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

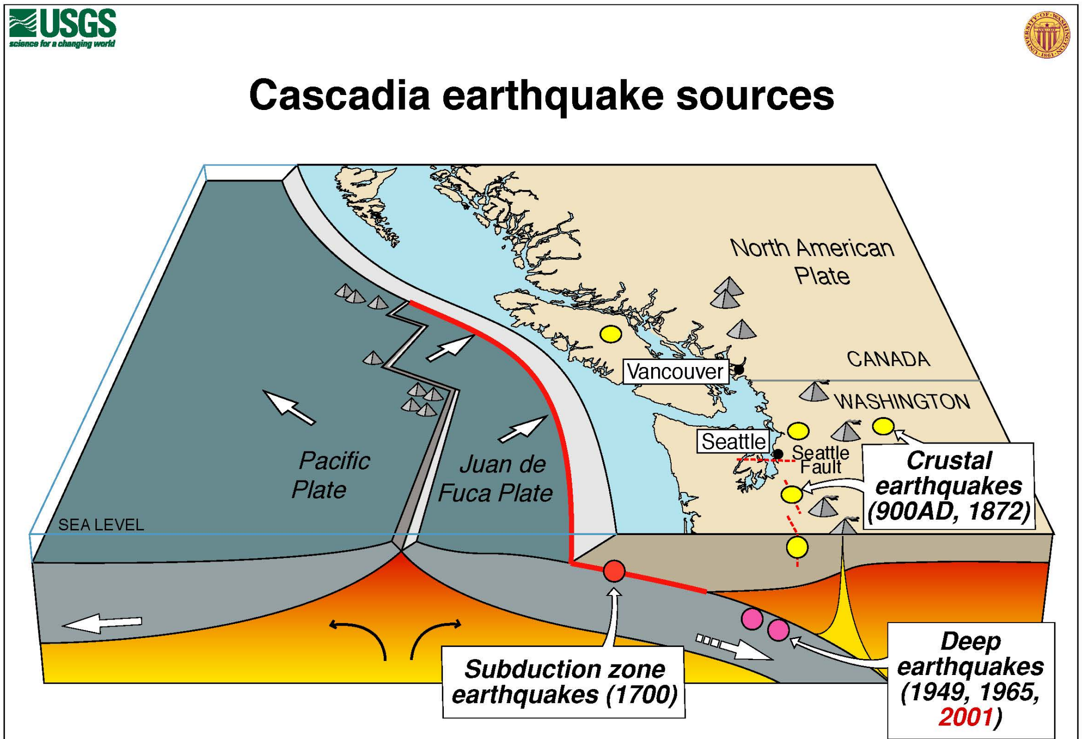
The Puget Sound region lies on the North American (tectonic) Plate. Figure 2-1 shows that, 30 to 50 miles below the Puget Sound region, the Juan de Fuca Plate is being subducted beneath the North American Plate. The interface, and surrounding area, forms the CSZ. This plate boundary extends for 700 miles 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
Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
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

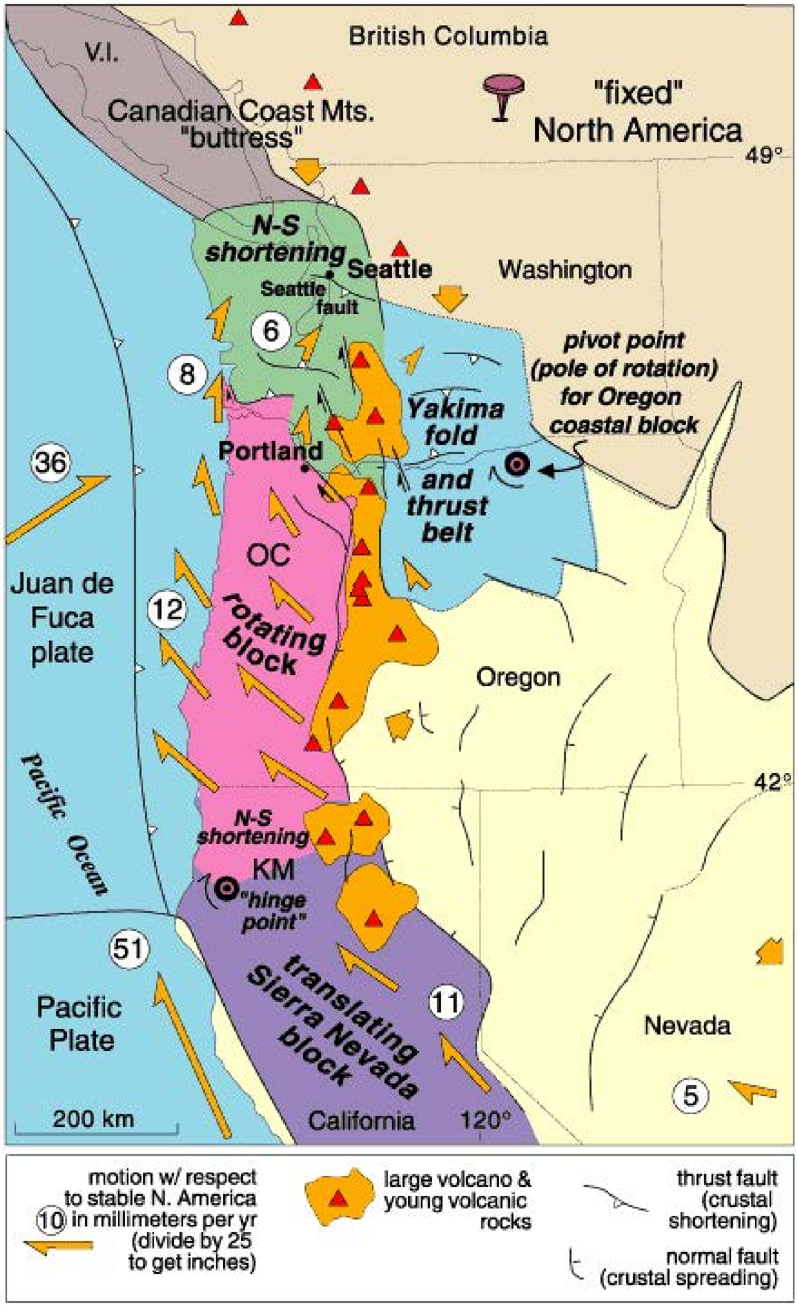


Figure 2-2. Tectonic plate block movement (Wells et al. 2000)

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.

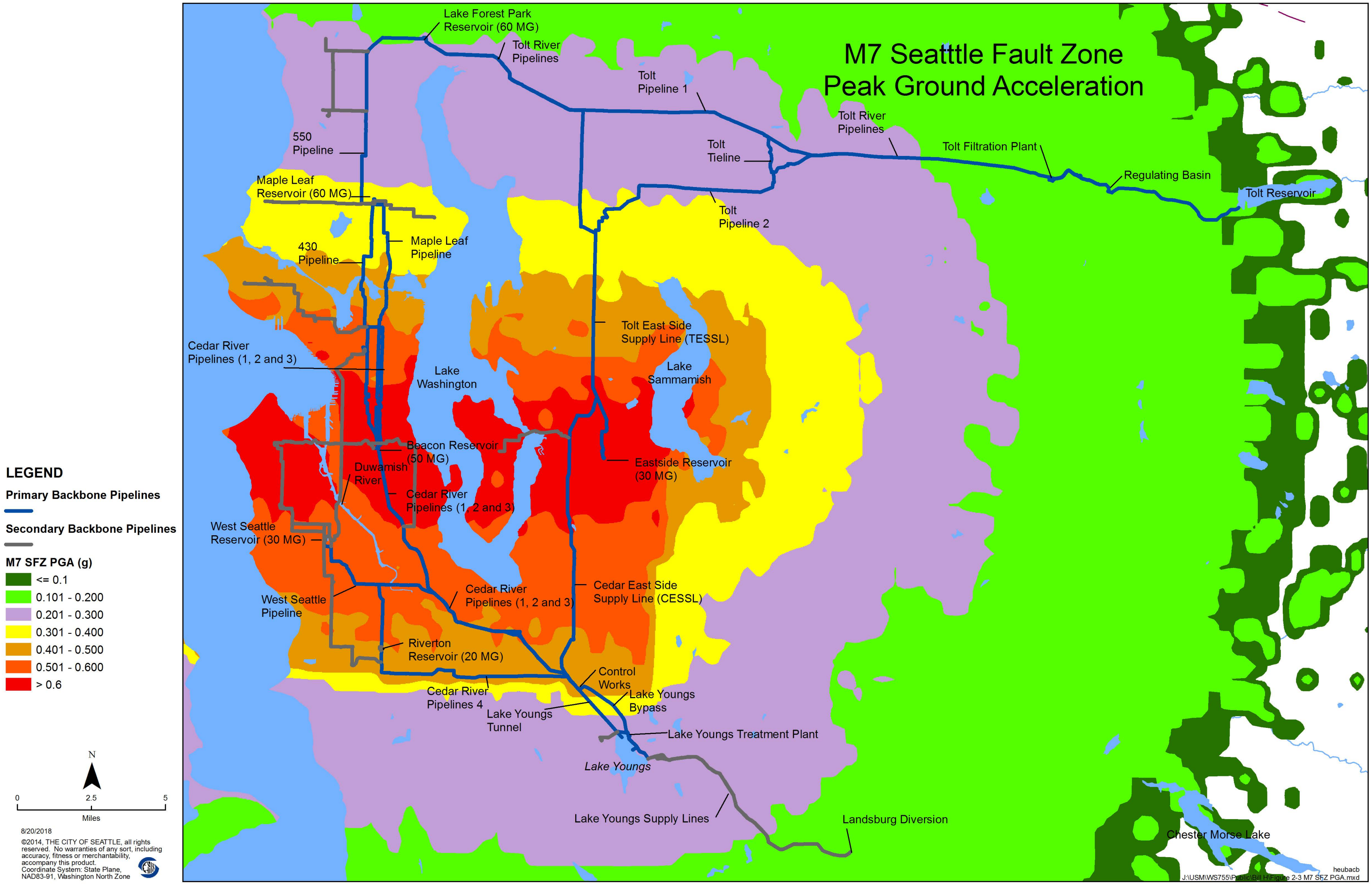


Figure 2-3. M7.0 SFZ peak ground accelerations

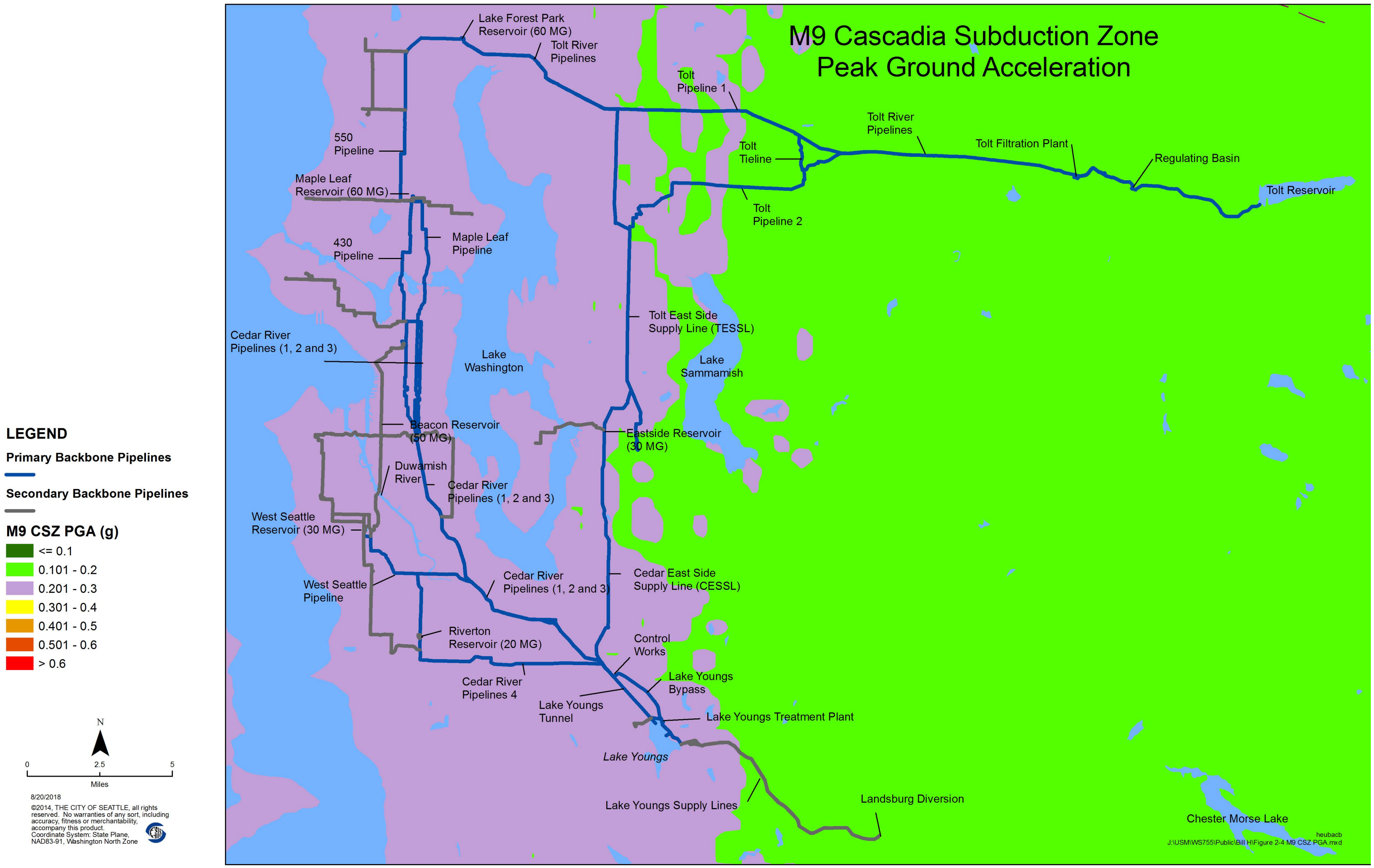


Figure 2-4. M9.0 CSZ peak ground accelerations

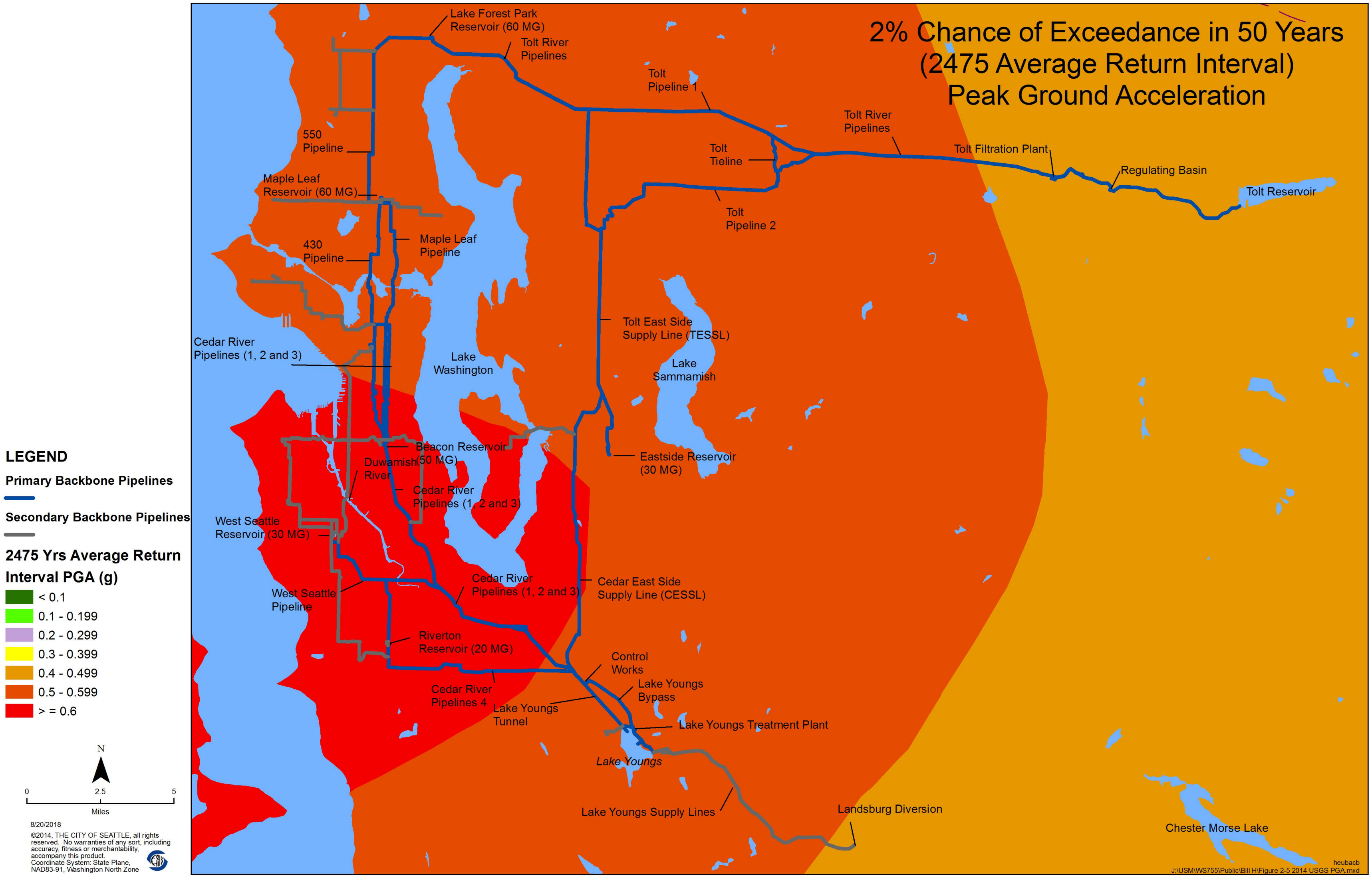


Figure 2-5. 2014 USGS probabilistic peak ground accelerations

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.

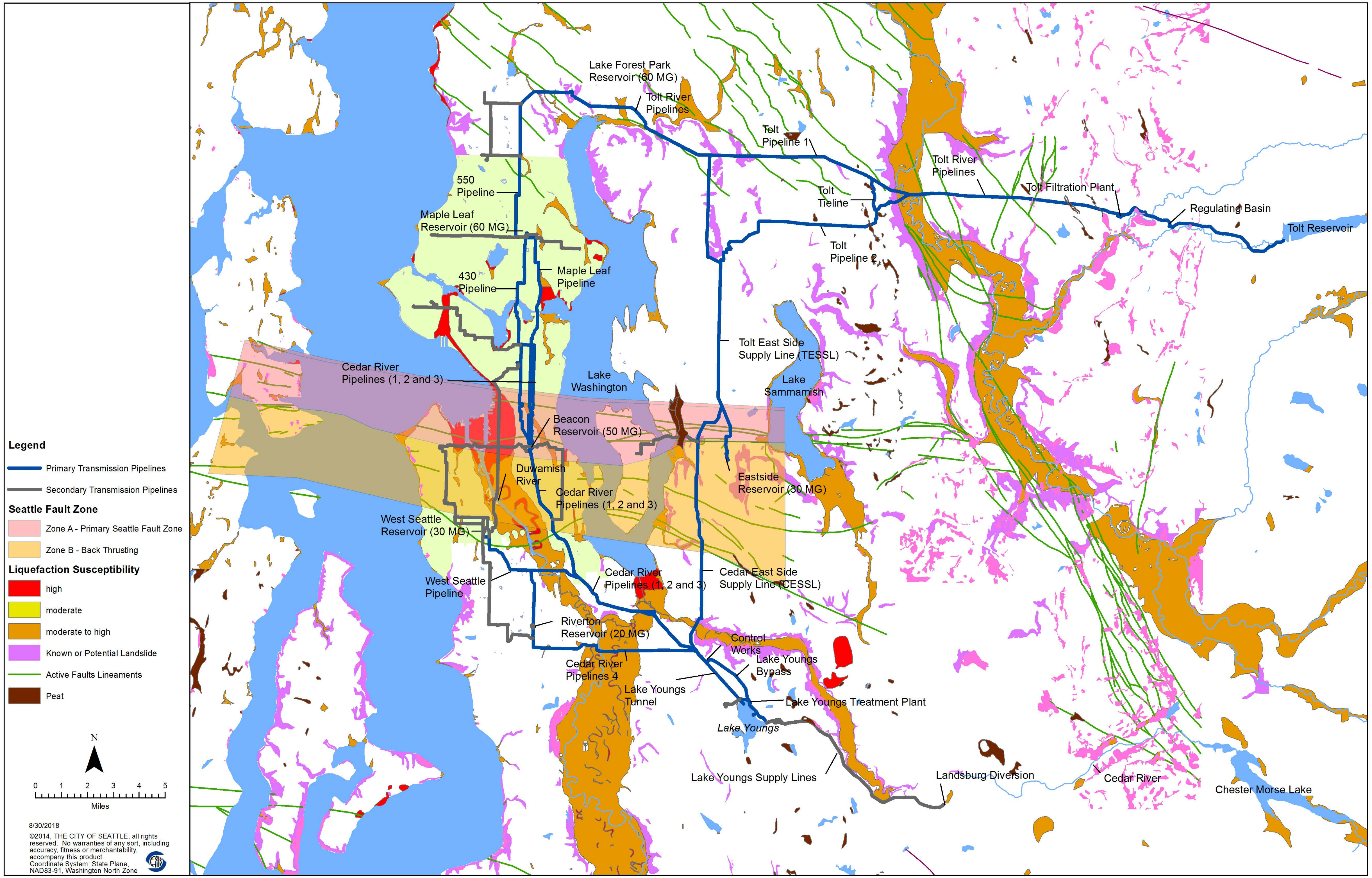


Figure 2-6. SPU distribution and transmission area seismic hazards (note: Seattle Fault Zone is believed to extend east of the shaded area that is shown out to the Cascade Mountain foothills)

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.

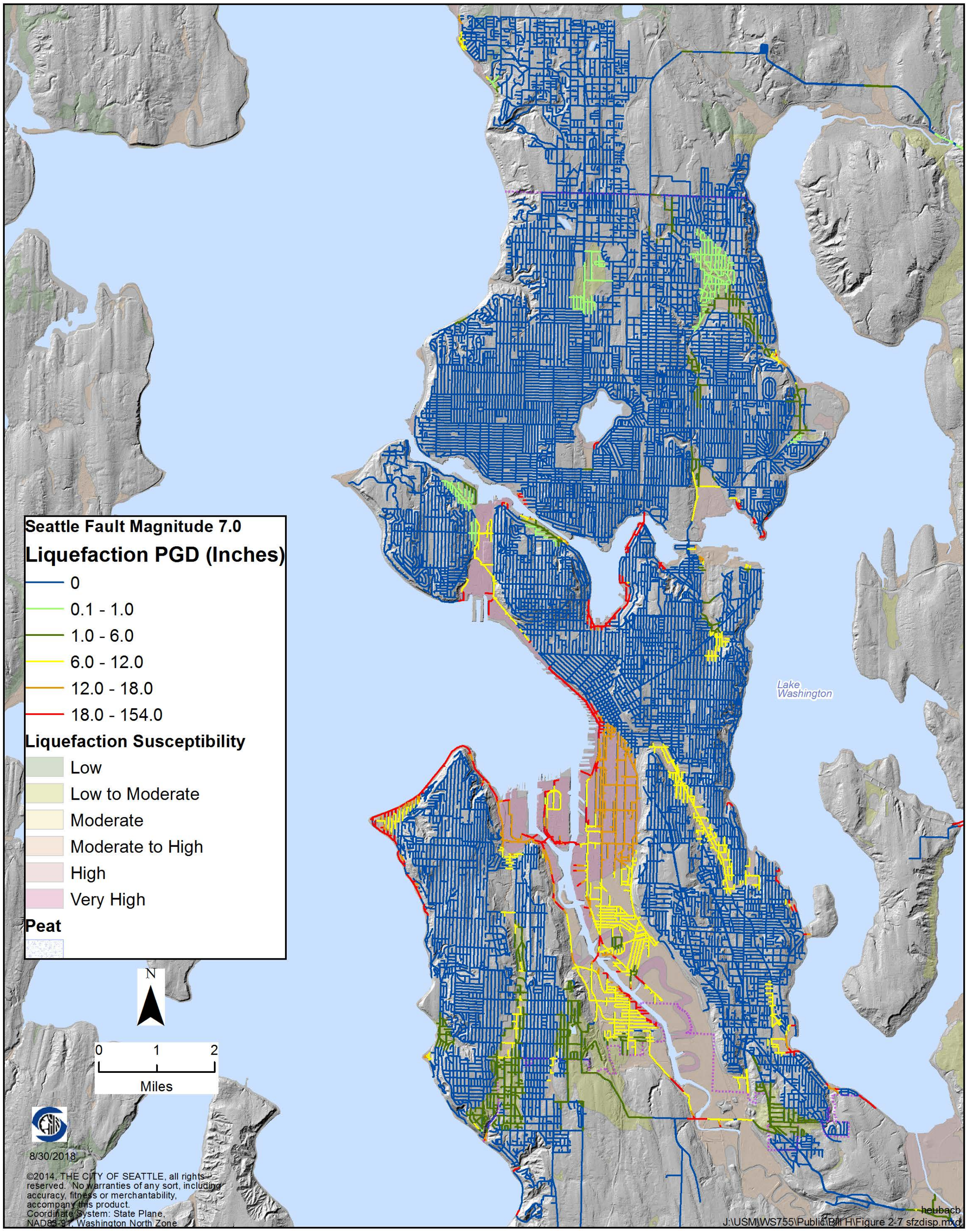


Figure 2-7. M7.0 SFZ distribution pipelines liquefaction displacement estimates

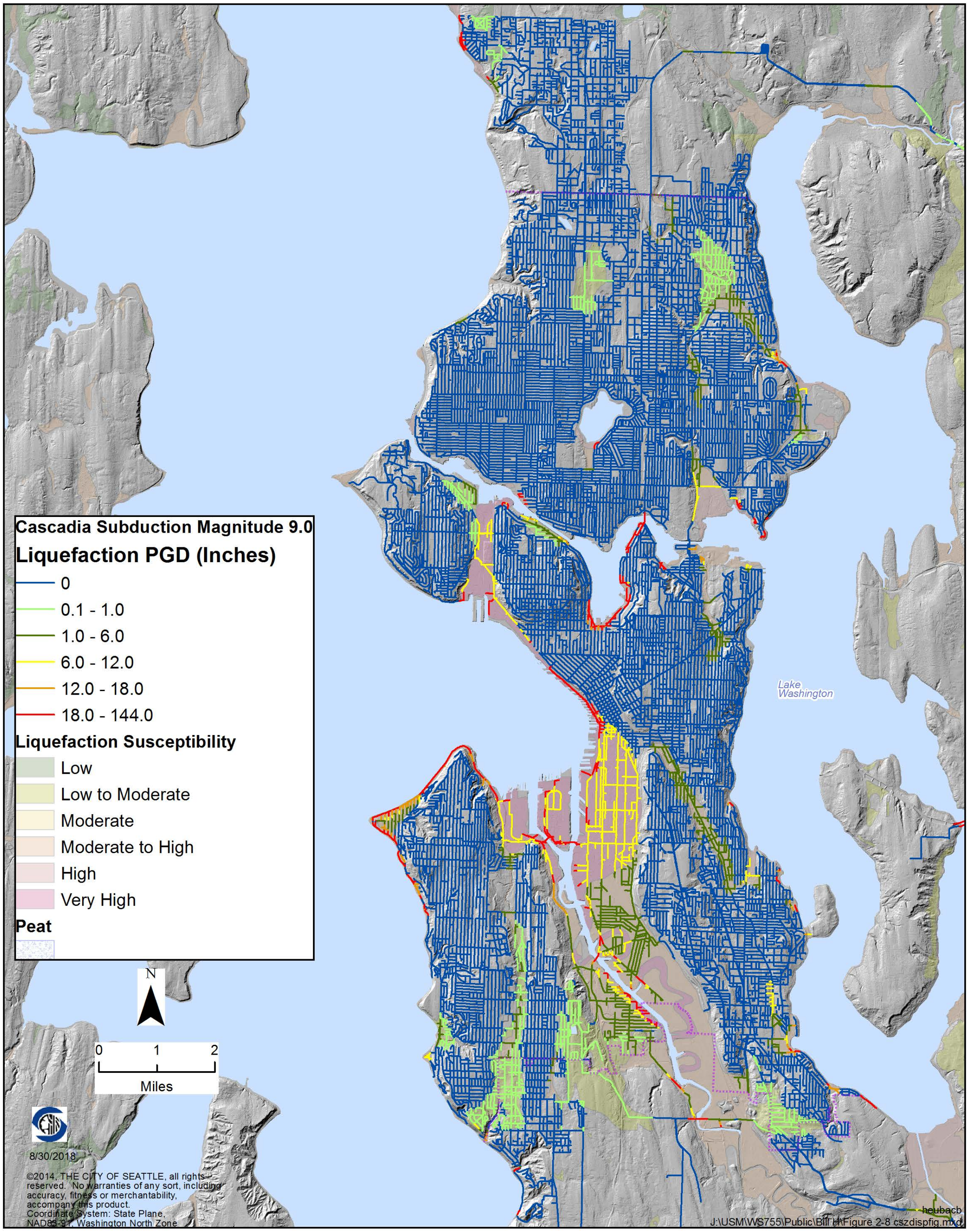


Figure 2-8. M9.0 CSZ distribution pipelines liquefaction displacement estimates

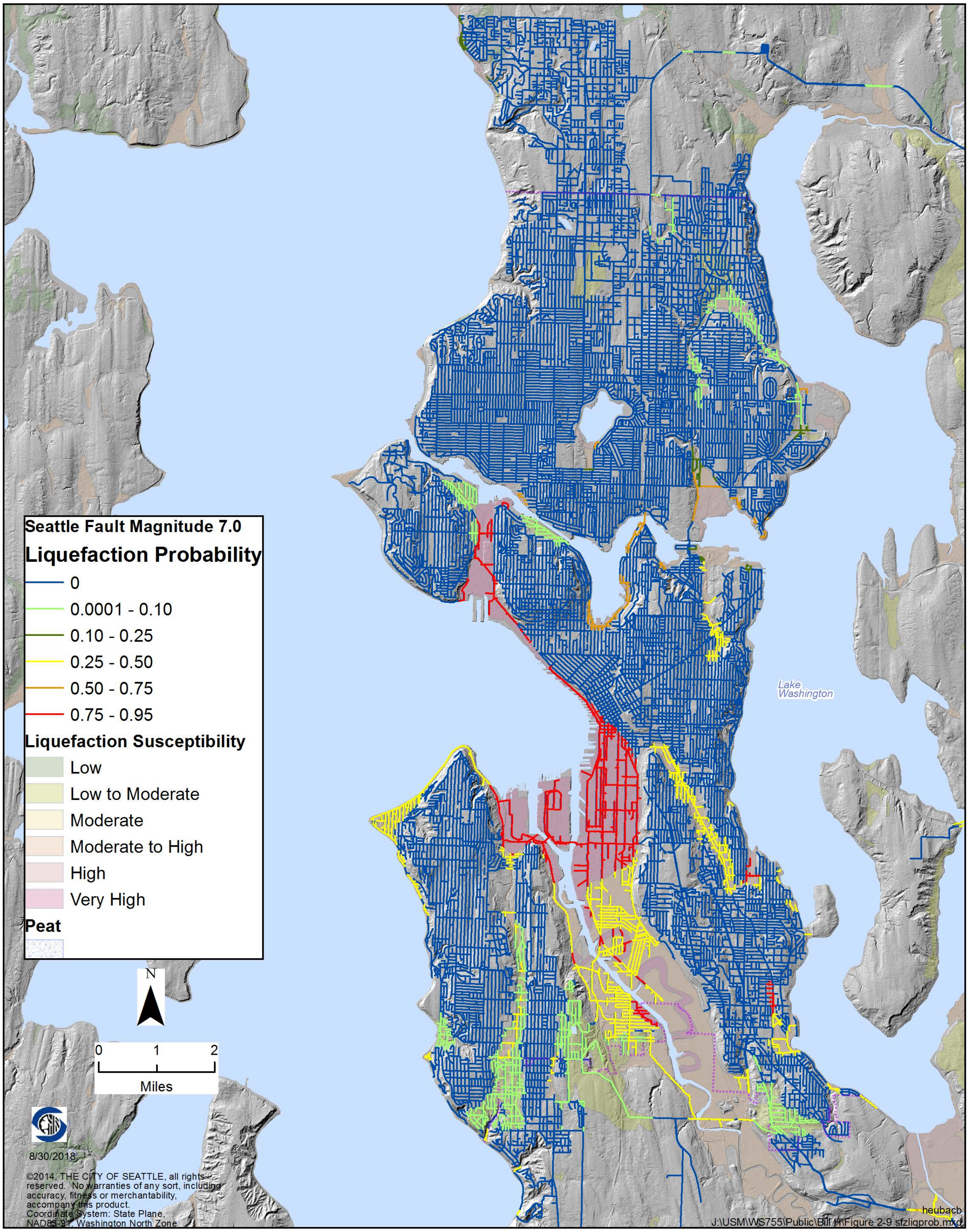


Figure 2-9. M7.0 SFZ liquefaction probability of occurrence estimates

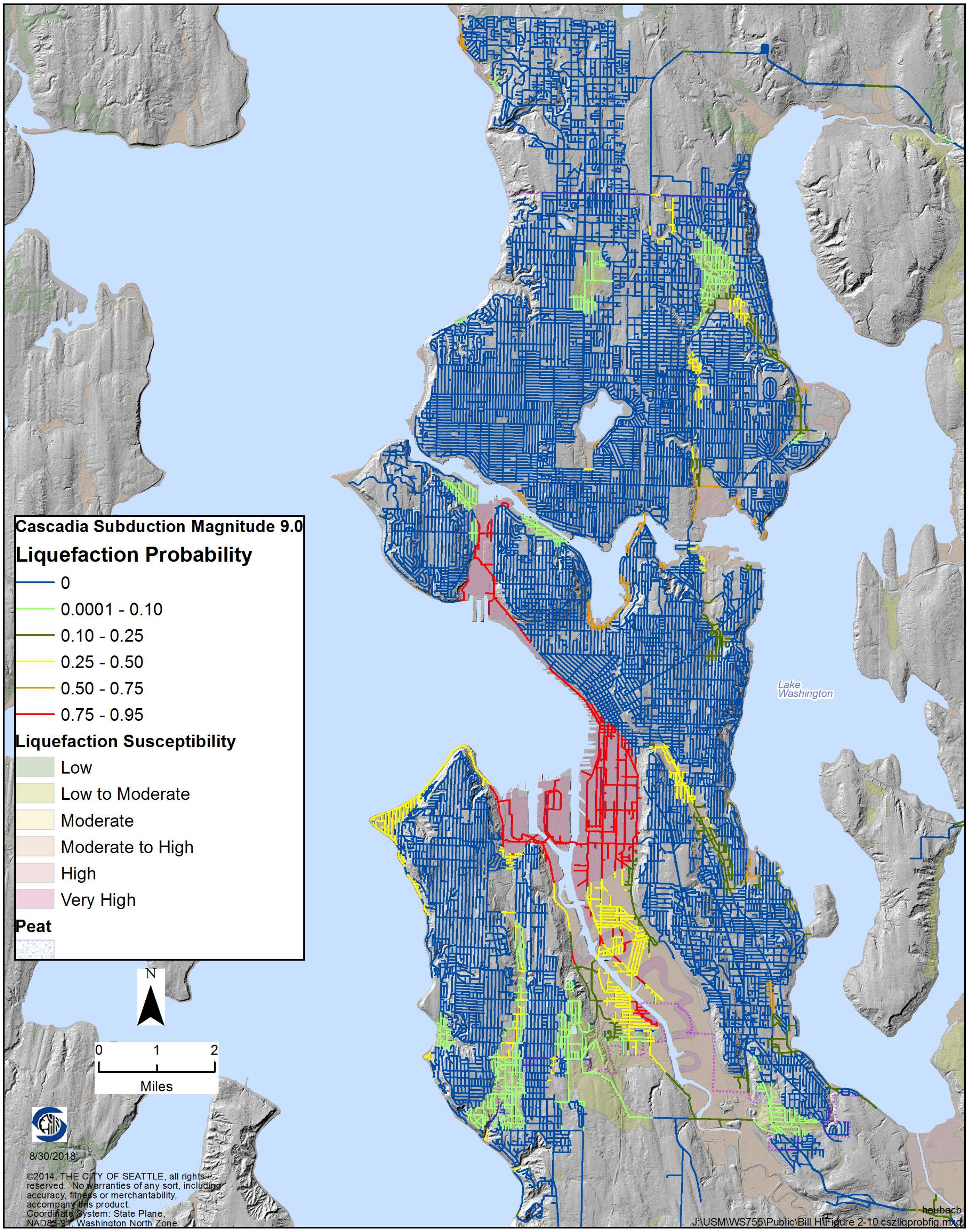


Figure 2-10. M9.0 CSZ liquefaction probability of occurrence estimates

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

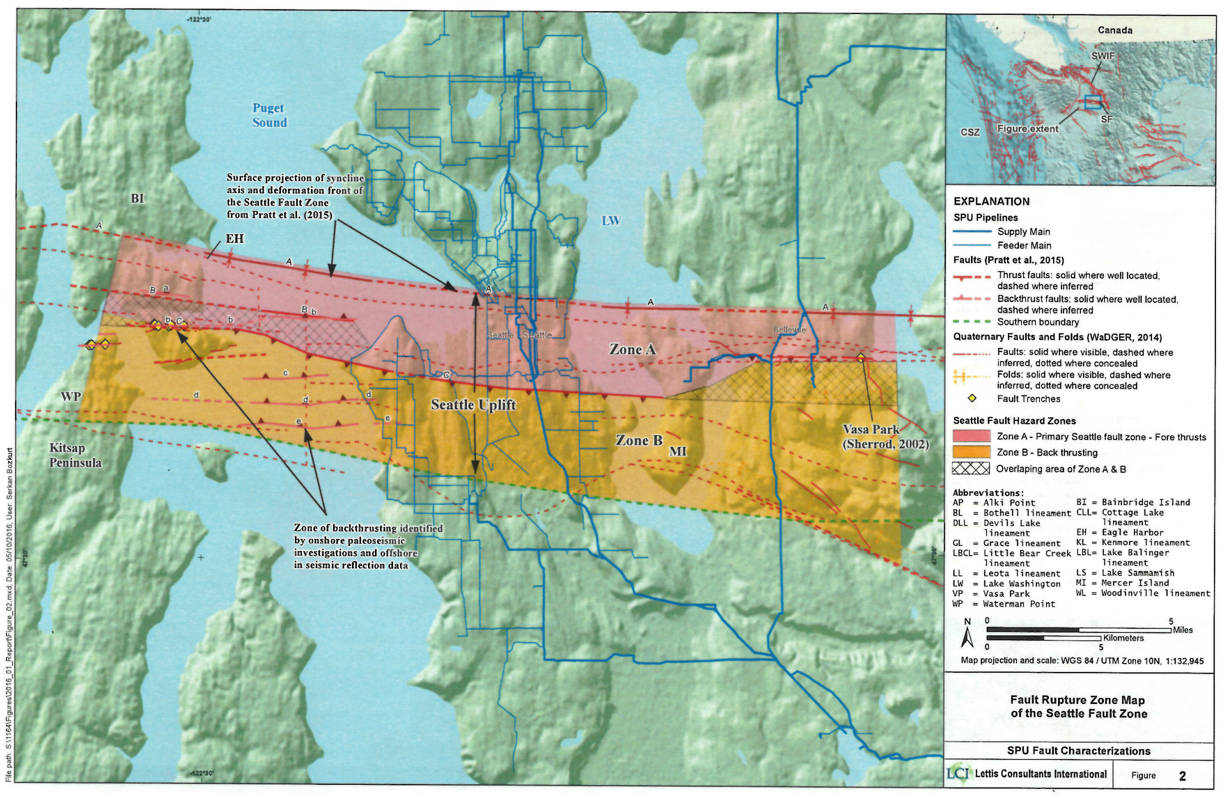


Figure 2-11. Seattle Fault Zone (Map by Lettis Consultants International 2016a)

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.

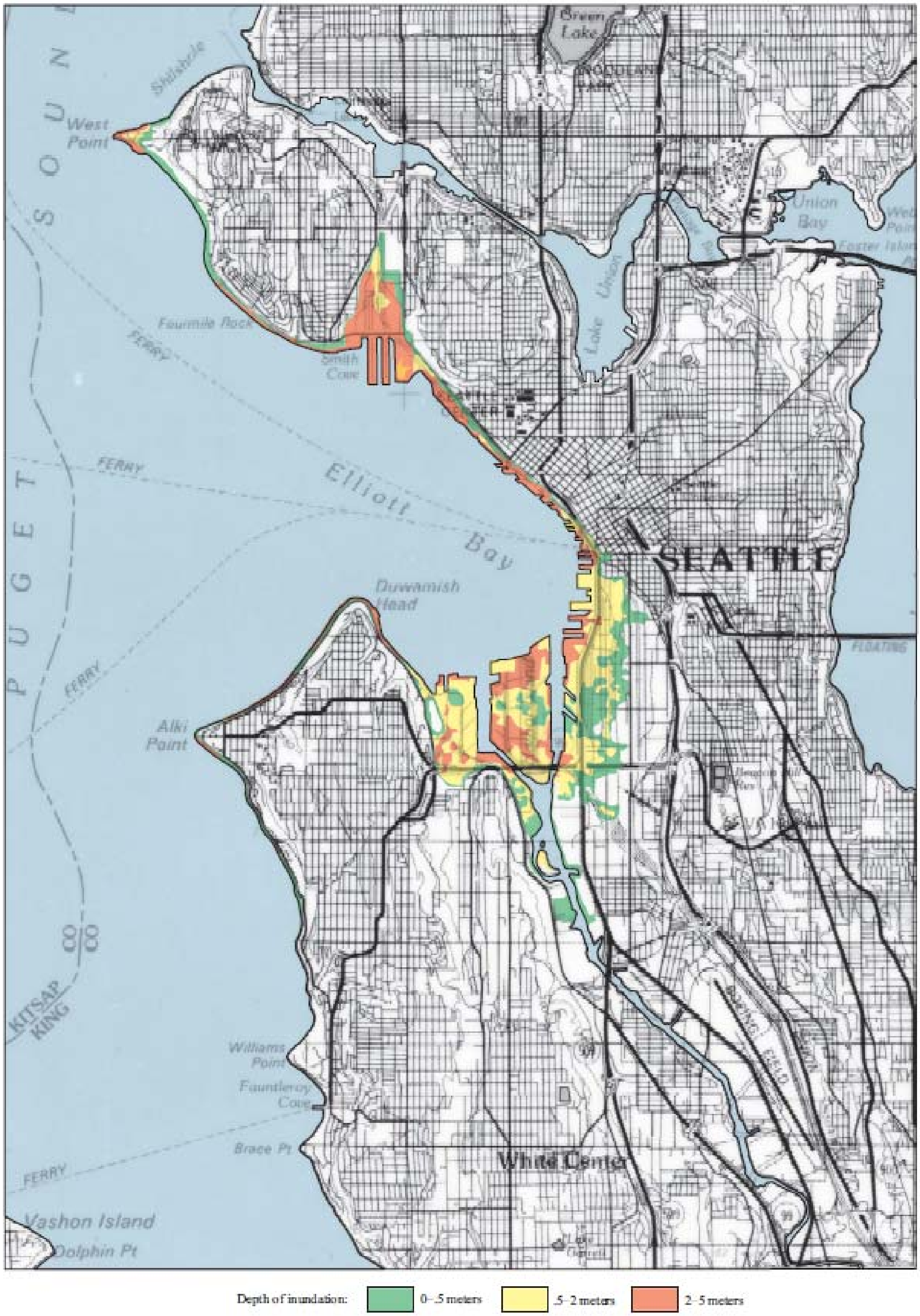


Figure 2-12. Tsunami inundation map for Seattle from a Seattle Fault event (Walsh et al. 2003)