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.

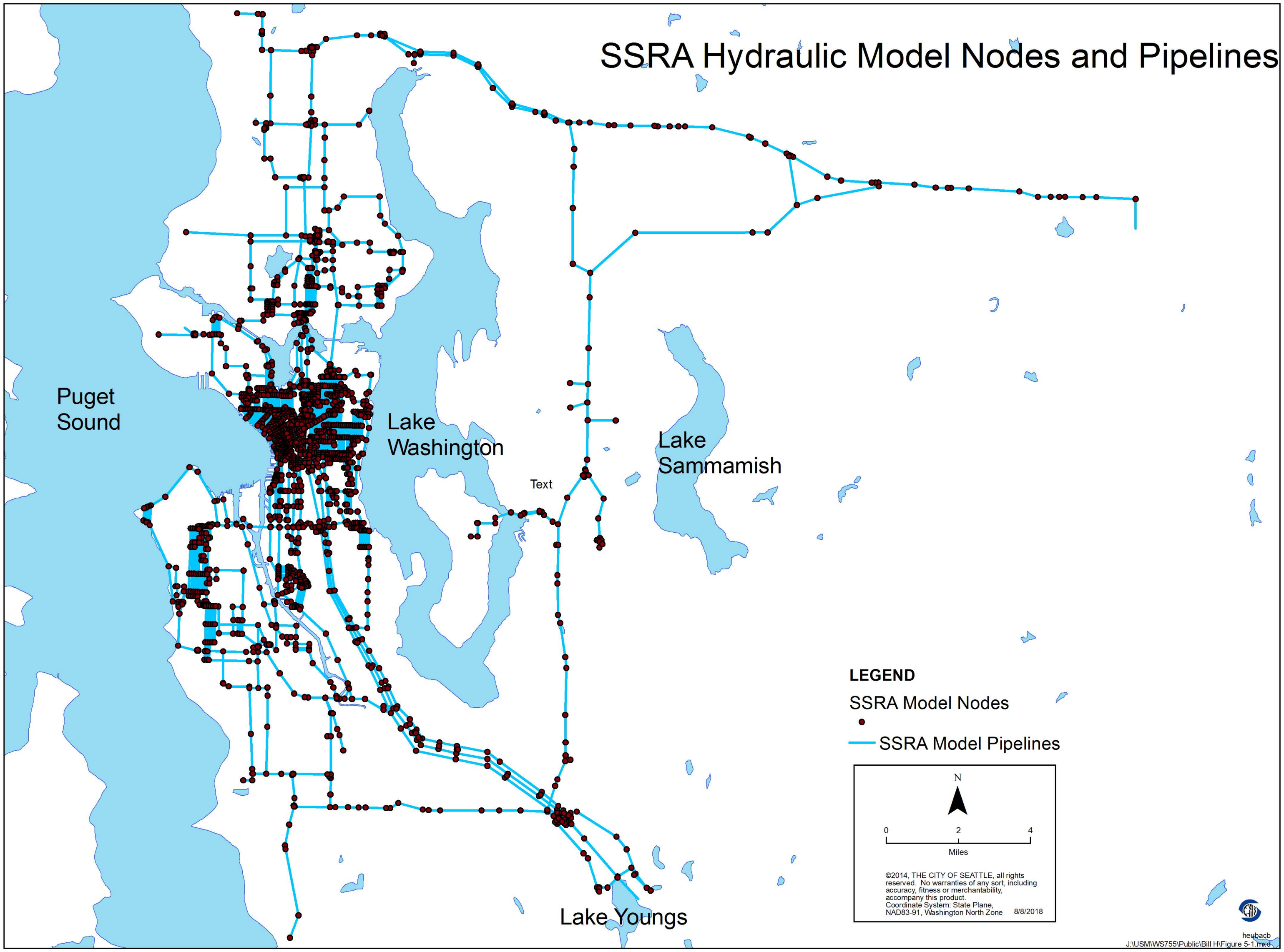

Figure 5-1. SSRA model schematic

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

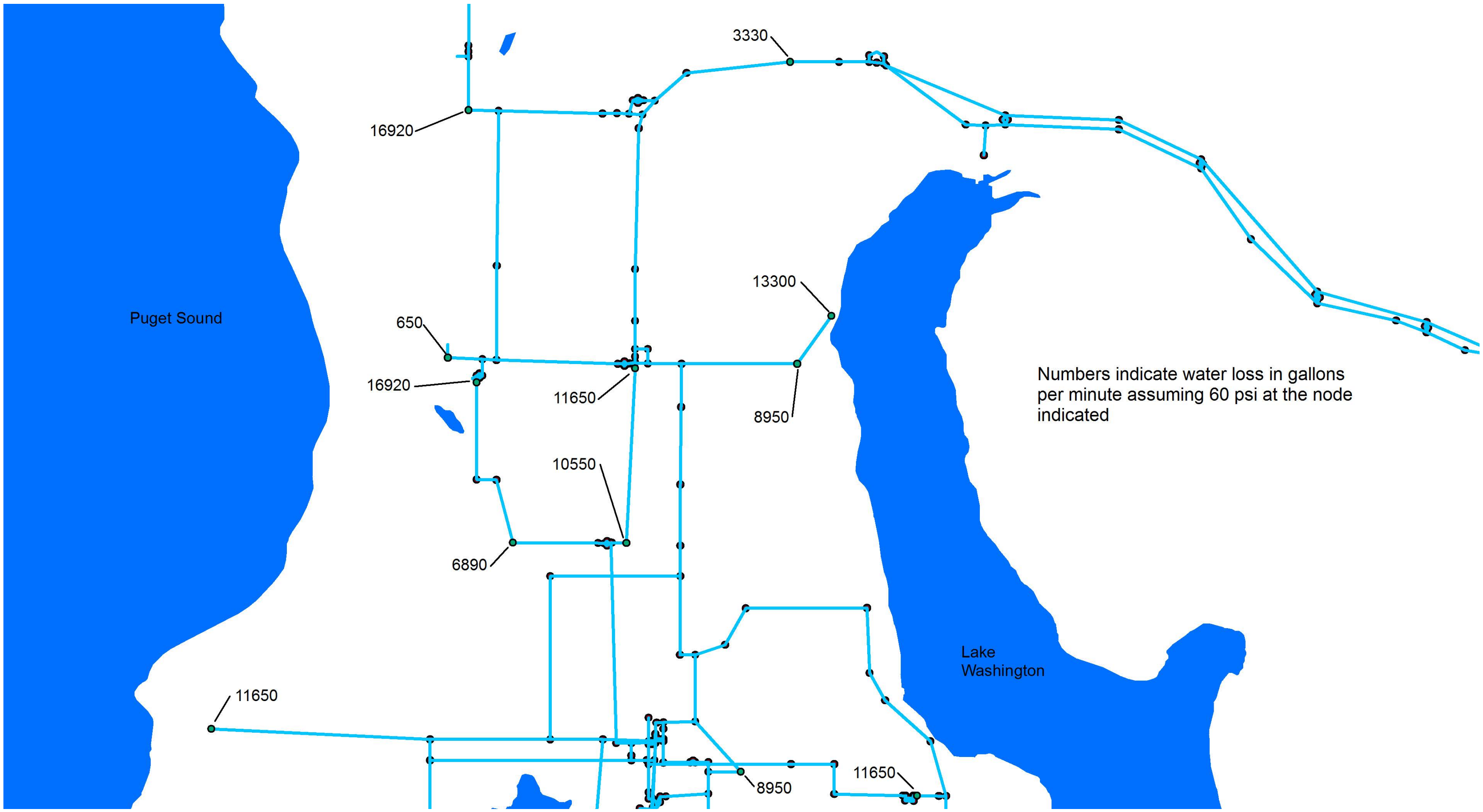

Figure 5-2. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (north service area)

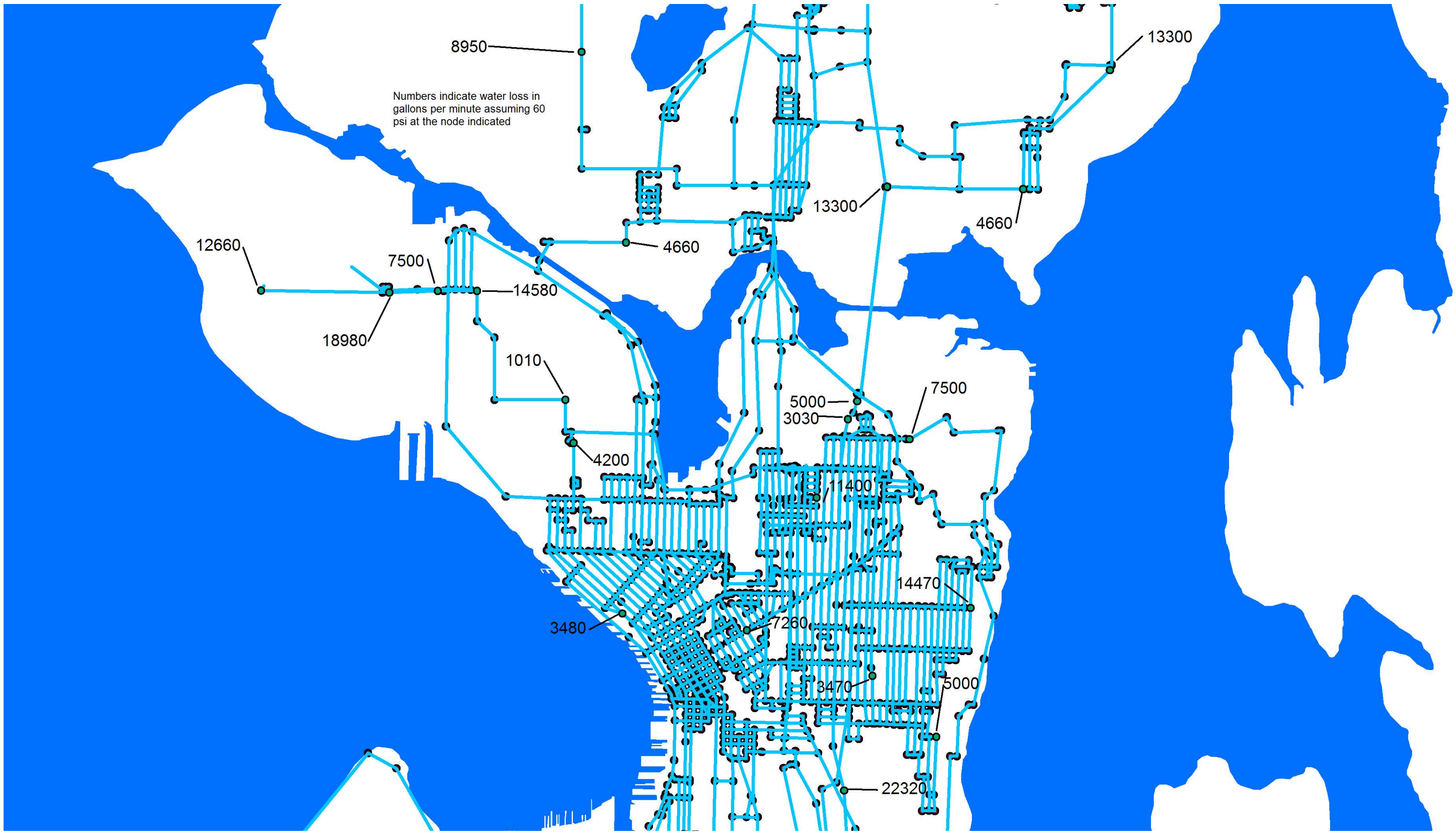

Figure 5-3. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (north central direct service area)

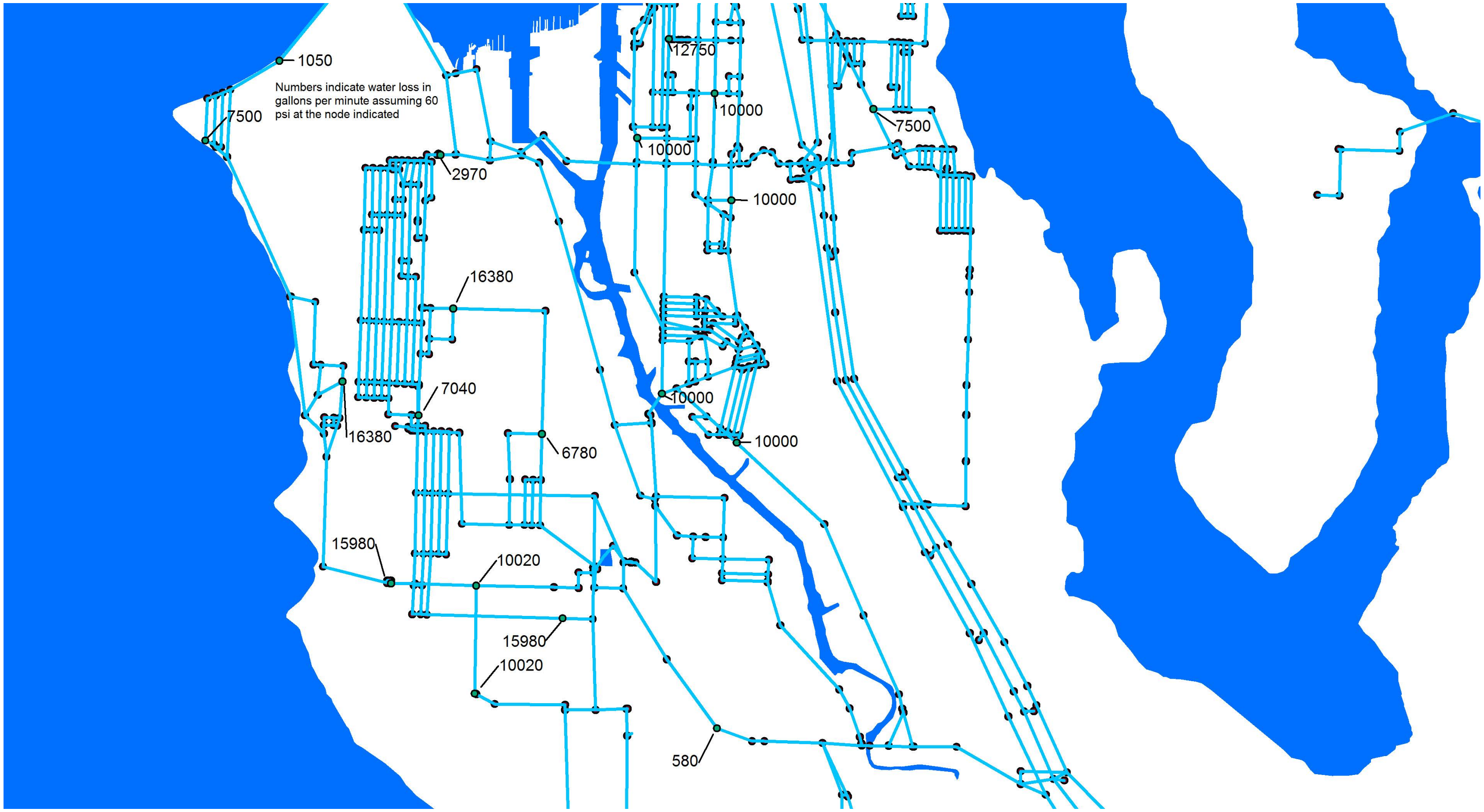

Figure 5-4. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (south central direct service area)

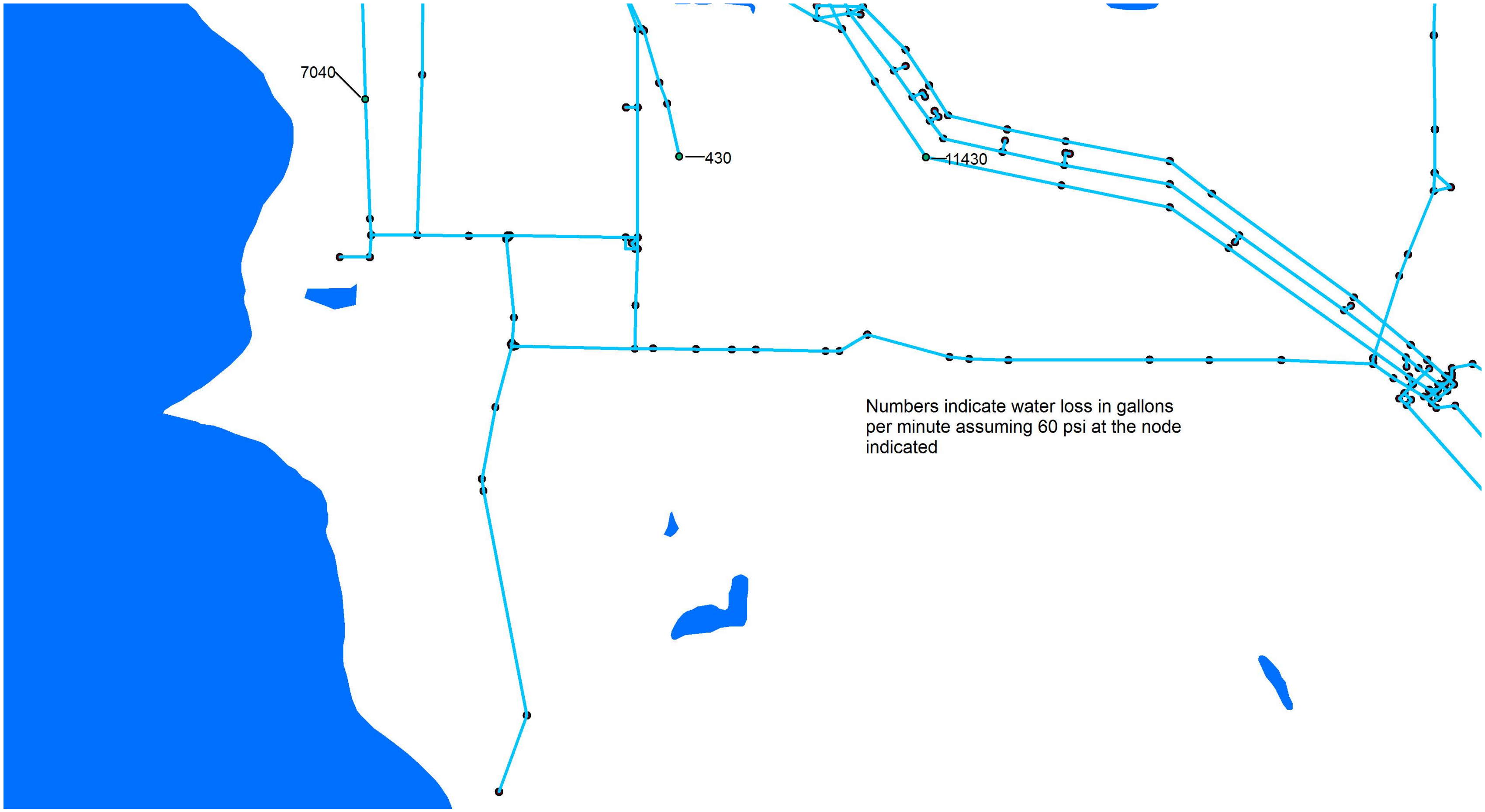

Figure 5-5. Water loss (gpm) at 60 psi for M7.0 SFZ scenario (southern direct service area)

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 a representative number of mitigation 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.

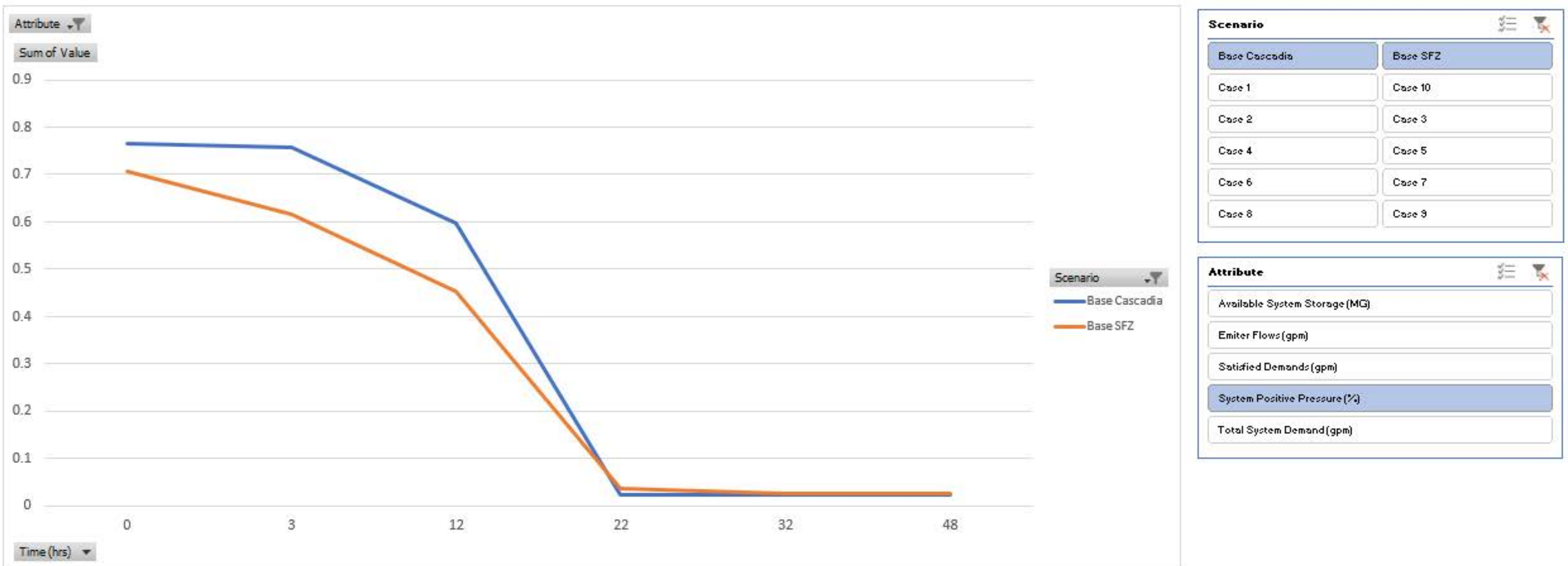

Figure 5-6. Fraction of direct service area (vertical axis) with water pressure versus time (horizontal axis) for M7.0 SFZ and M9.0 CSZ base cases

	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.

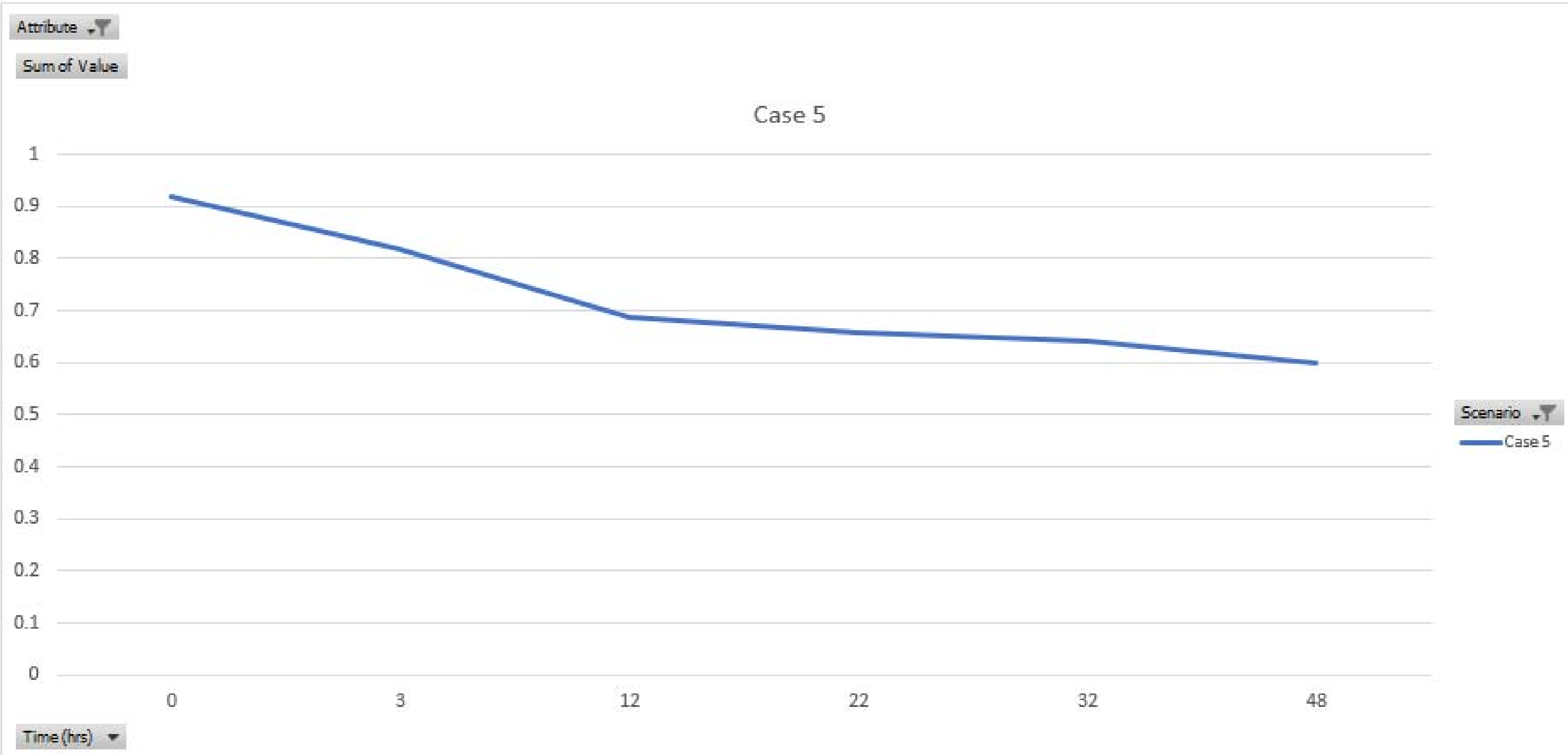

Figure 5-7. Fraction of direct service area with water pressure (vertical axis) versus time (horizontal axis) if the Cedar River transmission system could supply water to the direct service area

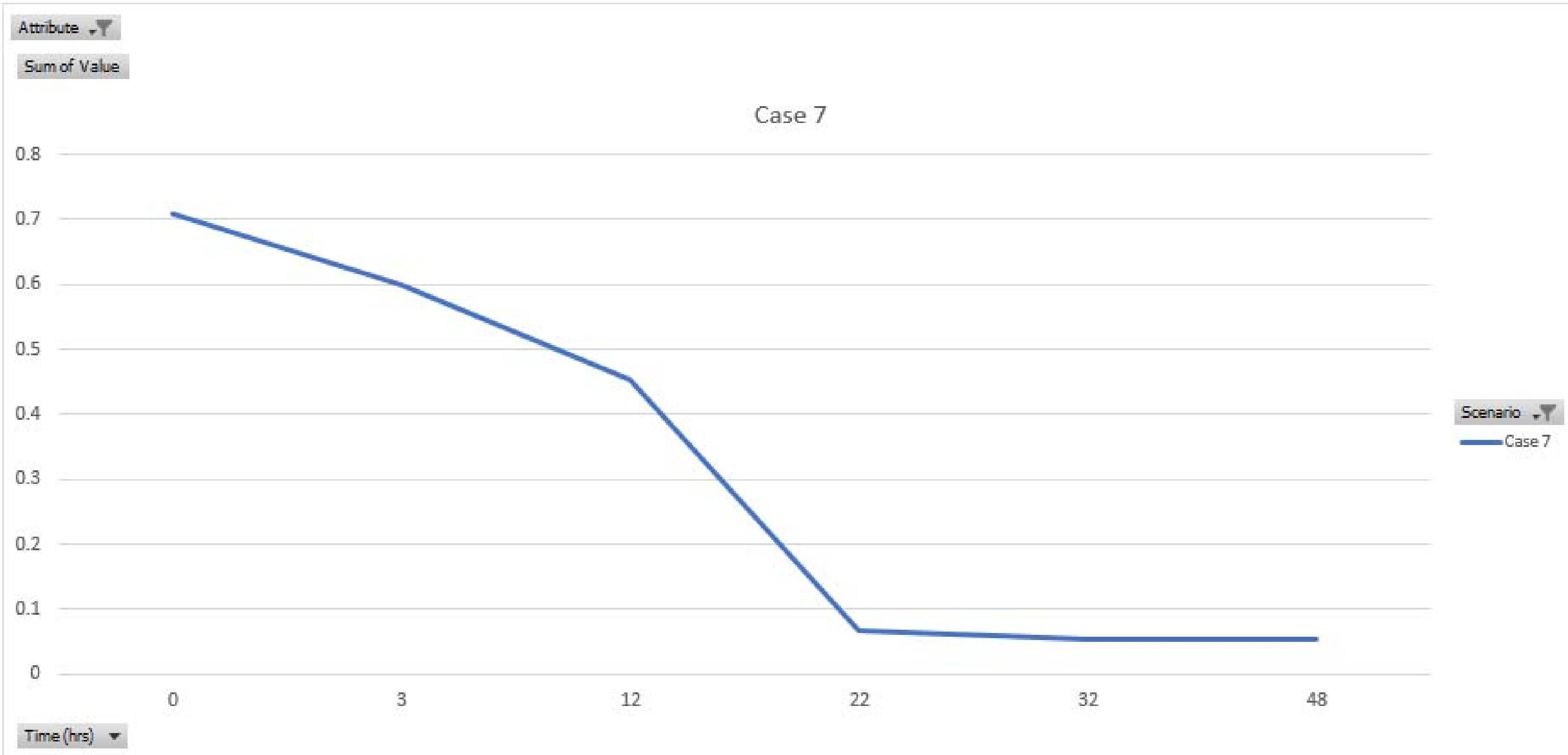

Figure 5-8. Fraction of direct service area with water pressure (vertical axis) versus time (horizontal axis) if the Tolt River transmission system could supply water to the direct service area

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

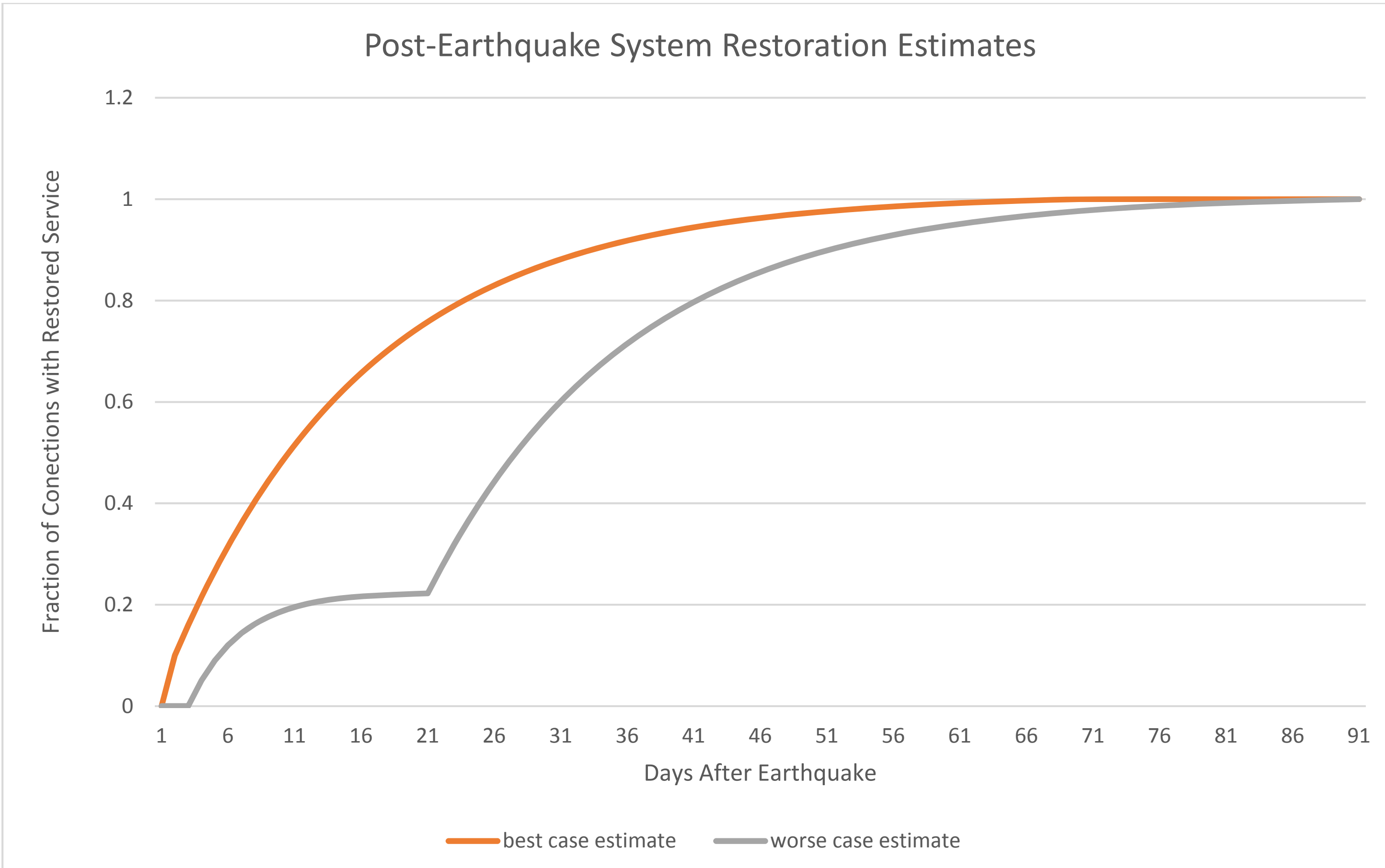

Figure 5-9. System restoration estimation curves for current SPU water system

- 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 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

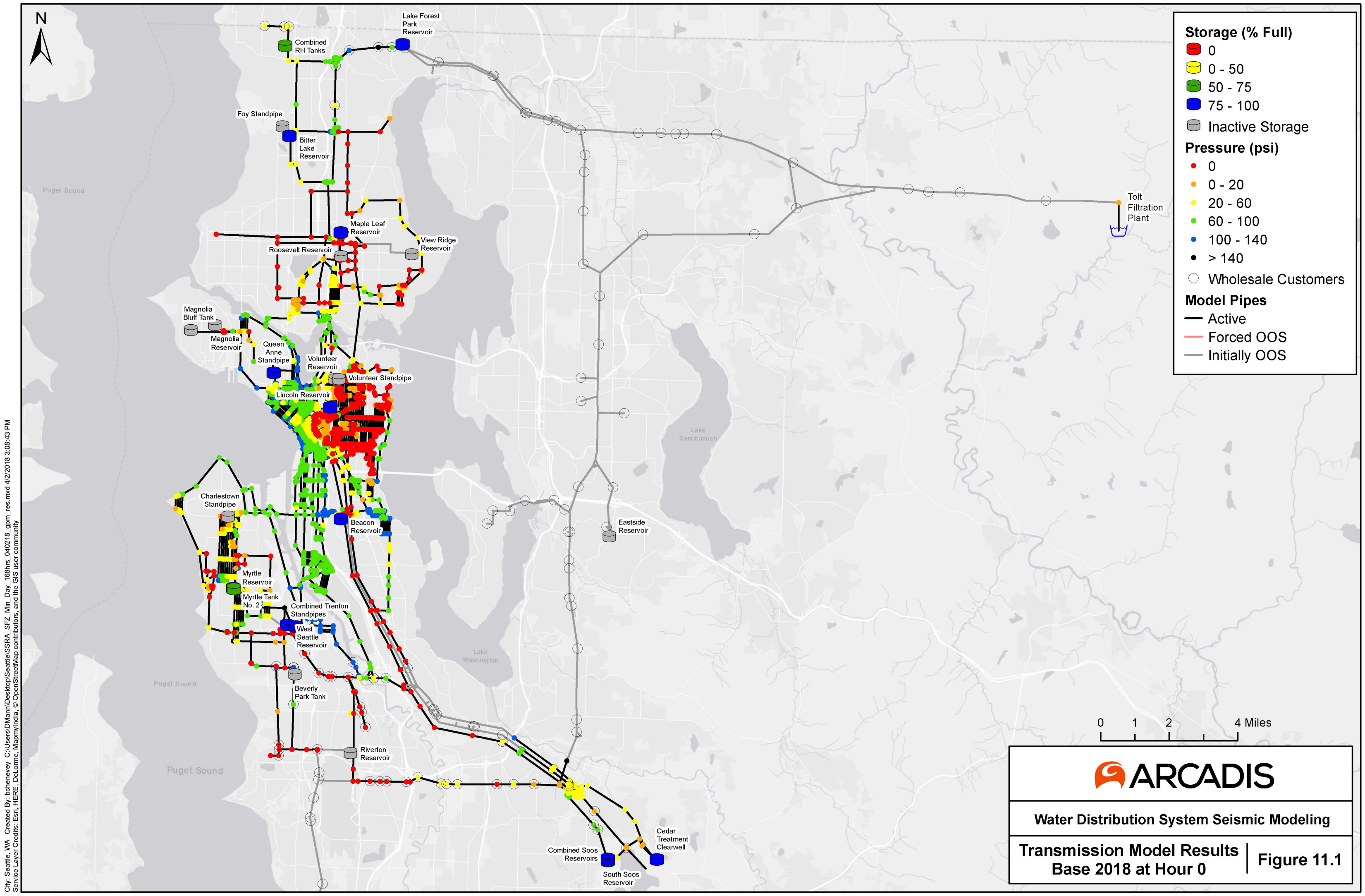

Figure 5-10. Post-earthquake water availability after the M7.0 SFZ earthquake scenario (gray circles indicate zero water pressure at wholesale turnouts/nodes east of Seattle)

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

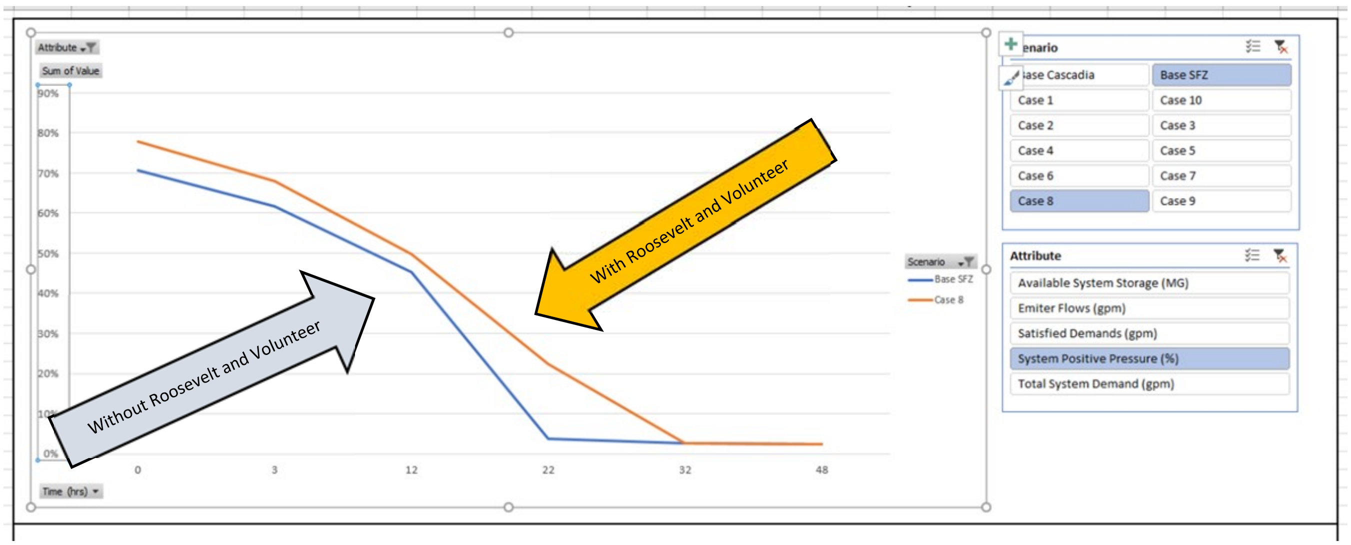

Figure 5-11. Baseline hydraulic analysis (percentage of direct service area with water pressure on the vertical versus hours after the event)

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.

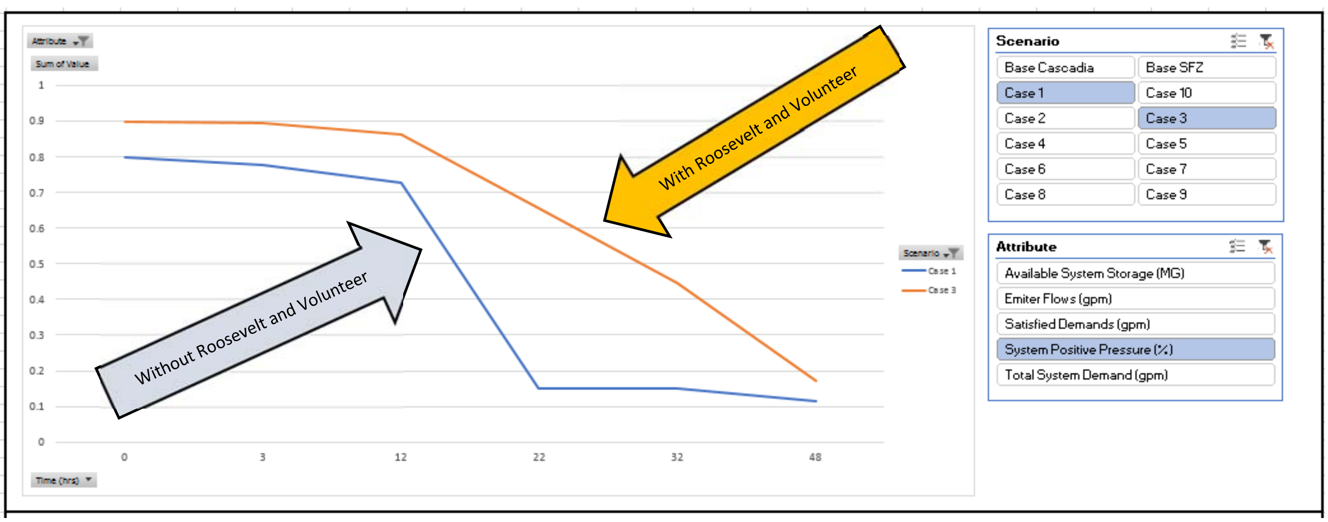

Figure 5-12. 20-year hydraulic model analysis (fraction of direct service area with water pressure on the vertical versus hours after the event)

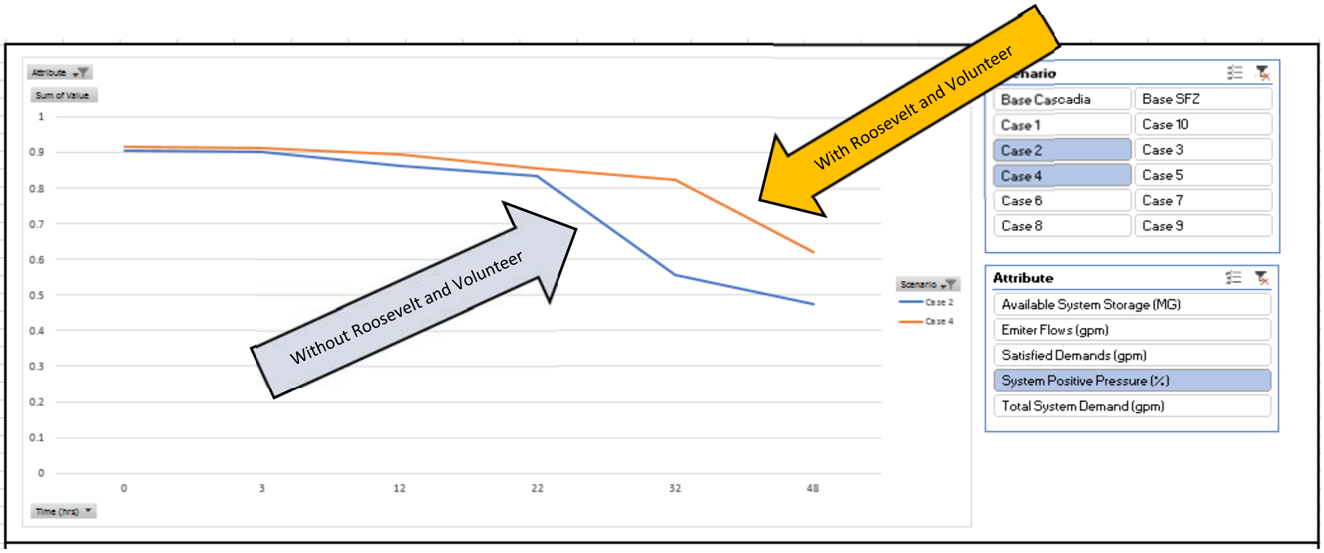

Figure 5-13. 50-year hydraulic model analysis (fraction of direct service area with water pressure on the vertical versus hours after the event)

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.