillsboro Airport	HIO	Hillsboro, OR	02/20	3,820	75	Asph-G	54,500	74,000	139,000	12,000	10,000	Unk	Airfield lighting
			13R/31L	6,600	150	Asph-G	50,000	70,000	110,000				
			13L/31R	3,600	60	Asph-E	28,000	NA	NA				
Newport Municipal Airport	ONP	Newport, OR	16/34	5,395	100	Asph-G	75,000	120,000	170,000	11,000	12,000	None	Airfield lighting NAVAIDS (VOR only) Airport rescue and fire
			02/20	3,001	75	Asph-G	33,000	50,000	84,000				
Portland International Airport	PDX	Portland, OR	10R/28L	11,000	150	Conc-G	200,000	200,000	360,000	12,000	600,000	Unk	Port Emergency Operations & Communications Center Central Utilities Plant: -Airfield lighting -Control tower -Passenger terminal
			10L/28R	9,825	150	Asph-E	200,000	200,000	400,000				
			03/21	3,000	150	Asph-E	120,000	250,000	380,000				
Redmond Municipal Airport - Roberts Field	RDM	Redmond, OR	11/29	7,006	100	Asph-G	109,000	178,000	NA	24,500	40,000	None	Airfield Lighting Control tower Passenger terminal Airport rescue & fire Access control
			05/23	7,038	150	Asph-G	120,000	216,000	399,000				
			H1	48	48	Conc-G	NA	NA	NA				
Rogue Valley International - Medford Airport	MFR	Medford, OR	14/32	8,800	150	Asph-G	75,000	200,000	400,000	20,000	40,000	None, but hook-ups for portable generation	Airfield lighting Control tower Passenger terminal Operations & equipment facility TSA Administrative Building Parking lots
Salem Municipal Airport - McNary Field	SLE	Salem, OR	16/34	5,146	100	Asph-G	39,500	52,000	NA	16,000	20,000	None	None
			13/31	5,811	150	Asph-G	105,000	147,000	NA				
			H1	37	37	Conc-E	NA	NA	NA				
Tillamook Airport	TMK	Tillamook, OR	13/31	5,001	75	Asph-E	60,000	75,000	125,000	12,000	12,000	None	Airfield lighting Fuel storage
			01/19	2,911	75	Asph-F	40,000	46,000	67,000				

[a] Runway pavement capacities vary depending on the pavement section.

Appendix E

Appendix E: Maritime Port Soil Liquefaction Susceptibility and Tsunami Inundation

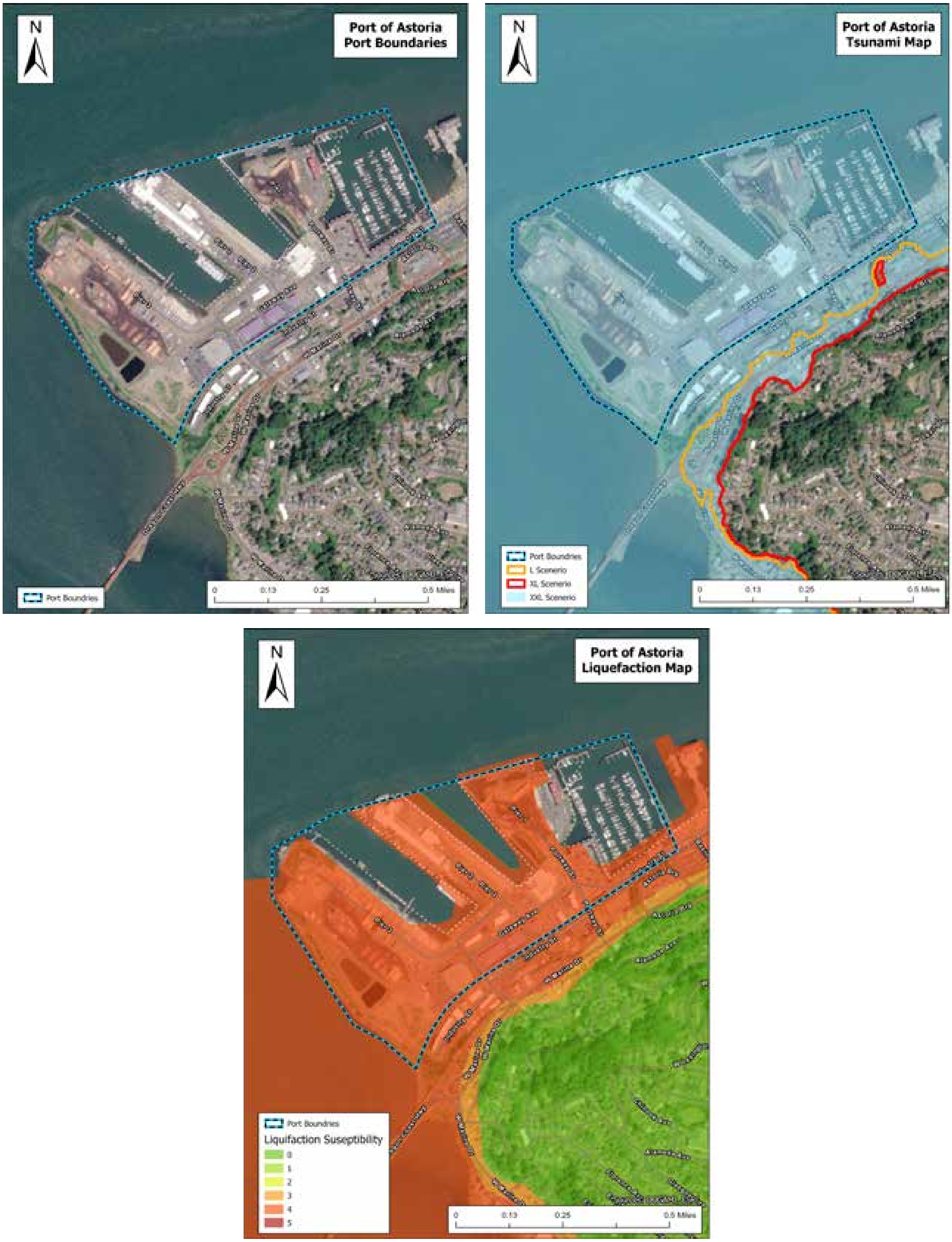


FIGURE E-1.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Astoria.

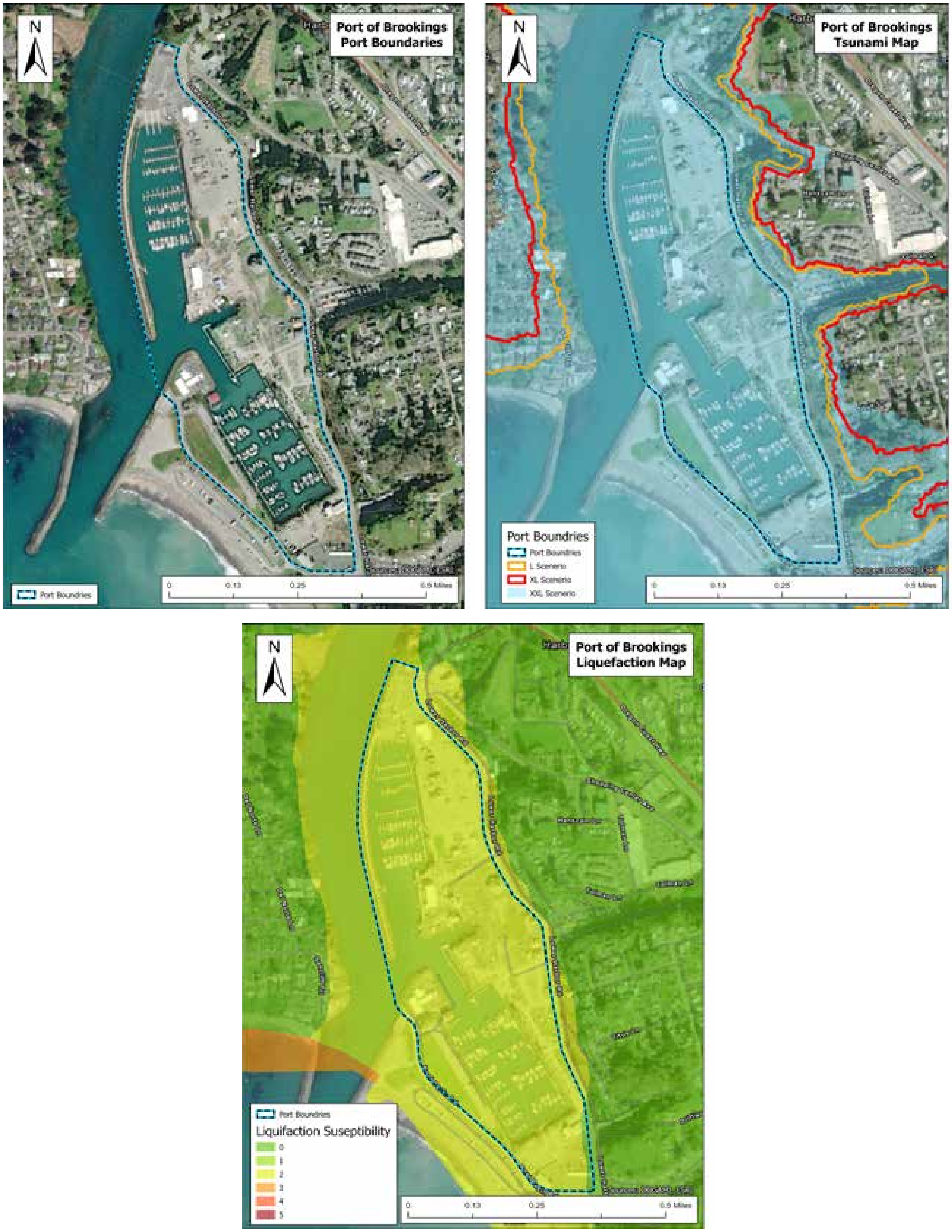


FIGURE E-2.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Brookings.

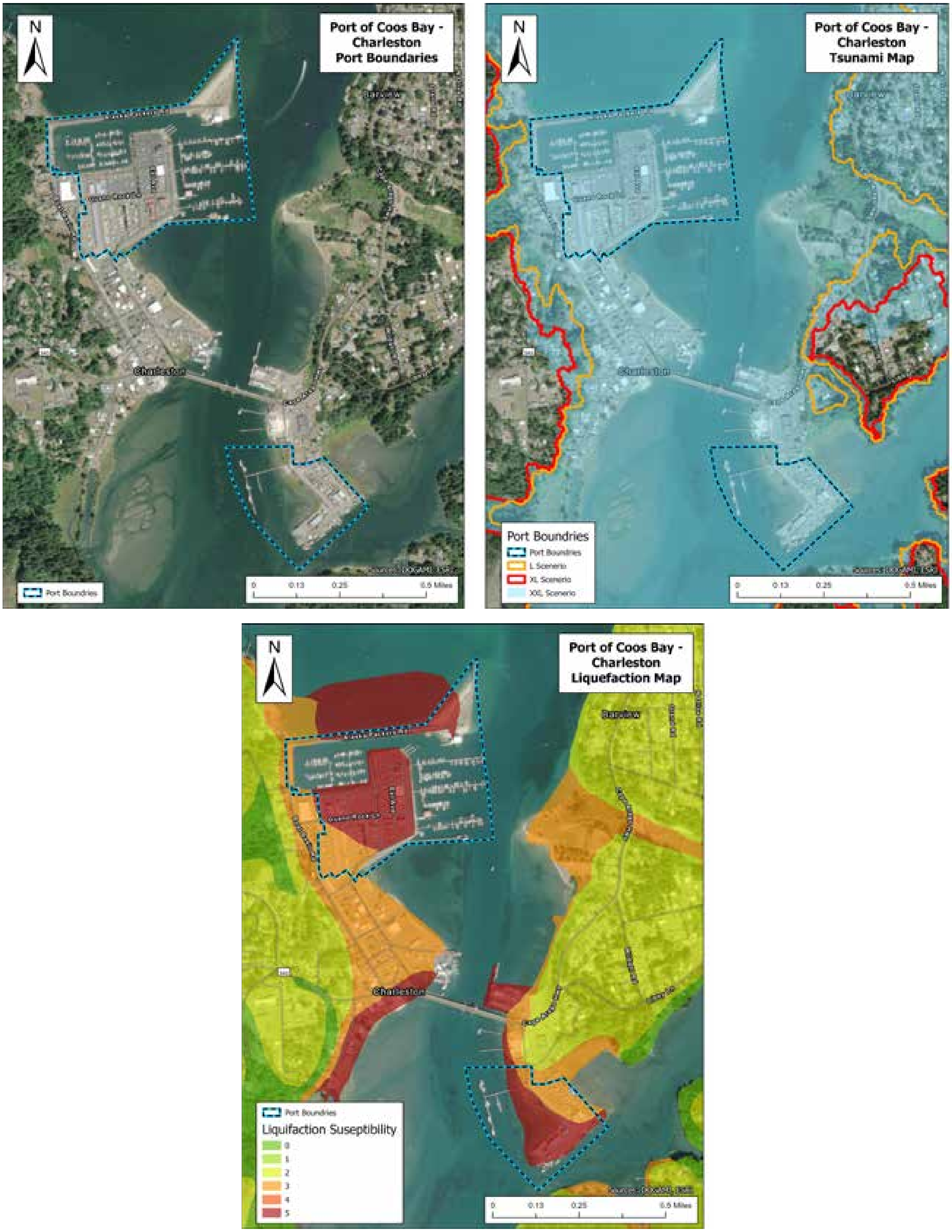


FIGURE E-3.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Coos Bay–Charleston.

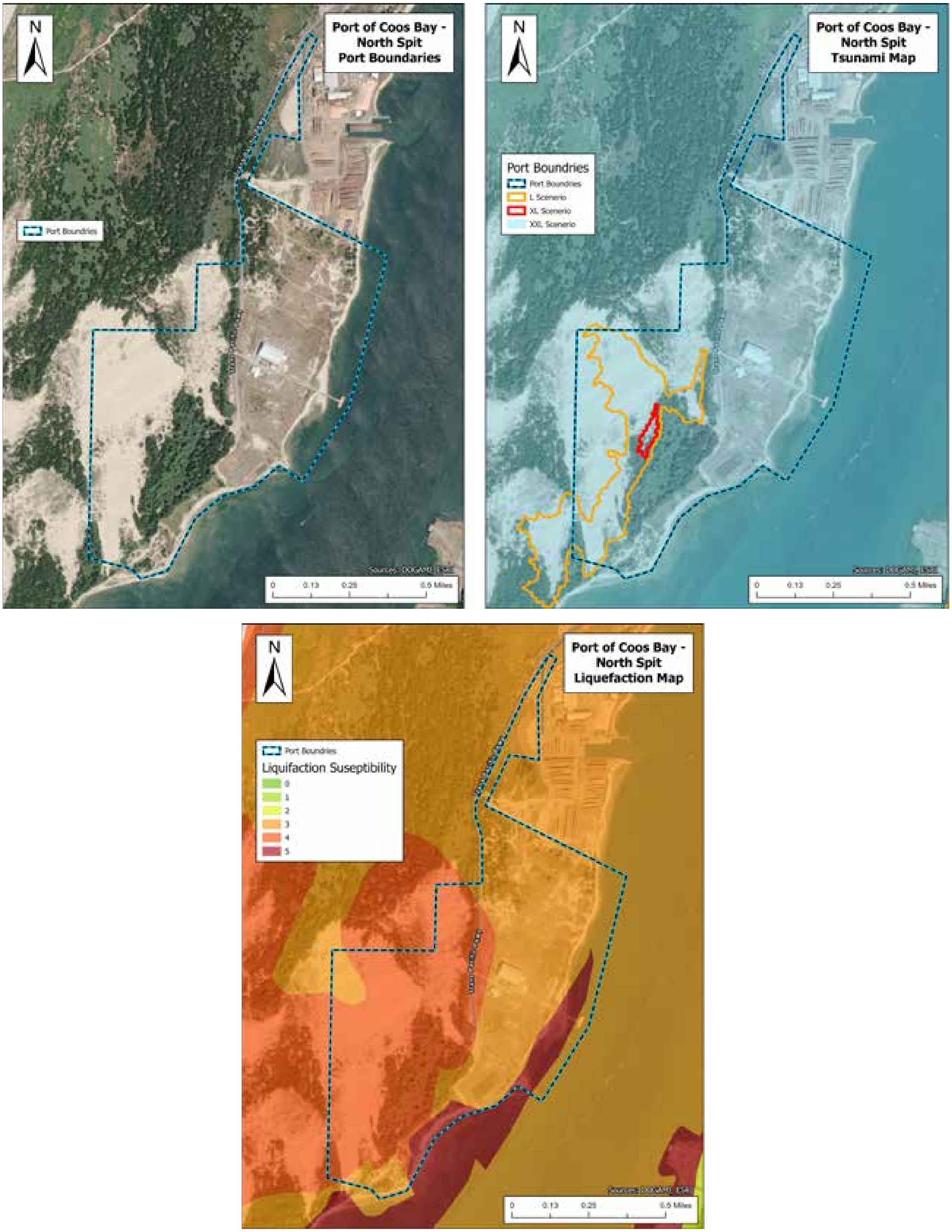


FIGURE E-4.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Coos Bay–North Split.

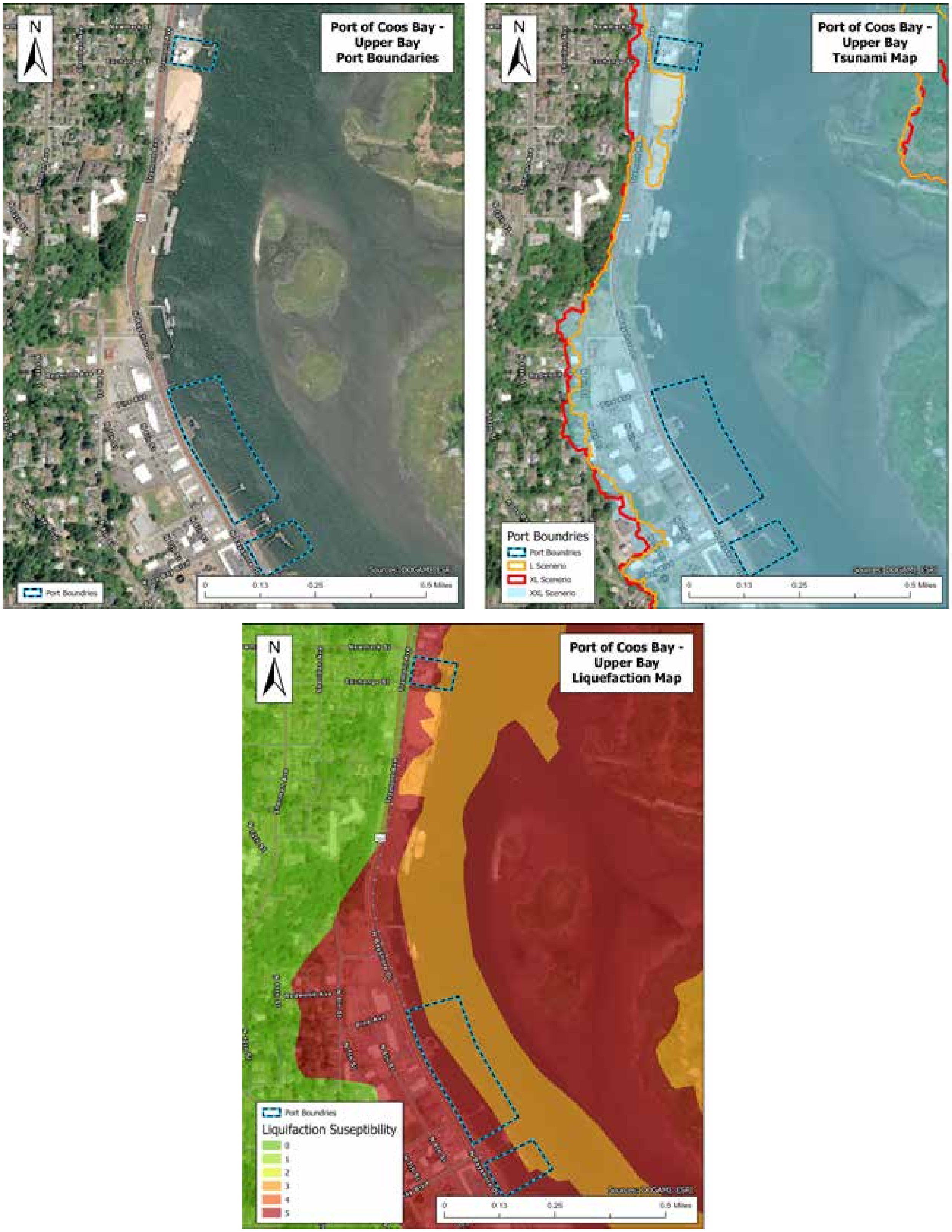


FIGURE E-5.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Coos Bay–Upper Bay.

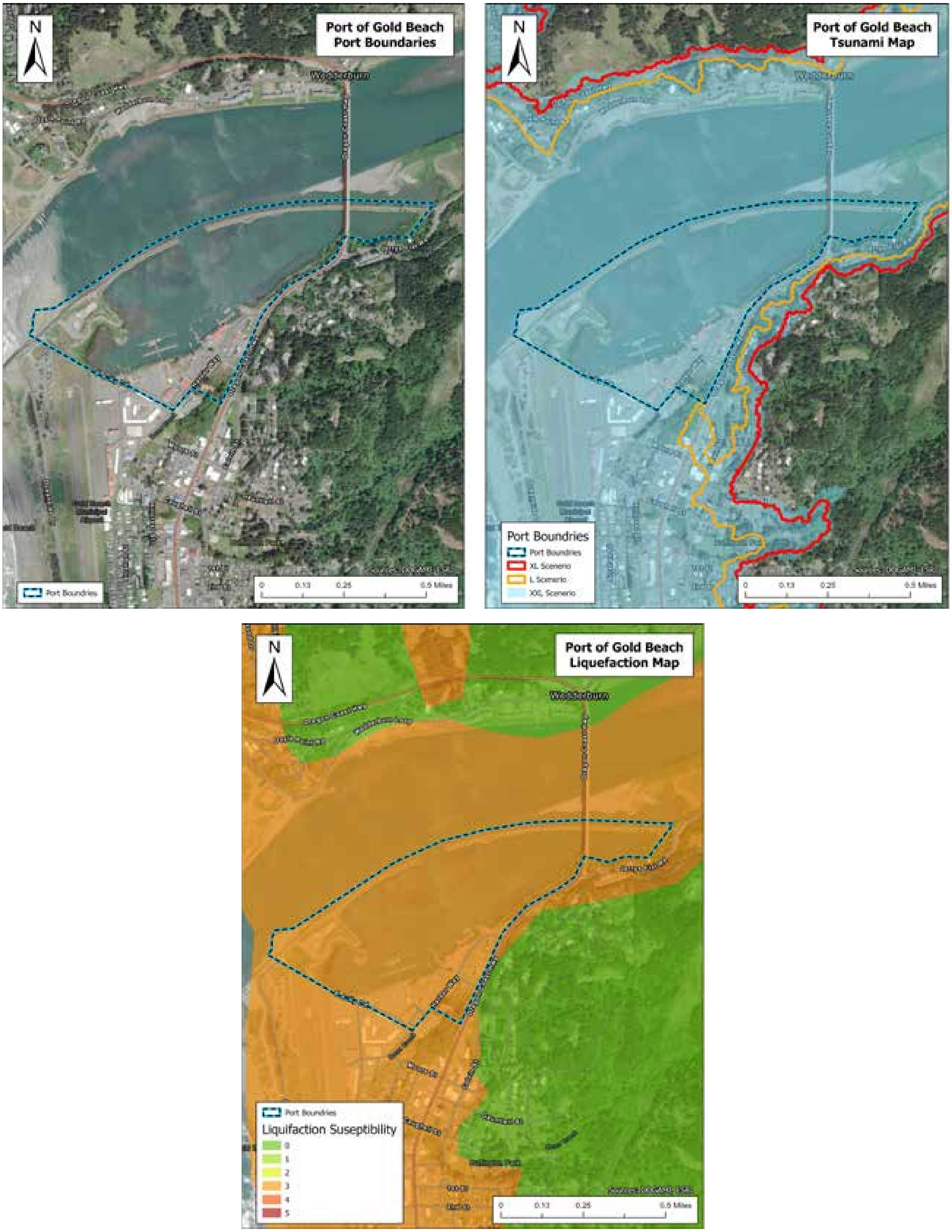


FIGURE E-6.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Gold Beach.

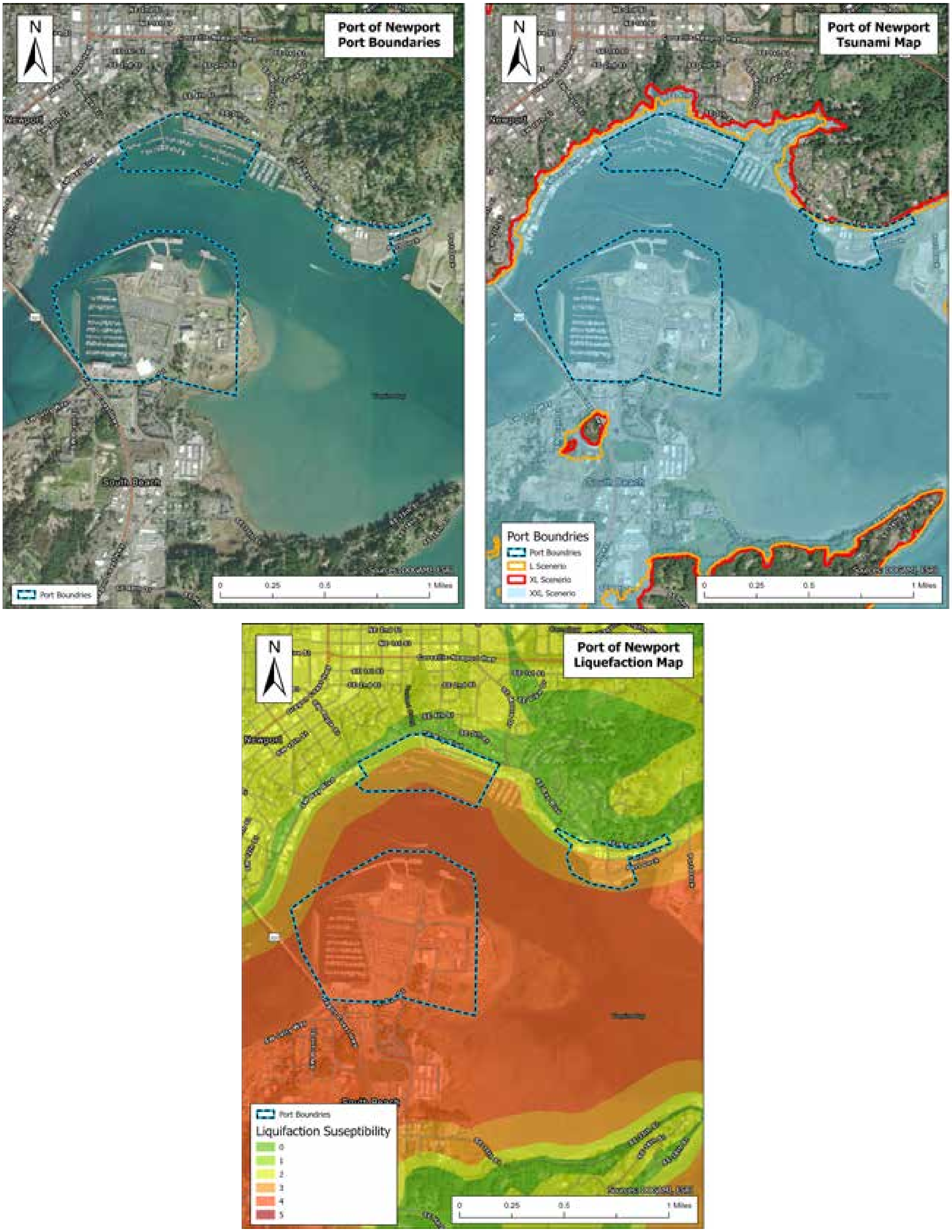


FIGURE E-7.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Newport.

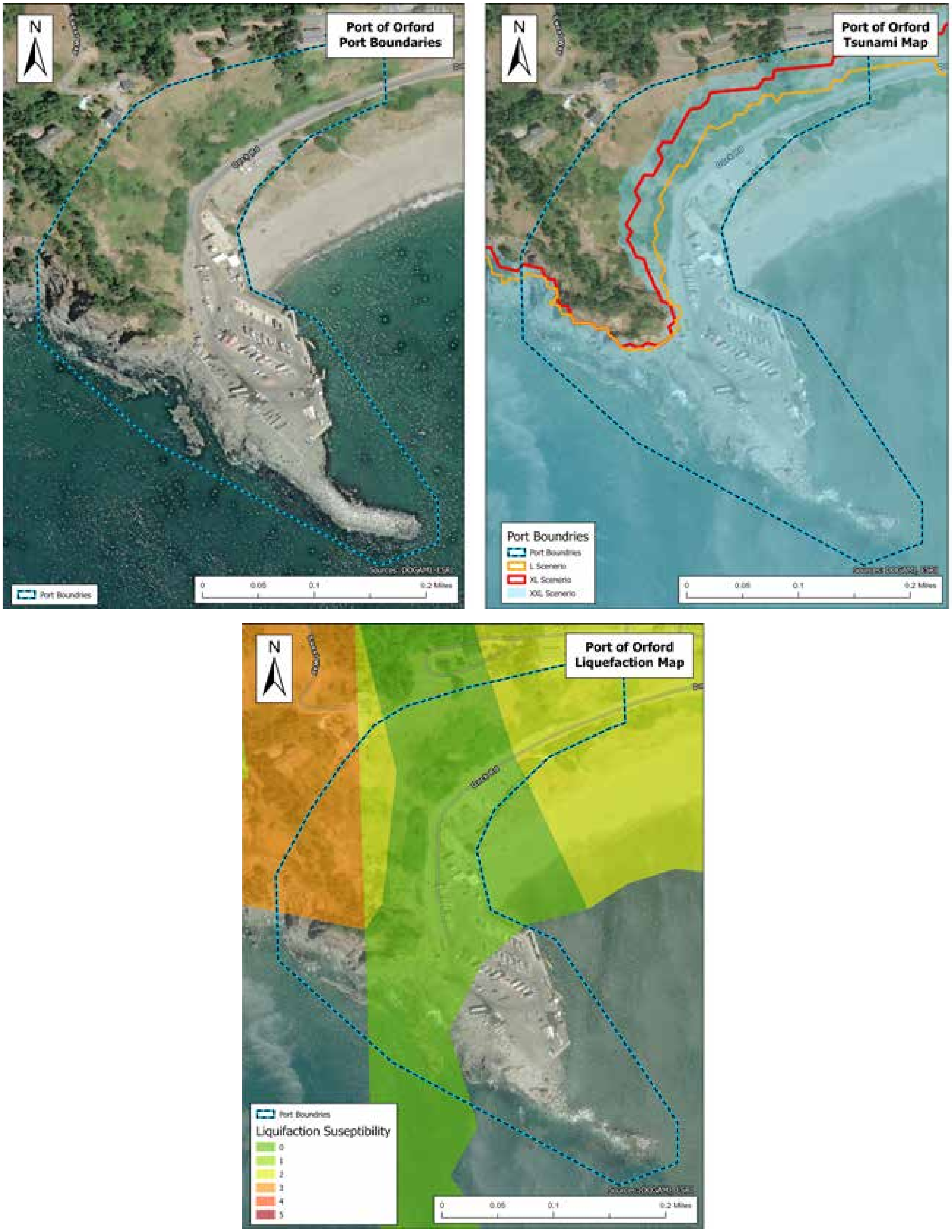


FIGURE E-8.—Port Boundaries, Tsunami Inundation, and Soil Liquefaction Susceptibility for the Port of Orford.

FIGURE E-9.—Tsunami Inundation and Soil Liquefaction Susceptibility for the Port of Portland–Terminal 2.

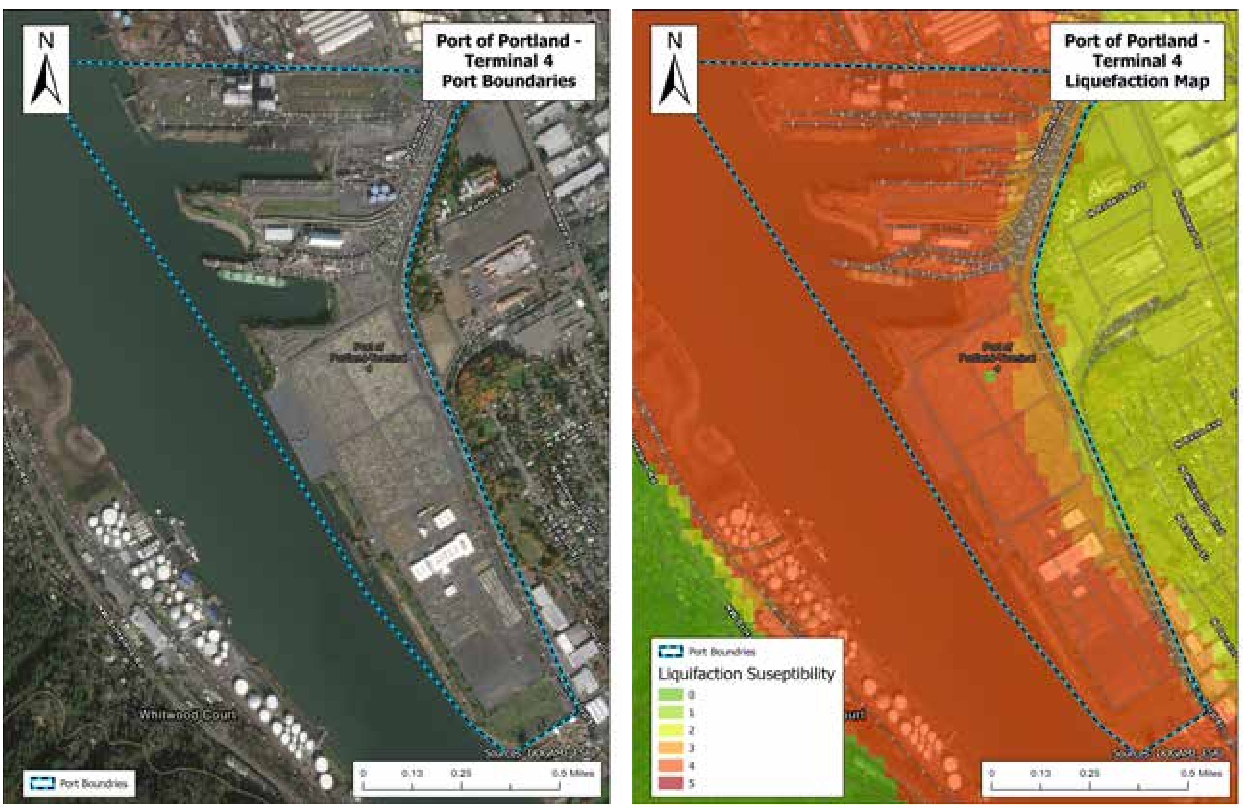


FIGURE E-10.—Tsunami Inundation and Soil Liquefaction Susceptibility for the Port of Portland–Terminal 4.

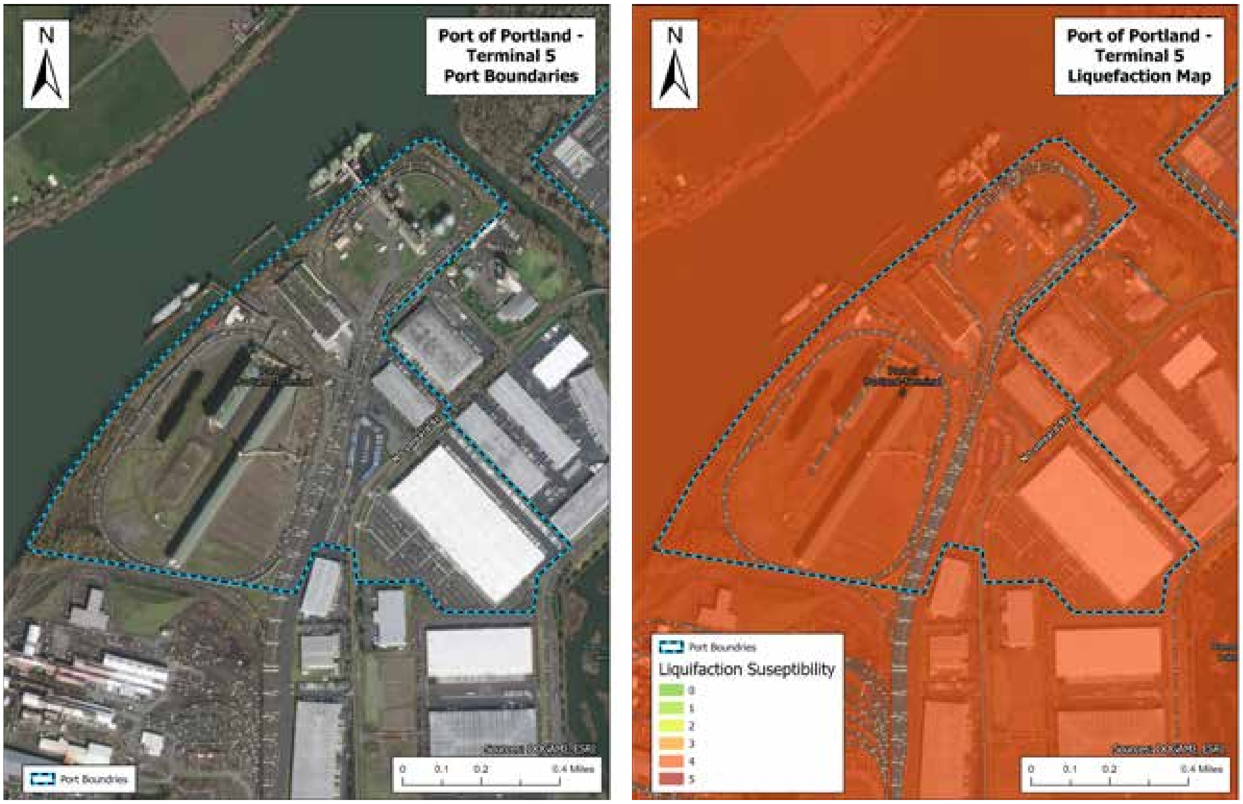


FIGURE E-11.—Tsunami Inundation and Soil Liquefaction Susceptibility for the Port of Portland–Terminal 5.

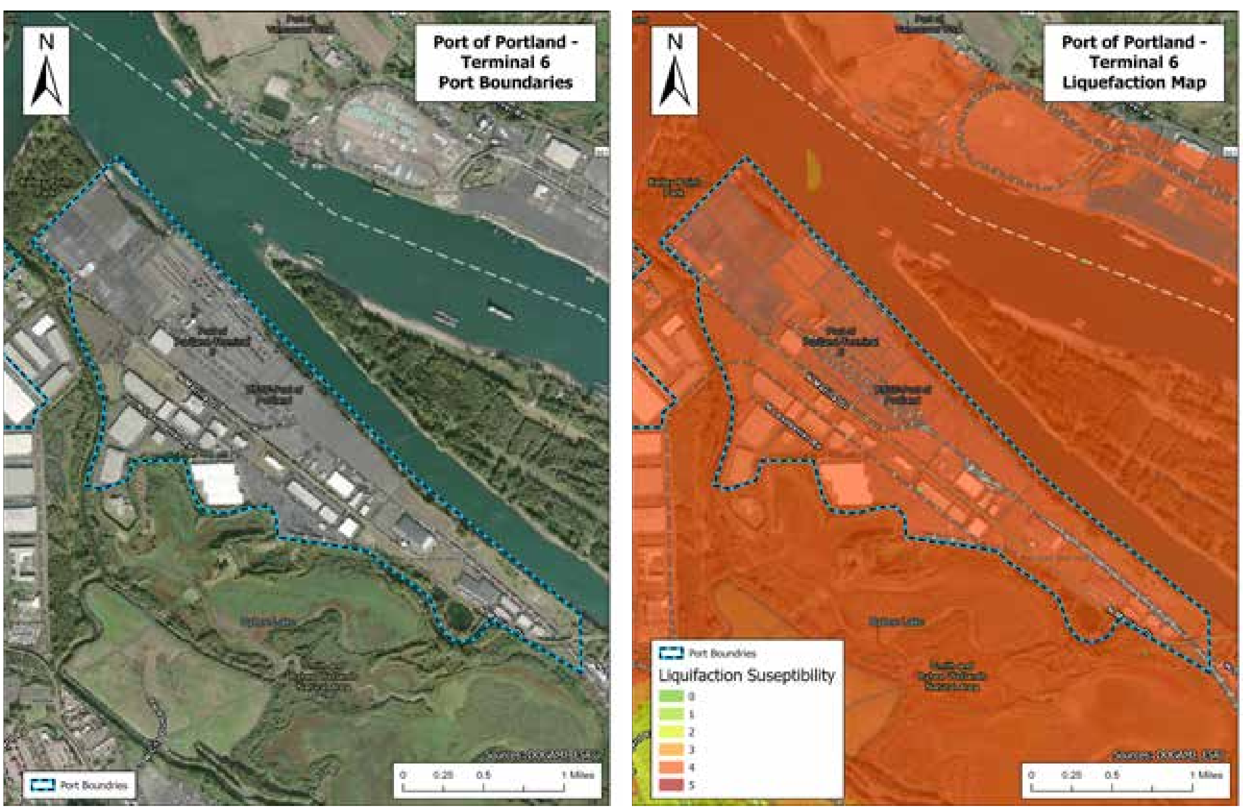


FIGURE E-12.—Tsunami Inundation and Soil Liquefaction Susceptibility for the Port of Portland-Terminal 6.

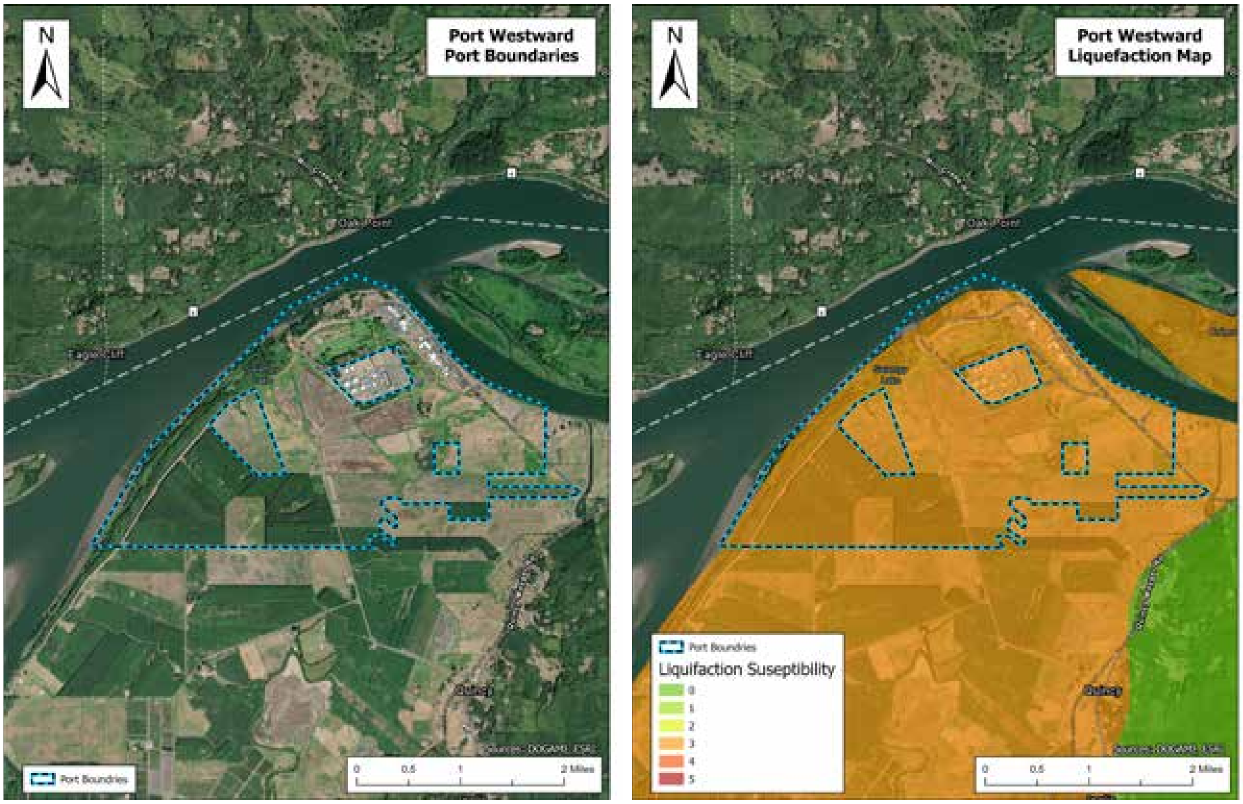


FIGURE E-13.—Tsunami Inundation and Soil Liquefaction Susceptibility for Port Westward.