


SEATTLE PUBLIC UTILITIES
WATER SYSTEM SEISMIC STUDY
SUMMARY REPORT
2018

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ABBREVIATIONS

α	slope angle
ACI	American Concrete Institute
ALA	American Lifelines Alliance
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
CEMP	Comprehensive Emergency Management Plan
CESSL	Cedar Eastside Supply Line
COOP	Continuity of Operations Plan
CMU	concrete masonry unit
CRPL	Cedar River Pipeline
CSZ	Cascadia Subduction Zone
Cygna	Cygna Energy Services
EOP	Emergency Operations Plan
EPANET	hydraulic modeling software developed by the Environmental Protection Agency
ERDIP	earthquake-resistant ductile-iron pipe
EWD	emergency drinking water distribution
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FS	factor of safety
g	acceleration due to gravity
G&E	G&E Engineering Systems Inc.
GMPEs	ground motion prediction equations

gpm	gallons per minute
HDPE	high-density polyethylene
HSS	hollow structural section
ISO	International Organization for Standardization
KN	kilonewton
k_y	ground acceleration that triggers landsliding
LADWP	Los Angeles Department of Water and Power
LCI	Lettis Consultants International
M7.0, M9.0, etc.	magnitude 7, magnitude 9, etc.
M7.0 SFZ	magnitude 7.0 Seattle Fault Zone
M9.0 CSZ	magnitude 9.0 Cascadia Subduction Zone
mg	million gallons
mgd	million gallons per day
NGA West2	Phase 2 of Next Generation Attenuation Models
OCC	Operations and Control Center
OSSPAC	Oregon Seismic Safety Policy Advisory Commission
PGA	peak ground acceleration
PGD	permanent ground displacement
PGV	peak ground velocity
psi	pounds per square inch
PVC	polyvinyl chloride
SCADA	supervisory control and data acquisition

ABBREVIATIONS

SEI	Structural Engineering Institute
SFZ	Seattle Fault Zone
SODO	south of downtown or south of the King Dome
SPU	Seattle Public Utilities
SSI	soil structure interaction
SSRA	System Storage and Reliability Analysis
SWIF	South Whidbey Island Fault
TCA	TCA Architecture Planning
TESSL	Tolt Eastside Supply Line
TIC	Tank Industry Consultants
TPL	Tolt Pipeline
UBC	Uniform Building Code
USGS	United States Geological Survey
V_s30	average shear wave velocity in the top 30 meters of the earth's surface

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1. INTRODUCTION

This report summarizes the findings of Seattle Public Utilities' (SPU) water system seismic vulnerability assessment. This assessment occurred in 2016 and 2017 and updates the 1990 seismic vulnerability assessment completed by Cygna Energy Services (Cygna).

1.1 Background

In 1990, the Seattle Water Department, which later merged with other city departments to form SPU, commissioned a seismic study of its water system. The study was initiated in response to growing concern about seismic risk in the Pacific Northwest region. Cygna conducted this comprehensive seismic vulnerability assessment of the Seattle Water Department's facilities (Cygna 1990).

For the past 28 years, SPU has been addressing the issues identified in the Cygna assessment, as well as planning for and incorporating modern seismic standards into new projects as mandated by federal and state regulations. Many vulnerable facilities have been upgraded to the seismic standards developed by Cygna, and new facilities, such as SPU's buried terminal reservoirs, were designed and constructed to remain functional if subjected to the ground-shaking levels stipulated by the Seattle Building Code.

However, scientific and engineering knowledge about the impact of earthquakes on water systems has increased dramatically since 1990 and understanding of the seismicity of the Pacific Northwest region—in particular the Seattle Fault Zone (SFZ) and Cascadia Subduction Zone (CSZ)—has also advanced substantially. As a result, SPU conducted another comprehensive seismic study in 2016 and 2017. This recent study evaluated facilities in accordance with current seismic code design ground motions, which are discussed in Section 2, and considered overall water system response to two earthquake scenarios.

1.2 Study Objectives

Study objectives were to update the Cygna assessment and

- Perform preliminary seismic vulnerability assessments with an emphasis on critical facilities and pipelines for
  - Two earthquake scenarios;
  - American Society of Civil Engineers/Structural Engineering Institute 7-10 (ASCE/SEI 7-10) code assessment ground motions.
- Estimate overall post-earthquake water system performance;
- Establish post-earthquake water system performance goals;
- Develop planning level mitigation measures, cost estimates, and a time frame to meet post-earthquake performance goals;
- Define seismic design standards for new SPU infrastructure with an emphasis on water transmission and distribution pipelines.

1.3 Seismic Study Team Members

The seismic study team consisted of SPU, two teams of consultants, and a project review panel. Consultants who worked on the project are:

G&E Engineering Systems Inc. (G&E) Team
- New Albion Geotechnical Inc.
- McMillen Jacobs Associates
- Lettis Consultants International Inc. (LCI)
- Leong Holston Associates

Reid Middleton Team
- Arcadis Inc.
- Doug Honegger Consulting
- John Stanton

Project Review Panel
- Tom O'Rourke
- Steve Kramer
- Don Ballantyne

The G&E team evaluated geotechnical hazards, used engineering judgment to estimate the seismic vulnerability of SPU's water system facilities, and made site visits to SPU facilities and some of the critical pipeline locations. The Reid Middleton team performed further evaluations (using American Concrete Institute (ACI), ASCE 41-13 Tier 1, and American Water Works Association (AWWA) procedures) for buildings, tanks, and reservoirs believed to be most critical, and addressed questions regarding previous assessments. SPU assessed distribution pipeline vulnerability, developed recommendations to improve SPU's earthquake emergency preparedness and response planning and prepared this summary report. A review panel of seismic experts comprised of Tom O'Rourke, Don Ballantyne, Doug Honegger, Reid Middleton, and SPU staff evaluated transmission pipeline vulnerability. Arcadis Inc., a subconsultant to Reid Middleton, performed hydraulic modeling to estimate the overall system response. Tom O'Rourke, Steve Kramer, and Don Ballantyne reviewed the seismic study's direction and methodologies.

1.4 Study Approach

The study team looked at both the response of SPU's individual water system facilities and the overall water system response during two earthquake scenarios. The first earthquake scenario was a magnitude 7.0 SFZ (M7.0 SFZ) event with an epicenter in Seattle, and the second was a magnitude 9.0 CSZ (M9.0 CSZ) event that would occur off the Pacific Northwest coast. A M9.0 CSZ earthquake or an approximately M6.5 or higher SFZ earthquake are the earthquake scenarios that would likely have the most significant impact on SPU's water system.

1. INTRODUCTION

A South Whidbey Island Fault (SWIF) scenario and an earthquake scenario deep within the Juan de Fuca Plate were not modeled in this study. Although a SWIF scenario could significantly affect SPU's Tolt transmission facilities, and potentially its Cedar transmission facilities, available resources were used to assess the higher probability and likely more damaging SFZ and CSZ scenarios.

Deep Juan de Fuca intraplate earthquakes similar to the 1949, 1965 and 2001 Puget Sound earthquakes occur much more frequently than the two scenarios used in this study. These intraplate earthquakes occur at large depths below the ground surface and have not significantly affected the SPU water system. It is possible that a deep Juan de Fuca intraplate earthquake could occur that is somewhat stronger and/or closer to Seattle than previously documented intraplate earthquakes, but such an intraplate event is not expected to have nearly as much impact on SPU's system operation as the SFZ or CSZ scenarios. Mitigation measures recommended in this report were thus developed for more severe conditions than those that would generally be expected from an intraplate earthquake scenario.

Ground-shaking-attenuation models were used to estimate the ground-shaking intensity at facility locations under each scenario. SPU water system facilities were also evaluated using the 0.02 probability (2% chance) of exceedance in 50 years (2,475-year average-return period) ground motions, which are approximately equal to the design ground motions used in the Seattle Building Code. Estimates of the typical permanent ground displacements (PGDs) that may occur were estimated with regional earthquake PGD susceptibility maps and models that consider soil properties, ground-shaking intensity, and ground-shaking duration.

Most of SPU's water system facilities and pipelines were evaluated. Notable exceptions include major dams, such as the Masonry and Landsburg Dams on the Cedar River, and the Tolt River Dam. These dams are constantly monitored and evaluated by others, including SPU's dam safety group and Seattle City Light. Facilities that were not included in SPU's seismic study are listed in Table 1-1.

For less critical SPU facilities, or recently constructed facilities that meet current seismic standards, engineering judgment was used to estimate seismic vulnerability. Pseudo static and visual techniques described in ASCE, AWWA, and ACI standards were used for more critical facilities.

Regional distribution pipeline breakage for the two earthquake scenarios was estimated using American Lifelines Alliance (ALA) watermain fragility models. These models estimate damage as a function of pipeline characteristics, peak ground velocity, and permanent ground displacement. Transmission pipeline vulnerability was based on transmission pipeline characteristics and earthquake hazards along each pipeline alignment.

An iterative process was used to develop post-earthquake performance goals that balance system performance with limited resources. A hydraulic model was used to estimate overall system response to the two earthquake scenarios and to evaluate seismic improvement concepts. These improvement concepts included infrastructure upgrades, emergency preparedness, response planning enhancement, and consideration of isolation and control strategies.

1.5 Report Structure

This report includes an executive summary, eight sections, a list of abbreviations, four appendices, and references. Section 1 presents the study background, approach, and report structure. In Section 2, permanent ground displacement and ground-shaking intensity parameter development are summarized for each earthquake scenario. Pump stations, tanks, and other vertical facility assessment findings are presented in Section 3. Pipeline assessment findings are presented in Section 4. Taking into account the results presented in Sections 3 and 4, Section 5 describes the overall system response to each earthquake scenario. Suggested post-earthquake performance goals and mitigation recommendations and costs needed to achieve those performance goals are discussed in Section 6. Recommendations to improve SPU's earthquake emergency preparedness and response planning are outlined in Section 7. The background for the proposed seismic standards for SPU facilities is presented in Section 8. References and a list of abbreviations follow Section 8. The four appendices contain a list of the critical facilities that were re-evaluated by the Reid Middleton team, the hydraulic modeling results, representative water utility post-earthquake performance goals, and proposed seismic standards for SPU watermains.

Facility	Comments
Cedar Falls Education Center	This facility is not necessary for water system operation.
Tolt Bridges	Tolt Bridge No. 1 (North Fork Tolt River crossing) has been seismically upgraded.
Landsburg Dam	Landsburg Dam would not likely lose functionality, but detailed analysis may be needed.
Masonry Dam	Masonry Dam is a Seattle City Light facility; follows FERC regulations.
Tolt Dam	Tolt Dam is FERC compliant.
SW Spokane Street Pump Station	This pump station is currently being rehabilitated and seismically upgraded.
Seattle Municipal Tower	This facility falls under the purview of Finance and Administrative Services.
Water Quality Lab	
Cedar River Pipelines No. 1, 2, and 3 Isolation Vaults in Renton	G&E noted these vaults are seismically rugged.
Lake Youngs Corrosion Building	This facility is no longer in use.
Beacon Reservoir	These four reservoirs were recently seismically upgraded. The probability of any of these reservoirs losing functionality because of structural failure is considered to be low. A nonstructural assessment is needed to verify that there are no significant nonstructural issues.
Maple Leaf Reservoir	
Myrtle Reservoir	
West Seattle Reservoir	
Barton Standpipe	These four facilities have been removed from service. It is unlikely that they will be returned to service.
Woodland Park Standpipe	
Maple Leaf Elevated Tank	
Myrtle Elevated Tank No.1	
Roosevelt Reservoir	This reservoir is not currently in service. The geotechnical investigation and assessment needed to assess the seismic vulnerability of Roosevelt Reservoir was not performed as part of this study. Previous seismic assessments suggest that the embankments at Roosevelt Reservoir may start to experience significant deformations at seismic accelerations of 0.39g (see Section 2) or possibly lower. The last significant assessment appears to have been performed in 1985. If Roosevelt Reservoir is returned to service, a more comprehensive assessment that incorporates the current understanding of seismic hazards and geotechnical response should be performed.
Volunteer Park Reservoir	This reservoir is not currently in service. The geotechnical investigation and assessment needed to assess the seismic vulnerability of Volunteer Park Reservoir was not performed as part of this study. If Volunteer Park Reservoir is returned to service, a comprehensive assessment that incorporates the current understanding of the seismic hazards and geotechnical response should be performed.

Table 1-1. Facilities not included in SPU's seismic study

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2. REGIONAL SEISMICITY, EARTHQUAKE SCENARIOS, AND SEISMIC HAZARDS

SPU's water system facilities are located in a seismically active region of the Pacific Northwest. Devastating earthquakes, equal in severity to events in California and Japan, have occurred in the Puget Sound region in the past—prior to the arrival of European settlers. In this section, the seismicity of the Puget Sound region is summarized, earthquake scenarios are defined, and potential ground motions and other seismic hazards are developed.

2.1 Seismicity of the Puget Sound Region

2.1.1 Cascadia Subduction Zone Interplate Earthquakes

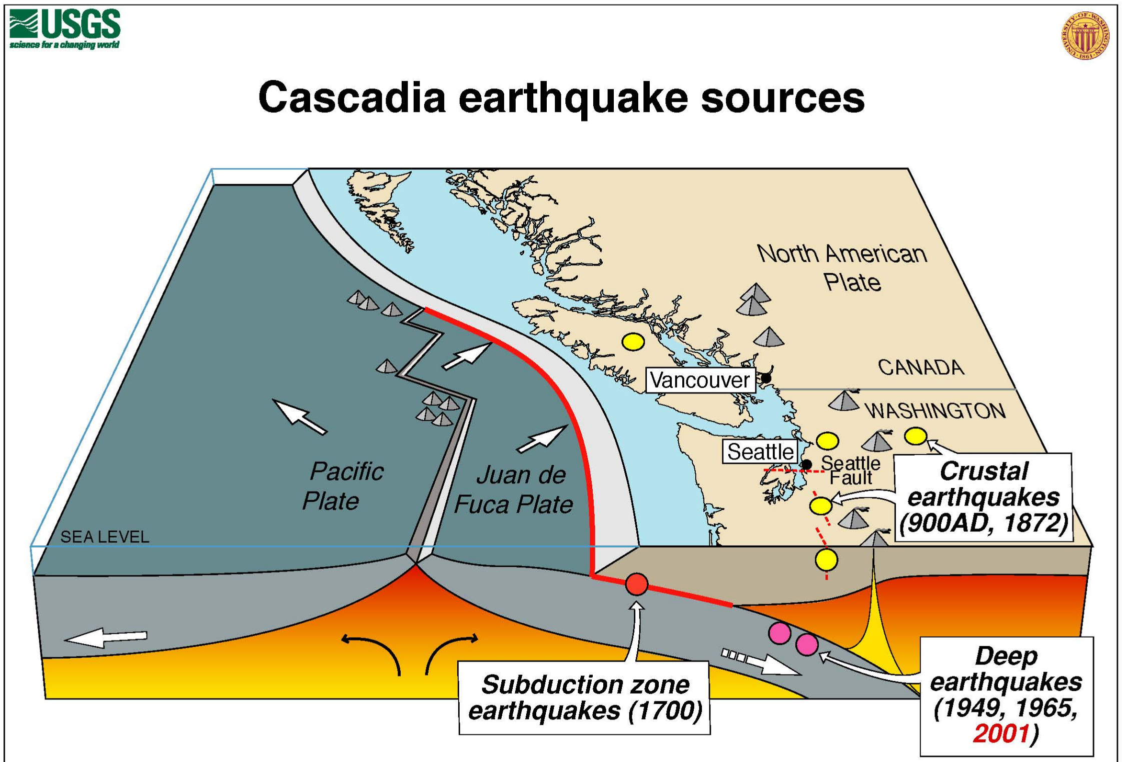
The Puget Sound region lies on the North American (tectonic) Plate. Figure 2-1 shows that, 30 to 50 miles below the Puget Sound region, the Juan de Fuca Plate is being subducted beneath the North American Plate. The interface, and surrounding area, forms the CSZ. This plate boundary extends for 700 miles from Northern California to southern British Columbia. The two plates are currently locked together off the Pacific Northwest coast. When the stresses created as the locked plates attempt to slide past each other exceed the frictional strength that keeps the plates locked together, the interface ruptures and causes an earthquake.

In the past 3,500 years, at least seven giant subduction earthquakes of approximately M9.0 are believed to have occurred at this interface (Pacific Northwest Seismic Network). Tsunami records from Japan indicate that the last giant subduction earthquake in the Pacific Northwest occurred on January 26, 1700. The average return interval for these giant interplate subduction earthquakes is believed to be approximately 500 years. The last M9.0 subduction earthquake occurred over 300 years ago so seismologists estimate there is a 0.14 probability (14% chance) of a M9.0 CSZ earthquake occurring within the next 50 years (Steele 2013). The 2011 M9.0 Tohoku, Japan earthquake and tsunami are examples of the impact of a large interplate subduction zone earthquake.

Although seismic waves would be greatly diminished by the time they reached Seattle, SPU facilities would still be subjected to strong ground-shaking from a CSZ interplate earthquake. Peak ground accelerations (PGAs) from between 0.2g ("g" is equivalent to the force/acceleration produced by gravity, except, in this case, the seismic force/acceleration often occurs primarily in the horizontal direction) and 0.3g are expected and strong ground shaking could last for 3 to 4 minutes. Similar ground-shaking in Sendai, Japan during the 2011 Tohoku earthquake caused significant damage to water system facilities. For comparison, the ground-shaking intensity in Seattle during the 2001 M6.8 Nisqually earthquake was generally around 0.1g or less and the significant duration (one measure used by seismologist to characterize the strong ground shaking duration) was approximately 45 seconds (Bray et al. 2001).

2.1.2 Cascadia Subduction Zone Intraplate Earthquakes

Another source of earthquakes that could affect SPU's water system facilities is located below the Puget Sound region where the Juan de Fuca Plate fractures as it is being subducted beneath the North American Plate. M6.5 to M7.5 intraplate earthquakes are believed to occur approximately every 30 years in the Puget Sound region. The 1949 M7.1 Olympia, 1965 M6.7 Seattle-Tacoma, and 2001 M6.8 Nisqually earthquakes are examples of deep intraplate earthquakes.



	Source	Affected area	Max. Size	Recurrence
● (red)	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
● (pink)	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
● (yellow)	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Figure 2-1. Western Washington earthquake hazards (United States Geological Survey 2001)

Seismologists estimate there is a 0.84 probability (84% chance) of a Magnitude 6.5 or larger deep intraplate earthquake similar to the 2001 Nisqually earthquake occurring in the next 50 years (Steele 2013).

The September 2017 M7.1 and M8.1 earthquakes that took place in Mexico are examples of deep intraplate earthquakes that occur in a tectonic plate that is being subducted beneath another plate. Because these earthquakes occur at considerable depth, the ground-shaking intensity is usually not as severe as that produced by shallow earthquakes. Although the ground shaking intensity from Puget Sound intraplate events has not been extremely strong, there have been scattered areas of liquefaction and large ground movements that has caused significant damage to some facilities.

2.1.3 Crustal/Shallow Earthquakes

The third earthquake mechanism that threatens the Puget Sound region originates from shallow fault systems that crisscross the area. As Figure 2-2 shows, the Pacific (tectonic) Plate’s northward movement causes blocks within the North American Plate to rotate, while in southern British Columbia, the North American (tectonic) Plate is fixed. Consequently, folds (or faults) have been created to accommodate compression in western Washington. These shallow faults are believed to be capable of producing earthquakes up to M7.5 in the Puget Sound region. Because shallow faults rupture and release energy close to the earth’s surface, the ground-shaking intensity can be significantly stronger than the shaking intensity from comparable earthquakes on deeper faults.

The Seattle Fault and SWIF pass through the area where SPU facilities are located. At least five significant SFZ earthquakes are believed to have occurred in the past 3,500 years (Pratt 2015). And the last large SFZ earthquake is thought to have occurred approximately 1,100 years ago between AD 900 and 930 (Nelson et al. 2003). There is an estimated 0.05 probability (5% chance) of a M6.5 or larger Seattle Fault seismic event in the next 50 years (Steele 2013). For comparison, the February 2011 earthquake that devastated Christchurch, New Zealand was a M6.3 earthquake on a shallow fault, and the 1995 Great Hanshin-Awaji shallow earthquake that devastated Kobe, Japan was M6.9.

At least four approximately M6 to M7 earthquake events are believed to have occurred on the SWIF system in the past 16,400 years (Sherrod et al. 2008). The last event on the SWIF system is believed to have been a M6.5 to M7.0 event that occurred approximately 3,000 years ago (Kelsey et al. 2004). A SFZ or SWIF earthquake could produce ground-shaking intensities as high as 0.6g or greater. However, attenuation of seismic waves from one of these events means that not all SPU facilities would be subjected to such high intensities.

2.1.4 Evolution of the Seismological Understanding in the Pacific Northwest

Seismic design of SPU facilities has followed the evolving understanding of the seismology of the Pacific Northwest. SPU still maintains facilities that were built in the early 1900s. It wasn’t until after the 1933 M6.4 Long Beach earthquake in California that seismic design requirements

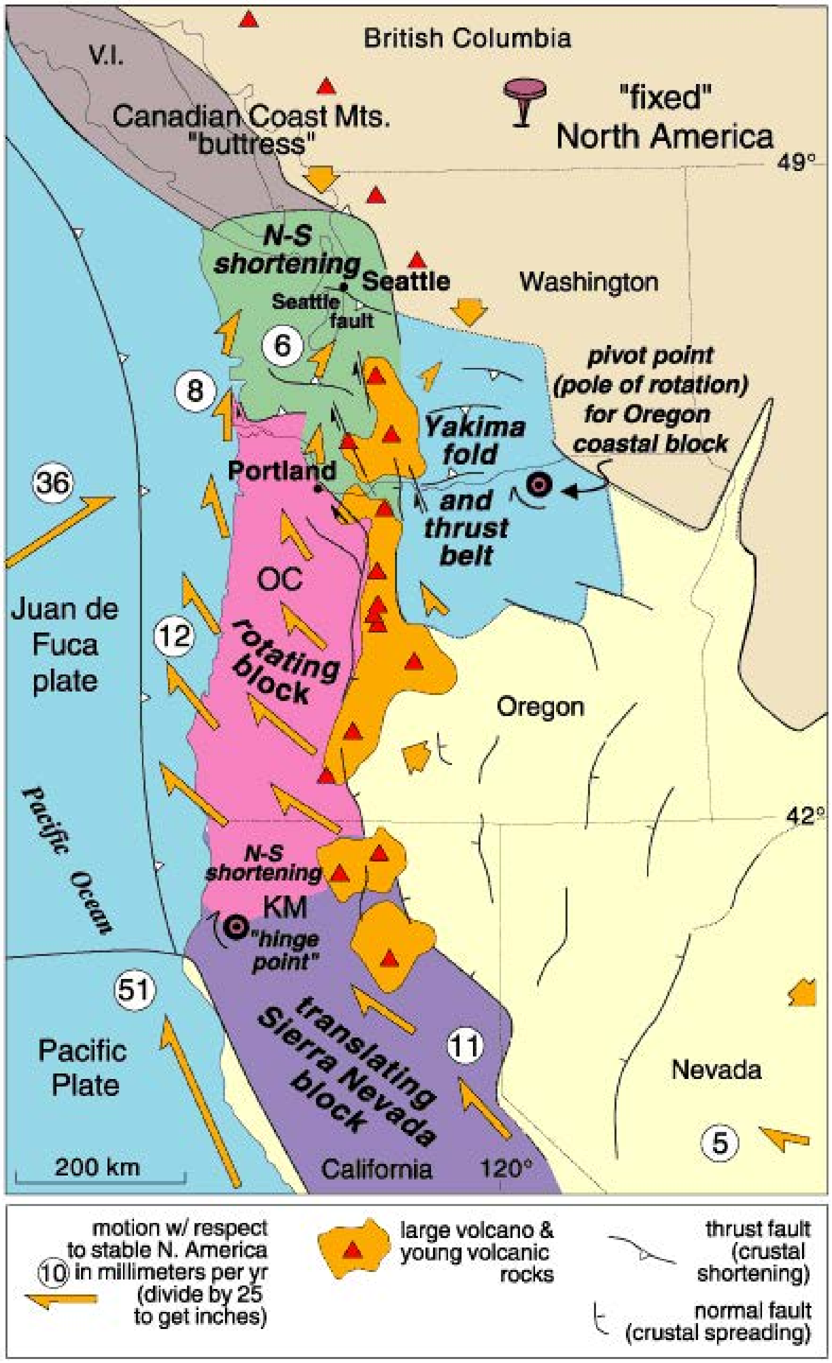


Figure 2-2. Tectonic plate block movement (Wells et al. 2000)

were initiated in the United States. The ground motions expected from intraplate earthquakes were used as the primary driver behind seismic design in the Pacific Northwest through the 1980s, but almost universal acceptance of the potential for large interplate subduction zone earthquakes did not occur until then. In the 1990s, the SFZ and other shallow faults were also determined to be active and the potential for stronger ground-shaking intensity in the Puget Sound region was incorporated into seismic design codes.

2.2 Earthquake Scenarios

The ground-shaking intensity stipulated by seismic design codes is based on a probability of occurrence. Building codes, such as the Seattle Building Code, use risk-targeted ground motions, and are based on a philosophy that a building designed to resist these ground motions would have a 0.01 probability (1% chance) of collapsing in 50 years (data suggests that actual collapse probabilities are less). In the Puget Sound region, these ground motions are approximately equal to ground motions that have a 0.02 probability (2% chance) of exceedance in 50 years. Because SPU's facilities are geographically distributed over a large area, these "code level" ground motions will not occur simultaneously at all SPU facilities.

To estimate how SPU's overall water system would react to seismic events, the system was evaluated using two earthquake scenarios:

- M9.0 CSZ earthquake that is defined by the rupture of the interface of the Juan de Fuca and North American Plates off the Pacific Northwest coast from Northern California to southern British Columbia
- M7.0 SFZ earthquake with an epicenter in central Seattle

The M7.0 SFZ and M9.0 CSZ scenarios are representative of the types of events that are considered in the ASCE 7 and Seattle Building Code. With average return intervals of 500 to over 1000 years, the likelihood of one of these catastrophic events occurring in a given year is relatively small. The occurrence likelihood of a much less damaging intraplate earthquake in the next 50 years is approximately four times as great as the occurrence likelihood of an earthquake that would cause damage similar to the damage expected from a catastrophic earthquake like the scenarios used in this study. However, catastrophic earthquakes have previously occurred in Seattle and will eventually occur in the future.

A M9.0 earthquake was chosen for the CSZ event because it is representative of an event that would result in rupture of the entire locked portion of the interplate boundary. Although larger events than M7.0 may be possible on the Seattle Fault, a M7.0 event is large enough to cause surface fault ruptures. Such an event is close to the size of the last major Seattle Fault earthquake and is representative of some of the events used to establish the 0.02 probability (2% chance) of exceedance in 50 years ground motions. Because the Seattle Fault system is an east-west trending reverse thrust fault (one earth block moves vertically with respect to an adjacent block and the angle between the two blocks is 45 degrees or less) system where the southern block moves vertically upward with respect to the northern block, areas south of the fault will generally experience stronger shaking than areas equidistant that are north of the fault.

For this study, resources were concentrated on the SFZ and CSZ scenarios. Uncertainty regarding the seismological characterization of the SWIF zone and resource limitations prevented inclusion of a SWIF event in the seismic assessment. Although a SWIF event could cause damage to SPU's transmission facilities, the effect on SPU's overall water system is expected to be less than that from the other two scenarios, since ground motions would be significantly lower once they reached most of SPU's direct service area.

Deep intraplate earthquakes in 1949, 1965, and 2001 resulted in some damage to SPU's water system, but overall effects were minimal. Depending on the earthquake's size and location, future intraplate events may cause higher or lower levels of damage to SPU facilities. The serious, long lasting effects that would result from a M9.0 interplate subduction and M7.0 crustal event are much less likely due the lower probabilities of these events. Mitigation measures for the M9.0 CSZ and M7.0 SFZ scenarios would most likely address any vulnerabilities associated with a deep intraplate event. Consequently, an intraplate event was not included in the seismic assessment.

In addition to the scenario earthquake ground motions, SPU facilities were evaluated using the 2014 probabilistic ground motions defined by the United States Geological Survey (USGS) (Peterson et al. 2014). These ground motions are the 0.02 probability (2% chance) of exceedance in 50 years ground motions discussed above. Throughout this report, these ground motions are referred to as the 2014 USGS Ground Motions. Baker (2013) outlined general procedures used to calculate probabilistic ground motions. These ground motions are not the same as the ground motions used by the ASCE 7-10 standard and the Seattle Building Code. However, for the Puget Sound region, the 2014 USGS Ground Motions are typically within a few percentage points of Seattle Building Code values. This difference does not affect the conclusions reached in this study.

2.3 Ground-Shaking Intensity

Ground motion prediction equations (GMPEs) were used to estimate the ground-shaking intensity at each SPU facility. For a defined fault rupture location, length and rupture direction, GMPEs model the propagation of seismic waves through the earth and estimate the ground-shaking intensity at the earth's surface. Ground-shaking intensity is often expressed in terms of peak ground acceleration (PGA) or peak ground velocity (PGV). PGA is often expressed as a decimal fraction of the earth's gravitational acceleration. For example, PGA as a specific location may be expressed as "0.47g," which means that the earthquake results in ground acceleration that is 47% of the acceleration that a free-falling object (assuming no air resistance) would experience. PGV is typically expressed in centimeters per second or inches per second.

In addition to estimating PGAs and PGVs, GMPEs predict spectral accelerations that buildings may experience. Spectral accelerations relate structure-shaking intensity, expressed in "g," to the structure's natural/fundamental period of vibration. Spectral acceleration is often denoted as $S_{x,}$ where "S" is the spectral acceleration for a structure with a natural period of vibration equal to "x" seconds.

BC Hydro's ground motion prediction equations (G&E 2016a; BC Hydro 2012) were used to estimate ground motions and structure response motions for the M9.0 CSZ scenario. The average of five NGA-West2 (Next Generation Attenuation Models for the Western United States, Bozorgnia et al. 2014) GMPEs was used to estimate ground motions for the M7 SFZ earthquake (G&E 2016a; G&E 2016b; Abrahamson, Gregor, and Addo 2016). The 2014 USGS probabilistic ground motions (Peterson et al. 2014) have been used as a proxy for the ASCE 7-10 ground motions.

PGAs, 0.1 second spectral accelerations (the acceleration a building with 0.1 second natural period of vibration would experience), and 1.0 second spectral accelerations were calculated for each earthquake scenario at each SPU facility location. In addition, PGA, 0.2 second and 1.0 second spectral accelerations were calculated for the USGS probabilistic ground motions.

Figures 2-3 and 2-4 show PGAs for the M7.0 SFZ and M9.0 CSZ scenarios. The 2014 USGS Ground Motion PGAs are shown on Figure 2-5.

2.4 Permanent Ground Displacement Hazards

In addition to ground-shaking, earthquakes can cause PGD. There are several different types of PGD. Soil liquefaction can occur in cohesionless soils, such as sand, if the water table is high enough and the ground-shaking intensity is strong enough to cause the pore water pressure in the soil to overcome the confining pressure. When soil liquefies, it loses much of its strength and stiffness and behaves in many respects like a liquid. The liquefied soil can flow to and be ejected at the ground surface. The volume loss from the ejected soil and water (ejecta) and subsequent densification of the remaining material can result in substantial settlement. On gently sloping ground or on ground near a free face (unconstrained/exposed ground surface) liquefied soils may also spread laterally. Large cyclic ground deformations can also occur in liquefiable soils. The chaotic nature of lateral ground displacements can induce high loads in buried infrastructure.

Ground-shaking can also trigger landslides. Fault rupture can result in discrete offsets in soil at the ground surface. Land subsidence or uplift is possible. Even if soils do not liquefy, ground-shaking may cause soils to densify and settle. Figure 2-6 shows the liquefaction-susceptible and landslide-susceptible areas within SPU’s distribution and transmission system region. Inferred locations of lineaments within the SFZ and SWIF zone are also shown on Figure 2-6.

2.4.1 Liquefaction

Two different approaches were used to estimate liquefaction potential. Within SPU's direct service area, New Albion Geotechnical Inc. (2017) used existing liquefaction susceptibility maps and liquefaction displacement models to estimate liquefaction displacements for the M9.0 CSZ and M7.0 SFZ earthquake scenarios. Soil properties were assumed to be constant within the different regions identified by the Washington State Department of Natural Resources (Palmer et al. 2004). Liquefaction estimates are intended to represent regional averages and behavior but are not intended to be used for design at specific sites. Three components of liquefaction displacement were estimated:

- PGD_h, the horizontal component due to lateral spread
- $PGD_{v\text{-}vol}$, the vertical component due to ground settlement and ejecta
- $PGD_{v\text{-}dev}$, the vertical component due to deviatoric strains caused by lateral displacement

Total PGD from liquefaction was estimated at each watermain location using the equation $PGD_{total} = \sqrt{[(\mathrm{PGD}_h)^2 + (\mathrm{PGD}_{v-vol} + \mathrm{PGD}_{v-dev})^2]}$.

All points within a given region will not necessarily liquefy and engineering judgment was used to estimate the areal extent of liquefaction in a particular region. The areal extent is a function of soil properties and ground-shaking intensity. Shaking duration was considered by applying a magnitude-scaling factor. The magnitude-scaling factor accounts for the longer duration of ground-shaking expected with the M9.0 CSZ earthquake when compared with the anticipated shorter duration M7.0 SFZ earthquake.

In addition to liquefiable soils, some of SPU's pipelines cross peat deposits. Although peat does not liquefy, high cyclic stresses in the soil during an earthquake can cause PGD. To account for PGD in this type of soil, the settlement displacements were assumed to be equivalent to the settlement PGDs in high liquefaction susceptibility areas.

The investigation into liquefaction potential also included review of discrete sites along SPU's transmission pipeline alignments. Where available, soil borings were reviewed, and engineering judgment was used to estimate the liquefaction potential.

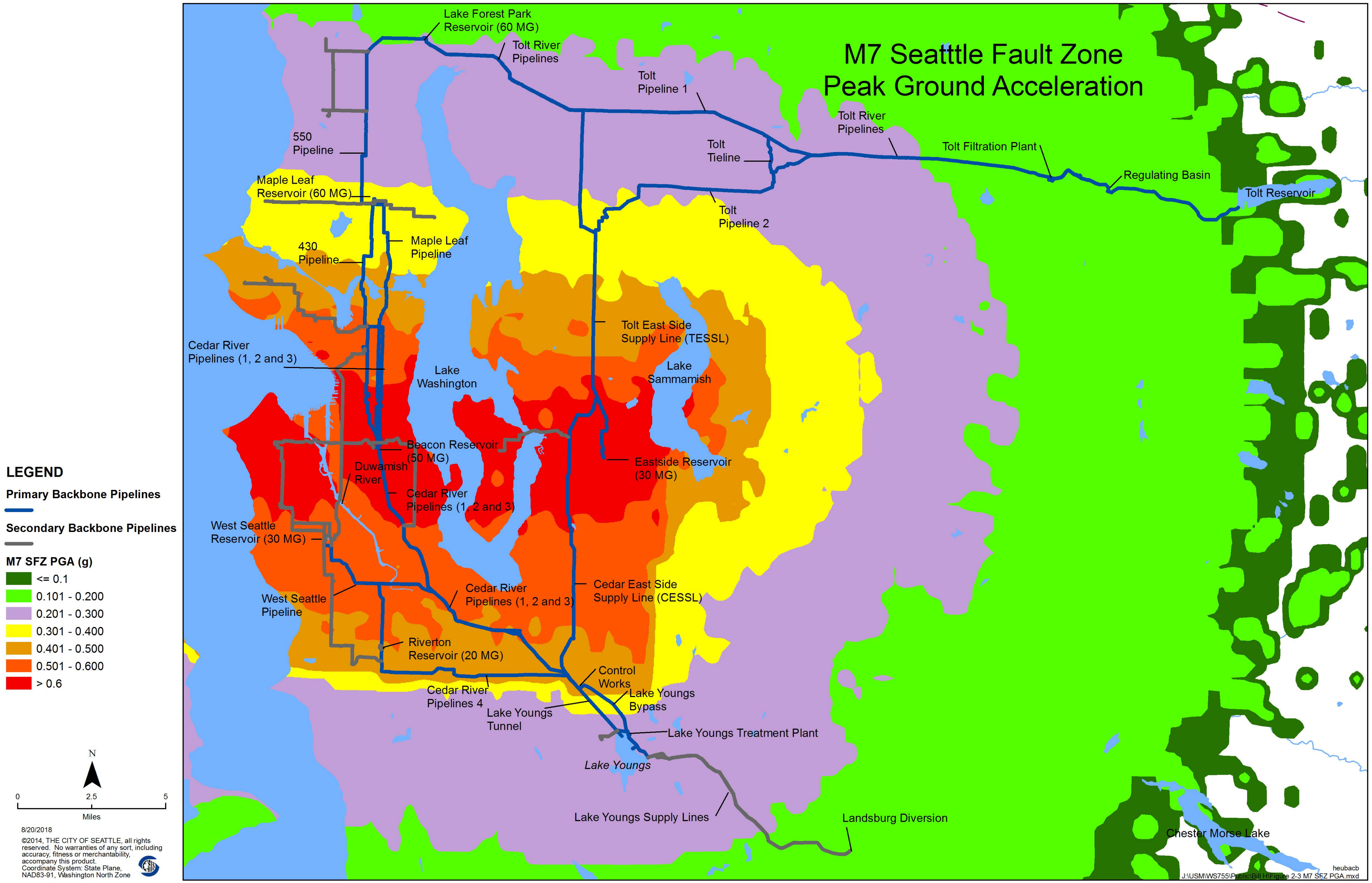


Figure 2-3. M7.0 SFZ peak ground accelerations

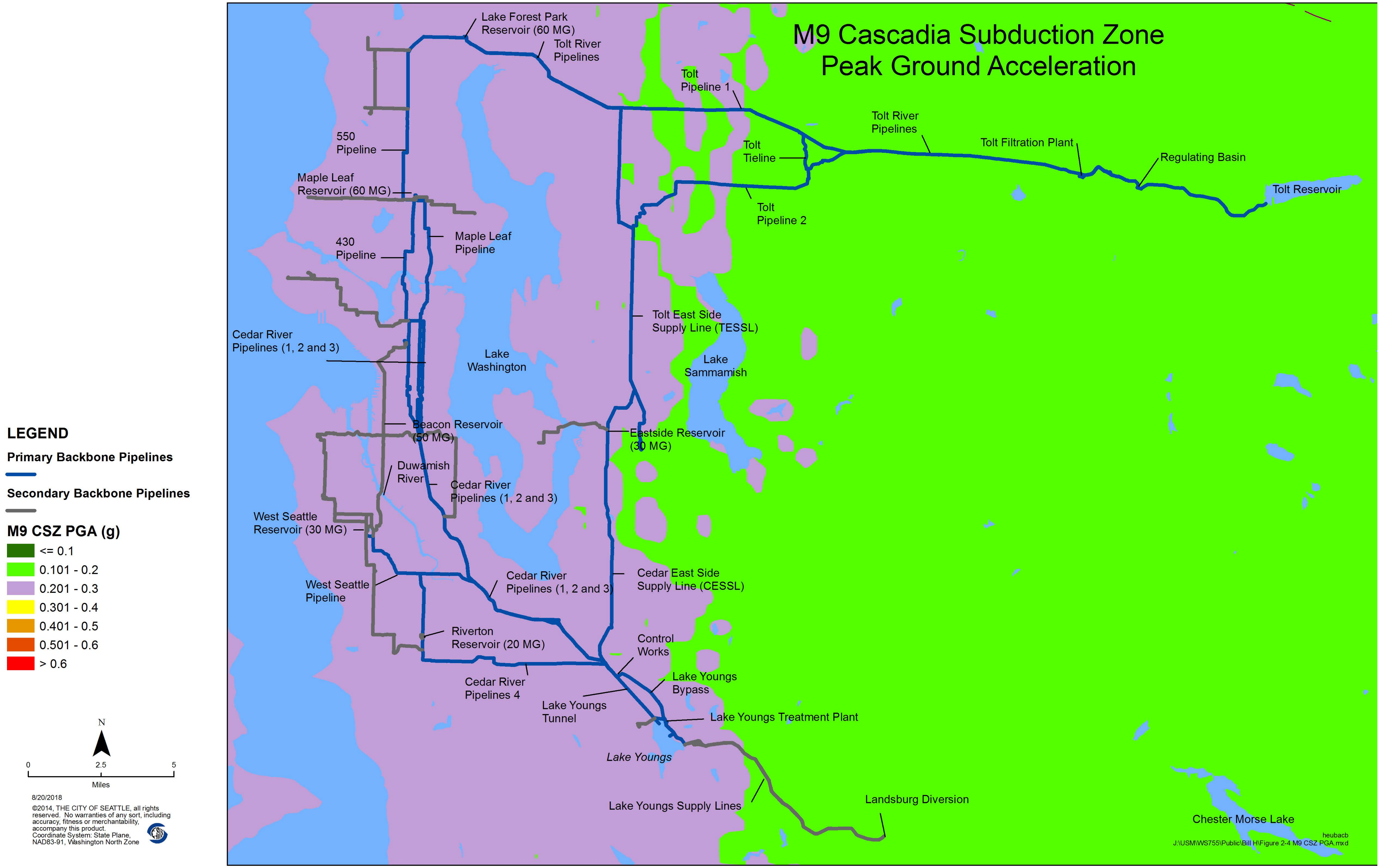


Figure 2-4. M9.0 CSZ peak ground accelerations

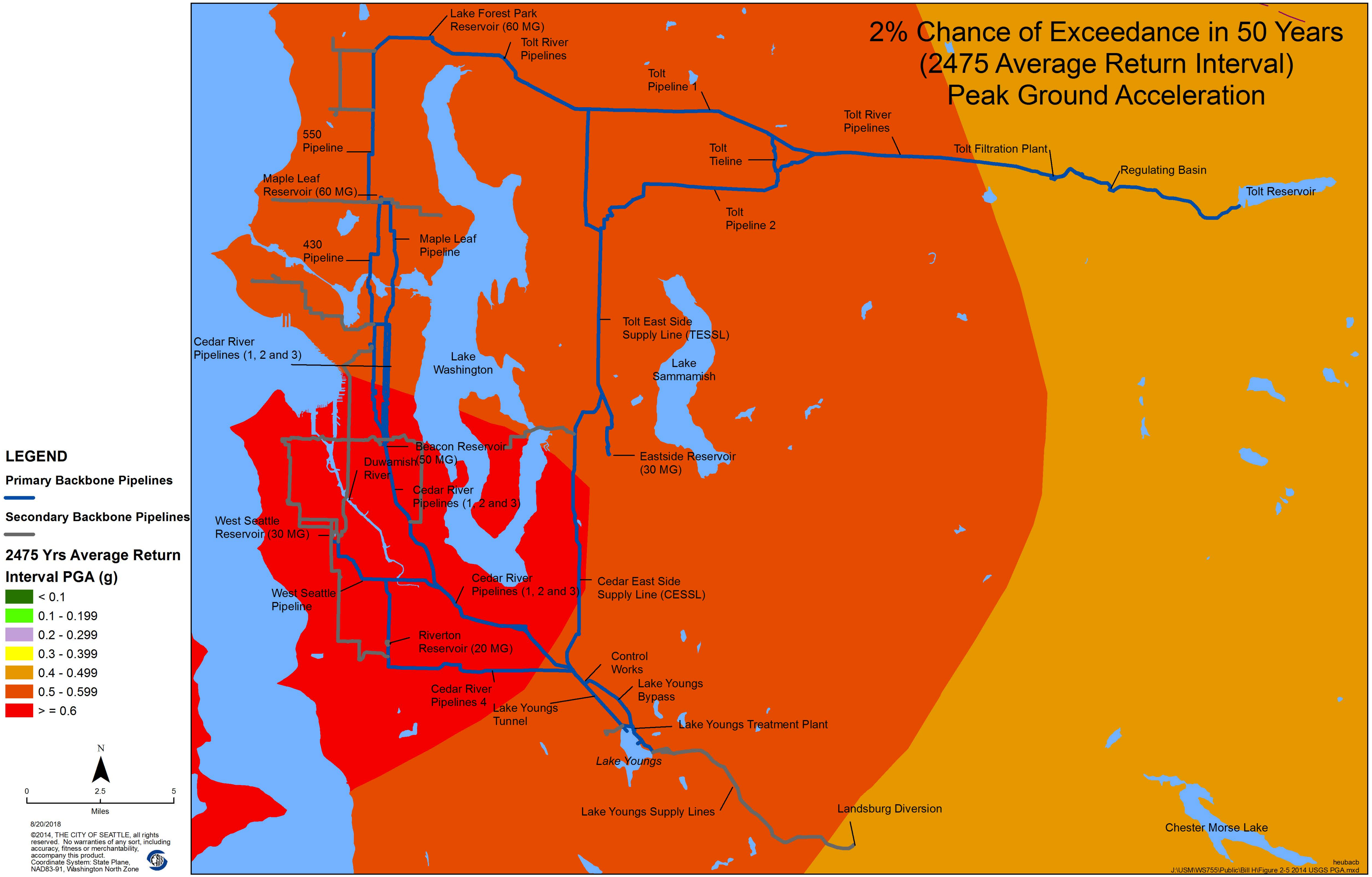


Figure 2-5. 2014 USGS probabilistic peak ground accelerations

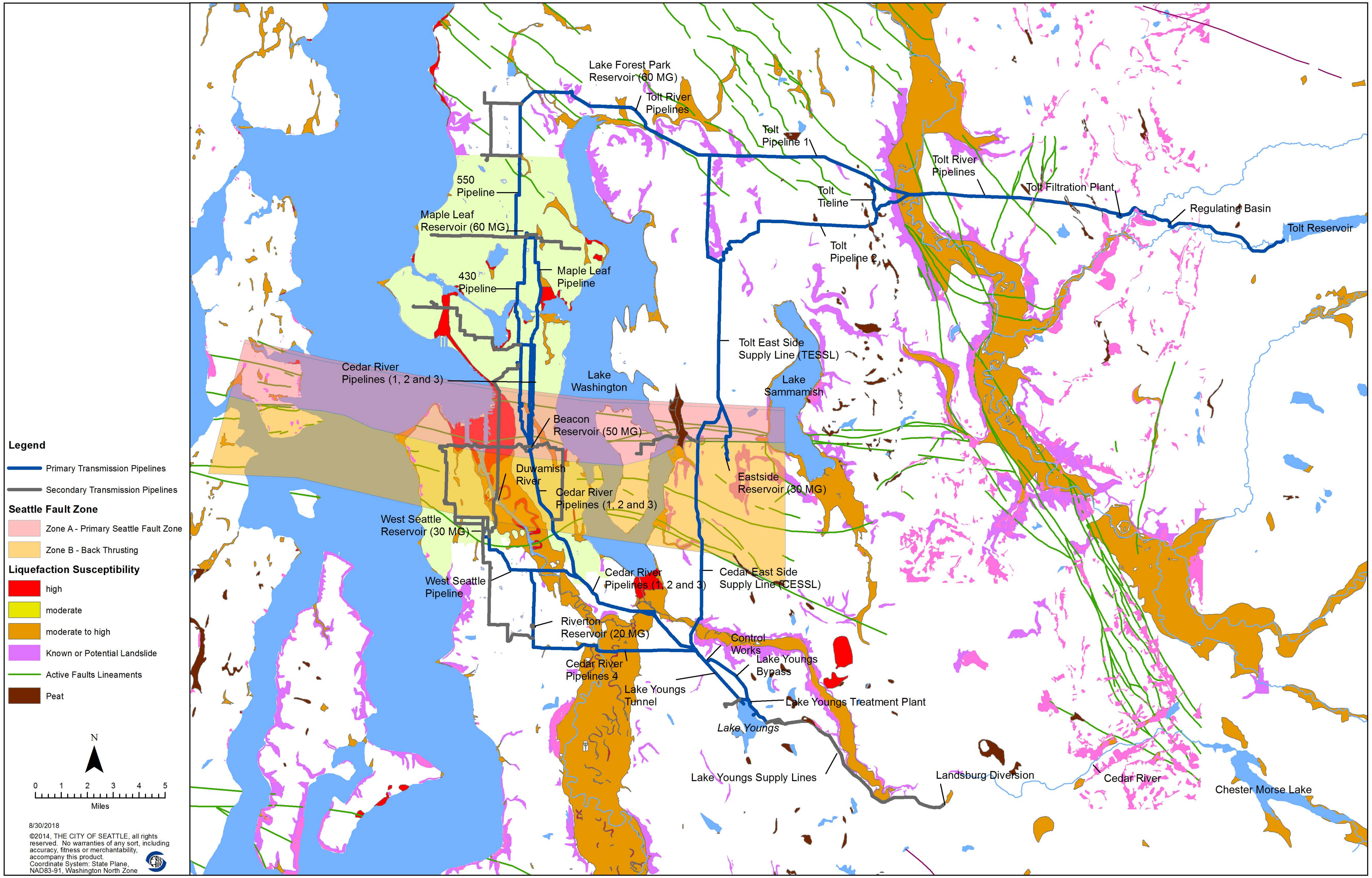


Figure 2-6. SPU distribution and transmission area seismic hazards (note: Seattle Fault Zone is believed to extend east of the shaded area that is shown out to the Cascade Mountain foothills)

2.4.2 Landslides

City of Seattle (City of Seattle 2011), King County (King County GIS Portal), and Washington State Department of Natural Resources landslide hazard GIS layers were used to identify potential landslide areas. Using the factor of safety for landslides in Seattle under static conditions estimated by Harp et al. (2006), a simplified Newmark sliding block model was calculated as:

$$k_y = (FS - 1)\, g \sin \alpha$$

where,

k_y = *the ground acceleration that triggers landsliding,*
FS = *the factor of safety,*
g = *the acceleration due to gravity,*
α = *the slope angle.*

The factor of safety used in the equation was assumed to be uniformly distributed within the factor of safety ranges identified by Harp et al. For those landslide-susceptible areas that appear on the City of Seattle, King County, or Washington State Department of Natural Resources maps, but were not evaluated by Harp et al., a factor of safety range from 1.5 to 2.0 was assumed. The slope angle used in the equation was assumed to be uniformly distributed between 30 and 60 degrees. A Monte Carlo simulation generated a probability density function for the ground acceleration that would trigger landsliding in each factor of safety range. For a given site and PGA, the probability density function generated by the Monte Carlo simulation was used to estimate the landslide probability. The Makdisi and Seed (1978) relationships were used to estimate the landslide displacement for the median of the portion of the probability density function less than the site PGA.

Liquefaction displacement estimates for SPU watermains for the M7.0 SFZ and M9.0 CSZ scenarios are shown on Figures 2-7 and 2-8. For the M7.0 SFZ and M9.0 CSZ scenarios, liquefaction occurrence probabilities are shown on Figures 2-9 and 2-10.

The procedures used to estimate regional liquefaction and landslide permanent displacements are very approximate and are intended to be indicative only of regional averages. These regional displacement estimates should not be used for site-specific analyses. These PGD estimates are only intended to be used as input for pipeline failure models that produce order-of-magnitude estimates of pipe damage.

2.4.3 Fault Rupture and Subsidence/Uplift

An interplate CSZ fault rupture would be located approximately 60 to 80 miles from Seattle. Consequently, surface faulting would not be expected in Seattle during a M9.0 CSZ earthquake.

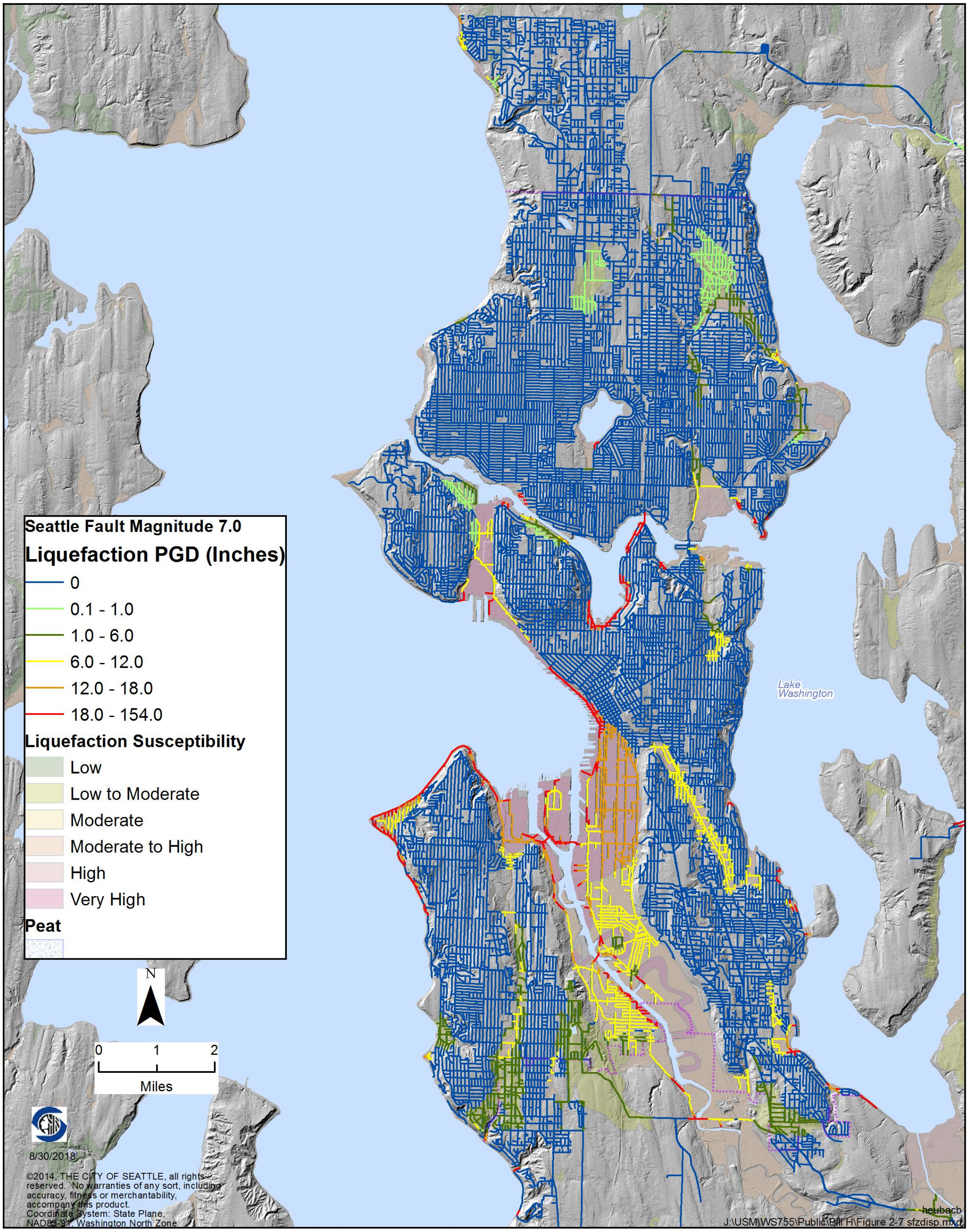


Figure 2-7. M7.0 SFZ distribution pipelines liquefaction displacement estimates

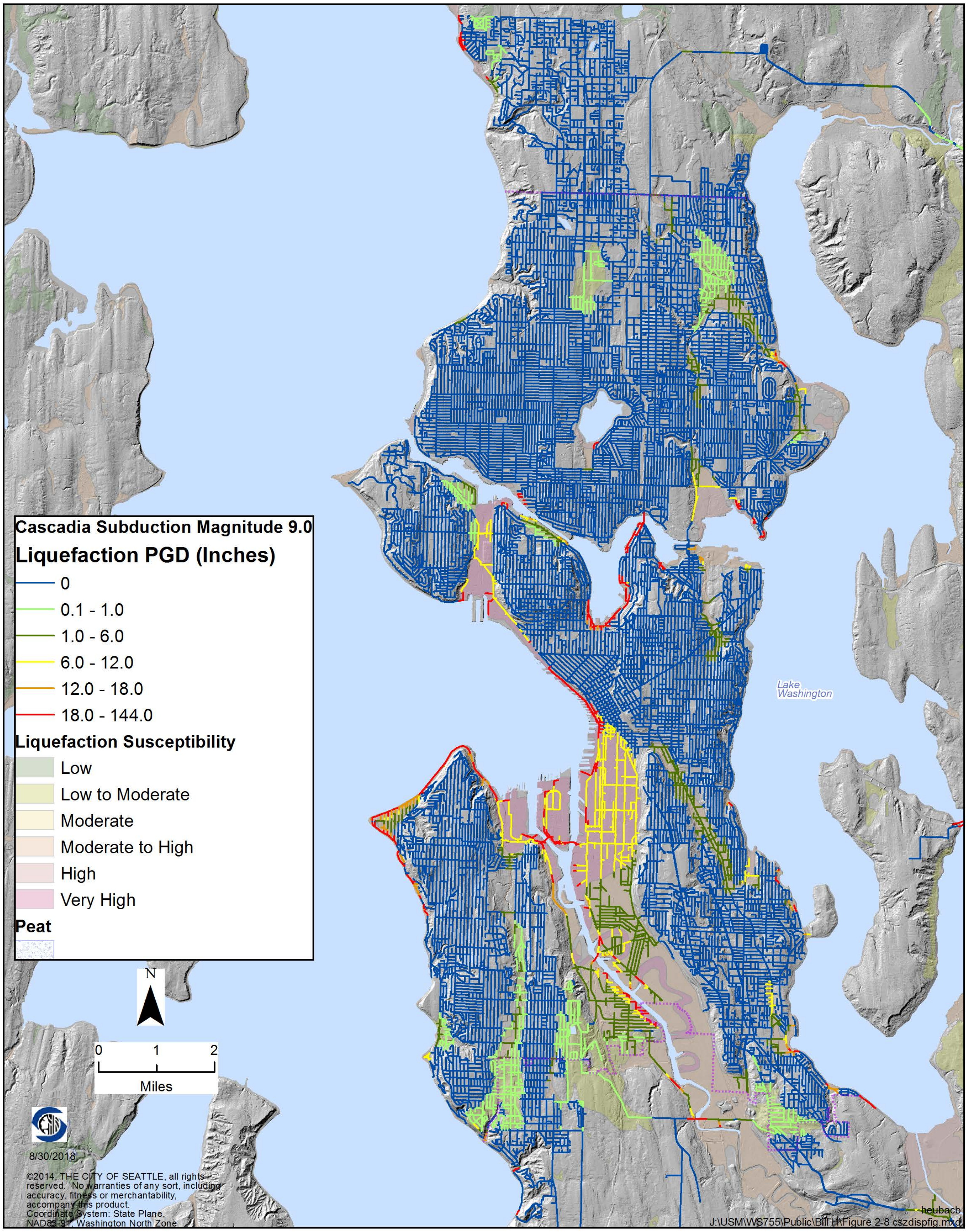


Figure 2-8. M9.0 CSZ distribution pipelines liquefaction displacement estimates

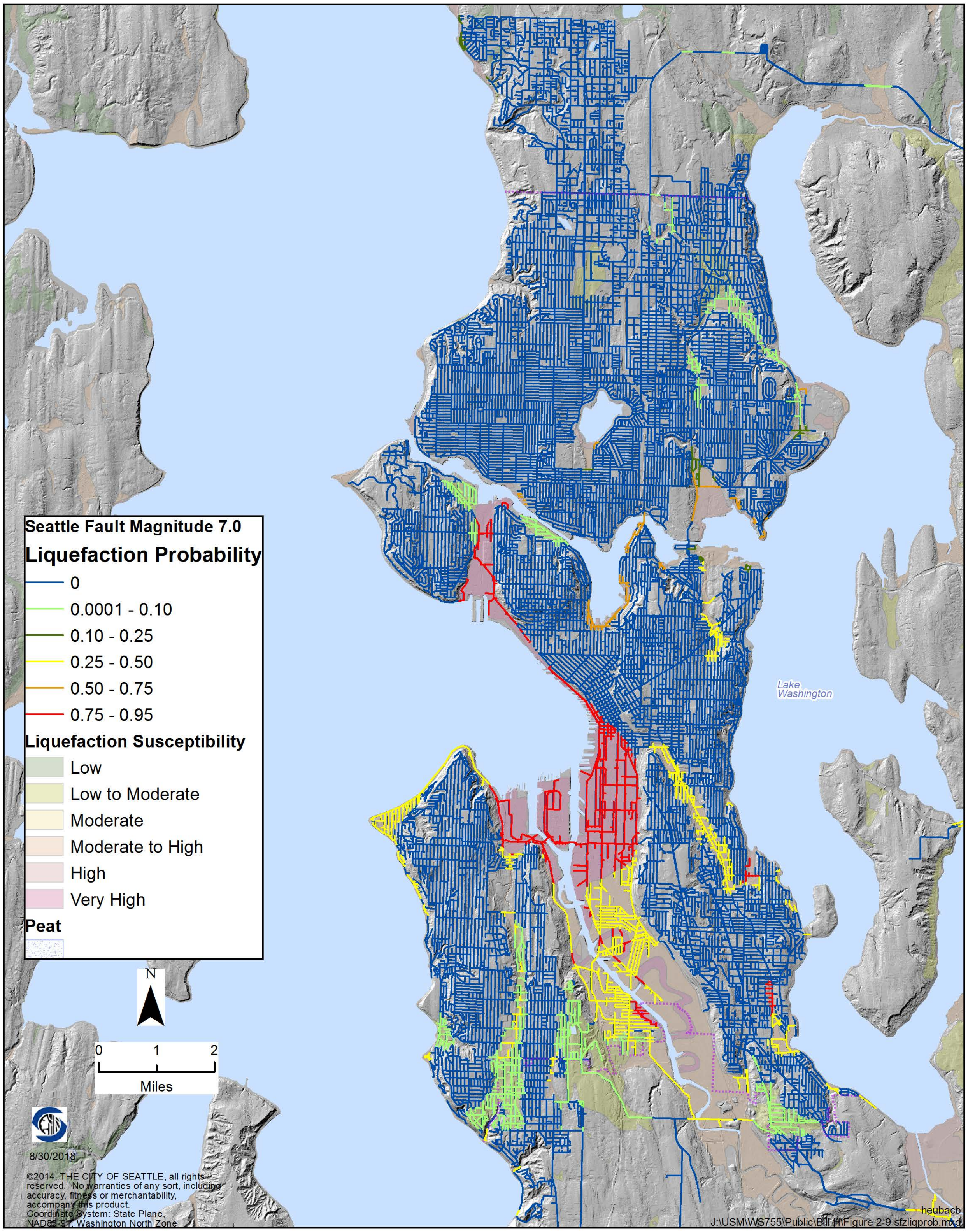


Figure 2-9. M7.0 SFZ liquefaction probability of occurrence estimates

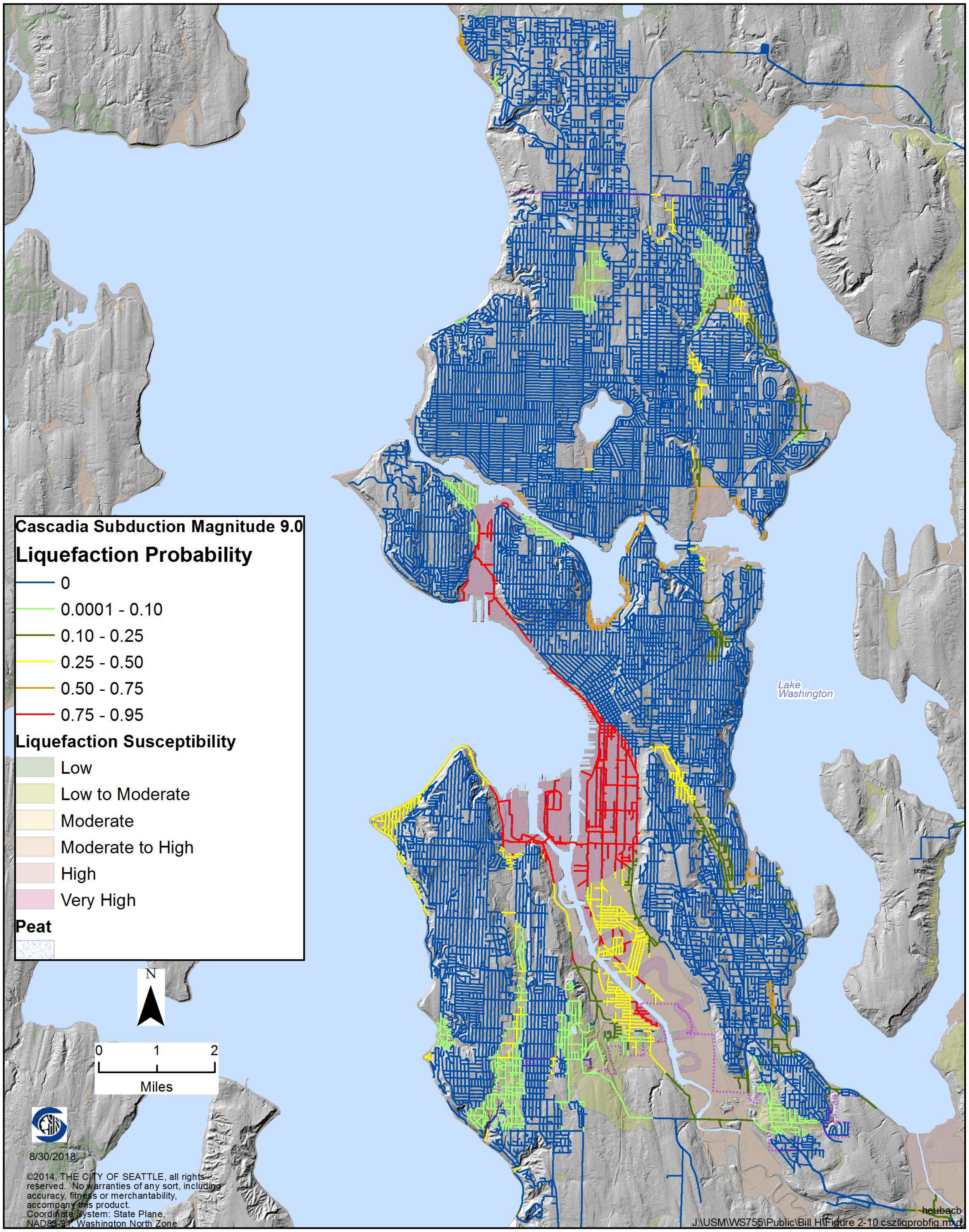


Figure 2-10. M9.0 CSZ liquefaction probability of occurrence estimates

2. REGIONAL SEISMICITY, EARTHQUAKE SCENARIOS, AND SEISMIC HAZARDS

There is evidence that surface faulting has occurred in Seattle during past Seattle Fault earthquakes. At least 3 meters (10 feet) of uplift occurred in Seattle during the most recent Seattle Fault event (Arcos 2012).

The shallow faults that comprise the SFZ and SWIF systems are complex seismologic structures that are not fully understood. The Seattle Fault is actually a fault zone that is 80 kilometers (50 miles) long and up to 8 kilometers (5 miles) wide. The fault zone is comprised of two distinct zones that are shown on Figure 2-11:

- Zone A: where north-directed tilting/monoclinal folding and discrete fault rupture are possible
- Zone B: where surface deformations form north-dipping back thrusts are possible

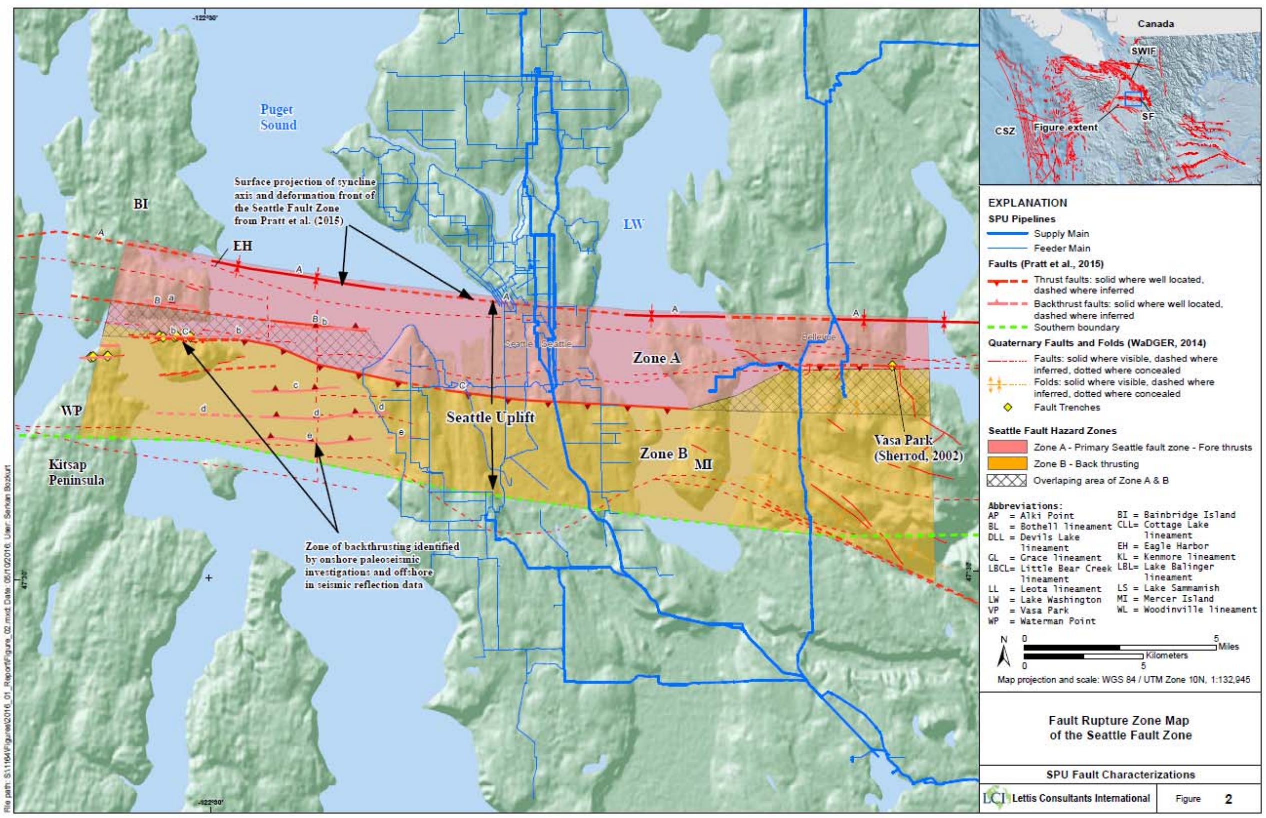


Figure 2-11. Seattle Fault Zone (Map by Lettis Consultants International 2016a)

Estimates show that 6 meters (approximately 20 feet) of uplift, distributed over 100 to 200 meters (approximately 110 to 220 yards), in addition to 1 to 3 meters (approximately 3 to 10 feet) of discrete surface displacements, is possible in Zone A (Lettis Consultants International 2016a). In Zone B, there is the possibility of 1 to 3 meters (approximately 3 to 10 feet) of discrete surface displacement.

2.4.4 Tsunami and Seiche

Although a M9.0 CSZ earthquake could generate large tsunamis comparable to those observed in Japan in 2011, natural attenuation of the tsunamis and the interference of the San Juan Islands would likely reduce the tsunami height to less than a meter (or 3 feet) (Meyers and Baptista 2016) by the time the tsunami reached Seattle. However, uplift and/or subsidence of the Seattle Fault below Puget Sound could create a more significant tsunami along Puget Sound shores. As Figure 2-12 shows, inundation depths could exceed 2 meters (approximately 6 feet) in some parts of Seattle.

The only SPU water system facilities that might be impacted by a tsunami are some buried pipelines along the shoreline. Scouring and/or brackish water inundation could affect the performance of these pipelines. Because pipeline damage from PGDs would likely be the predominant type of damage, pipeline repairs from potential tsunami effects were not modeled. However, if pipelines are inundated by brackish water, special disinfection measures will be needed to return the pipelines to service.

Ground-shaking can cause large waves and sloshing in lakes and other bodies of water. This phenomenon is called a seiche. SPU has dams and some facilities that are located close to large bodies of water that may be impacted by seiches.

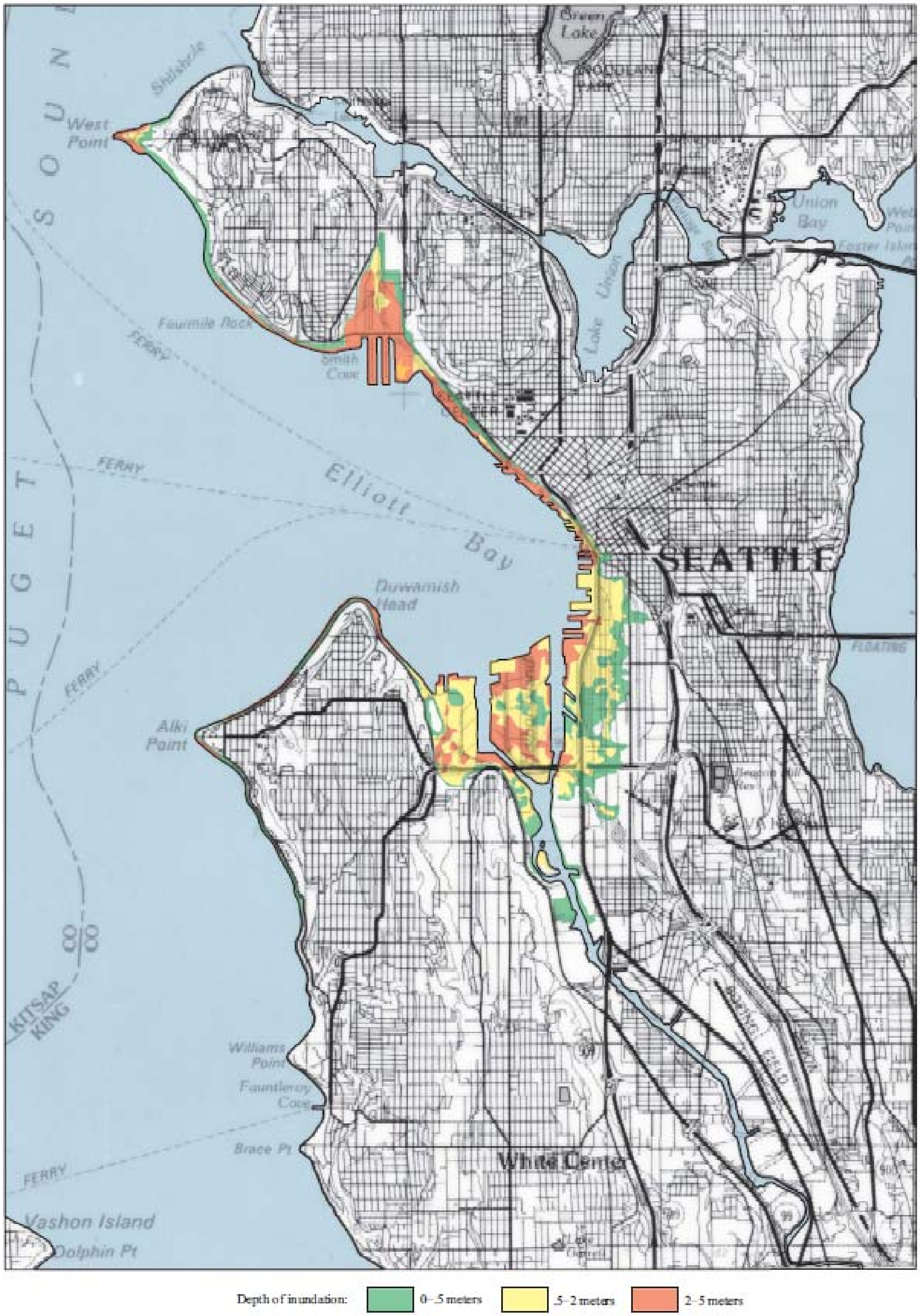


Figure 2-12. Tsunami inundation map for Seattle from a Seattle Fault event (Walsh et al. 2003)

5. WATER SYSTEM POST-EARTHQUAKE PEFORMANCE AND RESTORATION

This section describes how the overall SPU water system would be expected to respond to the M7.0 SFZ and M9.0 CSZ earthquake scenarios. The individual facility vulnerabilities summarized in Sections 3 and 4 were used to estimate the system response. The impact of the two earthquake scenarios was assessed, but because 2014 USGS Ground Motions will not occur simultaneously at every location throughout the system, the system response to the 2014 USGS Ground Motions was not evaluated.

5.1 System Response Model

5.1.1 Model Choice and Format

InfoWater (uses EPANET hydraulic model engine) hydraulic modeling software was used to estimate system response for approximately the first 48 hours after each scenario. SPU's System Storage and Reliability Analysis (SSRA) water system model was used. Instead of modeling all of the pipes in SPU's system, the SSRA model uses a skeletonized model of the SPU system. Only the downtown area is not skeletonized. This primarily skeletonized model aggregates pipeline demand locations, so there are approximately 2,640 nodes that connect 3,338 pipelines. The SSRA model was chosen because the EPANET hydraulic model engine was not originally intended to analyze system response after extreme events, such as post-earthquake performance. The reduction in the number of pipelines and nodes makes it easier for EPANET to converge to produce results, while still realistically modeling the system.

The SSRA model schematic is shown on Figure 5-1. The blue lines represent the SSRA model pipelines and the brown dots represent the nodes. For clarity, the reservoirs and pump stations in the model are omitted from Figure 5-1.

5.1.2 Model Inputs and Assumptions

Vertical facility (i.e., pump stations, reservoirs, tanks, etc.) availability after an earthquake was based on the findings summarized in Section 3. Because the Seattle Wells, which can supply up to 10 mgd in an emergency, do not have backup power, they were assumed to be nonfunctional for the hydraulic modeling runs. Pump stations that would remain functional were assumed to have backup power available after each earthquake scenario.

The assumptions used to estimate the severity of pipeline repairs were based on the Federal Emergency Management Agency's (FEMA) Hazus model (2015). Breaks were defined when a pipeline could no longer carry water. A leak was defined when water escaped from the pipeline, but the pipeline could still convey flow. Per Hazus, PGD failures were assumed to consist of 80% breaks and 20% leaks. Conversely, 20% of the wave propagation failures were assumed to be complete breaks and the other 80% were assumed to be pipeline leaks.

For modeling purposes, the individual flow rate through a break was estimated as the amount of flow that could be provided at the end of a 2,000-foot-long open pipe that was supplied with water at 60 pounds per square inch (psi). In order to account for multiple distribution network pipelines that may be feeding a break, the first 1000 feet was assumed to have a diameter equal to twice the diameter of the broken pipeline. The second 1000 feet was assumed to have a pipe diameter equal to the diameter of the broken pipeline. Because a break may be fed from both sides, the water loss through a break was estimated as 1.5 multiplied by the water loss flowing in one direction. A 2.0 multiplier was not used because the flow from one side may affect (reduce) the available flow from the other side.

The water flow through an average leak was estimated as the flow through a circumferential opening of 0.04 inches, such as the opening that might occur from a circumferential crack in a brittle joint, at 60 psi. These assumptions were analogous to the assumptions used by Kennedy/Jenks/Chilton and Dames and Moore (1990) in a study sponsored by USGS.

The leaks in each pressure zone were converted to equivalent breaks by multiplying the number of leaks by the ratio of the calculated leak rate to the calculated break rate. Because nearby pipeline breaks and leaks will influence the volume of water that could flow out of each repair, the effective volume of water that would be lost was reduced in each pressure zone such that

$$WL_{rate} = N_{equiv} WL_1 \left\{ \frac{0.000001}{\frac{N_{equiv}}{L}\left[1 - exp\left(\frac{-N_{equiv}}{10}\right)\right]} \right\}$$

Where

$WL_{rate} = the\ total\ water\ loss\ in\ area\ or\ pressure\ zone$
$N_{equiv} = the\ number\ of\ equivalent\ breaks$
$WL_1 = the\ water\ loss\ from\ one\ break$
$L = length\ of\ water\ mains\ in\ pressure\ zone\ (feet)$

This equation is based on engineering judgement. The philosophy behind the equation is that the amount of water that can be lost in a pressure zone or area break rate is a function of both the number of equivalent breaks and the equivalent break rate. The maximum water loss rate is set as the number of equivalent breaks multiplied by the water loss through a single break. Although a complex analysis may yield a more representative equation, the overall hydraulic modeling results would likely not be significantly affected.

The aggregated water loss values were then assigned to representative nodes in the SSRA model that most closely matched the node(s) the aggregated pipe failure would affect. The water loss in gallons per minute (gpm) at 60 psi, and assigned locations (SSRA model nodes), are shown on Figures 5-2, 5-3, 5-4, and 5-5 for the M7.0 SFZ scenario. The water losses

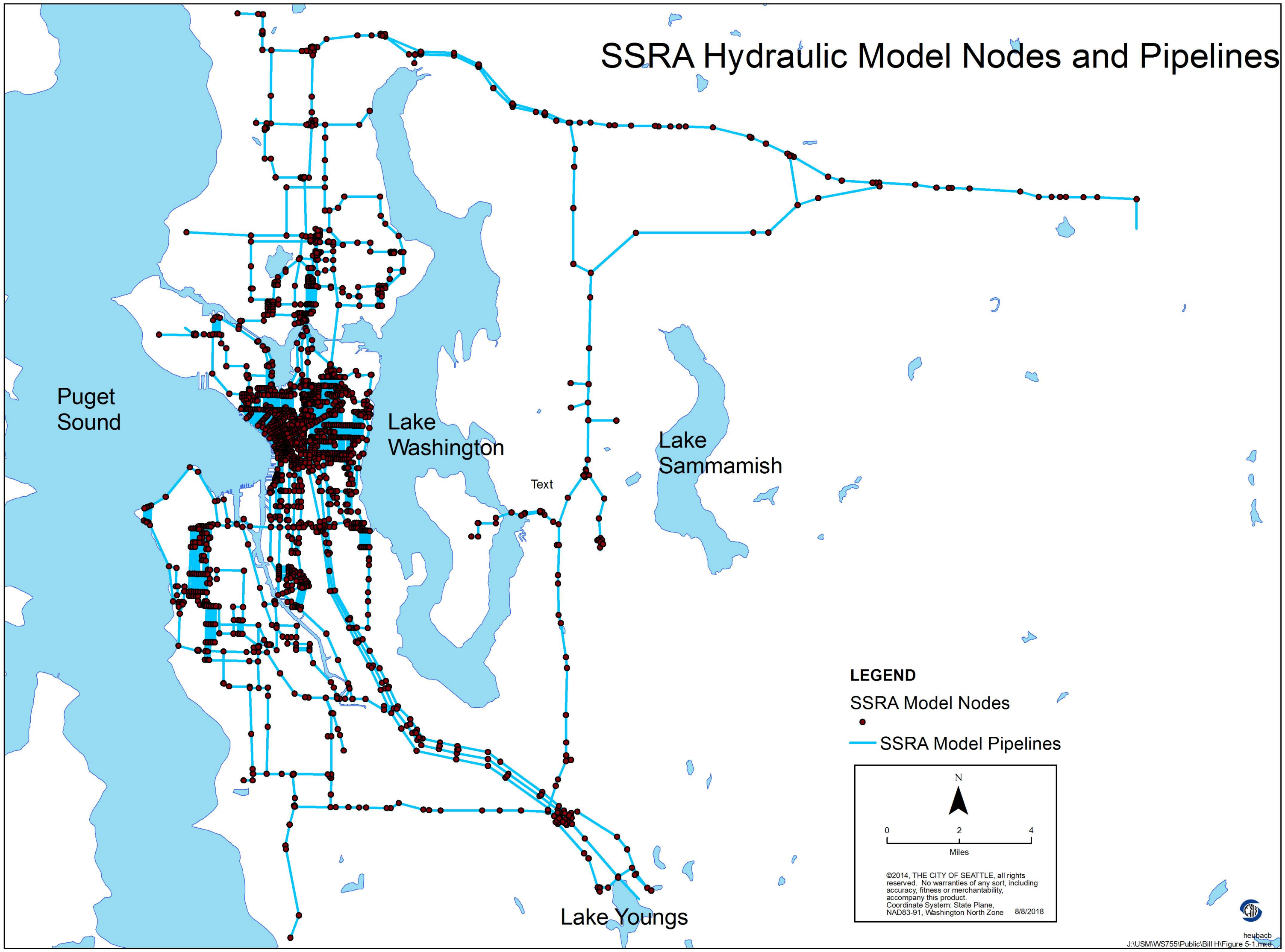


Figure 5-1. SSRA model schematic

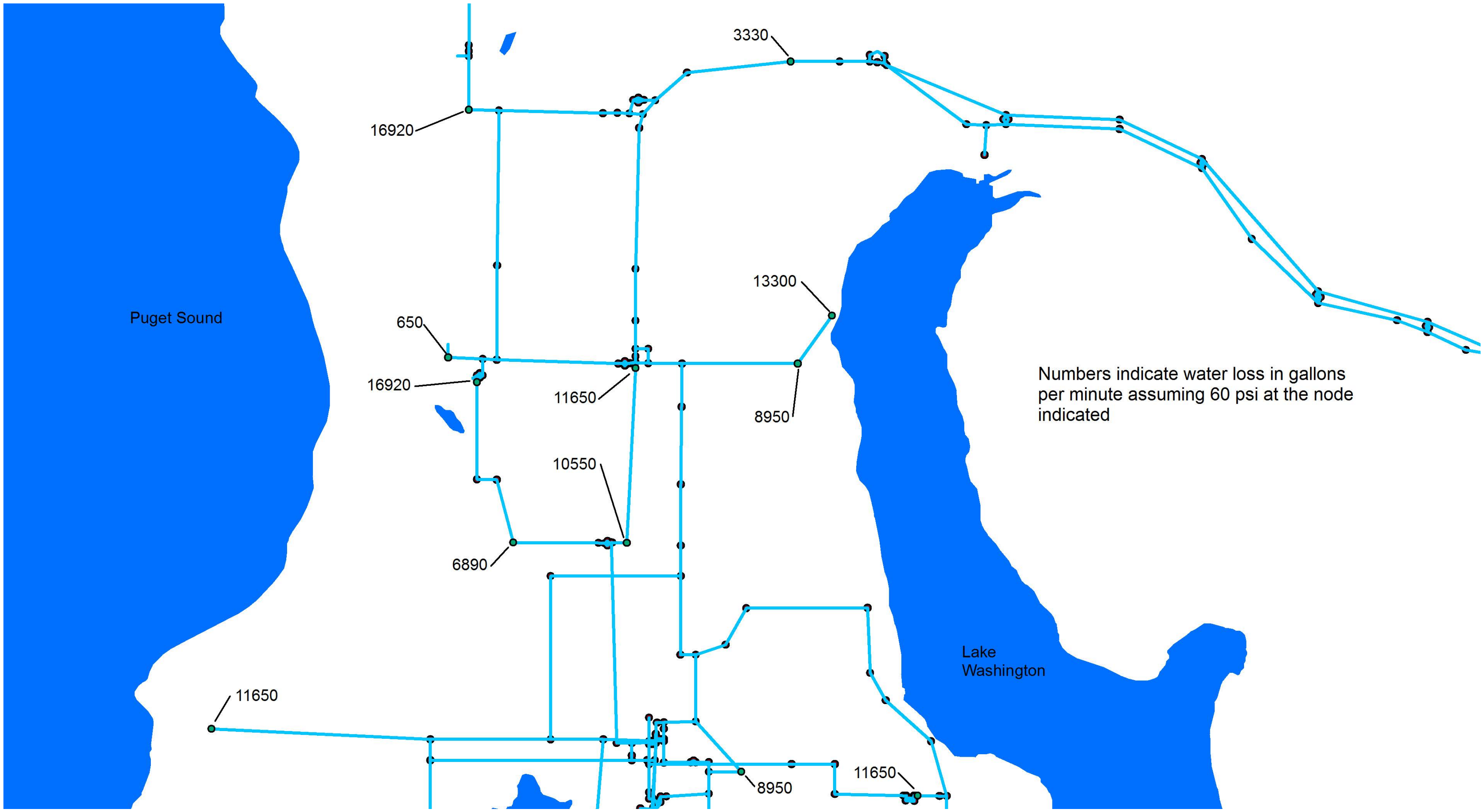


Figure 5-2. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (north service area)

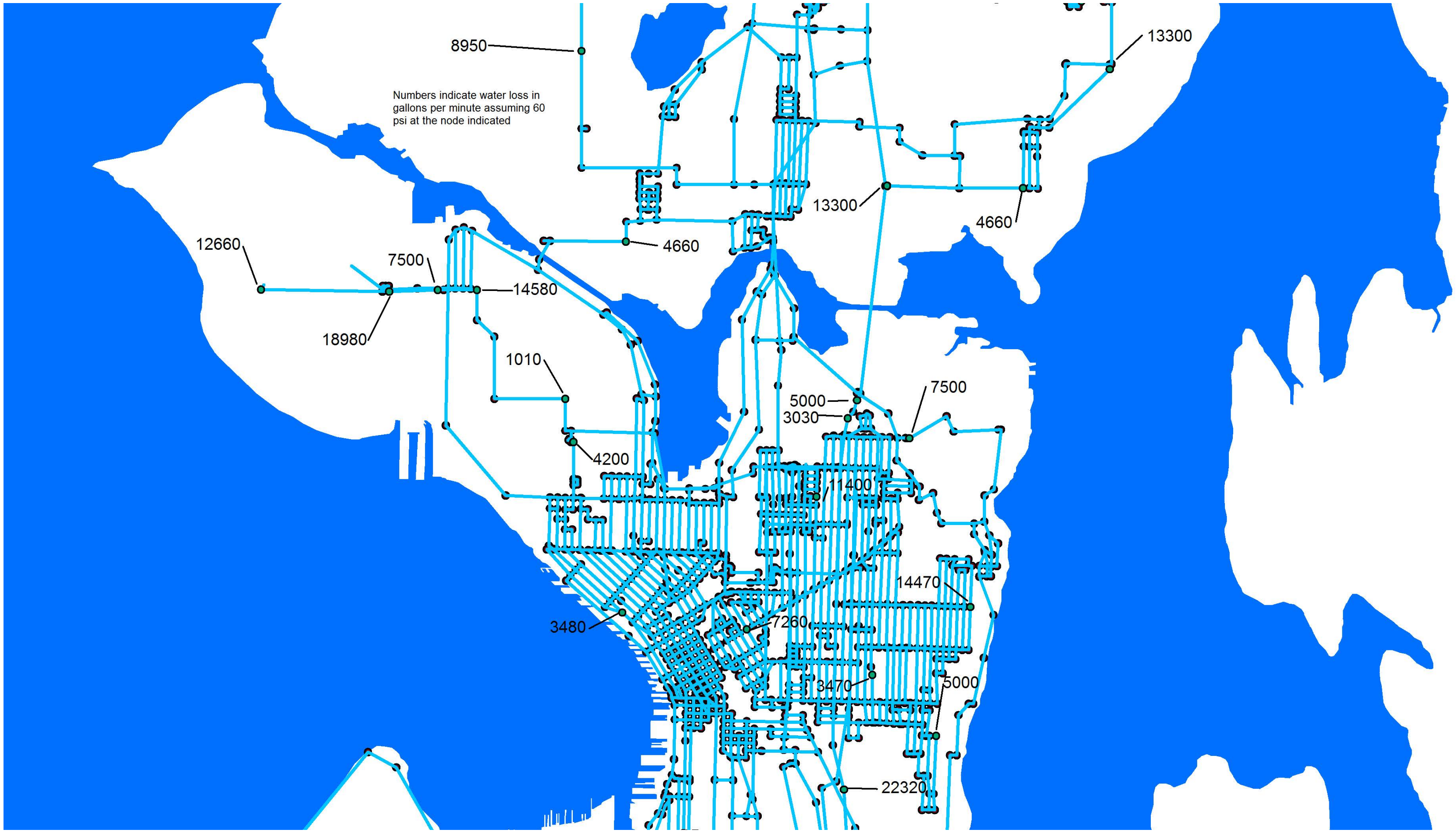


Figure 5-3. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (north central direct service area)

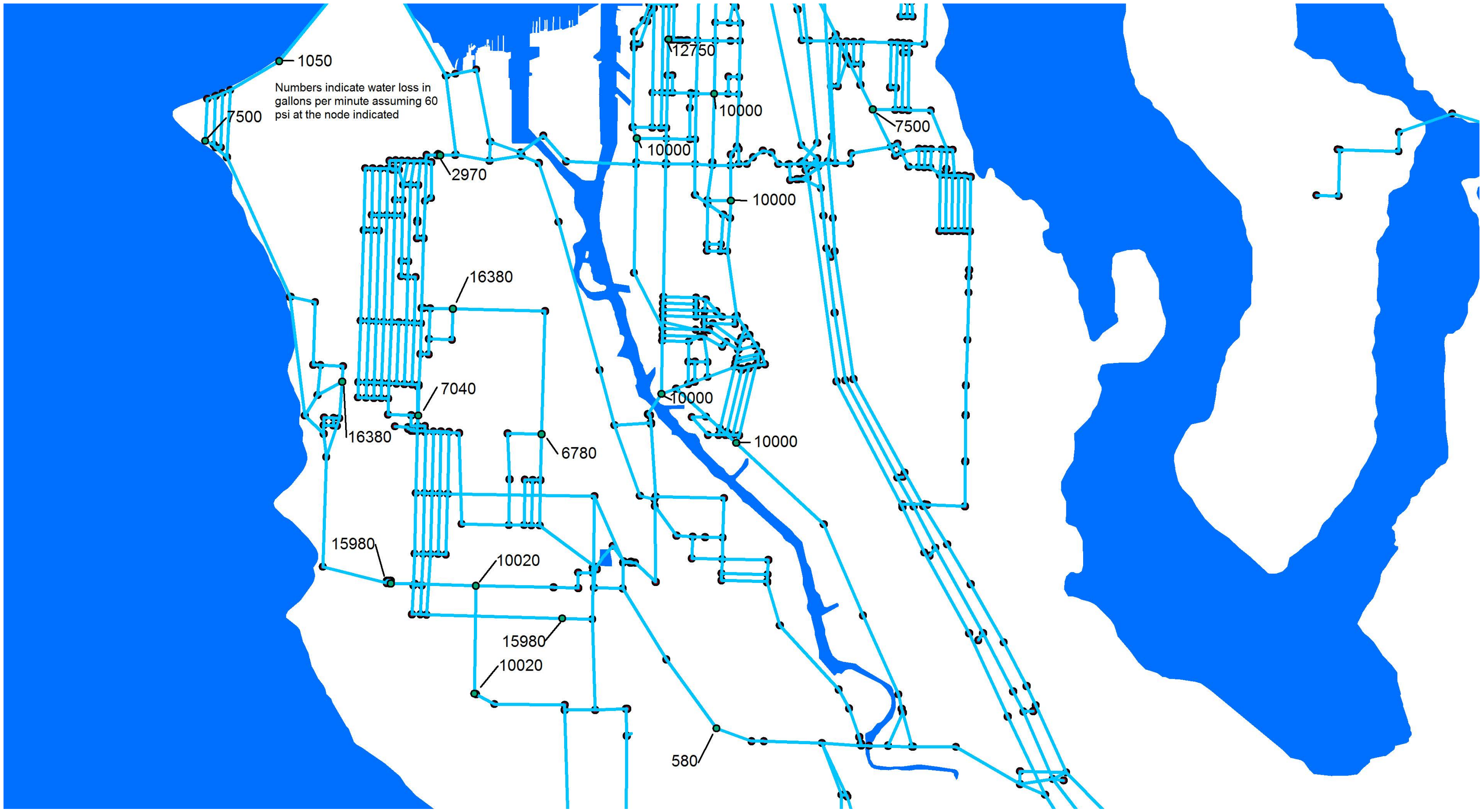


Figure 5-4. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (south central direct service area)

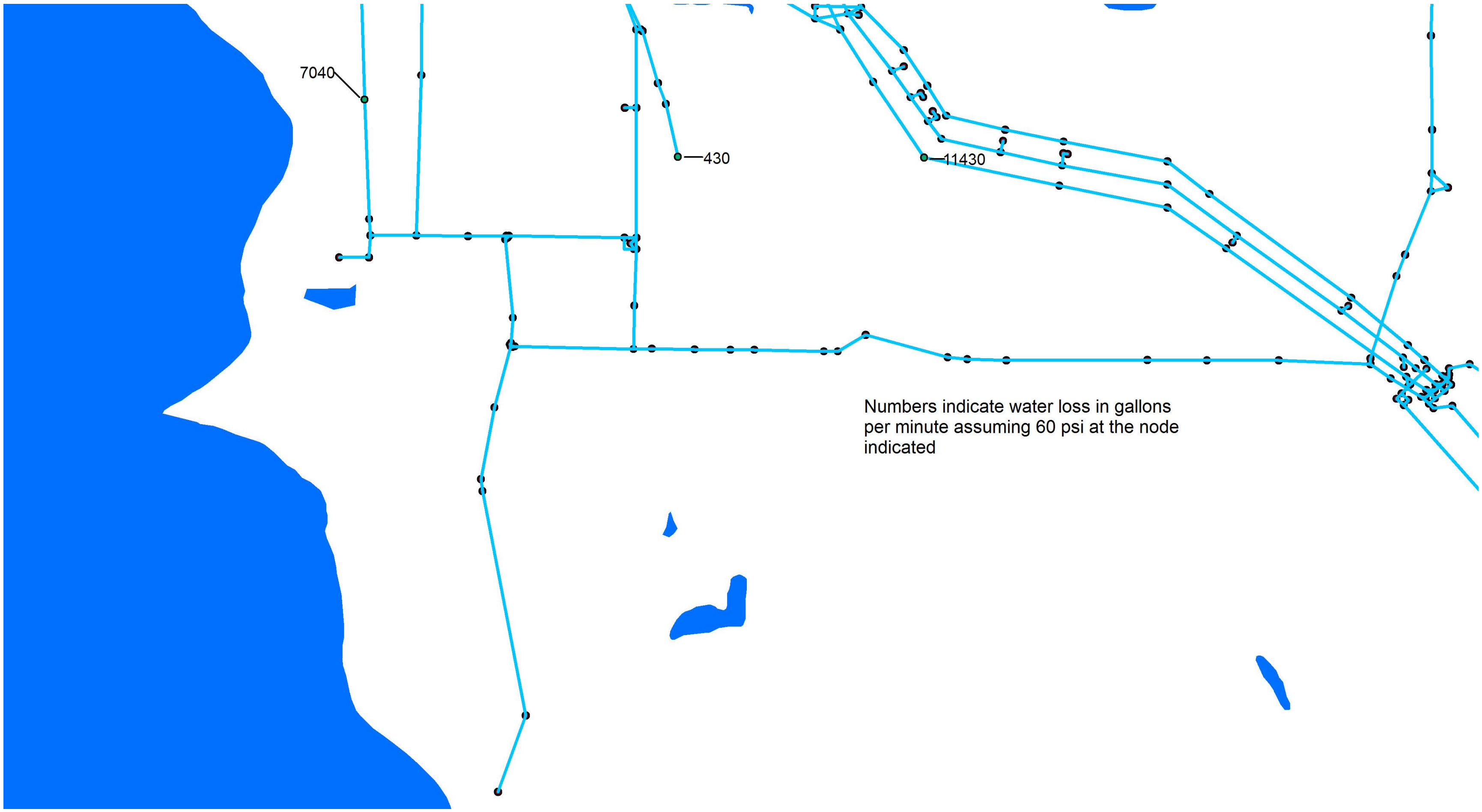


Figure 5-5. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (southern direct service area)

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through broken pipes were modeled in accordance with the equation:

$$Q = Cp^{\gamma}$$

Where,

Q = *the flow rate.*
C = *the emitter coefficient.*
p = *the pressure.*
γ = *the pressure coefficient (assumed to be 0.5).*

For both the M7.0 SFZ and M9.0 CSZ scenarios, the approximate water loss through all pipe failures was approximately 500,000 gpm at 60 psi (equivalent to 720 mgd).

After a major earthquake, nonessential water demand would likely be curtailed and industries that use large volumes of water would also be expected to curtail operations until damage assessments could be completed. Consequently, low winter demand (water only for essential purposes) was assumed. As water pressure dropped, demand would also drop. Because demands that are independent of pressure can cause the model to calculate negative pressures and become unstable, Arcadis zoned off areas when the area pressures dropped below zero. A future refinement could be to define demand only as equivalent emitters or a combination of emitters and demand.

The transmission pipeline vulnerability assessments presented in Section 4 showed that it is unlikely that the transmission systems would be able to supply water to the direct service area immediately after the M7.0 SFZ or M9.0 CSZ scenarios.

The following vertical facilities were assumed to be nonfunctional after the M7.0 SFZ scenario:

- Pump Stations
    - Augusta Pump Station
    - Broadway Pump Station
    - Fairwood Pump Station
    - Lincoln Pump Station
    - Maplewood Pump Station
    - SW Spokane Street Pump Station
    - SW Trenton Pump Station
    - West Seattle Pump Station

- Reservoirs and Tanks
    - Beverly Park Elevated Tank
    - Charlestown Standpipe
    - Eastside Reservoir
    - Foy Standpipe
    - Magnolia Bluff Elevated Tank
    - Magnolia Reservoir
    - Riverton Heights Reservoir
    - View Ridge Reservoir

  - Volunteer Park Standpipe

After the M9.0 CSZ scenario, the following vertical facilities are assumed to be nonfunctional:

- Pump Stations
  - Augusta Pump Station
  - Broadway Pump Station
  - Lincoln Pump Station
  - SW Spokane Street Pump Station

- Reservoirs and Tanks
  - Beverly Park Elevated Tank
  - Foy Standpipe
  - Magnolia Bluff Elevated Tank
  - Riverton Heights Reservoir
  - View Ridge Reservoir
  - Volunteer Park Standpipe

5.2 Direct Service Area Model Results

Direct service area response was modeled for 12 cases. Each case represented different assumptions based on SPU water system infrastructure seismic improvements. A base case was run for the M7.0 SFZ and M9.0 CSZ scenarios that used the results of this study's seismic vulnerability assessments to model system response in the "as-is" condition. Comparison of the base case results for the M7.0 SFZ and M9.0 CSZ scenarios shows that although more of the system initially stays pressurized for the M9.0 CSZ scenario, water pressure is completely lost throughout the system in both scenarios approximately 22 hours after the earthquake and the pressure loss follows the same pattern (see Figure 5-6 which shows the fraction of the direct service area with water pressure versus time after the earthquake). In order to run representative cases with the available resources, subsequent cases that showed system response for potential mitigation improvements were only run for the M7.0 SFZ scenario.

The cases are summarized in Table 5-1. These cases are representative of different mitigation approaches, but do not represent all potential mitigation approaches. The scenarios shown in Table 5-1 are mitigation strategies that are believed to provide the most cost-effective improvements to SPU's water system resiliency. It will take 100 years or more SPU's distribution pipelines can be made earthquake-resistant. Proposed mitigation strategies that are evaluated include transmission pipeline improvements, isolating areas of expected distribution pipeline damage, and evaluating the effects of direct service storage capacity. As mitigation strategies are further defined and developed, SPU's intent is to use the SSRA hydraulic model to evaluate the system response improvements that the mitigation approaches would provide.

The hydraulic models were run from the time of the earthquake to 48 hours after the earthquake. Within approximately 24 hours of an actual earthquake, system controls and valves would start to be reset so system response shown by the hydraulic modeling results may be significantly different than the actual response.

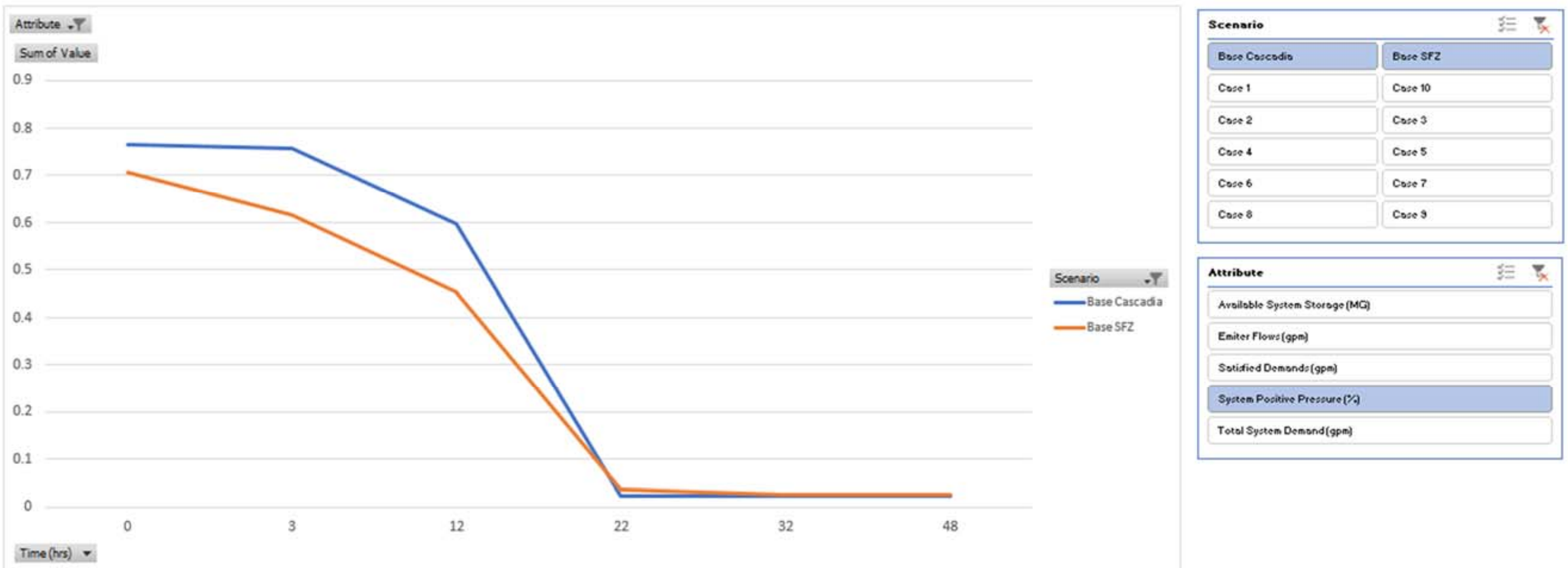

Figure 5-6. Fraction of direct service area (vertical axis) with water pressure versus time (horizontal axis) for M7.0 SFZ and M9.0 CSZ base cases

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	Mitigation Improvements									
Case	A-1	A-2	A-3	B-1	B-2	C	D	E	F	G
CSZ – Base										
SFZ – Base										
SFZ – 1				✓		✓				
SFZ – 2	✓	✓	✓	✓	✓	✓				
SFZ – 3				✓		✓	✓	✓		
SFZ – 4	✓	✓	✓	✓	✓	✓	✓	✓		
SFZ – 5									✓	
SFZ – 6						✓			✓	
SFZ – 7										✓
SFZ – 8							✓	✓		
SFZ – 9						✓				✓
SFZ – 10	✓			✓		✓				

Table 5-1. Hydraulic modeling cases

Mitigation improvement key:

A-1 Make one of the CRPLs seismic resistant from Lake Youngs to Maple Leaf Reservoir

A-2 Make the West Seattle Pipeline seismic resistant

A-3 Seismically upgrade CRPLs at Martin Luther King Boulevard slide area, and CRPLs through Renton and Tolt Pipelines at Norway Hill.

B-1 Seismically upgrade the following facilities: Eastside Reservoir, Magnolia Bluff Elevated Tank, Magnolia Reservoir, Riverton Heights Reservoir, Broadway Pump Station, Lincoln Pump Station, SW Spokane Street Pump Station, and West Seattle Pump Station

B-2 In addition to the B-1 upgrades, seismically upgrade Beverly Park Elevated Tank, Charlestown Standpipe, Foy Standpipe, View Ridge Reservoir, Volunteer Park Standpipe, Augusta Pump Station, Fairwood Pump Station, Maplewood Pump Station, and Trenton Pump Station

C Isolate areas with heavy distribution pipe damage

D Assume Volunteer Park Reservoir is online

E Assume Roosevelt Reservoir is online

F Assume the Cedar transmission system can convey water into the direct service area

G Assume the Tolt transmission system can convey water into the direct service area

The complete hydraulic modeling results are presented in Appendix B. Significant findings include the following:

- Under the M7.0 SFZ and M9.0 CSZ scenarios, SPU's direct service area served by the distribution system could completely lose pressure in 16 to 24 hours after the earthquake (see Figure 5-6).
- The higher elevation pressure zones would be more likely to lose pressure first (see Appendix B, SFZ Result Base), since the lower elevation areas tend to be served by larger reservoirs that take longer to drain out. The model also showed that because the southern area of the 326 pressure zone can be supplied by several large reservoirs and is the lowest zone that can be supplied by these reservoirs, it would be the last zone to lose pressure. This is somewhat surprising and may not be indicative of actual performance since so many main failures are expected in this area. Although the watermains would be draining in this area for 20 hours, water may not be available in many areas, particularly where the system had been cut off from the reservoirs by pipeline breaks.
- Isolating the area south of downtown would keep the downtown area pressurized for about six hours longer (see Appendix B, SFZ Results Base and SFZ Results Case 1). However, the downtown area would still run out of water once Lincoln Reservoir drained unless the pipeline that supplies Beacon Reservoir water to downtown has been upsized and made seismically resilient. If isolated, SODO would be immediately cut off from water after the earthquake.
- Seismically upgrading larger reservoirs, such as the Riverton Reservoir, could enable those areas served by these reservoirs to maintain water pressure for 16 hours or more. Even if seismically upgraded, smaller reservoirs and tanks, such as the Magnolia Elevated Tank, may only be able to provide water for an hour or two before pipe breakage drained the water from these smaller reservoirs.
- The ability to supply the direct service area from the Cedar River transmission system would have a significant impact on the system's ability to maintain water pressure throughout much of the direct service area. For the M7.0 SFZ scenario, Case 5 (SFZ Results Case 5 in Appendix B) suggests that over 50% of the direct service area could maintain pressure if the Cedar River transmission system was able to supply the direct service area, even if no other improvements to the system were made (see Figure 5-7). If only the Tolt River transmission system supplied the direct service area, pressure could still be lost throughout the direct service area (see Figure 5-8). Comparison of Figures 5-7 and 5-8 indicates that based on direct service area benefit, maintaining functionality of the Cedar transmission system should be given higher priority over the Tolt transmission system.

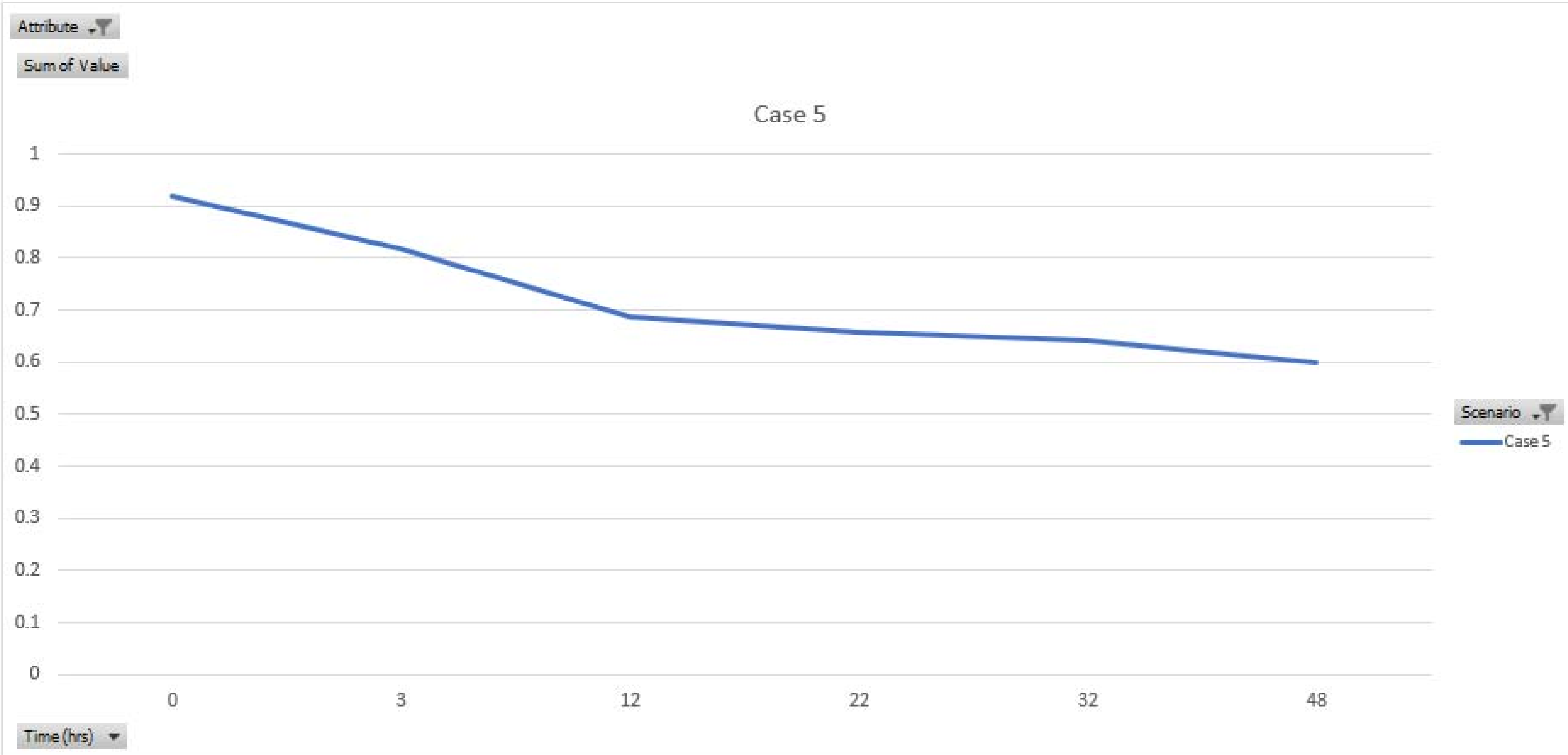

Figure 5-7. Fraction of direct service area with water pressure (vertical axis) versus time (horizontal axis) if the Cedar River transmission system could supply water to the direct service area

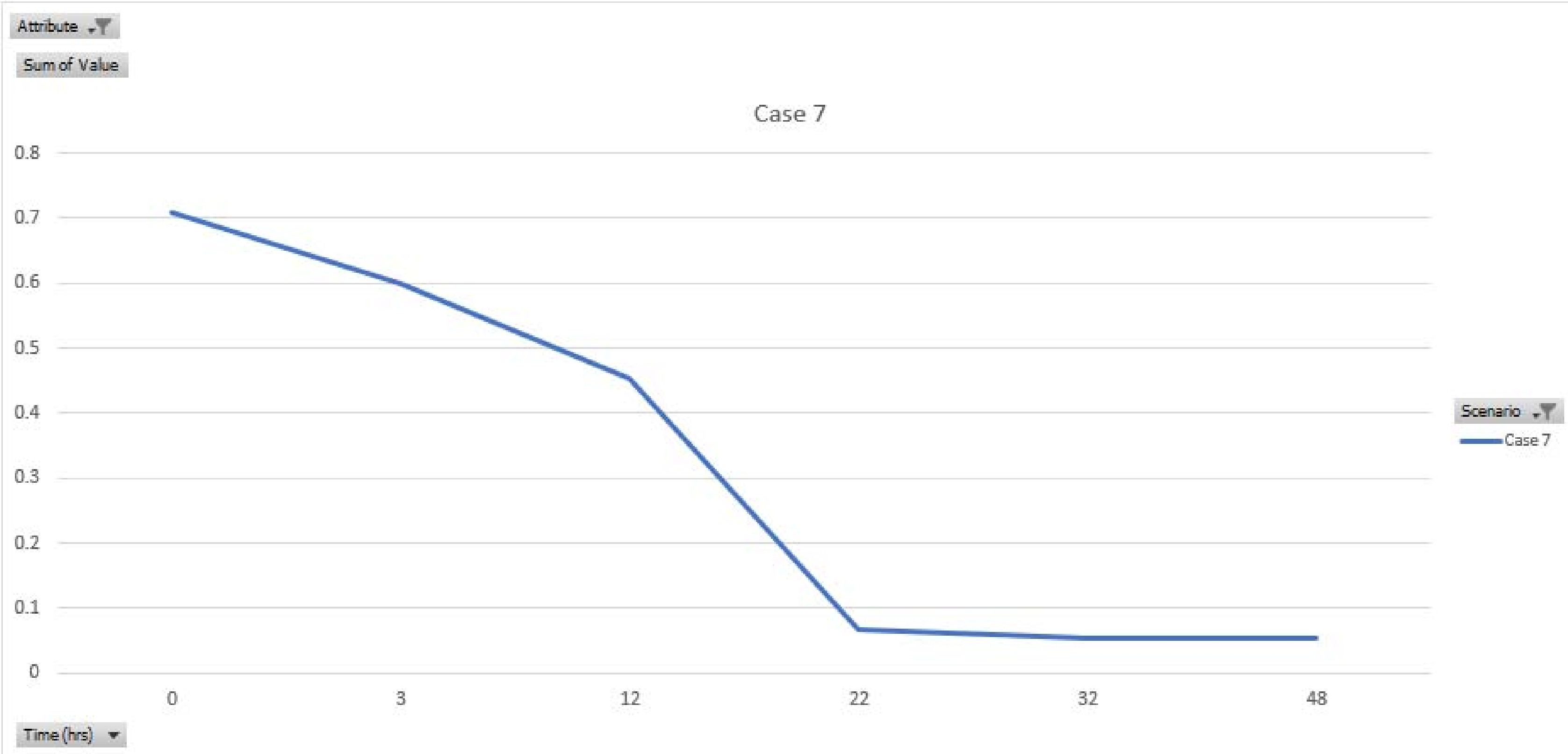

Figure 5-8. Fraction of direct service area with water pressure (vertical axis) versus time (horizontal axis) if the Tolt River transmission system could supply water to the direct service area

5.3 Water Service Restoration to the Direct Service Area

A workshop was held with SPU Field Operations staff to estimate how long it may take to repair damaged facilities. Because it can take years to replace some vertical facilities, work-arounds would have to be developed out of necessity. The emphasis at this workshop was on pipeline repairs. During the workshop, it was recognized that there is uncertainty regarding how many crews may be available, when they would be available, and the availability of other resources, such as equipment and repair materials. With the recognition that there is uncertainty in the repair capability assumptions, the following pipeline repair assumptions were made at this workshop:

- Distribution system repair priorities
    1. Hospitals/Hospital Zones
    2. Undamaged Residential
    3. Economic Zones

- Distribution system repair capabilities and assumptions
    - It is assumed that 8 to 12 hours plus preparation time would be needed per repair.
    - Crews would likely work shifts of 12 hours on, 12 hours off. For 12-inch diameter and smaller pipe, a typical crew consists of two pipe workers, a truck driver and an equipment operator. The truck is typically a Class 8 (10 yards) dump truck that pulls a trailered backhoe. More staff may be needed for larger diameter pipe repairs or in streets with heavy traffic.
    - Immediate availability of crews would depend on whether the earthquake occurs during working hours, or if the event happens off-hours when it would be difficult for staff to make it into Seattle.
    - SPU Field Operations estimated that it could probably have 15 crews repairing distribution pipelines within three days, and have 30 crews available in seven days.
    - It would take mutual aid crews from other agencies two weeks to arrive.
    - Including both preparation and actual repair time, it is assumed one crew could complete one repair per 12-hour shift.
    - Repairs could only be made if the system could be pressurized (i.e., water needs to be available in the areas being repaired).

- Transmission pipeline repair
    - Repair crew availability
        - SPU Field Operations advised that there would probably be two transmission pipeline repair crews, though more crews might be available if distribution system staff and watershed equipment could be used.
        - SPU would probably not use mutual aid crews for this repair work, given that they might not have the necessary large diameter pipeline experience.
    - Leak repair time
        - Repair time will depend on accessibility, the amount of pipe that needs to be dewatered, proximity to valves, regulations that would need to be

followed when pipelines are dewatered, welder availability (for steel pipe), and pipe size/diameter.
    - In the best-case scenario, a leak repair could probably be done in three days, but it may take as long as seven days depending on the factors mentioned above.
  - Break repair time
    - Repair time will depend on accessibility, the amount of pipe that needs to be dewatered, proximity to valves, regulations that would need to be followed when pipe is dewatered, welder availability (steel pipe), pipe size/diameter, the length of pipe that must be replaced, and pipe depth.
    - SPU personnel expressed concerns regarding shoring and safe access to deep trenches as aftershocks may occur at any time.
    - Assuming that pipe materials would be readily available, in the best-case scenario, it would take crews five days to replace a single standard length of pipe. However, repair time could be as long as 10 days.
    - Lock-bar and riveted pipe would be more difficult to repair, but extra repair time is likely on the order of hours.
  - Leaks and breaks below rivers
    - SPU Field Operations advised that they may have to delay repairing a leak in these locations until the emergency is over.
    - Repair time would depend on accessibility, amount of pipe that needs to be dewatered, proximity to valves, regulations that would need to be followed when pipe is dewatered, welder availability (steel pipe), pipe size/diameter, length of pipe that must be replaced, and pipe depth.
    - Depending on the repair method that is required, repair time at these locations could take from six months to a year.
    - It would likely take approximately one month to install a temporary pipeline, such as floating high-density polyethylene (HDPE) pipe across a river to bypass a leak or break.

Repair time estimates for vulnerable transmission pipeline locations are shown in Table 5-2.

There is uncertainty as to how long it would take SPU to restore water pressure to the direct service area. Although the Water Research Foundation, working with consulting firm SPA Risk and member utilities, recently completed a more rigorous water system restoration model (Porter 2018), this model was not available for this study. Best-case and worst-case scenarios were developed to generate the restoration curves shown on Figure 5-9. These curves are representative of both the M7.0 SFZ and M9.0 CSZ events.

The underlying assumptions of the best-case curve are:

- There is always enough supply from the transmission system to meet whatever amount of water the distribution system can provide.
- After two days, enough valves can be closed to restore 10% of the system.

Failure Location	Estimated Restoration Time	Comments
CRPLs @ Renton	3 to 4 weeks	CRPL 1 and CRPL 3 pass through the old Black River channel and CRPL 2 passes below the Black River channel; multiple sections could break.
CRPLs @ MLK	1 to 2 weeks (bottom of hill) 3 to 4 weeks (top of hill)	If break occurs near top of the hill, much of hill could be washed away. There could also be issues with tree debris.
CRPLs @ I-90	5 to 10 days	
CRPLs @ Seattle Fault Rupture	6 to 8 weeks	Assumes 10 feet of offset. If offset occurs across a plain, extensive regrading would be needed. If offset were more gradual, approximately 100+ feet of pipe would need to be replaced.
CRPL 4 @ Green River Valley	8 to 12 weeks (failure at riverbank(s)) 6 to 12 months (failure below river)	
West Seattle Pipeline @ Duwamish River Valley	8 to 12 weeks (failure at riverbank(s)) 6 to 12 months (failure below river)	
Tolt Pipelines @ Norway Hill	3 to 4 weeks	Assumes hillside is eroded out
CESSL @ Cedar River	3 to 4 weeks	Assumes failure occurs in the valley and not under the river or in the steep slope north of the river
CESSL @ Seattle Fault Rupture	6 to 8 weeks	Assumes 10 feet of offset. If offset occurs across a plane extensive regrading would be needed. If offset were more gradual, approximately 100+ feet of pipe would need to be replaced.

Table 5-2. Transmission pipeline repair time estimates

Note: All restoration times assume specific repair materials would be available locally when needed

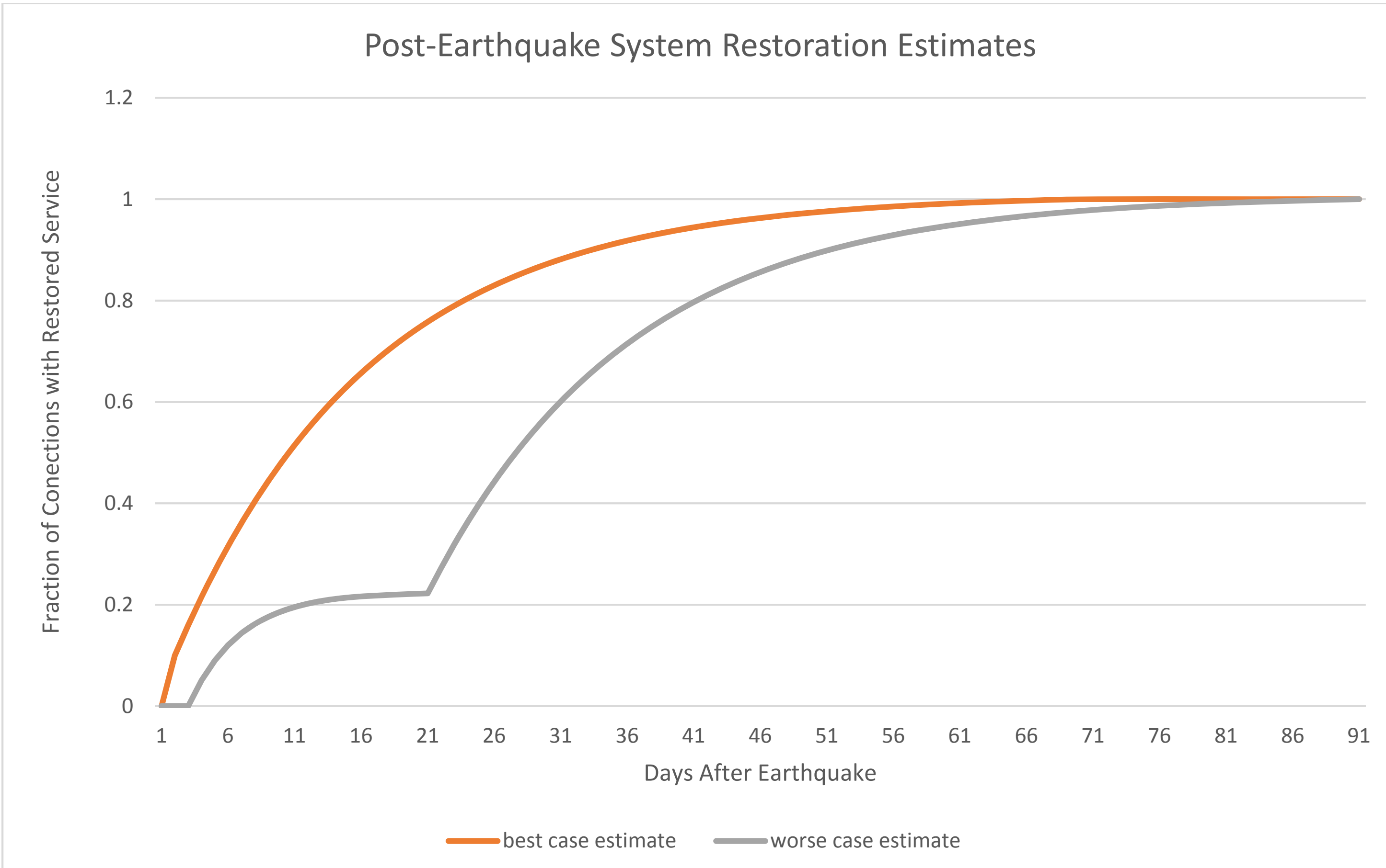

Figure 5-9. System restoration estimation curves for current SPU water system

- Fifty repairs are done in the first five days, and then 30 repairs a day after that so that it takes 70 days to complete the distribution repairs.
- The percentage of customers without water is modeled by a decaying exponential curve from Day 3 through 70. This means that it is assumed that those repairs that return service to the largest areas will be given highest priority.

The underlying assumptions of the worst-case curve are:

- The Tolt and Cedar Watershed sources are unavailable due to transmission system damage for 21 days following the earthquake.
- After 21 days, enough water to supply low winter day demand is available from the transmission systems. The sharp change in the slope of the worst-case curve results from the assumption that until 21 days after the earthquake, only water from the Seattle Wells will be available. When water from the Tolt and/or Cedar system becomes available, restoration of service will begin to occur more rapidly since the wells can only provide 10 mgd which is only approximately 20% of the direct service area winter day demand.
- All storage in the system, except for the reservoirs adjacent to or upstream of the Cedar and Tolt treatment plants, drain out completely.
- The Seattle Wells become operational three days after the earthquake and provide 10 mgd. It is possible that well-casing damage or turbidity could prevent the wells from immediately reaching full capacity. Because use of the full well capacity is assumed to take time (see following assumptions), the assumption of immediately reaching full capacity will not significantly affect the restoration curve.
- Forty-five mgd is needed to supply the direct service area at low winter demand.
- It takes 18 days to make full use of the water from the Seattle Wells, and the restoration curve is shaped like a decaying exponential.
- After enough water from the Cedar and/or Tolt systems becomes available to supply low winter demand to the direct service area, it takes 70 more days to completely restore service (a decaying exponential curve is again assumed).

5.4 Wholesale Turnout Water Availability

It is likely that in both scenarios, there would be multiple transmission pipeline failures. Fault rupture may even occur across the CRPL and CESSL alignments in the M7.0 SFZ scenario. Based on the SPU Field Operation workshop findings, it could take at least six to eight weeks to make repairs if large surface ruptures occurred. Repairs to permanent river crossings may even take longer. The Eastside Reservoir would likely lose functionality.

5.4.1 General Vulnerability of Transmission Pipelines that Serve Wholesale Customers

Although there are numerous areas that may be susceptible to geotechnical hazards along the Tolt Pipeline alignments, much of the alignment consists of welded-steel pipe with single lap-welded joints. These joints are not considered to be completely earthquake-resistant, but they do offer significantly more earthquake-resistance than concrete-cylinder pipe and riveted- and lock-bar steel pipe. Drawings seem to indicate that the designers were aware of the geotechnical conditions. In most instances, the designers likely did not consider large seismic movements, but at least allowed for the possibility of some nonseismic related ground instability.

The expected ground motions along most of the Tolt Pipeline alignment east of the Tolt Pipeline and TESSL junction (also known as TESS Junction) for both scenarios would be generally less than 0.25g. These ground motions are capable of causing PGDs along the Tolt Pipeline alignments. Damage to the Tolt Pipelines east of Norway Hill and the TESSL is possible, but even if damage occurs, there is a good chance that at least one pipeline would remain functional, or if repair was needed, emergency repairs could be completed in a week to 10 days.

The Cedar River Pipelines are generally older than the Tolt pipelines. They are more susceptible to damage since many portions were constructed with riveted steel and/or lock-bar steel pipe. There are long segments of concrete-cylinder pipe in both the Tolt and Cedar alignments, which are also highly susceptible to seismic damage.

Although the M7.0 SFZ and M9.0 CSZ will probably have the biggest impact on SPU's direct service area, a SWIF scenario could have an equal or greater impact on the SPU transmission system and some of SPU's wholesale customers. The SWIF zone runs southward from Whidbey Island across the Tolt Pipeline alignment and perhaps all the way to near to the Chester Morse Dam and beyond. Three to eight M6.0 to approximately M7.0 events are believed to have occurred in the SWIF zone in the last 16,400 years (Sherrod et. al. 2008) compared to at least five significant SFZ events in the last 3,500 years (Pratt et. al. 2015). A SWIF event could rupture the Tolt Pipelines upstream of the wholesale turnouts and also cause damage to the Eastside Supply Line severe enough to isolate many SPU wholesale customers for several weeks. The closer proximity of the SWIF zone to the Tolt Transmission System will likely result in more severe damage to the Tolt Transmission System. Many of SPU's wholesale customers will experience higher ground motions than those from the M7.0 SFZ or M9.0 CSZ scenarios and thus experience more damage within their individual distribution systems.

5.4.2 Transmission System Hydraulic Modeling Results

Because of the expected damage along the Cedar and Tolt River Pipeline alignments, it is likely that the transmission system will be unable to supply most wholesale turnouts after either the M7.0 SFZ or M9.0 CSZ scenarios. Figure 5-10 shows the water pressure throughout the SPU system immediately after the M7.0 SFZ scenario. The gray circles/nodes that indicate water pressure is not available at many of the wholesale turnouts. The expected loss of the Eastside Reservoir in the M7.0 SFZ scenario will mean that water will not be available for those turnouts that depend on this reservoir. In the M9.0 CSZ scenario, there is a higher likelihood that the Eastside Reservoir will remain functional.

5.5 Distribution System Storage Analysis

SPU operates several treated water storage facilities downstream of its Cedar and Tolt water treatment facilities, including covered reservoirs, standpipes, and elevated tanks. Some of the storage facilities are considered part of the transmission system and some are considered part

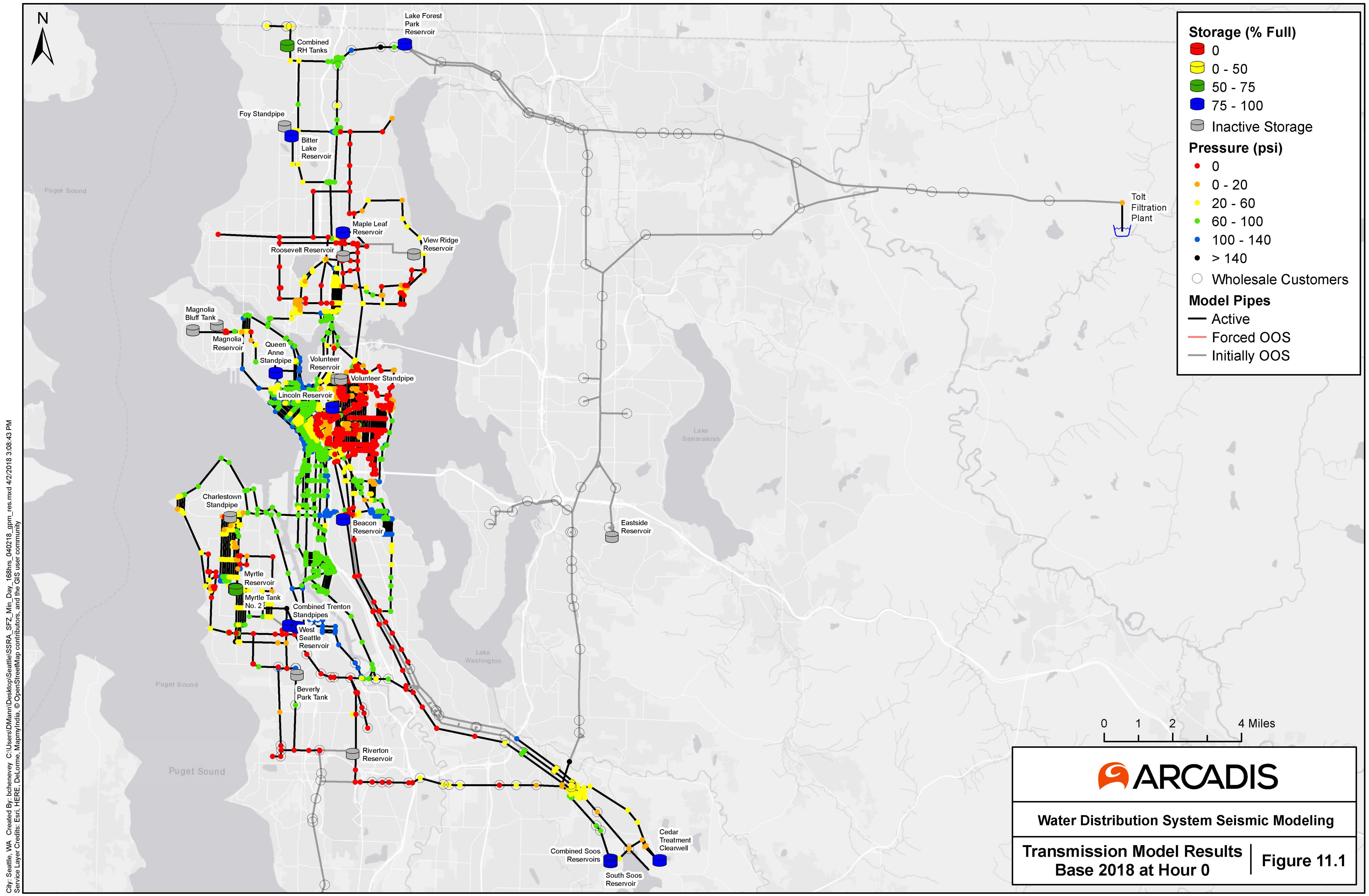

Figure 5-10. Post-earthquake water availability after the M7.0 SFZ earthquake scenario (gray circles indicate zero water pressure at wholesale turnouts/nodes east of Seattle)

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of the distribution system, although there is some overlap. A list of the largest storage facilities within or close to the direct service area is presented in Table 5-3.

Facility	Facility Size (million gallons)
Bitter Lake	21.3
Lake Forest Park	60
Lincoln	12.7
Myrtle	5
Beacon	48
Magnolia	5.5
West Seattle	29
Maple Leaf	60
Roosevelt	50
Volunteer	20
Total (without Roosevelt and Volunteer)	**241.5**
Total (with Roosevelt and Volunteer)	**311.5**

Table 5-3. SPU Major Distribution Reservoirs

In the 1990s and 2000s SPU conducted a comprehensive system analysis called the System Storage and Reliability Analysis (SSRA). Among other aspects, the SSRA evaluated the sizing of treated water storage. The analysis was based on the loss of either Tolt or Cedar supply for up to seven days. One of the driving factors for the SSRA was the requirement to cover open reservoirs to meet newer drinking water quality regulations. The analysis concluded that, of the large distribution system reservoirs, Roosevelt and Volunteer Reservoirs might not be needed, based on the assumptions for scope and duration of system outages. It is important to note that emergency response is one of the main functions of water storage. The less severe the system outage (including loss of source water supply and/or transmission system), the less storage is generally needed.

Following the SSRA, most open storage reservoirs were covered to meet the regulatory requirements, except Roosevelt and Volunteer. Roosevelt and Volunteer were disconnected from the drinking water system pending a decommissioning analysis.

Given the evolving understanding of seismic risk described in this report, SPU re-examined the storage analysis as part of this seismic study, including the potential role of Roosevelt and Volunteer reservoirs.

The role of storage was analyzed in three ways:

1. Comparing storage relative to water demands against other West Coast water utilities, especially those having completed (or undergoing) seismic planning analyses
2. Using computer hydraulic model analysis to estimate the impact of storage on post-seismic response and recovery
3. Examining other factors, such as operational flexibility and resiliency

5.5.1 Storage Comparisons

As a simple comparison, Table 5-4 illustrates relative amounts of storage compared to typical water demands for SPU and some West Coast utilities in various stages of seismic analysis. The values in the table should be considered ballpark estimations only; each utility has different specific drivers for storage sizing, based on its unique configuration and system needs.

Utility	Average Demand (mgd), including wholesale customers	Total Storage (mg)	Days of Emergency Storage (w/o leaks)	Notes
SPU (without Roosevelt/Volunteer)	*125*	*273*	**2.2**	Storage also includes Eastside Reservoir (some overlap between transmission and distribution storage facilities)
SPU (with Roosevelt/Volunteer)	*125*	*343*	**2.7**	Storage also includes Eastside Reservoir (some overlap between transmission and distribution storage facilities)
Tacoma Water	*70*	*275*	**3.9**	
Portland Water	*70*	*300*	**4.3**	
San Francisco Public Utilities	*80*	*400*	**5.0**	Demand shown is retail only; San Francisco Public Utilities has already seismically upgraded transmission system and separate firefighting system.
East Bay MUD (Oakland, CA)	*190*	*830*	**4.4**	Already seismically upgraded transmission system
San Diego County Water Authority				Added about 6 months of additional storage (dams and reservoirs) closer to service area, to address resiliency and emergency response concerns

Table 5-4. Storage comparison with other West Coast utilities

The table indicates that SPU has less storage (relative to water demands) than other utilities, including those utilities that have already seismically upgraded their transmission and distribution systems and in theory should need somewhat less storage to offset transmission and distribution system failures.

5.5.2 Hydraulic Analysis

The computer hydraulic model described above was used to estimate the water system's response and recovery after a major earthquake. To evaluate storage size in the system, the model was run for several cases:

1. Baseline analysis: No further seismic improvements. Model was run with and without Roosevelt and Volunteer Reservoirs.
2. 20-Year Improvements: Assumes suggested 20-year seismic upgrades have taken place. Model was run with and without Roosevelt and Volunteer Reservoirs.
3. 50-Year Improvements: Assumes suggested 50-year seismic upgrades have taken place. Model was run with and without Roosevelt and Volunteer Reservoirs.

The results of the baseline model runs are shown below in Figure 5-11. The model runs incorporate the results of a M7.0 Seattle Fault Zone earthquake scenario. The runs show the percent of the system that has positive pressure, meaning there would at least be nominal pressure for firefighting, domestic use, and sanitation purposes.

5.5.3 Baseline Analysis

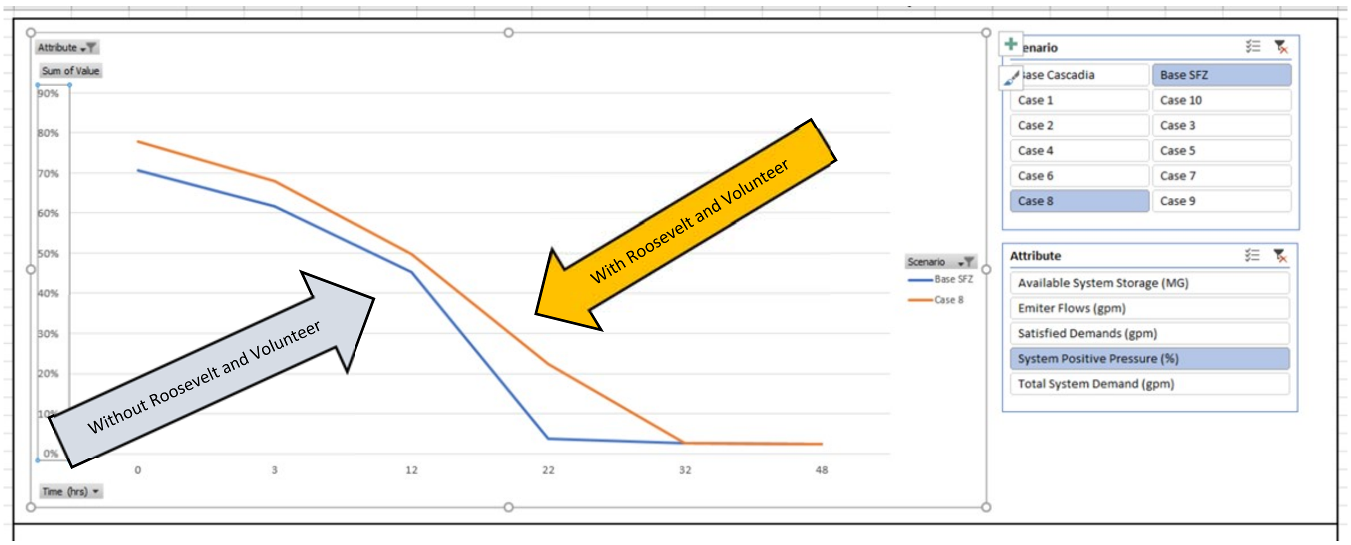

Figure 5-11. Baseline hydraulic analysis (percentage of direct service area with water pressure on the vertical versus hours after the event)

The baseline analysis indicates that without Roosevelt and Volunteer, the drinking water system will totally depressurize in about 22 hours. With Roosevelt and Volunteer, the drinking water system will totally depressurize in about 32 hours. Those 10 additional hours may be significant, particularly to meet firefighting needs after a major earthquake.

With Roosevelt and Volunteer in service, that will also allow the drinking water system to remain about 10% more pressurized than without the two reservoirs in service. It is worth noting that 10% of Seattle's direct service area represents about 70,000 people.

It is also worth noting that both reservoirs can serve critical customers. For example, Roosevelt Reservoir can serve the water zone that feeds Children's Hospital, a major emergency care center north of the Ship Canal. Volunteer Reservoir can serve the First Hill Zone, which includes most of the major hospitals and emergency care centers in Seattle (although First Hill Zone pressure is typically boosted from the Volunteer pressure zone to improve pressure).

5.5.4 20-Year and 50-Year Analysis

Results for the 20-year and 50-year analyses (Figures 5-12 and 5-13) are similar to those for the baseline analysis. As expected, model results indicate that the water system would perform better after 20 or 50 years of seismic upgrades, and better still if Roosevelt and Volunteer Reservoirs are part of the system. With Roosevelt and Volunteer in service, it adds more time and capacity of the drinking water system to stay pressurized for firefighting, domestic consumption, and sanitation needs.

5.5.5 Other Factors

As noted above, Roosevelt and Volunteer Reservoirs are currently not covered. They are disconnected from the drinking water system to meet recent water quality regulations. Volunteer Reservoir is currently filled with water from the drinking water system and is periodically drained and flushed to maintain overall water quality in the reservoir. Roosevelt Reservoir is currently empty due to operational considerations, pending a decision on its future use.

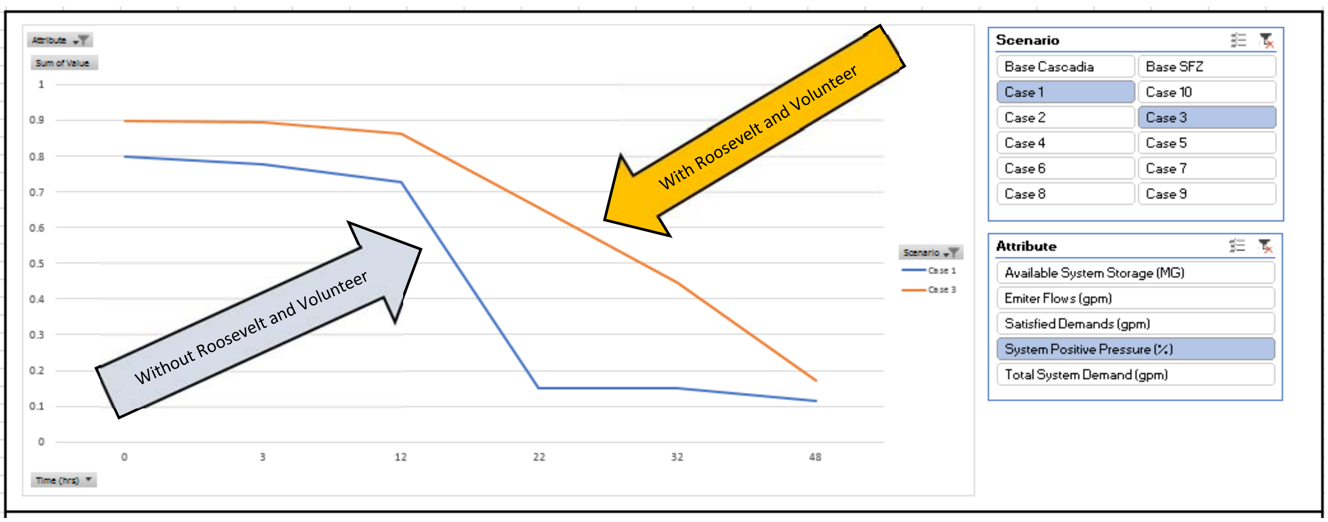

Figure 5-12. 20-year hydraulic model analysis (fraction of direct service area with water pressure on the vertical versus hours after the event)

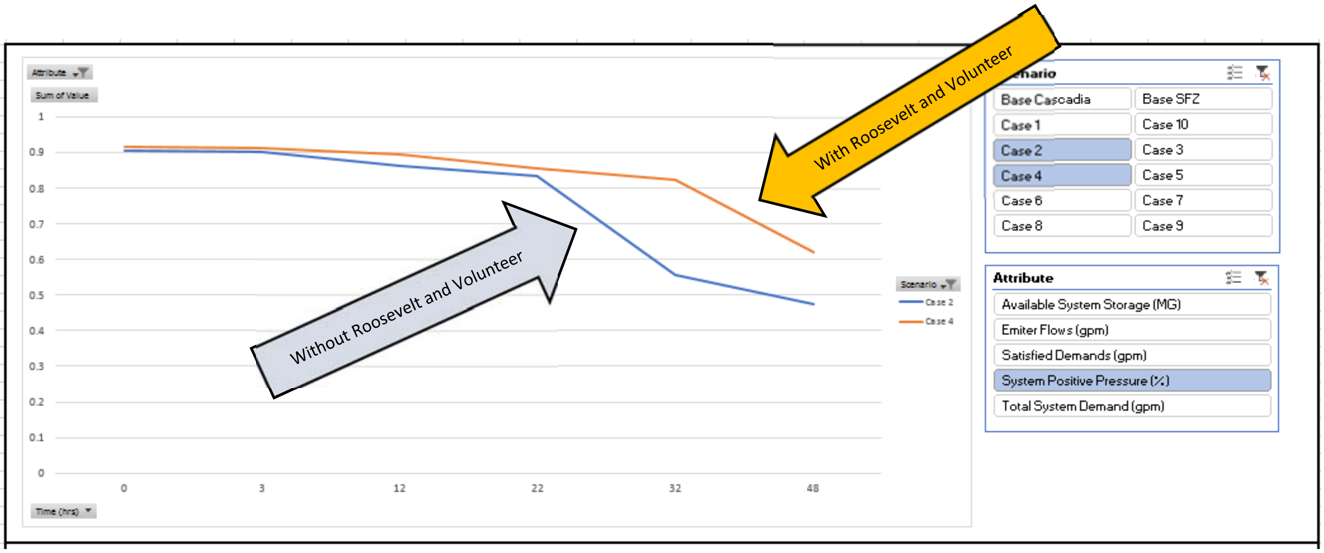

Figure 5-13. 50-year hydraulic model analysis (fraction of direct service area with water pressure on the vertical versus hours after the event)

Both reservoirs are filled from the drinking water system and, if desired, could be reconnected to feed the downstream portion of the drinking water system. Since they are not covered, the water inside is considered nonpotable from a regulatory standpoint. Due to the nonpotable status, using the reservoirs to feed the downstream drinking water system would require the issuance of a boil-water notice. It is worth noting that after a major earthquake, a boil-water notice is likely due to the extent of system depressurization and potential for contaminants entering the pipes when they have depressurized.

The additional 70 million gallons of storage for emergency response would provide SPU with opportunities for improved system recovery. For example, the two reservoirs could remain disconnected from the system until SPU elects to reconnect them post-earthquake. At that point, the water could be used as needed for targeted purposes, such as serving critical customers, and for firefighting, temporarily pressurizing the system to locate and fix leaks, and for central points of water distribution to the public.

The reservoirs also have the potential to be covered in the future, when future growth and/or regulations indicate the need for more potable storage.

5.5.6 Recommendation

Based on the analysis, it is recommended that Roosevelt and Volunteer Reservoirs remain as nonpotable storage elements of SPU's drinking water system. SPU should keep them disconnected from the drinking water system and give them the ability to be reconnected in the event of an emergency. In the future, these reservoirs could be covered and reconnected to the drinking water system if future needs require it.

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6. SEISMIC MITIGATION RECOMMENDATIONS AND COST ESTIMATES

Sections 4 and 5 demonstrated that damage to SPU's transmission and distribution systems from a major earthquake in the Puget Sound region could be extensive. Even under a best-case scenario, the time to restore limited water supplies to all customers would be measured in months, rather than days and weeks. To address the need to improve seismic resiliency, this section details proposed post-earthquake water system performance goals and the seismic upgrades that would be needed to achieve those goals. Planning level cost estimates for these seismic upgrades are also presented in this section.

6.1 Proposed Post-earthquake Performance Goals

Most SPU water system facilities were constructed before the current understanding of the seismology and associated seismic hazards in the Puget Sound was developed. Historically, water systems have consistently performed poorly in major earthquakes. Water has been unavailable for firefighting immediately after earthquakes, and restoration of even minimal service to all customers has sometimes exceeded two months. For example, the Los Angeles Department of Water and Power (Davis 2015) estimated that it took over five years to bring the LADWP water system close to the same level of service and reliability that existed prior to the 1994 Northridge earthquake. Under a M7.8 San Andreas Fault earthquake scenario, it would likely take three weeks to restore minimal water service to all LADWP customers. Water use restrictions would likely be in place for 15 months (Davis 2015).

The replacement value of SPU's water system assets is measured in the billions of dollars. The replacement cost for only SPU's distribution pipelines (which does not include the transmission pipelines or other assets, such as tanks, pump stations, buildings, etc.) is approximately $19 billion (SPU 2018b). It is not economically feasible to replace all seismically vulnerable assets over a short period of time. Water system post-earthquake performance goals are needed to let ratepayers know what seismic improvements would accomplish and what preparations would still be necessary. These performance goals will also help identify mitigation needs and let stakeholders know what to expect after a major earthquake.

Several water utilities have established post-earthquake performance goals (Eidinger and Davis 2012). Examples of these goals are shown in Appendix C. The Oregon Seismic Safety Policy Advisory Commission (OSSPAC) also developed model performance goals (OSSPAC 2013). The OSSPAC goals were influenced by the desire to restore water service in a timely manner to minimize the impact on the regional economy. The performance goals have been adopted by some Oregon water utilities and are included in Appendix C.

SPU's draft performance goals are modeled after the Oregon Resilience Plan goals. Although *Resilient Washington State* (Washington State Seismic Safety Committee Emergency Management Council 2012) listed some generic goals, the Oregon Resilience Plan was further developed and included more stakeholder involvement and input.

The categories addressed by the SPU draft performance goals are:

- Providing fire suppression water
- Providing water to essential facilities, such as hospitals and other emergency response centers
- Providing water to SPU's direct service customers/areas
- Providing water to SPU's wholesale customer turnouts
- Providing an emergency drinking water supply

The performance goals previously developed by other utilities, the Oregon Resilience Plan, and the current estimated performance of the SPU water system under the M7.0 SFZ scenario were used as the basis for SPU's proposed post-earthquake system performance goals. Because it is not practical or cost-effective to fully implement a water system seismic mitigation program over a short period of time, two sets of goals were developed for two successive timelines that end in 2045 and 2075.

The 2045 and 2075 proposed performance goals are listed in Tables 6-1 and 6-2, respectively. The intent is for these goals to be reviewed by SPU's stakeholders, including SPU's ratepayers, wholesale customers, the Seattle Fire Department, SPU management, and the City of Seattle leadership, before they are finalized.

SPU performance goals have been developed in concert with water system improvements, which are to be accomplished over two successive timeframes for which the second set of improvements is an integrated extension of the first set.

6.1.1 SPU Water System Performance Goals for 2045

Achievement of the 2045 goals (by 2045) assumes that full funding is available from 2024 through 2045 and the following mitigation projects outlined in Table 6-3 are completed per the Table 6-3 schedule:

- Critical vertical facility and transmission pipeline improvements
- Isolation and control strategies to mitigate water distribution pipeline breakage
- Ninety miles of distribution watermains have been replaced in accordance with the proposed pipeline standards presented in Section 8 and Appendix D
- Emergency preparedness and response procedure enhancements, in combination with transmission pipeline upgrades, to allow minimal (low winter demand) transmission pipeline water conveyance to most areas in seven to 10 days

6.1.2 SPU Water System Performance Goals for 2075

Achievement of the 2075 goals (by 2075) assumes that full funding is available from 2045 through 2075 and the mitigation projects outlined in Table 6-3 are completed per the Table 6-3 schedule:

- Critical vertical facility and transmission pipeline improvements
- Isolation and control strategies to mitigate water distribution pipeline breakage

		Immediately After	**3 Days**	**7 Days**	**14 Days**	**1 Month**	**2 Months**
Water Supply at Wholesale Meters	Minimum Water Volume	Winter Demand	Winter demand	Winter demand	Winter Demand	Winter Demand	Normal
	Water Quality	Nonpotable	Nonpotable	Nonpotable	Nonpotable	Potable	Potable
	Water Availability	25% of Meters	25% of Meters	50% of Meters	75% of Meters	100% of Meters	100% of Meters
Fire Suppression Water–Water to Within 2,500 Feet of Any Point Within the City Via Seismic-Resistant Pipelines	Minimum Water Volume	3,000 gpm for 3 hours	3,000 gpm for 3 hours	3,000 gpm for 3 hours	3,000 gpm for 3 hours	3,000 gpm for 3 hours	5,000 gpm for 4 hours
	Water Availability	25% of City Covered	33% of City Covered	50% of City Covered	75% of City Covered	90% of City Covered	100% of City Covered
Water Supply for Critical Retail Customers (e.g., hospitals)	Water Quality	Nonpotable	Nonpotable	Nonpotable	Nonpotable	Potable	Potable
	Water Availability	25% of critical customers	50% of critical customers	100% of critical customers	100% of critical customers	100% of critical customers	100% of critical customers
Water Supply to Direct Service Area	Water Quality	Nonpotable	Nonpotable	Nonpotable	Nonpotable	Nonpotable	Potable
	Water Availability	25% of direct service customers	33% of direct service customers	50% of direct service customers	75% of direct service customers	90% of direct service customers	100% of direct service customer
Water Supply at Retail Customer Emergency Supply Points	Water Quality	Potable	Potable	Potable			
	Water Availability	0%	50%	100%			

Table 6-1. Proposed post-earthquake water system level of service goals for 2045 after M7.0 Seattle Fault Zone or M9.0 Cascadia Subduction Zone earthquake scenarios

		Immediately After	3 Days	7 Days	14 Days	1 Month	45 Days
Water Supply at Wholesale Meters	Minimum Water Volume	Winter demand	Winter demand	Winter demand	Winter demand	Normal	
	Water Quality	Nonpotable	Nonpotable	Nonpotable	Potable	Potable	
	Water Availability	50% of Meters	50% of Meters	90% of Meters	100% of Meters	100% of Meters	
Fire Suppression Water–Water to Within 2,500 Feet of Any Point Within the City Via Seismic-Resistant Pipelines	Minimum Water Volume	3,000 gpm for 3 hours	3,000 gpm for 3 hours	3,000 gpm for 3 hours	3,000 gpm for 3 hours	5,000 gpm for 4 hours	
	Water Availability	50% of City Covered	67% of City Covered	90% of City Covered	100% of City Covered	100% of City Covered	
Water Supply for Critical Retail Customers (e.g., hospitals)	Water Quality	Nonpotable	Nonpotable	Nonpotable	Potable		
	Water Availability	50% of critical customers	90% of critical customers	100% of critical customers	100% of critical customers		
Water Supply to Direct Service Area	Water Quality	Nonpotable	Nonpotable	Nonpotable	Potable	Potable	Potable
	Water Availability	50% of direct service customers	67% of direct service customers	75% of direct service customers	90% of direct service customers	95% of direct service customers	100% of direct service customers
Water Supply at Retail Customer Emergency Supply Points	Water Quality	Potable	Potable				
	Water Availability	90%	100%				

Table 6-2. Proposed post-earthquake water system level of service goals for 2075 after M7.0 Seattle Fault Zone or M9.0 Cascadia Subduction Zone earthquake scenarios

	Approximate Time Frame (values in 2018 dollars)												
Mitigation Element	**2018 – 2022**	**2023 - 2027**	**2028 - 2032**	**2033 - 2037**	**2038 - 2042**	**2043 - 2047**	**2048 - 2052**	**2053 - 2057**	**2058 - 2062**	**2063 - 2067**	**2068 - 2072**	**Total**	**Notes**
Isolation and Control													
Analysis	$50,000												
Reservoir and Tank Seismic Valves		$5,000,000	$5,000,000									$10,000,000	
Distribution System Isolation Valves		$5,000,000	$5,000,000									$10,000,000	
Transmission System Isolation Valves		$5,000,000	$5,000,000									$10,000,000	
Transmission Pipelines - Discrete Locations													
Analysis/Design	$500,000												
CRPLs in Renton		$35,000,000	$40,000,000									$75,000,000	
CRPLs in MLK Slide Area				$20,000,000	$20,000,000							$40,000,000	
CESSL in Cedar R. Liquefact & Slide Area				$10,000,000	$10,000,000							$20,000,000	
TPLs in Norway Hill				$15,000,000	$15,000,000							$30,000,000	
WSPL Duwamish River Crossing						$10,000,000	$10,000,000					$20,000,000	
Other point location upgrades, including TPLs in Bent/Pile Support Crossings		$1,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$19,000,000	
CRPL No. 4 in Green River Crossing										$6,500,000	$6,500,000	$13,000,000	
Transmission Pipelines - Other Areas Along Pipeline Routes	*These numbers assume total replacement of remaining pipe segments in liquefiable, landslide, or fault zones. This approach reflects a most conservative approach, and there may be more cost-effective strategies, including waiting until the pipe sections are replaced due to end of life, and blending emergency response and targeted upgrades.*												
Seismic Resistant CRPL (1 CRPL)						$20,000,000	$20,000,000	$20,000,000	$20,000,000	$20,000,000	$20,000,000	$120,000,000	Total cost $244M - half in years 20-50, half after that
Seismic Resistant TPL (focus on area of only one TPL, assumes total slipline)						$12,000,000	$12,000,000	$12,000,000	$12,000,000	$12,000,000	$12,000,000	$72,000,000	Total cost $144M - half in years 20-50, half after that
Seismic Resistant TESSL/CESSL						$15,000,000	$15,000,000	$15,000,000	$15,000,000	$15,000,000	$15,000,000	$90,000,000	Total cost $186M - half in years 20-50, half after that
WSPL Duwamish River Valley								$10,000,000	$10,000,000	$10,000,000	$10,000,000	$40,000,000	Total cost $80M - half in years 20-50, half after that
EQ-Resistant Critical Pipelines (Distribution Watermain Focused)	*These numbers are on top of separate annual costs for replacing/rehabilitating distribution pipes. They reflect the additional costs to make upgrades seismically resistant where needed.*												
EQ Resistant Pipe in PGD Areas	$2,500,000	$5,000,000	$7,500,000	$10,000,000	$12,500,000	$15,000,000	$17,500,000	$20,000,000	$20,000,000	$20,000,000	$20,000,000	$150,000,000	
Vertical Facilities	*These numbers reflect relatively conservative assumptions for full functionality after the design earthquake. Other approaches, such as performance-based criteria, will be considered.*												
Analysis/Design	$400,000											$400,000	trans. pipelines, trenton tanks, control works bldg., occ wh and tolt chl. bldg
Storage													
Myrtle Elevated Tank No. 2 Pipe Clearance		$100,000										$100,000	
Riverton Heights Reservoir		$10,000,000										$10,000,000	
Eastside Reservoir		$12,000,000										$12,000,000	
Beverly Park Elevated			$12,000,000									$12,000,000	
Control Works Surge Tanks				$5,000,000								$5,000,000	
Cascades Dam				$5,000,000	$5,000,000							$10,000,000	Placeholder - options analysis beginning 2018. Eval. indep. of seismic study
Volunteer Standpipe				$12,000,000								$12,000,000	
Magnolia Reservoir					$2,000,000							$2,000,000	Assumes roof-to-wall connection upgrade only
Magnolia Elevated Tank					$7,500,000							$7,500,000	
Richmond Highlands #2						$5,000,000						$5,000,000	
View Ridge Reservoir							$5,000,000					$5,000,000	
Foy Standpipe							$4,000,000					$4,000,000	Only if determined to be life safety concern and standpipe is needed
Charleston Standpipe								$4,000,000				$4,000,000	
Staffed Buildings													
North Operations Center		$4,000,000											Ongoing study about staff buildings
OCC Warehouse					$1,500,000							$1,500,000	Ongoing study about staff buildings
OCC Admin Building					$100,000							$100,000	Ongoing study about staff buildings
OCC Meter Shop					$1,000,000							$1,000,000	Ongoing study about staff buildings
OCC Pipe Carpentry Shop					$1,000,000							$1,000,000	Ongoing study about staff buildings
Lake Youngs Office Building					$300,000							$300,000	
OCC Vehicle Maintenance Building						$4,000,000						$4,000,000	Ongoing study about staff buildings
Other Buildings													
Nonstructural Upgrades		$400,000	$400,000	$400,000	$400,000							$1,600,000	
Tolt Reservoir Bridge Connection		$100,000										$100,000	
Maple Leaf Gate House		$2,000,000										$2,000,000	
Roosevelt Gate House		$2,500,000										$2,500,000	
Lincoln Gatehouse/Pump Station			$4,000,000									$4,000,000	
Broadway Pump Station			$1,000,000									$1,000,000	
Boulevard Pk and Riverton Well Emerg. Power			$500,000									$500,000	
Landsburg Tunnel Gatehouse				$1,000,000								$1,000,000	
Lake Youngs Pump Station (old)				$500,000								$500,000	
West Seattle Pump Station					$1,000,000							$1,000,000	
Trenton Pump Station						$2,000,000						$2,000,000	
Fairwood Pump Station							$1,000,000					$1,000,000	
Lake Forest Park Chlorination							$1,000,000					$1,000,000	
Emergency Preparedness & Response Planning													
Repair Mat'l & Resource Acquisition	$6,000,000											$6,000,000	
Post-EQ Response Plan Augmentation		$1,000,000	$1,000,000									$2,000,000	
Post-EQ Emerg Drinking Wtr Supply Stations		$1,000,000	$1,000,000									$2,000,000	
Subtotals													
Isolation and Control	$50,000	$15,000,000	$15,000,000	$0	$0	$0	$0	$0	$0	$0	$0	$30,050,000	
Transmission - Discrete Locations	$500,000	$36,000,000	$42,000,000	$47,000,000	$47,000,000	$12,000,000	$12,000,000	$2,000,000	$2,000,000	$8,500,000	$8,500,000	$217,500,000	
Transmission - Other Areas Along Pipeline Routes	$0	$0	$0	$0	$0	$47,000,000	$47,000,000	$57,000,000	$57,000,000	$57,000,000	$57,000,000	$322,000,000	
Distribution Pipes	$2,500,000	$5,000,000	$7,500,000	$10,000,000	$12,500,000	$15,000,000	$17,500,000	$20,000,000	$20,000,000	$20,000,000	$20,000,000	$150,000,000	
Facilities	$400,000	$31,100,000	$17,900,000	$23,900,000	$19,800,000	$11,000,000	$11,000,000	$4,000,000	$0	$0	$0	$119,100,000	
Emergency Preparedness	$6,000,000	$2,000,000	$2,000,000	$0	$0	$0	$0	$0	$0	$0	$0	$10,000,000	
Total (5-yr increments)													
Total per 5-year increment	**$9,450,000**	**$89,100,000**	**$84,400,000**	**$80,900,000**	**$79,300,000**	**$85,000,000**	**$87,500,000**	**$83,000,000**	**$79,000,000**	**$85,500,000**	**$85,500,000**	**$848,650,000**	
Total per year	*$1,890,000*	*$17,820,000*	*$16,880,000*	*$16,180,000*	*$15,860,000*	*$17,000,000*	*$17,500,000*	*$16,600,000*	*$15,800,000*	*$17,100,000*	*$17,100,000*		

Table 6-3. Preliminary mitigation schedule and planning level (order of magnitude) cost estimates

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- In accordance with the proposed pipeline standards presented in Section 8 and Appendix D, 330 miles of distribution watermains have been replaced
- Emergency preparedness and response procedure enhancement, in combination with transmission pipeline upgrades, to allow minimal (low winter demand) transmission pipeline water conveyance to be restored in seven to 10 days

6.1.3 Water Supply at Wholesale Meters

In addition to SPU's direct service area, SPU also supplies water to 19 municipalities and special purpose districts, and the Cascade Water Alliance. Currently, the M7.0 SFZ and M9.0 CSZ scenarios would likely cut off supply to most or all wholesale customers. It might take more than one month to restore supply to many wholesale customers. This metric is used as an indicator of SPU's ability to supply its wholesale customers.

6.1.4 Fire Suppression Water–Water to Within 2,500 Feet of Any Point Within the City Via Seismic-Resistant Pipelines

Until SPU's vulnerable transmission and distribution system pipelines can be replaced with earthquake-resistant pipelines there will be areas within the direct service area that will lose pressure after a catastrophic earthquake. Except for the most critical pipelines, the intent is to wait until pipeline condition requires replacement to seismically upgrade pipelines. Some SPU pipelines have over 100 years of remaining useful life left so it will take that long to complete the installation of seismic resistant pipe throughout SPU's system. To provide firefighting water throughout the direct service area, a grid of watermains that will convey water to within approximately 2,500 feet of any point within the direct service area has been defined. With hoses and other means, firefighting water can then be conveyed to all locations within the direct service area.

6.1.5 Water Supply for Critical Retail Customers

This performance category is analogous to the fire-suppression water performance category except that the pipeline grid that is defined will supply water directly to SPU's critical facility customers. Critical customers include those facilities, such as hospitals and emergency response centers that must remain operational after a major earthquake.

6.1.6 Water Supply to the Direct Service Area

This performance category relates to SPU's retail customers with piped water supply. The metric used to define adequate water supply is the low winter demand. The supply should be adequate for basic health and sanitation needs and provide business and industry with the water they need to operate. However, there would likely be water restrictions to limit nonessential uses, such as irrigation for landscaping.

6.1.7 Emergency Water Supply

Because drinking water will be initially unavailable in many parts of the direct service area, this performance category will define the time needed to provide emergency drinking water supplies, such as bottled water, or water blivets (portable water bladders), that can fill small water containers throughout the direct service area.

6.1.8 Water Potability

Water potability is not specifically addressed in these performance goals. Although the treatment plants are expected to suffer only relatively minor damage and remain largely functional, or be quickly returned to functionality, there will be a "disinfect before drinking" order because of significant pipeline damage. The length of time for this order will depend on how long it takes to ensure that potential contaminants are not entering the drinking water system in areas where the pressure boundary is not intact. As more earthquake-resistant pipe is installed in the SPU water system, the number of breaks and leaks after a major earthquake is expected to decrease and the time needed to lift a "disinfect before drinking" order is also expected to decrease. Because electricity and/or gas may not be available, and stoves or other heat sources could ignite gas that has escaped from broken gas lines, chemical treatment is preferred over boiling water.

6.1.9 Life Safety and Property Damage

Life safety and property damage are also not specifically addressed in the performance goals. Implicit in the goals is the prevention of any damage that could cause death, injury, or significant amounts of property damage.

6.2 Seismic Mitigation and Improvement Strategies

To increase seismic resiliency of SPU's water system, SPU has developed five strategies. These strategies are interconnected and intended to complement one another. They have been designed to cost effectively mitigate the effects of facility damage that are currently expected from an earthquake in the near future, and greatly reduce the amount of damage over the long term. The strategies are:

1. Transmission pipelines
    a. Seismically upgrade one of the CRPLs from Lake Youngs to Maple Leaf Reservoir so that it would likely survive a major earthquake and provide at least minimal water (i.e., water to fight fires and supply basic needs, but not enough for landscaping or other noncritical uses). The Cedar River system was chosen over the Tolt system because it is easier to supply water from the Cedar River system throughout the SPU service area. The CRPLs are also older than the Tolt pipelines and many sections may need replacement or rehabilitation over the next 50 years regardless of seismic concerns. Because Lake Youngs stores enough water to supply water for approximately one month, upgrade of Cedar system pipelines upstream of Lake Youngs is not considered as critical. This

seismic-resistant transmission pipeline will be constructed over a 50- to 75-year time frame.

   b. Upgrade the transmission pipeline sites with the highest vulnerability and longest estimated repair times (longest potential out-of-service time). Currently, there are some vulnerable river crossings and pipelines in landslide areas that may take several weeks or even months to repair. If damage is limited to more accessible areas, restoration times can be greatly reduced.
   c. When transmission pipelines are replaced, pipeline systems will be used that are likely to withstand the expected seismic hazards at each location.

2. Isolation and control
   a. Add isolation systems to appropriate reservoirs so that reservoirs do not completely drain out if there is excessive pipeline damage.
   b. Evaluate the feasibility of isolating those areas within the distribution system where significant distribution pipeline damage would drain reservoirs. Design and implement the isolation system. This strategy will be implemented over a 10-year time frame and is intended to mitigate distribution pipe breakage effects.

3. Require seismic resistant design for new facilities
   a. Require the use of earthquake-resistant pipe
      i. When new pipelines are installed or replaced in areas that are susceptible to PGDs or subject to intense ground-shaking;
      ii. For watermains that are essential for firefighting (mains needed to provide water within 2,500 feet of anywhere within the direct service area);
      iii. For watermains that serve essential facilities, such as hospitals and emergency response centers.
   b. Require site-specific seismic design when transmission pipelines are replaced or rehabilitated
   c. Require that new vertical facilities be designed to remain functional for the ASCE 7 seismic design ground motions.

4. Seismically retrofit the most critical facilities (tanks, pump stations, etc.). Less critical facilities will not be seismically upgraded, particularly those facilities with shorter remaining useful lives. The probability of the occurrence of a major earthquake before these facilities are replaced is relatively small and it is more cost-effective to use limited resources to address the seismic vulnerability of more critical facilities that have a bigger impact on system performance. These upgrades will be done over a 20- to 50-year time frame.
5. Improve emergency preparedness and response planning. Needed repair materials and resources, and methods to obtain them, will be identified. Particular emphasis will be placed on resources and materials needed for large diameter pipeline repair, with the goal of reducing outage times. Strategies and resources needed to provide emergency drinking water after an earthquake will be augmented. An earthquake-specific emergency action plan will be developed. These plans, procedures, and storage of repair materials will be implemented over a 10-year time frame.

6.2.1 Transmission System Upgrades

The vulnerability of selective transmission pipeline locations is summarized on Figure 4-4. Figure 6-1 shows the current vulnerability of the transmission pipeline alignments and the estimated minimum repair times. In an emergency, it may take up to 21 days to restore enough transmission pipeline capacity to provide minimal service (enough flow to supply low winter demand) to SPU's direct service area and wholesale customers in the M7.0 SFZ and M9.0 CSZ scenarios.

In addition to liquefaction- and landslide-induced permanent ground displacements, surface faulting across the CRPLs or CESSL could further complicate and delay restoration to some areas in M7.0 SFZ scenario. SPU Field Operations estimates that it could take six to eight weeks to restore water conveyance across significant surface fault ruptures. Even after minimal water conveyance is restored, it would still take significantly longer to restore the transmission pipelines to their pre-earthquake service levels. As an example, in the M7.8 San Andreas Fault Scenario, estimates by LADWP personnel show that it could take over one year to restore all of the aqueducts that provide water to Los Angeles (Davis 2015).

A SWIF scenario was not assessed as part of this study. Although SPU's direct service area would likely fare much better in a SWIF scenario, much more intense ground-shaking would be expected for the Tolt transmission system. Additionally, there could be surface fault ruptures across the Tolt Pipeline alignments. In a SWIF scenario, even minimal restoration of the Tolt system may take 21 or more days. Depending on the size and location of a SWIF event, the Cedar system could also take upwards of 21 days before even minimal flows could be restored.

As Figure 4-6 and Table 4-2 show, there are dozens of potentially vulnerable locations along the transmission pipeline alignments that need further analysis. The transmission system upgrade strategy is to first upgrade those vulnerable locations subject to liquefaction- or landslide-induced permanent ground displacements that would require complex and time-consuming repairs so that even if the transmission system went down, minimal service could be restored in seven to 10 days. These "critical" locations are typically river crossings and steep sloped areas. The time frame for these upgrades is over the 20-year period ending in 2045. Figure 6-2 projects transmission system vulnerability in 2045.

Over the next 50 to 75 years, targeted upgrades and replacement of aging transmission lines would be used to create a seismic-resistant transmission pipeline network that would be more likely (but not guaranteed) to maintain at least minimal service to SPU's direct service area and SPU's wholesale customers after a major earthquake. The transmission pipelines will be designed to accommodate PGDs that may occur in liquefaction-, landslide-, and settlement-susceptible areas. Upgrade will likely include a combination of rehabilitation of existing lines with techniques such as sliplining, and replacement of existing lines with new pipe. As much as possible, the upgrades would be coordinated with condition-related replacement and rehabilitation to optimize the seismic improvement costs. In stable soil areas that already have pipe that is able to accommodate the expected seismic hazards, the existing pipe would not be replaced or rehabilitated.

A different approach is recommended for mitigating possible damage from surface faulting. There is much uncertainty about the surface displacements that may occur in the Seattle Fault or SWIF zones. Depending on the size and location of the earthquake, there may not be any surface expression of faulting, or there may be up to one to three meters (three to 10 feet) of

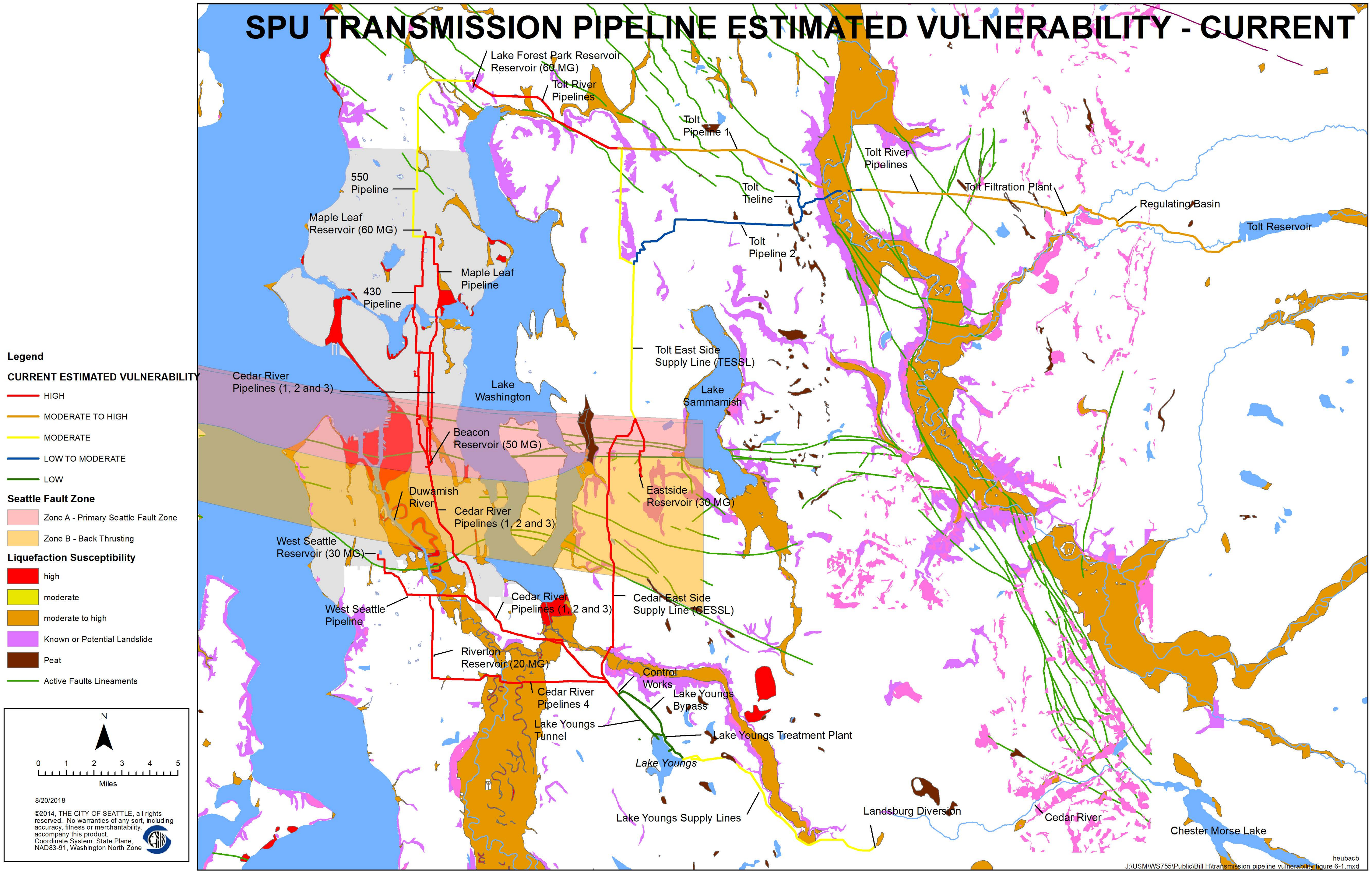

Figure 6-1. Current estimated transmission pipeline seismic vulnerability for M7.0 SFZ and M9.0 CSZ and restoration time

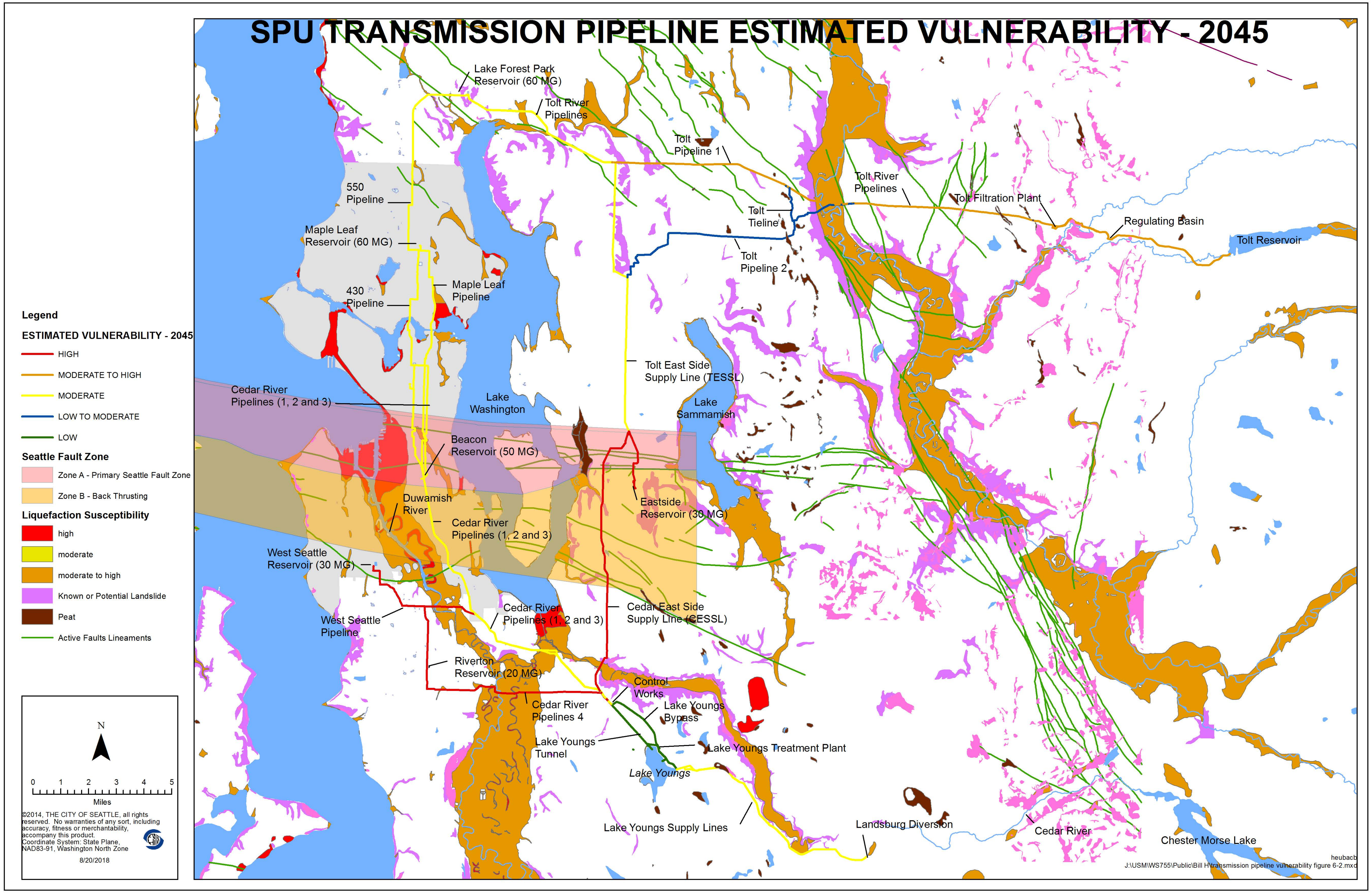

Figure 6-2. Estimated transmission pipeline seismic vulnerability for M7.0 SFZ and M9.0 CSZ and restoration time in 2045

displacement that could occur abruptly along a discrete plane, or there could be up to six meters (20 feet) of uplift distributed over 100 to 200 meters (330 to 660 feet) in the Seattle Fault Zone (Lettis Consultants International 2016a). Specific locations where these displacements may occur is not known. Even less is currently known about the SWIF zone.

The USGS suggests there is an approximately 0.05 probability (5% chance) of a M6.5 or higher shallow fault earthquake in the Puget Sound region in the next 50 years (Steele 2013). The likelihood of surface rupture across one of SPU's transmission pipelines during the next 50 years, or even before condition-related issues require pipeline replacement, is much less. The cost to "immediately" (do not wait until pipeline condition requires replacement) replace all of the transmission pipelines throughout the Seattle Fault and SWIF zones with pipelines designed to resist fault movements would likely be in at least the $500 million to $1 billion range.

The recommended strategy for the transmission pipeline alignments in fault zones is to wait to replace these mains with earthquake-resistant pipe when they are closer to the time when condition-related replacement is required. In the meantime, the strategy is to identify the materials that would be needed to repair key pipelines impaired by fault movement and stockpile these materials so that in the unlikely event of critical pipeline rupture, minimal water conveyance past the break could be restored within seven to 10 days. Consideration will also be given to identifying locations where manifolds could be installed to allow bypassing of broken transmission pipeline sections. The installation of additional line valves and interties so that damaged areas can be bypassed will also be evaluated.

The 50- to 75-year upgrades would not reduce the vulnerability to a low level for all transmission pipelines but would make it likely that minimal water could be supplied to SPU's direct service area and most wholesale customers within seven days of the event. After 100 years or more, as the transmission pipelines are replaced due to aging effects, the entire transmission system would be constructed with pipe that has the appropriate earthquake resistance.

Because there are still uncertainties with the transmission pipeline system vulnerability, further investigation is needed to assess those areas that could not be evaluated more rigorously during this study. Additional tasks would include estimating the inventories of repair materials that should be kept and determining if manifolds to connect bypass piping and more line valves are needed.

Figure 6-3 shows the projected transmission system vulnerability after 50 years. After 100 plus years, when most transmission mains have been replaced for condition-related reasons, there would be a high likelihood that at least minimal water could be supplied to SPU's direct service area and SPU's wholesale customers following a major earthquake.

6.2.2 Isolation and Control

Isolation and control are intended to mitigate the effects of the current seismic vulnerability of the SPU water system and enable quicker recovery if a major earthquake occurs before the water system can be seismically upgraded. There are two components to the isolation and control mitigation strategy. The first component considers isolating reservoirs before water loss caused by pipe breakage allows the reservoirs to drain. The second component considers isolating areas of the distribution system where severe pipe damage is expected.

The hydraulic modeling results and the experience of other utilities show that the extensive distribution pipeline damage expected after the M7.0 SFZ and M9 CSZ scenarios could completely drain SPU's direct service reservoirs within 24 hours. Isolation systems have already been installed on Beacon, Maple Leaf, Myrtle, and West Seattle Reservoirs. These systems allow each reservoir to drain until the reservoirs are half full. The remaining water could continue to be released uncontrolled to the system or it could be stored in the reservoir so it could be used for firefighting or drinking water.

Another measure that should be investigated is using valves to isolate areas after severe pipeline damage has occurred. Hydraulic modeling runs indicate that if these areas of expected damage are isolated, water system performance is greatly enhanced in other areas because less water is able to drain from the system, thereby preserving water supply for a longer time.

There are many issues that need to be resolved before distribution pipeline seismic isolation could be installed. For example:

- The optimal area(s) to be isolated would need to be identified
- A decision would have to be made as to whether it is acceptable to cut off areas from their water supply
- Should the system be automatic, and, if so, what should be used as the triggering mechanism? Manual and remote control override would be necessary.
- If the system controls were manual, would operators have time to operate them appropriately in emergency conditions?
- The installation and operation of an isolation system would need to be coordinated with the Seattle Fire Department
- Will the benefits be worth the installation and ongoing maintenance costs?
- Appropriate hardware and software will need to be identified.

6.2.3 Seismic Design Standards

Proposed seismic design standards for new SPU water system facilities are described in Section 8 and presented in Appendix D. These standards mainly address new watermains. Buildings, tanks, and other types of structures are already covered by existing codes and standards. However, it is important to note that all new SPU facilities that directly relate to water supply or emergency response are designed as essential facilities that must remain functional after the design-level earthquake. The goal of these standards is to ensure that as SPU water system facilities age, they will be replaced with seismic-resistant facilities so the entire system becomes seismic-resistant.

6.2.4 Critical Vertical Facility Upgrades

Because there is currently a high likelihood that SPU's direct service area may lose the Cedar and Tolt River sources after a major earthquake, maintaining storage within the direct service

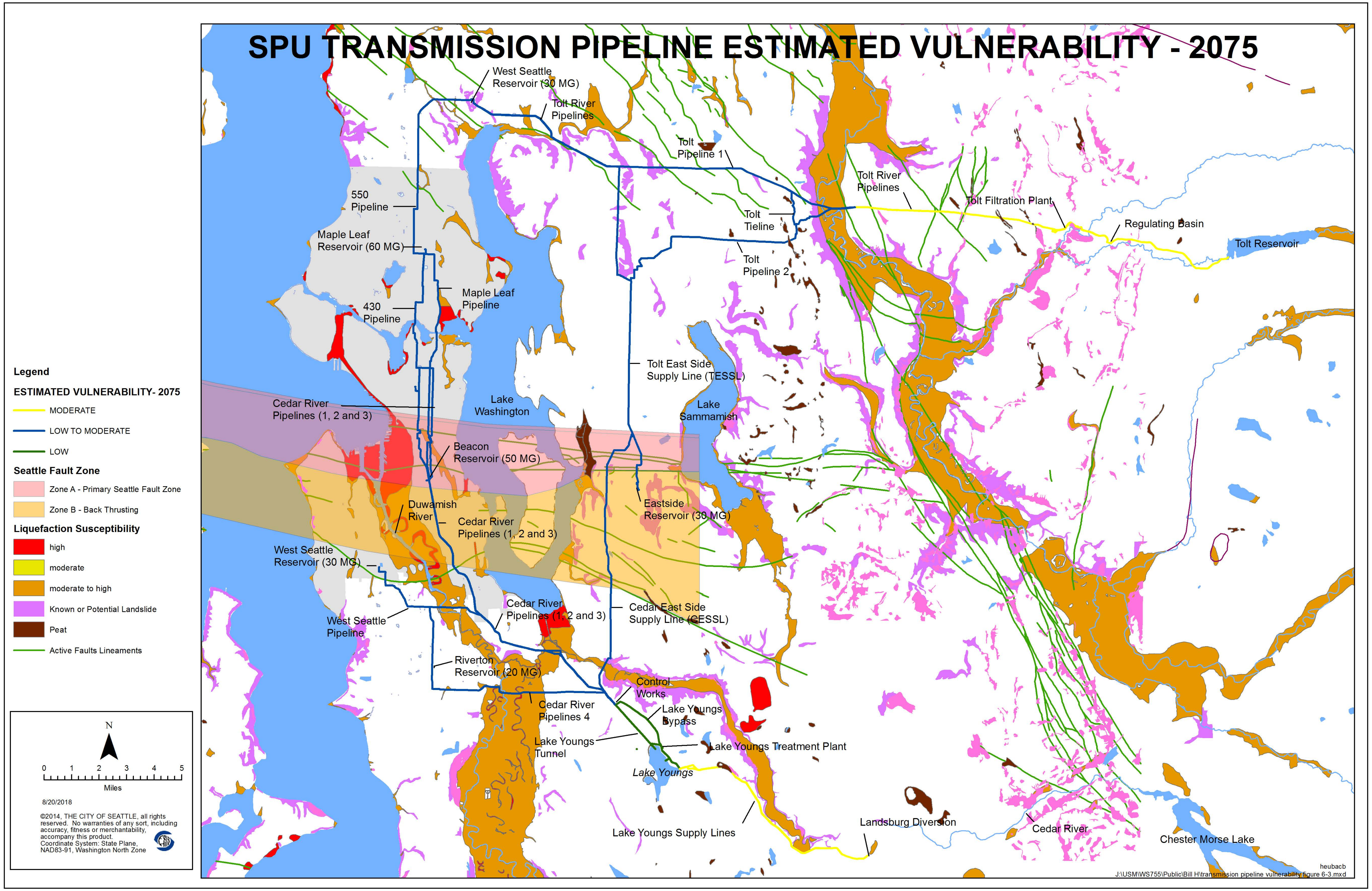

Figure 6-3. Estimated transmission pipeline seismic vulnerability for M7.0 SFZ and M9.0 CSZ and restoration time in 2075

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area is essential. This goal will be accomplished by upgrading the largest vulnerable reservoirs and using isolation and control strategies to prevent distribution pipeline damage from depleting storage. Because the Eastside Reservoir is a crucial storage facility for SPU's wholesale customers, it also has a high priority for upgrade. Additionally, those tanks that could endanger life safety if they failed will also have high priority for upgrade.

Basic procedures were used to evaluate all of the reservoirs and tanks. Soil structure interaction (SSI) was not considered in the evaluations. Because SSI can reduce seismic demands on buried structures, SSI analysis should be used to verify that those buried reservoirs and tanks identified for upgrade actually need to be retrofitted and to establish the degree of retrofitting that is actually needed.

Although Roosevelt and Volunteer Park Reservoirs have been temporarily removed from service, hydraulic modeling results have shown that these two reservoirs would maintain water pressure in the areas they serve for as long as an additional 16 hours if they were connected to the system after an earthquake. Another benefit of Roosevelt and Volunteer Park Reservoirs is that if they are kept disconnected from the system until needed, the water they store could be directed to the areas where it is needed for firefighting after an earthquake. In-town storage is crucial given the currently vulnerability of SPU's water transmission system.

Several critical gatehouses and pump stations are seismically vulnerable. Gatehouses and pump stations that are needed to achieve SPU's post-earthquake performance goals should also be upgraded. Other buildings and facilities, including those vulnerable nonstructural components that could endanger building occupants or affect building functionality needed for emergency response, should also be upgraded.

6.3 Seismic Resiliency Improvement Program, Proposed Schedule, and Planning Level Cost Estimates

The recommended schedule and planning level cost estimates for the mitigation measures is presented in Table 6-3. This table is intended as a starting point and will likely be modified as SPU's water system seismic mitigation program matures.

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7. EMERGENCY PREPAREDNESS AND RESPONSE PLANNING

Because of the large costs, it will likely take 50 years or more to substantially improve the seismic performance of SPU's water system, particularly the distribution and transmission pipeline systems. Improving SPU's earthquake emergency preparedness and response capabilities is a strategy that can be used to help mitigate earthquake effects until SPU's water system infrastructure can be made more seismically resilient. There are three aspects to improving SPU's emergency preparedness and response:

- Inventory current repair materials; determine what type and quantity of repair materials should be stockpiled, and obtain and stockpile those materials
- Develop an earthquake-specific response plan to reflect the findings of this report
- Review current plans/logistics, infrastructure, and equipment needed to supply emergency drinking water and enhance them to reflect the findings in this report

7.1 Post-earthquake Repair Resources

Depending on the pipeline size, pipe material, and earthquake scenario, it will take anywhere from a few days to months to obtain the pipeline repair materials and resources needed to repair the damage caused by a major earthquake, such as a M7.0 SFZ or M9.0 CSZ event. Based on the expected pipeline damage for the M7.0 SFZ and M9.0 CSZ scenarios, SPU staff has developed preliminary recommendations for pipeline repair material quantities that should be kept in stock in the event of a major earthquake. As storage logistics and normal pipeline repair material usage are better understood, these recommendations will likely be refined.

The pipeline repair material and resource needs were developed with the following considerations:

1. A major earthquake is a relatively low-probability event, meaning materials would likely not be used for 50 or more years.
2. Space is needed to store the repair materials, and the areas where the materials are stored need to provide a minimal level of protection from the environment so the materials do not prematurely degrade.
3. Ideally, the repair materials would be used over time during the normal course of business, so that the stockpiled materials get used before they become too old.
4. The repair resources would not need to repair everything, but would, at a minimum, provide low winter demand (water for needed for essential purposes) from the watersheds into the direct service area and wholesale turnouts. The resources would also be used to improve restoration of the distribution system.
5. After an event, the additional repair materials needed to complete the repairs could be ordered. Only enough repair materials would be needed until the post-earthquake requests for supplemental materials arrive. Supplemental repair materials may arrive within a week or so for a localized event, such as a Seattle Fault Zone event, but would

likely take longer if it were a Cascadia Subduction Zone event that impacted the entire Pacific Northwest coast.

The preliminary recommendations for transmission and distribution pipe repair materials are summarized in Tables 7-1 and 7-2. These tables also list the current pipe repair materials SPU had in stock as of March 2018.

The following auxiliary materials, equipment, and resources would also be needed to complete the pipe repairs:

- HDPE pipe installation
    - To install HDPE pipe, a heat-fusion machine and heat-fusion machine operator would be needed. Because 36-inch HDPE pipe is very thick, and the operating pressures approach 200 psi in some locations, some mechanical couplings are not practical. Preflanging the HDPE pipe and using bolted connections may be an option. Electrofusion may be another option. The materials needed to transition the HDPE pipe to pipe of different materials and diameters would also be needed.
- Auxiliary materials and parts
    - Timber, blocking, and backfill material would be needed. These materials may not need to be stockpiled, but the logistics for obtaining these materials immediately after a major earthquake would need to be developed and included in the emergency response plan.
    - Dished heads (used to plug or cap pipe) would be needed, sizes and quantities to be determined.
    - Cones, signs, shoring boxes, and steel plates would be needed. The current inventory of these items should be compared to the estimated maximum number of concurrent repair sites to determine if it would make sense to purchase more.
- Welders/Pipe Fitters
    - Welders who are also pipe fitters would be needed for the larger diameter pipe repairs. Currently, SPU does not have any welders who can fit pipe together. Local and more distantly located welders/pipe fitters who could promptly respond and weld larger diameter pipe should be identified and included in the emergency response plan. Consideration should be given to negotiating emergency work agreements with appropriately skilled and experienced contractors.
- Lifting equipment

SPU owns and operates backhoes that could be used to lift pipe as large as 89-inch-diameter, 15-foot-long pipe. In general, construction equipment would be in heavy demand after an earthquake. The SPU emergency response plan should identify sources of heavy equipment, including contractor-owned and -operated equipment that could be used after a major earthquake.

Pipe Length/Size/Material	Notes	Current Inventory of Exact or Similarly Sized Pipe
1,000 feet of 36-inch pipe Dimension ratio = 11 (200 psi) HDPE	Float across CESSL Cedar River crossing; float across CRPL 4 Green River crossing (with 60 x 36 reducers/fittings); float across West Seattle Pipeline Duwamish River crossing (with 48 × 36 reducers/fittings); use for repairs on CESSL and TESSL; note that 36 inches is largest HDPE pipe with 200 psi rating	None
1,500 feet of 66-inch pipe welded steel	To replace one CRPL through MLK slide area and Renton liquefaction area; use in other repair areas	260 feet of 66-inch welded-steel pipe
200 feet of 60-inch pipe welded steel	General repair for 60-inch pipe; need fittings for odd-sized pipe and different materials	300 feet of 60-inch welded-steel pipe
200 feet of 54-inch pipe welded steel	General repair for 54-inch pipe; need fittings for odd-sized pipe and different materials	260 feet of 54-inch welded-steel pipe
200 feet of 48-inch pipe welded steel	General repair for 48-inch pipe; need fittings for odd-sized pipe and different materials	240 feet of 50-inch welded-steel pipe
200 feet of 42-inch pipe welded steel	General repair for 42-inch pipe; need fittings for odd-sized pipe and different materials	160 feet of 44-inch welded-steel pipe 91 feet of 38-inch welded-steel pipe 18 feet of 36-inch ductile-iron pipe 249 feet of 32-inch welded-steel pipe
60 feet of 81-inch pipe welded steel	For TPL 1	105 feet of 89-inch welded-steel pipe 120 feet of 76-inch welded steel pipe

Table 7-1. Recommended transmission pipeline repair pipe

Table 7-1 Notes:

1. Store in 20-foot segments for 66-inch-diameter and less pipe. Store in 15-foot lengths for 81-inch-diameter pipe.
2. Store two butt straps for each segment.

Use epoxy or polyurethane-interior coating. Most of the current spare inventory is cement-mortar lined.

Pipe Length/Size/Material/Other	Notes	Current Inventory of Exact or Similarly Sized Pipe
100 feet of 2-inch pipe HDPE	Five repairs at 20 feet per repair; low priority because of size; can order repair materials after event	
100 feet of 4-inch pipe ductile iron 10 repair clamps	Five repairs at 20 feet per repair; low priority because of size; can order repair materials after event	
100 feet of 6-inch pipe ductile iron 25 repair clamps	Five repairs at 20 feet per repair; low priority because of size; can order repair materials after event	40 feet of 6-inch PVC pipe
2,000 feet of 8-inch pipe ductile iron 75 repair clamps	100 repairs at 20 feet per repair; moderate priority because of size; can order repair materials after event	1,801 feet of 8-inch ductile- iron pipe 20 feet of 8-inch PVC pipe 831 feet of 10-inch ductile-iron pipe
2,000 feet of 12-inch pipe ductile iron 50 repair clamps	100 repairs at 20 feet/repair,	666 feet of 12-inch ductile-iron pipe 40 feet of 12-inch PVC pipe 72 feet of 14-inch ductile-iron pipe
1,000 feet of 16-inch pipe ductile iron 50 repair clamps	50 repairs at 20 feet per repair; high priority because of size	342 feet of 16-inch ductile-iron pipe
1,500 feet of 20-inch pipe ductile iron 50 repair clamps	75 repairs at 20 feet per repair; high priority because of size	
1,500 feet of 24-inch ductile iron 50 repair clamps	75 repairs at 20 feet per repair; high priority because of size	108 feet of 24-inch ductile-iron pipe 216 feet of 26-inch welded- steel pipe 378 feet of 25-inch welded- steel pipe
1,000 feet of 30-inch pipe 25 repair clamps	Significant amount of 30-inch pipe in liquefiable areas, such as Airport Way	

Table 7-2. Recommended distribution pipeline repair pipe

Table 7-2 Notes:

1. Store in 20-foot segments.
2. Store two MEGALUGS (joint restraint) for each segment.
3. Use epoxy or polyurethane-interior coating. Most of the current spare inventory is cement-mortar lined.
4. Need to determine appropriate quantities of mechanical joints and sleeve pipe.
5. The number and sizes of transition couplings and bends need to be determined.

7.2 Earthquake-Specific Emergency Preparedness and Response Planning

The overall strategic and programmatic approach to emergency management at Seattle Public Utilities is presented in the Seattle Public Utilities Comprehensive Emergency Management Plan (CEMP) and subordinate plans. The CEMP provides the planning and program guidance used to implement SPU's emergency management programs and plans. The CEMP is reviewed and revised every three to six years. The latest CEMP version is being reviewed in 2018.

The SPU Continuity of Operations Plan (COOP) is used to ensure SPU's mission-essential operations are performed efficiently and with minimal disruption during an emergency. The COOP is used to maintain, restore, and sustain essential functions identified in the COOP in the event of a threatened or actual interruption. The COOP is updated annually and revised every four or five years. The next COOP revision will be released in 2018.

The SPU Emergency Operations Plan (EOP) defines how an incident's impacts will be managed so that essential services can be stabilized and restored. The SPU draft EOP is scheduled to be completed in early 2019.

In conjunction with the EOP, SPU has developed

- All-Hazard response plans for emergencies such as water shortages, water quality and debris management
- Hazard specific response plans for hazards such as spill response, freeze response and West Nile Virus
- Site-specific response plans such as dam emergency action plans and emergency facility response procedures

Although there are some common issues among different types of emergencies, there are some that are unique or more likely to affect response during earthquake emergencies. Those unique issues need to be addressed in earthquake-specific preparedness and response planning. Currently, SPU does not have an earthquake-specific plan in its EOP plan portfolio.

An earthquake-specific response plan needs to be added to SPU's hazard specific response plan portfolio. This earthquake-specific plan should include:

- Developing procedures and protocols for remaining in or entering facilities that may be damaged or unsafe due to either structural failure, chemical release, or electrical hazards
- Encouraging home earthquake preparedness and response planning for SPU employees so they are more likely to be available after an earthquake
- Continuing to work with the City's Office of Emergency Management to encourage home earthquake preparedness and response planning for the public so they are more likely to be prepared following an earthquake

- Continuing to work with the Seattle Fire Department on identifying common goals and planning scenarios.
- Considering early warning systems that are being developed and ways they can be immediately shared with all SPU staff and used to mitigate earthquake effects
- Determining whether USGS ShakeMaps, remote sensing, and other rapid response software, such as One Concern, could be used to help identify where damage is most likely
- Addressing repair material storage hazards in OCC Warehouse
- Considering aftershock effects and using aftershock-forecast maps that the USGS is developing in response to the issue of employee safety while responding to the original earthquake
- Continuing to account for employee mobility issues (e.g., for employees that live out of town and may have trouble responding to an emergency) in earthquake emergency response
- Developing plans for post-earthquake response given that other critical lifeline systems, such as power, transportation, and communications, are likely to be severely compromised
- Developing post-earthquake response plans and strategies for prioritizing and carrying out water system repairs
- Continuing to work with the City's Office of Emergency Management on developing post-earthquake response plans and strategies for community shelter and resource sites
- Strengthening emergency contracting with regional and out-of-area heavy contractors, and mutual-aid relationships with similar utilities
- Reducing ignition sources that could ignite leaking gas, if the water supply is nonpotable, by asking residents to disinfect water with chemicals or filters instead of boiling it.

7.3 Emergency Drinking Water

One of the findings from the 2016 Cascadia Rising exercise was that it may take up to two weeks for outside aid to supply emergency drinking water (Washington Military Department 2017).

SPU currently has six portable emergency drinking water distribution (EWD) stations. Each system consists of a 1,700-gallon blivet and dispensing equipment. This equipment includes valves, piping, sanitizing equipment, and a manifold table that can be used to fill custom, one-gallon, aseptic water bags for the public. The system can be run in one of three configurations: directly off a hydrant, from a hydrant to a pump, which regulates water pressure, and from a blivet. The EWD stations do not have treatment capability. Water issued from the EWD stations would need to be disinfected if the EWD water source is nonpotable.

The emergency stations are operationally intensive. It takes up to twelve people per shift to staff each station and to manage and provide traffic control at the distribution site. Because there are approximately 700,000 residents in SPU's direct service area, even if staffing were available for each station, more than six stations would likely be needed to supply emergency drinking water in SPU's direct service area. SPU should revaluate current capabilities and develop an improved plan and approach to provide and distribute emergency drinking water following a major earthquake.

As part of federal disaster response, acquisition and regional distribution of potable water is the responsibility of the Defense Logistics Agency. Acquisition and distribution of potable water is overseen by the Washington State Department of Commerce and coordinated within the State Emergency Coordination Center logistics unit. Distribution is carried out by county and local resources to community points of distribution, in conjunction with food and other commodities.

It is critical for SPU to support community emergency preparedness programs for the public to prepare and store at least two weeks of water. This includes storage of potable water, and strategies to leverage additional water sources for nonpotable needs.

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8. SEISMIC DESIGN STANDARDS FOR NEW FACILITIES AND PIPELINES

One of the most important and cost-effective long-term seismic improvement strategies SPU can adopt is to ensure that all new facilities are designed to be earthquake-resistant. Almost all types of structures are covered under current seismic building codes and standards. Existing national building codes can be used to construct seismic-resistant facilities that are likely to meet desired performance requirements. However, buried water pipelines are not currently addressed in United States seismic standards and codes. A few water utilities, such as the East Bay Municipal Utility District and Los Angeles Department of Water and Power in California, have or are developing utility-specific seismic standards for all facilities.

8.1 New Nonpipeline Facilities

In the future, SPU may supplement established codes and standards with utility-specific requirements. For now, making sure that existing codes and standards are followed will enable SPU to gradually develop a seismic-resistant water system. There may be instances, such as for buried reservoir seismic upgrades, when facility-specific criteria that go beyond the building codes are needed. Because appropriate criteria will typically be project-specific, development of specialized analysis, design, and performance criteria will be prepared on a case-by-case basis.

8.2 Occupancy Category for Nonpipeline Facilities

In current codes and standards, determination of the appropriate occupancy category for a new facility is defined in ASCE 7. There are four occupancy categories that range from I for the least critical facilities to IV for facilities that need to remain functional after a seismic event. Any facility that is needed to supply fire suppression water is categorized as Occupancy Category IV, Essential Facilities. Consequently, most SPU water system facilities are considered essential facilities. Even administration and warehousing facilities may be considered essential facilities if they are needed to ensure the flow of firefighting water. By default, all new SPU facilities should be defined as essential facilities providing there is a mechanism to lower the occupancy category if warranted:

> All new facilities, including but not limited to water storage facilities, pump stations, emergency response facilities and office spaces, shall be designed as Essential Facilities, Occupancy Category IV in accordance with the latest edition of ASCE 7, Minimum Design Loads for Buildings and Other Structures, and the Seattle Building Code. The Transmission and Distribution Planning Section Manager may grant waivers that allow design to a lesser occupancy category on a case-by-case basis if the Transmission and Distribution Planning Manager believes the facility does not need to remain functional/operational after a seismic event.

8.3 Existing Facilities

Seismic upgrade design standards for existing facilities are not covered in this section. Facility criticality and function, remaining facility life, and financial costs are some of the considerations that must be considered when determining the appropriate upgrade criteria. The appropriate performance level design criteria should be determined on a case-by-case basis. ASCE 41 (American Society of Civil Engineers 2017) is an industry standard that can be used to guide existing facility upgrade analysis and design.

8.4 Seismic Design Standards for New Buried Pipelines

SPU's approximately 1900 miles of transmission and distribution pipelines constitute SPU's most valuable (in terms of replacement cost) asset class. With a total replacement cost that is in the billions of dollars, only the most critical and vulnerable (highest risk) pipelines can be considered for proactive replacement. Most pipelines will not be considered for seismic improvement until they are replaced for age, obsolescence or capacity reasons.

8.4.1 Pipeline Classifications

SPU's pipelines have been categorized/defined as follows:

Primary Backbone Pipelines: transmission pipelines that convey water from the Tolt Reservoir or Lake Youngs Treatment Plant to the terminal reservoirs.

Secondary Backbone Pipelines: Transmission pipelines that convey water from the terminal reservoirs to distribution reservoirs or large service areas. Because Lake Youngs can supply the Cedar system for approximately four weeks, the transmission pipelines from the Landsburg Diversion to Lake Youngs are defined as secondary backbone pipelines.

Hospital/Critical Facility Watermains: watermains that are needed to supply hospitals or other critical facilities that must remain operational after an earthquake.

Firefighting Mains: mains needed to supply water to within 2,500 feet of any location in the City of Seattle.

Ordinary Mains: all watermains that are not classified as backbone, hospital/critical facility, or firefighting mains.

A map of the backbone pipelines and hospital/critical watermains is shown on Figure 8-1. As upgrade opportunities arise and discussions with the fire department continue, some watermain classifications may change.

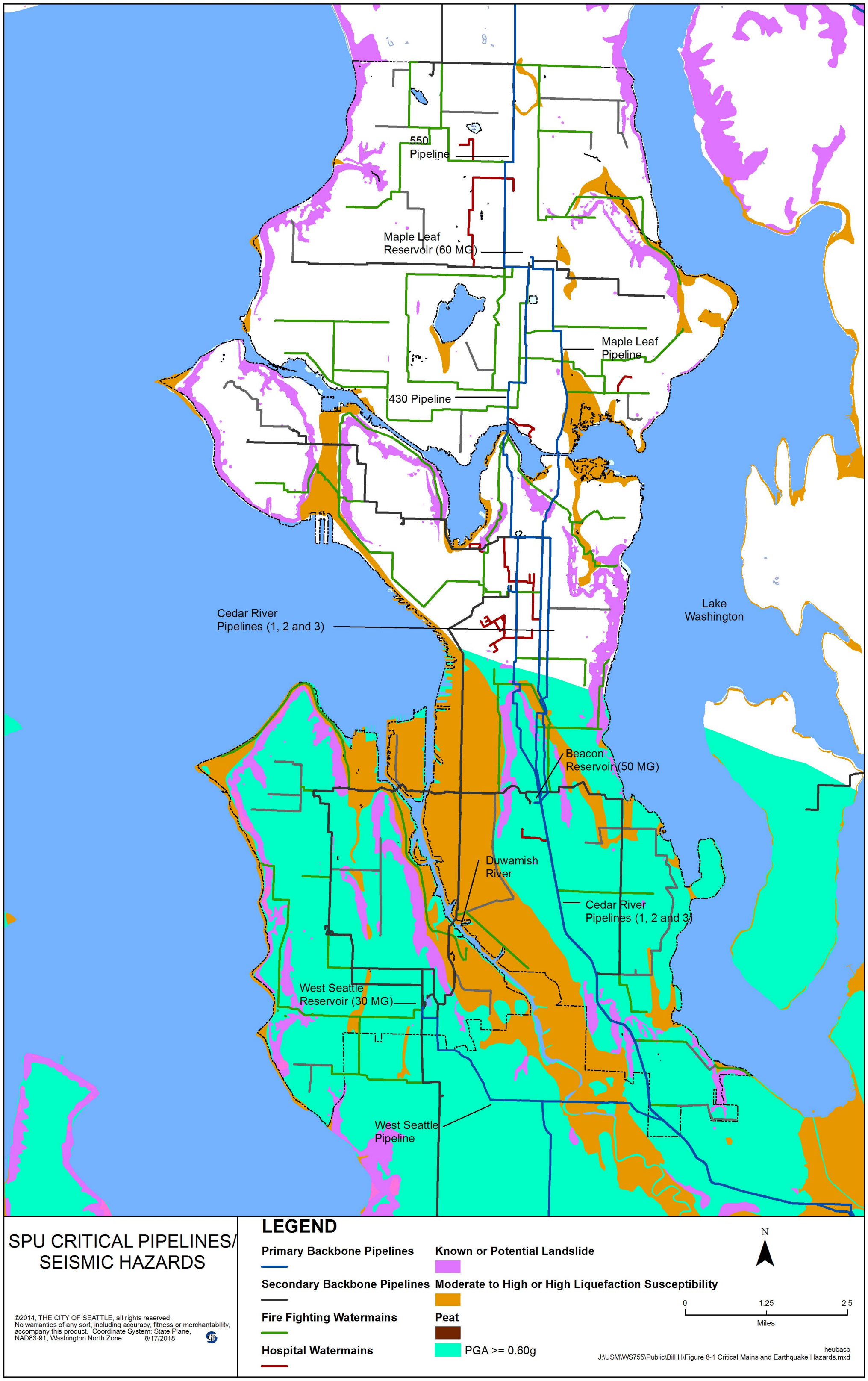

Figure 8-1. SPU critical pipeline map

8.4.2 Pipeline Standards Background

As discussed in Section 4, pipeline failures can be attributed to either failures caused by PGDs or transient effects caused by seismic wave propagation. Most pipeline damage is attributed to PGD.

Although ASCE is currently developing a manual of practice to address seismic design of buried water pipelines, there are no official standards that govern seismic design of water pipelines in the United States. The American Lifelines Alliance (ALA) published a set of pipeline guidelines in 2001 that are sometimes used, but they are nearly 20 years old and have never been officially recognized or adopted by organizations that publish standards. The standards presented in this section are based on ISO 16134, *Earthquake- and Subsidence Resistant-Design of Ductile Iron Pipe* (International Organization for Standardization 2006) and practices used in Japan for seismic-resistant watermains. Currently, there are no equivalent seismic standards for other types of pipe materials.

ISO 16134 defines three performance criteria, with performance levels for each criterion:

- The ability of the pipe joint to allow longitudinal expansion or contraction:
    - S-1: joint can expand or contract at least ±1% of each pipe segment length
    - S-2: joint can expand or contract at least ±0.5% of each pipe segment length
    - S-3: joint can expand or contract less than ±0.5% of each pipe segment length
- The tensile force that would be required to pull the pipe joint apart:
    - A: the force required to pull the joint apart, expressed in kilonewtons, is at least 3 multiplied by the pipe diameter expressed in millimeters
    - B: the force required to pull the joint apart, expressed in kilonewtons, is at least 1.5 multiplied by the pipe diameter expressed in millimeters
    - C: the force required to pull the joint apart, expressed in kilonewtons, is at least 0.75 multiplied by the pipe diameter expressed in millimeters
    - D: the force required to pull the joint apart, expressed in kilonewtons, is less than 0.75 multiplied by the pipe diameter expressed in millimeters
- The ability of the pipe joint to rotate:
    - M-1: joint can deflect at least ±15˚
    - M-2: joint can deflect at least ±7.5˚
    - M-3: joint can deflect less than ±7.5˚

Earthquake-resistant ductile-iron pipe (ERDIP) that meets the IS0 16134 S-1, A, and M-2 performance criteria has been in use for over 40 years in Japan. There have only been a few earthquake-related failures of ERDIP in Japan, and these failures have been attributed to improper installation. Recently, United States ductile-iron pipe manufacturers have developed, validated through testing and are marketing ERDIP that meets the ISO 16134 standards. Recent earthquakes have demonstrated that butt-welded steel pipe and fusion welded high-density polyethylene (HDPE) pipe provide superior ductility and robust performance during earthquakes. Polyvinyl chloride (PVC) pipe manufacturers have also developed, validated through large-scale testing, and are marketing PVC pipelines with restrained joints that are able to accommodate significant earthquake-induced ground deformation.

The ultimate intentions of the seismic pipeline standards developed by SPU are to:

1. Maximize the likelihood that backbone, hospital/critical facility, and firefighting mains remain functional after a major earthquake. It is recognized that although PGDs are most likely in those areas that have already been identified, PGDs can occur in other areas that may not yet have been identified as being susceptible to PGD. Consequently, earthquake-resistant pipe is required for all backbone, hospital/critical facility, and firefighting mains, regardless of whether or not the alignment lies in an area that has been identified as susceptible to PGD. Because backbone pipelines are the most critical pipelines, site-specific analysis is required for backbone pipelines.
2. Eliminate most, but not necessarily all, pipeline breaks in ordinary distribution system mains. Past earthquake experience has shown that by using earthquake-resistant pipe, almost all failures will be eliminated. Wave propagation effects and unexpected PGDs will result in some additional failures in areas that have not been identified as susceptible to PGD. Even if earthquake-resistant pipe is not used in these areas, the number of failures is expected to be manageable.
3. Acknowledge that if surface ruptures occur in the SFZ, there will be ordinary (noncritical) watermain failures in the SFZ. Require earthquake-resistant transmission pipelines in fault zones that will withstand small fault rupture displacements but that may not withstand displacements of several meters if they occur. Because the SFZ and SWIF fault zones are so wide and there is uncertainty in the location and size of potential abrupt surface displacements, pipelines within the fault zones would need to be designed for large abrupt displacements for miles and would likely be prohibitively expensive.

Because most distribution pipe damage is expected within areas that are susceptible to PGD, ERDIP, butt-welded steel or HDPE pipe should be required in all areas that are subject to PGD. In areas of intense ground-shaking, transient waves can also damage pipelines. To reduce pipe damage in the areas of intense ground-shaking, pipeline joints should be restrained.

The most vulnerable area of water service is often at the service connection to the main. To allow for differential movement between the main and the service, the proposed standards will require a steel sleeve be placed around the main cock and HDPE sleeves around the service. The service should be constructed with flexible tubing that allows for gradual deformation.

Hydrant runs are less vulnerable than service runs, but can still be damaged if PGDs are large enough. However, accommodating all possible PGD is expensive. The minimal amount of differential displacement provided in the standards may prevent most failures, but not all. American Pipe has developed a seismic-resistant fire hydrant assembly. However, SPU has had mechanical problems with these hydrants.

8.4.3 Proposed Standards for Incorporation Into SPU's Design Standards and Guidelines

The proposed standards for new buried watermains are presented in Appendix D. Before these standards can be officially included in SPU's Design Standards and Guidelines, they need to go through a formal review and acceptance process. After the ASCE manual of practice on the seismic design of water and wastewater pipelines is completed, the SPU standards may be updated so they are better coordinated with these guidelines.

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