Bellevue Water System Seismic Vulnerability Assessment

Final Project Report

October 7th, 2022

City of Bellevue, Washington

Bellevue Water System Seismic Vulnerability Assessment

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Executive Summary

Evolving understanding of seismic threats across western Washington and the Pacific Northwest is raising awareness of previously unrecognized risks relative to water supply system resiliency. In response, the City of Bellevue has completed a seismic vulnerability assessment (SVA) of the City's water system. The primary objectives of the SVA are to better understand these seismic risks, better understand potential impacts and develop a plan to increase seismic resiliency. Loss of water service, as is likely to occur after a major seismic event, can have an overwhelmingly negative impact on communities as well as local and regional economies. Figure 1 illustrates the process used to achieve the primary objectives of the Bellevue SVA.

Figure 1: Seismic Vulnerability Assessment process and objectives

Assessment Process

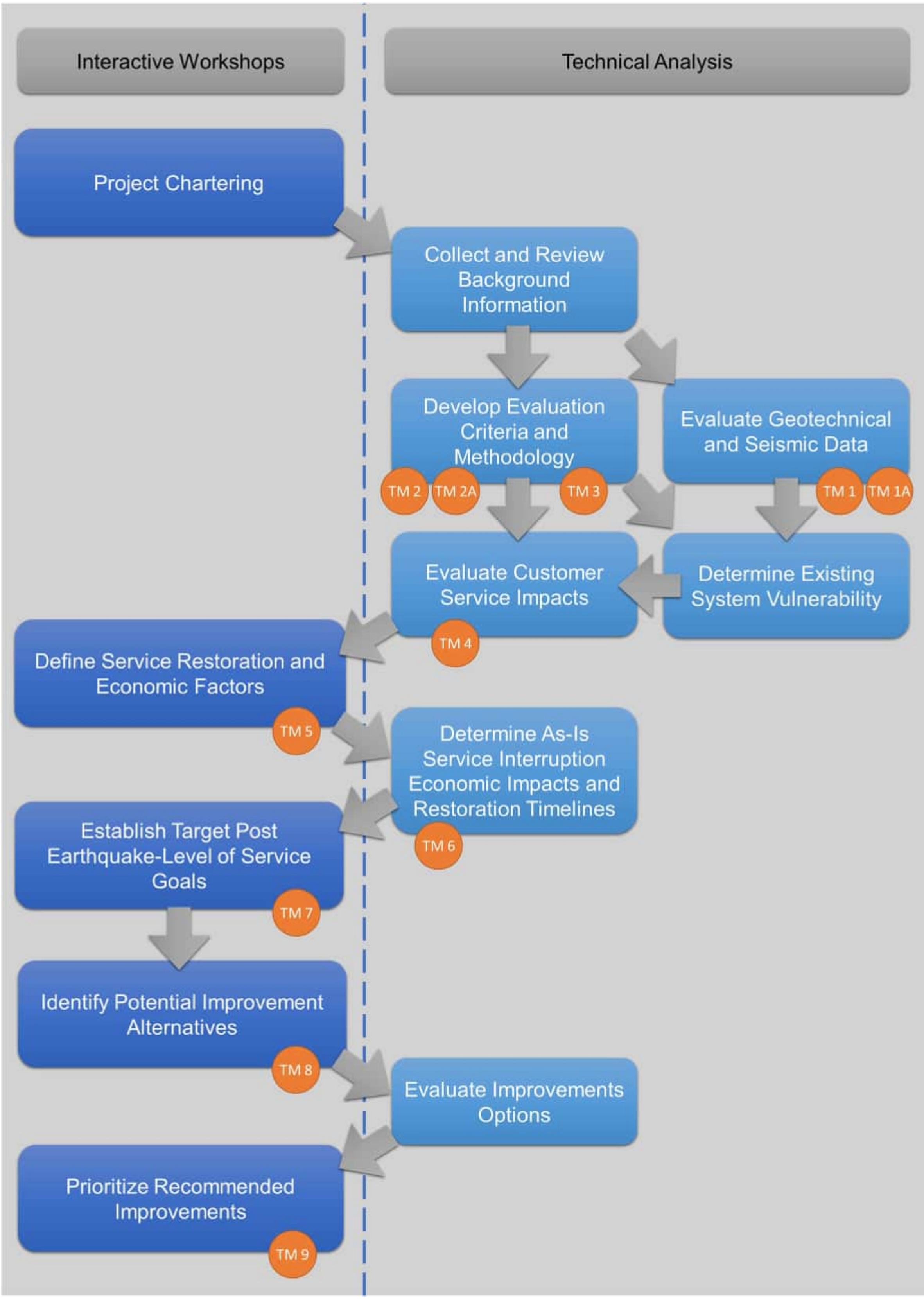
The SVA employed an innovative assessment process incorporating probabilistic system modeling and economic risk and cost-benefit analysis to predict the seismic resilience of existing water system infrastructure and proposed system improvements. This process provides an in-depth understanding of the current seismic risk and highlights the economic and social benefits of system resilience improvements. An overview of the assessment processes employed as part of the SVA effort is described Table 1. For additional information and detail, refer to technical memoranda (TMs) included in this report.

The seismic vulnerability analysis was advanced through a series of site visits and workshops with City staff, with technical analysis approaches, progression, and results documented via workshop summary presentations and detailed technical memoranda (TMs) as summarized in Table 1 and further illustrated Figure 2.

Table 1: SVA approach and Technical Memorandum summary

Assessment Process	Corresponding Technical Memo
Evaluated the seismic threats to Bellevue water system to define seismic event scenarios to be evaluated.	▪ TM1: Geotechnical Data Refinement ▪ TM1A: Seismic Vulnerability Assessment Scenario Selection
Evaluated potential impacts of seismic events on existing Bellevue water supply system to determine likely: ▪ Water system infrastructure damage and failure states (likely impacts to pipes and facilities) ▪ Resulting water service outages, durations, and water service restoration timelines ▪ Potential economic impacts of water service outages	▪ TM2: Seismic Analysis Methodology for Pipeline and Facilities Assessment ▪ TM2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data ▪ TM3: Modeling Methodology ▪ TM4: Existing System Vulnerability and Customer Outage Probability ▪ TM5: Economic Impact Parameters ▪ TM6: As-Is Service Outage, Restoration Times, and Economic Impacts
Assessed Post-Earthquake Level of Service (PE-LOS): ▪ Reviewed likely water system PE-LOS performance relative to water service outage and restoration times ▪ Established target PE-LOS improvement goals	▪ TM7: Post Earthquake-Level of Service Goals
Assessed and evaluated potential water system seismic resilience improvement alternatives and associated costs relative to: ▪ Improved system resilience and reduced likelihood of seismic infrastructure damage ▪ Ability to reduce likely water service outages and durations, improve water service restoration times, and reduce economic impacts of water service outages ▪ Ability to improve system performance to meet target PE-LOS goals	▪ TM8: Improvement Alternatives
Identified optimized water system seismic resilience improvements providing maximum benefits in terms of reduced economic risk relative to improvement costs while meeting PE-LOS goals	▪ TM9: Improvement Prioritization

Figure 2: SVA project approach and progression



Seismic Scenarios and Projections

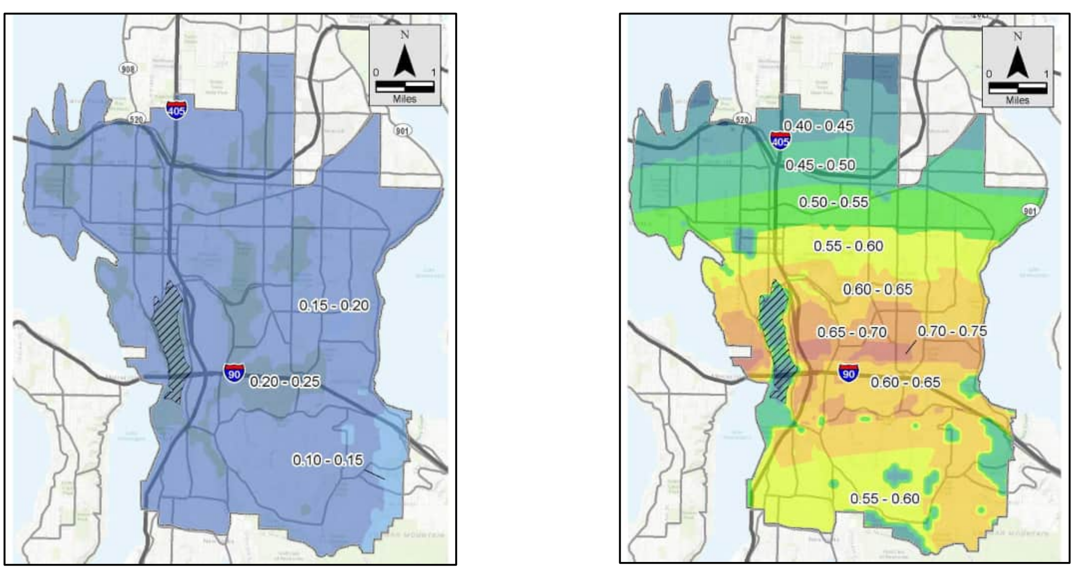
Earthquake risks associated with the Cascadia Subduction Zone (CSZ) and Seattle Fault Zone East (SFZE) were determined to pose the most significant seismic threats to the Bellevue water supply system based on both anticipated event severity and likely frequency of occurrence. Large earthquakes associated with the CSZ are expected to occur once every 500 years, and major event frequencies are likely to be every 800 years for portions of the Seattle Fault Zone. There is great uncertainty around the specific portions of the Seattle Fault Zone that are likely to rupture on this relatively frequent basis, especially along the eastern extent of the fault zone that runs through Bellevue. Figure 3 shows the proximity of local and regional fault zones to the City of Bellevue. Figure 4 illustrates the expected earthquake shaking intensity across the water service area for major CSZ and SFZE seismic events, and demonstrates the greater shaking intensity expected from a major SFZE event.

Figure 3: Washington seismic faults and threats (adapted from Washington Department of Natural Resources)

(Shaking hazard shown is for Cascadia Subduction Zone Only)

Figure 4: Projected seismic peak ground acceleration (PGA) shaking intensity

Cascadia Subduction Zone Mw 9.0 | Seattle Fault Zone East Mw 6.6



Existing System Seismic Vulnerability and Impacts

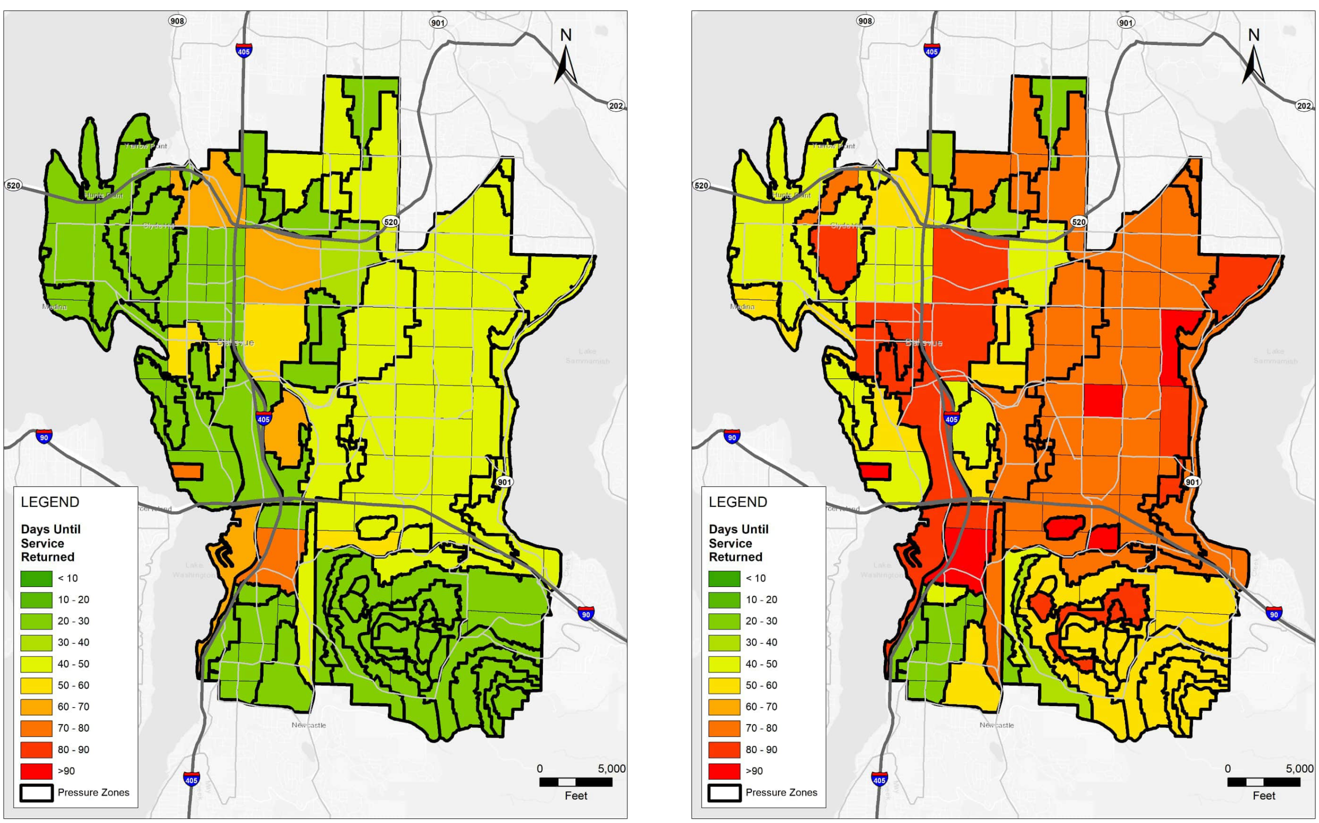
Estimated CSZ and SFZE seismic event severity, local geologic conditions, and water supply infrastructure condition, configuration, age, and materials were used to evaluate and estimate the seismic resilience of the existing system, and project likely system levels of service following major seismic events. Based on this information, it was determined that:

- Significant and widespread damage and failures in existing water supply pipes and facilities are likely under both CSZ and SFZE seismic scenarios including at least 200 to 400 pipe breaks, respectively, within the Bellevue water system and potential major damage to the regional Seattle Public Utilities (SPU) water infrastructure that supplies water to Bellevue.
- Resulting water service outage and restoration times following a significant CSZ or SFZE seismic event could be on the order of months. As illustrated in Figure 5, the greater shaking intensity predicted for the SFZE compared to the CSZ is likely to result in longer and more widespread water supply service outages, resulting in significant impacts on existing water system infrastructure and supply availability for months after a seismic event.
- The economic impacts of resulting Bellevue water service outages could accrue to totals on the order of \$2.4 to \$8.3 billion for the CSZ and SFZE earthquake scenarios, respectively.

Figure 5: Water service outage durations projected to result from major seismic events

Cascadia Subduction Zone Mw 9.0

Seattle Fault Zone East Mw 6.6

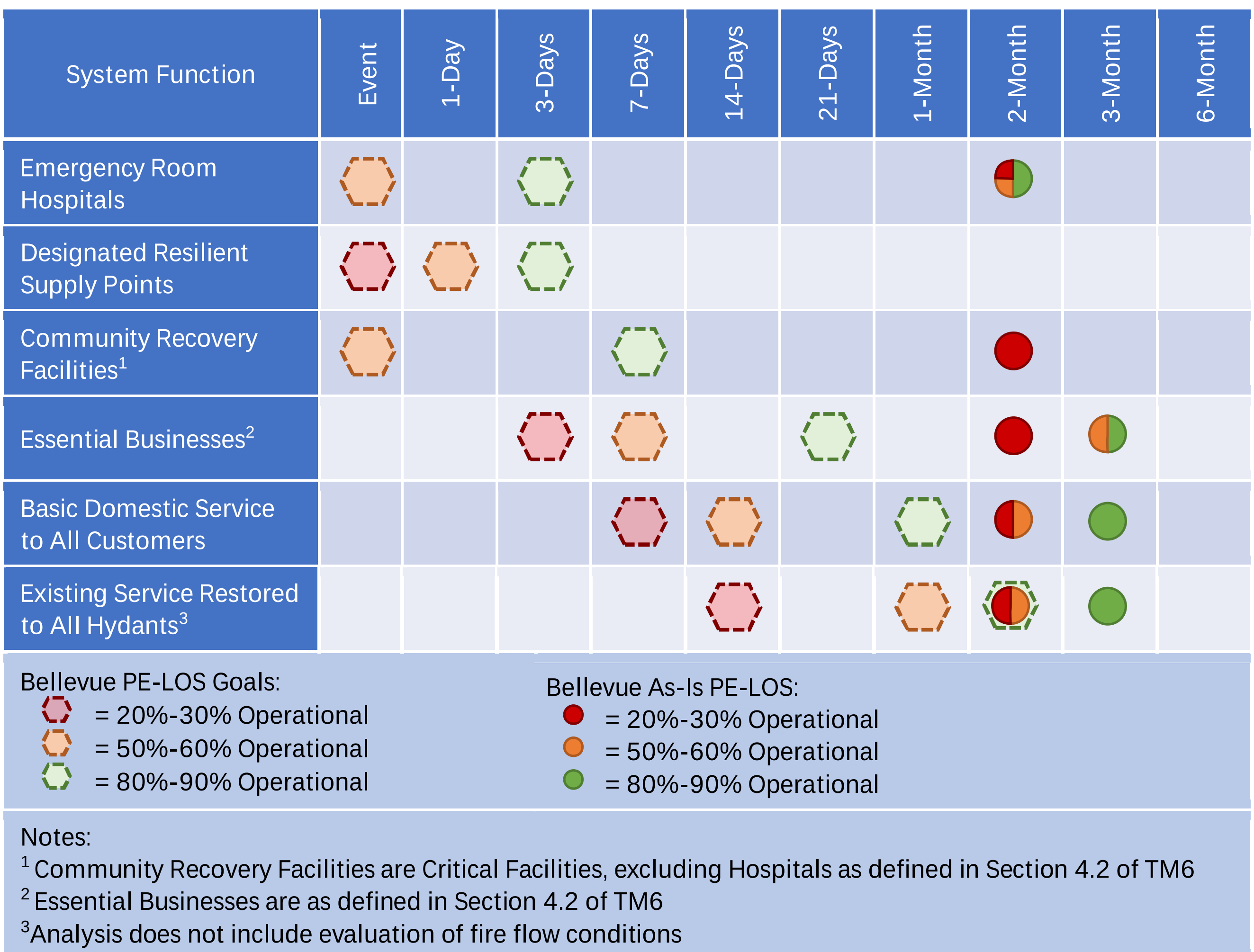


Post-Earthquake Level of Service Goals

Post-Earthquake Level of Service (PE-LOS) goals are used by water systems to define target levels of system seismic resilience and post event performance that should be expected following an earthquake. As-Is PE-LOS shows the amount of time that water supply service may be unavailable based on the state of the existing system infrastructure if no improvements are made. PE-LOS goals illustrate the outage durations that should be expected from a more resilient system after it has been seismically strengthened. SVA evaluations of the existing Bellevue water system indicate that water supply outage durations following a major seismic event are likely to extend well beyond acceptable timeframes. Based on an understanding of the existing system and a peer review of other municipal water system PE-LOS goals, incremental short-, mid-, and long-term PE-LOS goal targets were developed relative to various water user classifications. These goal targets can then be used to support development of appropriate and optimized system seismic resilience improvement priorities.

PE-LOS goals are structured to establish appropriate water service restoration time targets for different services and customer types. Figure 6 shows the target Long-Term PE-LOS goals developed for the Bellevue Water System as well as the expected outage durations in the as-is state of the system for the SFZE scenario as an example. The SFZE results in the longest restorations expected from the earthquake scenarios considered. For the CSZ and SFZE mid- and short-term goals, refer to TM 7: Post Earthquake-Level of Service Goals.

Figure 6: SFZE Long-Term Target PE-LOS Goals



Improvements Identified for Evaluation

Five categories of improvements were identified and specific alternatives in each category were developed to support improvements in water system seismic resilience, reduce potential water service outage durations, and accelerate likely water supply restoration times. The improvement categories included:

- Water Supply Resilience Improvements
- Resilient System Piping Backbone Corridors
- Seismic Improvements to Pump Stations
- Distribution Pipe Resilience Improvements
- Operational Adjustments and Improvements

Improvement Selection and Prioritization

An optimized suite of seismic resilience improvements, structured to reduce water supply outage durations following earthquake events, were developed to improve water system resilience and improve system performance consistent with the target PE-LOS goals for each timeframe. The selection of the specific combinations of improvements is based on those that most efficiently and effectively meet the PE-LOS goal targets for more critical water supply customers (as summarized in Figure 6), and the overall system as whole, and provide favorable risk reduction benefits relative to the projected improvement costs involved.

The water supply outage duration and economic impact reductions that can be expected to result from recommended seismic resilience improvements at each implementation milestone are illustrated in Figure 7 through Figure 9 (additional detail and comparative assessments of the various improvement combinations considered are detailed in TM9, included in the appendices). The selected improvement combinations provide improved system resilience and service recovery timelines to reduce predicted water system seismic economic impacts from as much as $8.3 billion for the existing system, down to $0.7 billion or less.

Figure 7: System-Wide Service Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0 | Seattle Fault Zone East Mw 6.6

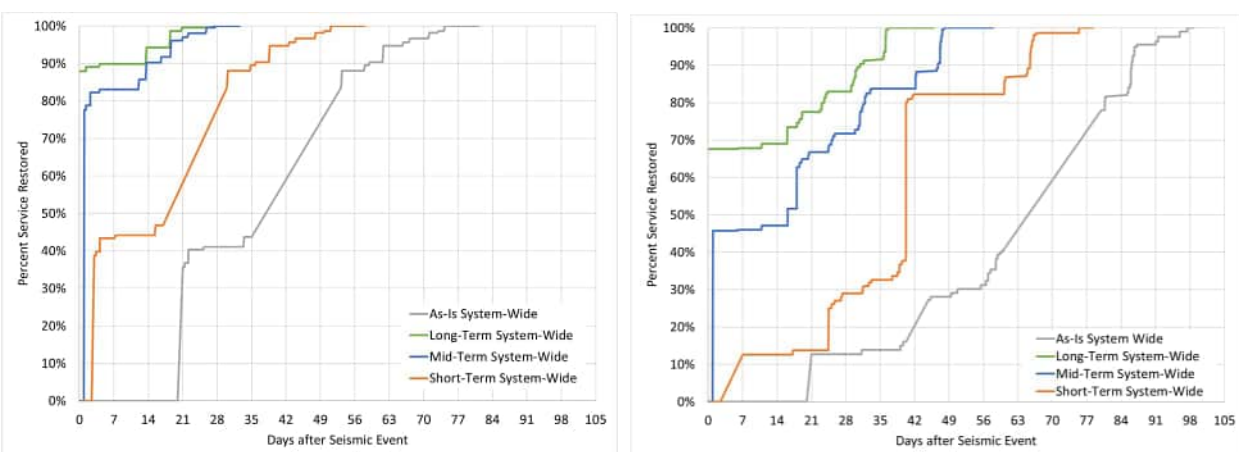
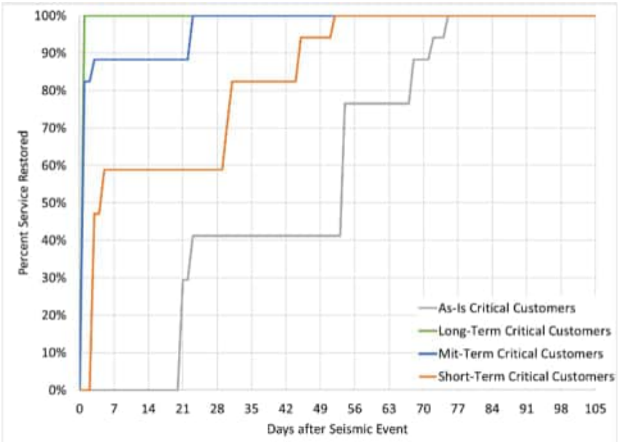


Figure 8: Critical Customer Service Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0



Seattle Fault Zone East Mw 6.6

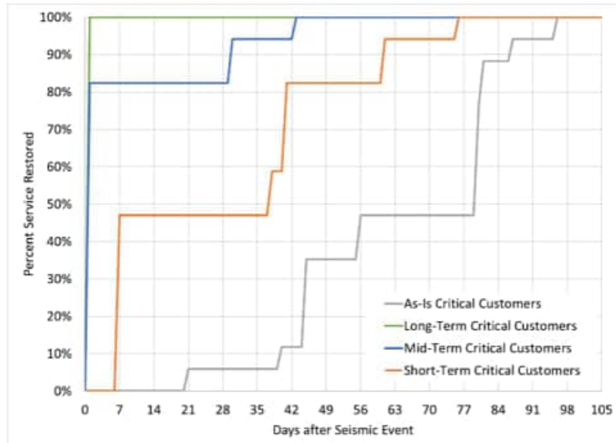
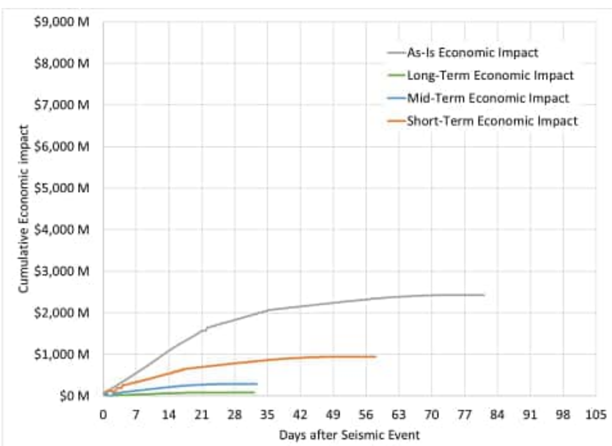


Figure 9: Economic Impact Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0



Seattle Fault Zone East Mw 6.6

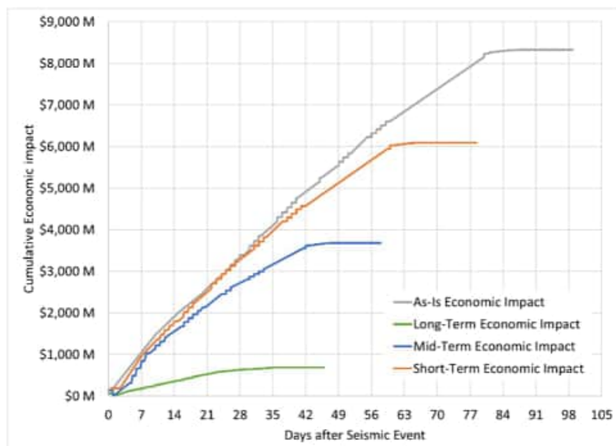


Figure 10 shows an overview of the improvements selected to achieve each of the short-, mid- and long-term PE-LOS goals.

Figure 10: Summary of recommended water system seismic resilience improvements

Water System Improvement Category	Short-Term (10-15 years)	Mid-Term (20-30 years)	Long-Term (40-50 years)
Water Supply	9 MGD of Emergency Wells	7-day SPU Supply Restoration	
Pump Station Facility Seismic Upgrades or Replacement	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Horizon View 2 Parksite	Forest Hills Newport 670	Woodridge
Pressure Zone Distribution Pipe Strengthening		LH 520 FA 293	BV 400 SS 850 EG 330
Backbone System Piping Strengthening	Partial Backbone	Expanded Partial Backbone	

The following summarizes the improvements for each of the three timeframes in more detail.

Short-term improvements

- Includes $55M[1] of investment over the next 10 to 15 years, $28M of which is for previously planned pipe replacement of asbestos cement (AC) and cast iron (CI) pipe and facility upgrades
- Develops Bellevue emergency water supply wells to provide 9 million gallons per day (mgd) of emergency supply capacity
- Implements initial strengthened system piping and pump stations along key backbone corridors, using ductile iron (DI) pipe at a minimum, and earthquake resistant ductile iron pipe (ERDIP) in more vulnerable areas

Mid-term improvements

- Includes $258M[1] of additional investment by year 2050, $187M of which is for replacement of asbestos cement (AC) and cast iron (CI) pipe already part of an ongoing replacement program
- Requires collaboration with Cascade Water Alliance and SPU to reduce regional water supply restoration times to 7-days or less for Bellevue and other eastside communities (It is recognized that this type of interagency coordination to improve water supply resilience will be challenging and require time to negotiate and implement. However, the analysis from the Bellevue SVA shows that this is a critical component to achieve a resilient water supply for Bellevue's customers. As such a target of 20 years has been assigned to accomplish this goal, with the assumption that coordination and negotiation to reach this goal will begin immediately.)
- Includes strengthening of all pipe in the Lake Hills 520 and Factoria 293 pressure zones by replacing seismically vulnerable water mains with DI pipe at a minimum, and with ERDIP in more seismically vulnerable areas.

[1] All Capital Costs are in January 2021 dollars and do not reflect inflation that occurred throughout 2021 and 2022.

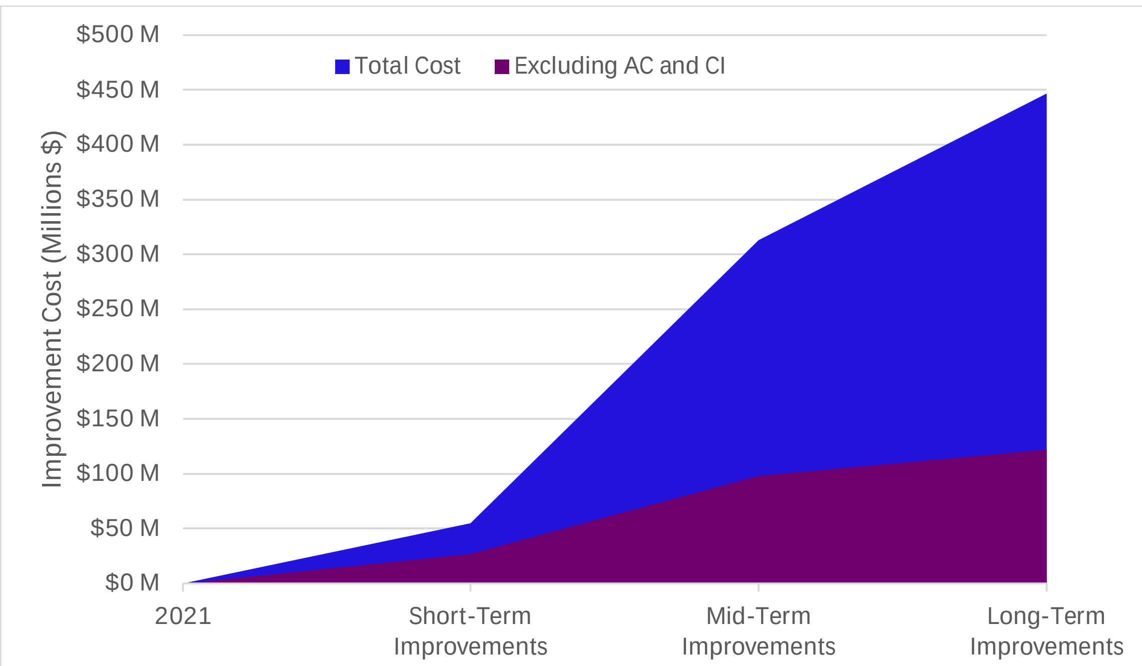
- Includes upgrades to additional pump station facilities

Long-term improvements

- Includes $134M[1] of additional investment by year 2070, $110M[1] of which is for pipe replacement of asbestos cement (AC) and cast iron (CI) pipe already part of an ongoing replacement program
- Incorporates strengthening of pipes in the Bellevue 400, Somerset 850 and Eastgate 330 pressure zones, similar to other zones completed in the mid-term improvements
- Expands the initial backbone corridor system strengthened in the short-term improvements to several additional critical corridors and upgrades one additional pump station

Figure 11 shows the cumulative spending by improvement timeframe for total improvement cost and improvement costs without inclusion of asbestos cement and cast iron pipe.

Figure 11: Cumulative Spending by Improvement Timeframe[1]



Summary and Recommendations

Based on SVA analysis, many of Bellevue's water customers are likely to experience service interruptions for up to 90 days following a major seismic event. These water supply interruptions can be expected to result in as much as $8.3 billion dollars of regional economic impact. Target Post-Earthquake Level of Service goals were defined, and improvements to achieve those goals identified, to reduce and mitigate these expected water supply outage durations and resulting economic impacts. Based on the results of the analysis, a suite of improvements are recommended to improve the seismic resiliency of water system infrastructure in a way that provides optimized reduction in seismic risks at the lowest overall cost, effectively meeting the proposed target PE-LOS goals.

Figure 12: Bellevue SVA "at a Glance"

Bellevue SVA
"At a Glance"

90 days

of water outage in existing system for many residents and businesses

$8 billion

economic impact resulting from loss of water service after a major earthquake

$125 million[1]

new investment needed over 50 years to reduce outage durations and mitigate impacts

The water system seismic resilience improvements identified include developing a 9 MGD emergency groundwater supply in Bellevue, navigating and working through collective regional water supply resilience issues with Cascade Water Alliance and Seattle Public Utilities to strengthen the regional eastside supply system, developing seismically resilient critical water supply backbone pipe routes, upgrading key system pump stations, and strengthening distribution system piping in 5 strategic pressure zones to reduce the total number of repairs required after an earthquake to allow system water supply service to be restored more quickly.

The proposed improvements are recommended to be completed in three phases over the course of the next 50 years, with a total cost of $450 million[1], of which $325 million[1] is for replacing seismically vulnerable and end of useful life AC and CI pipe already part of an ongoing replacement program and implementing resilience improvements at water system infrastructure facilities already planned for replacement or upgrade. This results in a need for $125 million[1] added investment over the next 50 years to achieve the recommended PE-LOS goals.

The proposed improvements provide economic risk reduction benefits 2.5 times greater than the cost of the associated system improvements, based on a 100-year life-cycle analysis. Adverse economic impacts stemming from seismically induced water service disruption can be expected to be reduced from $8.3 billion for the existing system condition down to just $700 million once the improvements are fully implemented.

SVA Project Technical Documentation (Appendices)

The following SVA Technical Memoranda provide additional detail to support the information provided in this executive summary.

TM1: Geotechnical Data Refinement
TM1A: Seismic Vulnerability Assessment Scenario Selection

Background and foundational information supporting the SVA effort, including details of the local/regional Bellevue seismic setting and relevant geotechnical conditions, are documented and summarized in the two initial project TMs. *TM1: Geotechnical Data Refinement*, characterizes the local/regional seismic settings and conditions, and the primary seismic risks facing Bellevue. *TM1A: Seismic Vulnerability Assessment Scenario Selection*, evaluates the spectrum of seismic scenarios and risks considered in TM1, and selects the key seismic scenarios to be explored in subsequent SVA evaluations. The result of the analysis documented in TM1 and TM1A include the geotechnical parameters used to support subsequent SVA analyses and the selection of the Cascadia Subduction Zone (CSZ) and Seattle Fault Zone East (SFZE) earthquake scenarios as the appropriate seismic events to consider throughout the SVA evaluations.

TM2: Seismic Analysis Methodology
TM2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data

Approaches, methodologies, and parameters used throughout the SVA to characterize and assess potential Bellevue water system seismic risks, impacts, and resilience for the City of Bellevue water system are captured and documented in TM 2 and TM 2A. *TM2: Seismic Analysis Methodology* details the data and approaches used to characterize seismic risks to Bellevue water system assets and supply systems. *TM2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data*, evaluates and leverages relevant supporting water system resilience data and studies from representative earthquake events to help inform pipeline and infrastructure seismic performance parameters for the Bellevue SVA effort.

TM3: Modeling Methodology

Approaches, system modeling, and evaluation methodologies and parameters used as part of the SVA to characterize, estimate, and assess potential Bellevue water system performance and service levels for the City of Bellevue water system are captured and documented in *TM3: Modeling Methodology*. This TM details computer modeling approaches used in the SVA to evaluate likely seismic impacts to the Bellevue water system and resulting system performance and service outage restoration times. These approaches provide a means to project potential seismic system, community, and economic impacts, and plan appropriate system resilience improvements that can cost effectively mitigate potential impacts and reduce risks.

TM4: Existing System Vulnerability and Customer Outage Probability

SVA modeling and evaluation results estimating the performance and service levels that can likely be expected from existing Bellevue water system pipe and facility infrastructure following a major CSZ or SFZE seismic event are described in *TM4: Existing System Vulnerability and Customer Outage Probability*. This TM describes the application of the modeling approaches described previously in TM3 and details projections of likely seismic damage to the existing water system under CSZ and SFZE scenarios in terms of the likelihood that different areas within the system may experience water supply interruptions after a major event, as well as how long it may take to restore water service to those areas.

TM5: Economic Impact Parameters

TM5: Economic Impact Parameters documents the methodologies used and economic impact parameters employed to estimate economic impacts that would occur following a major seismic event. The economic impact parameters considered evaluate four components that are combined to represent potential overall impacts to the local and regional economy resulting from potential loss of water service: impacts to residential customers and service, decreased economic activity, loss of life if hospitals and medical facilities are unable to operate effectively due to prolonged water service interruptions, and inability to deliver water to effectively support fire suppression activities.

TM6: As-Is Service Outage, Restoration Times, and Economic Impacts

The results of modeling the expected as-is performance of the existing water system and infrastructure, looking at the likely time to restore water supply to the system given specific repair and facility damage scenarios for each earthquake, and the corresponding economic impact to the community are described in *TM6: As-Is Service Outage, Restoration Times, and Economic Impacts*. This information forms the basis for estimating expected performance of the water system in its current state for comparison to customer expectations and seismic event recovery needs and sets expectations for future water system seismic resilience improvements.

TM7: Post-Earthquake Level of Service Goals

Post-Earthquake Level of Service (PE-LOS) goals are developed and compared against as-is performance and service levels that can be expected from the existing water system to identify and aid in the development of performance measure targets for water system seismic resilience improvements. The PE-LOS goals consider likely water supply quality, quantities, expected water supply outage durations, and critical locations where water service restoration needs to be prioritized following a major seismic event. The development of target PE-LOS goals and comparison against expected as-is performance from the existing water system is summarized in *TM7: Post-Earthquake Level of Service Goals.*

TM8: Improvement Alternatives

Improvement alternatives for the Bellevue water system to improve water system seismic resilience in order to achieve target PE-LOS goals are identified, categorized, and developed in *TM8: Improvement Alternatives.* The TM describes development of associated improvement costs, potential resulting benefits, and rationale for assessment of water system resilience improvements are detailed to support subsequent identification of optimized groups of improvements that can effectively mitigate likely seismic event economic impacts and cost effectively deliver on related PE-LOS goals.

TM9: Improvement Prioritization

Evaluation and prioritization of various potential combinations of improvements are defined in *TM9: Improvement Prioritization*. This evaluation incorporates a stepwise process that looked at effective combinations of short-, mid-, and long-term resilience improvements that support phased implementation and prioritize addressing the most critical system performance deficiencies. The analysis includes evaluating combinations of improvements that meet the target PE-LOS goals established for short-, mid-, and long-term timeframes. The selected improvements incrementally improve system resilience by sequencing a progression of improvements to achieve target PE-LOS goals and provide the highest benefit/cost ratios by providing the greatest reduction in economic seismic impacts at the lowest overall cost.

Appendix A. Geotechnical Data Refinement and Seismic Vulnerability Assessment Scenario Selection

A.1 TM1: Geotechnical Data Refinement

A.2 TM1A: Seismic Vulnerability Assessment Scenario Selection

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Technical Memorandum

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Subject	**TM 1: Geotechnical Data Refinement**
Project Name	Bellevue Water System Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs Shannon & Wilson
Date	October 7th, 2022

1. Introduction

The City of Bellevue Water System Seismic Vulnerability Assessment (SVA) will incorporate vulnerabilities of Bellevue water system pipelines and facilities into a comprehensive modeling analysis to predict the performance of the water system in seismic events and develop restoration expectations and mitigation alternatives. This Technical Memorandum summarizes the earthquake scenarios considered for the vulnerability assessment, the associated ground shaking level (ground motion) within the service area, permanent ground displacements related to potential fault rupture, and liquefaction and landslides induced by the scenario ground motions that will be used in this analysis.

TM 1A: Seismic Scenario Selection describes the selection of the scenarios developed under the work described in this TM that will be used for the remainder of the analysis.

TM 2: Seismic Vulnerability Assessment Methodology describes how this geotechnical information will be applied to determine the vulnerability of the Bellevue water system.

2. Scenario Earthquake Ground Motions

Scenario earthquakes were used to assess the seismic vulnerability of the Bellevue water system resulting from earthquake-induced transient and permanent ground displacements. The scenarios represent earthquake sources that could realistically affect the Bellevue water system. Each scenario has a different likelihood of occurrence and therefore presents a different level of risk to the Bellevue water system. For each scenario earthquake estimates of peak ground acceleration (PGA), peak ground velocity (PGV), and permanent ground displacement (PGD) were made for use in evaluating the seismic vulnerability of the Bellevue water system. This section briefly describes the regional earthquake sources and seismicity, the selected earthquake scenarios, and development of ground motion maps for the corresponding scenario PGA, PGV, PGD estimates.

2.1 Regional Seismological Setting

The Bellevue water system is located in the Puget Sound Lowland, an active tectonic region subjected to occasional strong earthquakes during the brief 170-year historical record. The regional tectonics and seismicity are the result of northeastward subduction of the Juan de Fuca Plate beneath the North American Plate along the Cascadia Subduction Zone (CSZ). The subduction results in east-west compression, dextral shear, clockwise rotation, and north-south compression of the leading edge of the North American Plate (Wells and others, 1998; Wells and Simpson, 2001). Within this regional tectonic framework, three seismogenic sources are identified.

- CSZ deep subcrustal zone (intraslab) in the subducted Juan de Fuca Plate.
- CSZ mega-thrust zone at the interface between the North American and Juan de Fuca plates.
- Shallow crustal zone within the North American Plate.

2.2 Intraslab Earthquakes

CSZ intraslab earthquakes occur in the subducted Juan de Fuca Plate at depths of about 40 to 60 kilometers (km). The Bellevue water system is situated above this zone. These earthquakes are associated with down-dip tension forces in the subducted plate due to density changes in the plate at depth.

The largest recorded intraslab earthquakes to affect the site include the surface-wave magnitude (M_S) 7.1 Olympia earthquake of April 13, 1949; the body-wave magnitude (M_b) 6.5 Seattle-Tacoma earthquake of April 29, 1965; and the February 28, 2001, moment magnitude (M_W) 6.8 Nisqually earthquake. The United States Geologic Survey (USGS) estimates the maximum moment magnitude from CSZ intraslab earthquake to be about M_W 7.5.

While these magnitudes are relatively large, the depth of the event results in only moderate ground motions. Levels of ground shaking from these intraslab events in Bellevue can range from less than 0.1 g (standard gravitational acceleration) to more than 0.5 g, depending on the location of the seismic event and the types of soils at the site For reference, accelerations of 0.1 to 0.3 g were measured in the 2001 Nisqually Earthquake, while accelerations of 0.5 to 0.8 g were common in the 2004 Northridge and 2005 Kobe earthquakes. The duration of shaking would likely be less than a minute. This category of earthquake controlled the regional building code until the 1980s.

2.3 Interface Earthquakes

CSZ mega-thrust earthquakes (greater than M_W 8.0) occur at the interface between the subducting Juan de Fuca and North American Plates. The most recent rupture occurred in roughly anno domini (AD) 1700 (Satake and others, 1996; Atwater and Hemphill-Haley, 1997; Clague, 1997; Yamaguchi and others, 1997; Goldfinger and others, 2003 and 2012). Paleo-seismic evidence indicates that ruptures have occurred at irregular time intervals ranging from about 100 to more than 1,200 years with an average recurrence interval of about 500 years (Atwater and Hemphill-Haley, 1997; Clague, 1997; Goldfinger and others, 2003 and 2012). Because of the significant uncertainty pertaining to the easterly extent of a potential rupture surface, estimates of the closest distance between the Bellevue water system and a potential rupture surface range from about 50 to 100 km horizontally at depths on the order of 20 to 35 km.

The moment magnitude (M_W) of the interface event can range from less than 8 to greater than 9, depending on the length and width of rupture. The rupture length of a M_W 9 event may extend from mid-Vancouver Island in British Columbia to Eureka, California. Typical ground accelerations in Bellevue might range from less than 0.1 to 0.3 g; the duration of shaking could be several minutes. These ground motions could occur even during smaller M_W events (e.g., 8 to 8.5) if the northern half of the CSZ were to rupture.

2.4 Crustal Earthquakes

Shallow crustal earthquakes within the North American Plate beneath western Washington have historically occurred within 20 km of the earth's surface, and with the exception of those associated with active volcanoes, typically occur in a diffuse pattern. However, crustal faults with evidence of pre-historic Holocene rupture (within 10,000 years) (e.g., Seattle Fault) have been identified beneath the Puget Sound Lowland to be capable of producing earthquakes with magnitudes on the order of M_W 7 to 7.5. The largest historic event is the 1872 North Cascades earthquake (estimated magnitude about 6.8 in the vicinity of Lake Chelan). Levels of ground shaking from the crustal events in Bellevue can be very high –

with levels of ground shaking ranging from less than 0.1 g to 0.7 g or higher. Durations of strong ground shaking could exceed a minute.

The most relevant active fault for the Bellevue water system seismic vulnerability study is the Seattle Fault Zone (SFZ). The SFZ is an east-west trending, south-dipping, largely concealed thrust fault that crosses the central Puget Sound near the latitude of Seattle and forms the northern structural boundary of the Seattle Uplift (Brocher and others, 2001 and 2004). The SFZ is a 4 to 7 km wide zone of active deformation that separates uplifted bedrock to the south from thick sequences of sediment that fill the Seattle Basin to the north (Blakely and others, 2002). The SFZ cuts east-west through the Bellevue water system with the northern edge along Interstate 90 (I-90); the hills on the south of I-90 are bedrock uplifts on the south side of the fault zone's leading edge.

At the ground surface, the SFZ deformation zone is defined by fault scarps and warped shorelines (e.g., Nelson and others, 2003; Haugerud, 2003; Kelsey and others, 2008). These shorelines were uplifted as much as 8 meters (m) during a single large event about 1,000 years ago (AD 900 to 930) (Bucknam and others, 1992; Atwater, 1999; Kelsey and others, 2008). On the western end of the fault zone (west of Puget Sound) Light Detection and Ranging (LiDAR)-identified fault scarps mark where several short north-dipping reverse faults have ruptured to the ground surface in the hanging wall of the south-dipping master fault (Nelson and others, 2003; Kelsey and others, 2008; Nelson and others, 2014).

Trench excavations and shoreline studies across these north-dipping faults indicate that: (a) they ruptured at least three times during the past 2,500 years (including during the AD 900 to 930 event) producing moderate-sized earthquakes (Nelson and others, 2003; Kelsey and others, 2008; Nelson and others, 2014), and (b) their rupture areas were small compared to the master fault rupture area during the AD 900 to 930 earthquake (Kelsey and others, 2008). Kelsey and others (2008) concluded that these shallower north-dipping faults may slip during large events along the master thrust or during moderate earthquakes (about M_W 6.5) independent of slip on the deeper master thrust.

In contrast, land-level-change studies of the uplifted shorelines suggest the master thrust likely ruptured only twice during the past 10,000 years: most recently during the AD 900 to 930 earthquake and previously, about 6,000 years before that (Bucknam and others, 1992; Sherrod, 2001).

3. Earthquake Scenarios

Within the framework of the regional seismological setting, four (4) potential earthquake scenarios were considered for use in the vulnerability assessment, one CSZ interface event and three SFZ events of various size and locations. The scenarios are listed in the Table 1. The CSZ intraslab source was not considered in the four scenarios because: (a) the ground shaking intensity is about the same or lower than the other potential scenarios, and (b) the large uncertainty in assigning a recurrence interval and specific location in the source zone (i.e., the source zone covers thousands of square km, and the location of faults within the source zone have not been mapped as it is 50 to 100 km below the ground surface).

Table 1: Considered Earthquake Scenarios

Scenario	*Magnitude*	*Distance from the Bellevue water system (km)*	*Ground Motion Data Source*	*Holocene Paleo-Seismicity*	*Earthquake Recurrence Interval (years)*
CSZ *(Cascadia Subduction Zone Interface)*	9	~120	Modified from USGS M9 project	Yes	~500
SFZ Full *(Seattle Fault Zone Full Rupture)*	7.2	0	USGS	Yes	~6,000
SFZ West *(Seattle Fault West Side Partial Rupture)*	6.6	18	This Project	Yes	~800
SFZ East *(Seattle Fault East Side Partial Rupture)*	6.6	0	This Project	?	~800

For each scenario Table 1 shows the magnitude, distance from the Bellevue water system, the data source for the mapped ground motions (ground motion data), whether-or-not there is geologic evidence this scenario has actually occurred in the last 10,000 years (Holocene paleo-seismicity), and an estimate of the typical time between events (earthquake recurrence interval). Additional descriptions of these scenarios, including the data source used for each event, are discussed below.

3.1 CSZ Interface

The CSZ scenario is a M_W 9 interface event that ruptures the entire subduction zone, from northern California to southern British Columbia. Because the best estimate of the rupture area extent is approximately 120 km from the Bellevue water system, the ground shaking levels are relatively moderate when compared to the nearer SFZ scenarios. However, the duration of shaking of a CSZ Interface event will be much longer (on the order of minutes) than the crustal SFZ scenarios.

3.2 SFZ

Three scenarios considered for the SFZ. An earthquake on a fault does not necessarily rupture the entire width and length of the fault, e.g., a fault may rupture in its entirety in one large earthquake or in smaller sections over time, resulting in a series of smaller earthquakes. Consequently, the three SFZ scenarios are based on the rupture surface size (length and width) and the location of the potential rupture surface along the fault: (a) full rupture of the entire fault, (b) west side partial rupture, (e) east side partial rupture

The SFZ Full rupture scenario represents complete rupture on the large master fault. Based on the paleo-seismic studies, such full rupture earthquakes have a recurrence interval of approximately 6,000 years. For reference, building codes are based on shorter, 2,500-year return period ground motions. This long recurrence interval makes the likelihood of ground motions from this scenario relatively low compared to the other scenarios.

The SFZ West side partial rupture scenario represents an earthquake with a smaller, partial rupture of the SFZ on the west side of the Puget Sound, where the paleo-seismic studies have found evidence of these partial ruptures. These paleo-seismic studies indicate that SFZ earthquakes with west side partial rupture have a recurrence interval of approximately 800 years. The distance from the source will result in lower levels of ground shaking; however, the likelihood of occurrence is higher than the full rupture.

The SFZ East side partial rupture scenario also represents an earthquake with a smaller, partial rupture of the SFZ but centered where the SFZ crosses the Bellevue water system. Because this scenario ruptures through the Bellevue water system it poses a significant hazard to the system. The assumption recommended for this vulnerability study is that the SFZ East scenario has the same recurrence interval as the SFZ West scenario (i.e., approximately 800 years). However, at present there are no paleo-seismic studies that have identified a partial east side rupture of the SFZ (the limited paleo-seismic studies in the Bellevue area have only identified events that likely ruptured the entire fault). Therefore, considering the lack of the paleo-seismic evidence to confirm or refute occurrence of a partial east side rupture of the SFZ, a 50 percent chance of occurrence is assumed for the SFZ East scenario. This will result in a likelihood of 1/800 x 0.5 = 0.000625 to be used in the risk calculation for the partial SFZ East scenario consequences.

4. Scenario Ground Motions

The earthquake ground motion parameters required to evaluate performance of the Bellevue water system for each earthquake rupture scenario include:

- Peak Ground Acceleration (PGA) used for facility assessment (units of standard gravitational acceleration, g)
- Peak Ground Velocity (PGV) used to assess wave propagation effects on pipe (units of cm/second)
- Permanent Ground Displacement (PGD) used to assess fault rupture and liquefaction effects on pipe (units in inches and feet)

PGA and PGV values were available in the literature or could be derived from published sources for the CSZ and SFZ Full rupture scenarios. Published SFZ East and West scenarios were not available in the literature and were therefore calculated specifically for this study. The following discussions provides a description of published ground motions, modifications, and how ground motions were developed specifically for this project where no ground motions previously existed. Scenario PGA and PGV maps are provided in Attachment A.

4.1 SFZ East and West Side Partial Rupture Scenarios

Ground motions were developed for the Bellevue water system on an approximately 200 m grid spacing. For each grid location the parameters required to calculate the SFZ West and East scenarios include:

- Fault parameters (i.e., rupture type, area and magnitude)
- Distance between the fault and the grid point
- Ground motion prediction equations (GMPEs) that use the above parameters and Site Class to estimate the ground motion
- Site Class information that accounts for local soil or rock conditions

For both the SFZ East and West scenarios, a M_W 6.6 and a corresponding fault rupture area were assumed. The rupture area dimensions had a length and aspect ratio (rupture length to width) of approximately 26 km and 1.2, respectively. The partial ruptures used the same 71-km long northernmost-strand of the SFZ, as used in the USGS 2014 National Seismic Hazard Mapping Project (NSHMP) (Petersen and others, 2014) source model. For the SFZ West scenario, the fault rupture area was assumed to be located west of the Puget Sound. For the SFZ East scenario, the fault rupture area was assumed to be centered in the Bellevue water system between Lake Sammamish and Lake Washington. These scenario fault rupture areas were used as the basis for determining the distance between the fault and a given site.

The median (50th percentile) deterministic ground motions for SFZ West and East scenarios were calculated using the same GMPEs as used to calculate shallow crustal ground motion in the 2014 USGS NSHMP model:

- Abrahamson and others (2014) (ASK14);
- Boore and others (2014) (BSSA14);
- Campbell and Bozorgnia (2014) (CB14);
- Chiou and Youngs (2014) (CY14); and
- Idriss (2014) (I14).

The 50th percentile ground motions represent average earthquake ground motions for the defined event, that would produce average damage estimates. In any given location, larger or smaller ground motions could occur.

In accordance with the 2014 USGS NSHMP model, the first four GMPEs above were weighted equally, but the I14 relationship was given a half of the weight for each of the other crustal GMPEs (i.e., I14 weighted 0.12 and each of the other GMPEs weighted 0.22). I14 was given a lower weight because it has less details in predicting the spectral values than the four other crustal GMPEs.

The soil or rock conditions across the Bellevue water system were characterized using National Earthquake Hazards Reduction Program (NEHRP) Site Classes obtained from Washington State Department of Natural Resources (WDNR) (i.e., www.dnr.wa.gov) Geologic Information Portal. Site Class is determined primarily by the time-weighted average of the shear wave velocity of the soil and/or rock within 30 meters (approximately 100 feet) of the ground surface (V_{S30}). All of the NGA-West2 ground motion models incorporates V_{S30} as a shallow site-response parameter. The V_{S30} corresponding to each Site Class definition used in the GMPEs is given in Table 2.

TABLE 2: V_{S30} Used for NEHRP Site Classes

NEHRP Site Class	*V_{S30} (m/sec)*
B	1,150
BC	760
C	537
CD	360
D	259
DE	180
E	150

m/sec = meters per second

PGA and PGV values were calculated for a grid with longitude and latitude increment of 0.0025 and 0.0015 degrees, respectively (less than 200 m grid spacing). The ground motions were calculated using the GMPE's reference values of $Z_{1.0}$ and $Z_{2.5}$ (depth to shear wave velocity of 1.0 and 2.5 kilometers per second (km/s), respectively), and then the site-specific basin effects factor from CB14 were applied to the ground motion values.

4.2 SFZ Full Rupture Scenario

The SFZ Full rupture scenario PGA and PGV data were directly obtained from the USGS Shake Map with a M_W 7.2 earthquake on SFZ northern strand.

https://earthquake.usgs.gov/scenarios/eventpage/bssc2014570n_m7p23_se#shakemap

The northern strand runs through the southern part of Bellevue. Strands that are located farther to the south beyond the Bellevue city limits were not evaluated in this project.

4.3 CSZ Interface Scenario

The PGA and spectral value at period (T) of 1.0 second (S_1) data were obtained from the USGS M9 project (Frankel and others [2018] and Wirth and others [2018]). The USGS data are the result of 30 simulated ruptures on CSZ interface considering variations in several of the ground motion parameters and a 3-dimensional shear wave velocity model on 1 km spacing grid in Puget Lowland area. The USGS provided the average of these simulated values for only sites with V_{S30} of 600 m/sec.

The PGA and S_1 site factors for the Bellevue water system were calculated from Abrahamson and others (2018) GMPE, and the USGS provided data were adjusted to include the appropriate site amplification. The PGV values were estimated from S_1 adjusted for soil condition using the methodology provided by American Lifelines Alliance (2005) guidelines.

5. Scenario Fault Rupture Ground Displacements

Ground surface fault displacements in the Bellevue water system were estimated for the SFZ East and SFZ Full scenarios using the methods in Wells and Coppersmith (1994). Table 3 presents estimates of the rupture displacement (expected permanent ground displacement) on the SFZ fault plane. The ground displacements in Table 3 are for both combined horizontal and vertical components of the rupture.

Table 3: Ground Rupture Displacement

	Average Ground Displacement (inches)			Expected Maximum Ground Displacement (inches)
Scenario	16th Percentile	Median	84th Percentile	
SFZ East (M_W 6.6)	15	27	48	39
SFZ Full (M_W 7.2)	27	51	93	99

These ground surface rupture displacements could occur on any one or multiple mapped or as-of-yet unmapped fault locations along the SFZ where it passes through the Bellevue water system. For the purposes of analyzing ground surface rupture associated with these scenarios, the estimated ground surface rupture was assumed to occur anywhere within the zone highlighted in Figure 1.

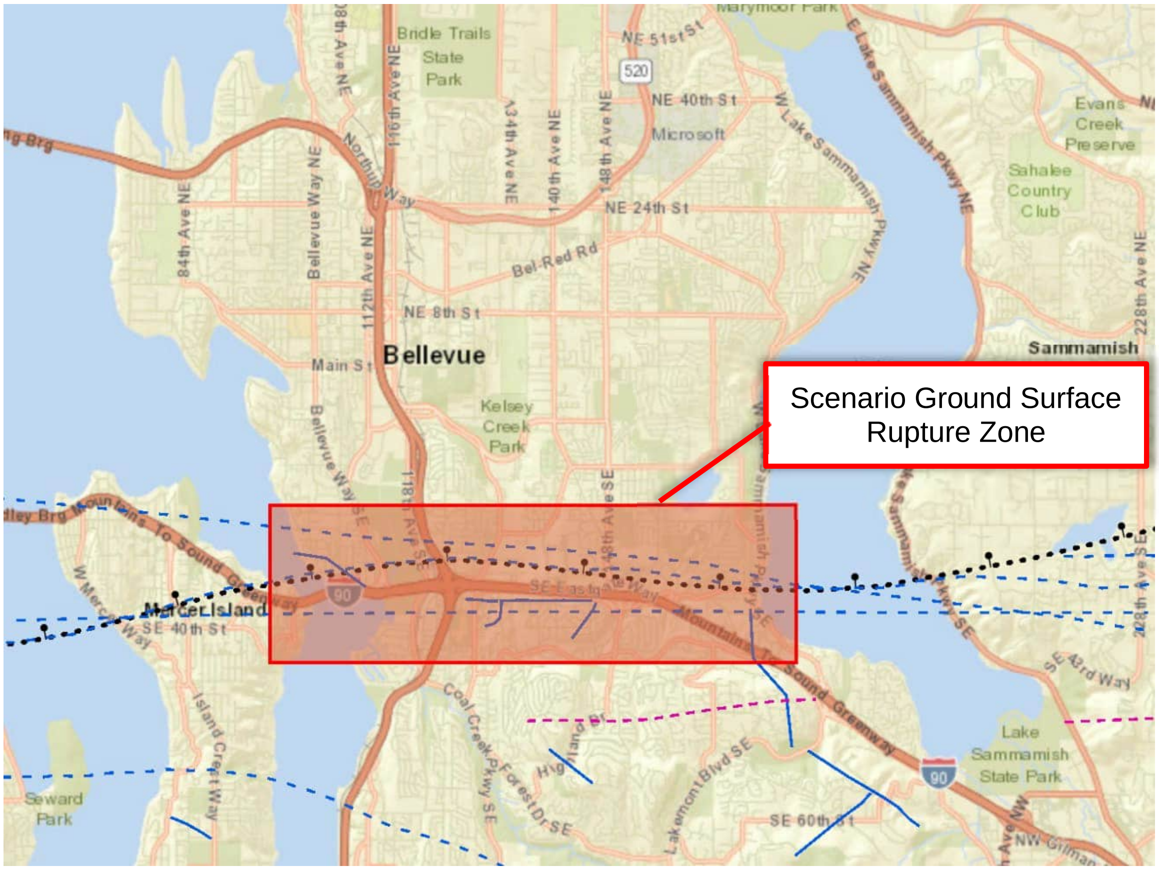

Figure 1: Surface fault rupture zone for SFZ full and east side scenarios

6. Liquefaction and Landslide Permanent Ground Displacements

This section summarizes the methodology followed to estimate permanent ground displacements within the boundaries of the Bellevue water system associated with liquefaction and slope instabilities. Based on a careful inspection among the four scenarios of the amplitude of predicted ground motions (e.g., SFZ West scenario ground motions are relatively low compared to the other scenarios) and associated recurrence intervals (e.g., SFZ Full recurrence interval is very long), the CSZ and the SFZ East scenarios were identified as the two main scenarios to be considered for the further seismic vulnerability analysis. Both the liquefaction- and seismic slope instability-induced permanent ground deformations were predicted for CSZ and the SFZ East scenarios.

6.1 Liquefaction Induced Permanent Ground Displacements

The liquefaction-induced permanent displacement throughout Bellevue's water system was estimated using the following information:

- PGA mapping for each scenario earthquake
- Magnitude associated with each scenario earthquake
- Local soil/rock conditions
- Sloping ground conditions and/or distance from a free face of a lake, stream, or river.

Approximate permanent ground deformations due to liquefaction-induced lateral spreading in areas designated as low-moderate, moderate, or moderate-high liquefaction susceptibility by WDNR were estimated in accordance with the predictions using simplified empirical methods developed by Youd and others (2002) and Kramer and Baska (2007). Note that published liquefaction hazard potential maps for the City of Bellevue appear to be similar to the WDNR liquefaction maps used in this study.

The liquefaction-induced permanent ground deformation maps are provided in Attachment B. These maps were developed to indicate three main zones with predicted maximum permanent ground deformations: (1) less than 6 inches (in), (2) between 6 in and 12 in, and (3) over 12 in.

It should be noted these maps were developed from generalized information and are appropriate only for planning level vulnerability studies. If a critical location is identified within the Bellevue water system, site-specific liquefaction hazard analysis should be performed at the location to establish a more accurate estimate of expected liquefaction-induced permanent ground motion.

6.2 Seismic Slope Instability Induced Permanent Ground Displacements

The potential for permanent displacement throughout the Bellevue water system from seismic slope instabilities was estimated using the following information:

- PGA mapping for each scenario earthquake
- Magnitude and approximate epicentral distance associated with each scenario earthquake
- Local soil/rock conditions
- Sloping ground conditions

The available terrain and steep slope maps from the City of Bellevue and the WDNR were used in combination with simplified empirical predictive method of Bray and Travasarou (2007) to predict approximate permanent ground deformations within the Bellevue water system. Similar to liquefaction-induced permanent ground displacements, seismic slope instability-induced permanent ground displacements were predicted without any site-specific subsurface data. Attachment C provides seismic slope instability-induced permanent ground motions maps for both the CSZ and SFZ East scenarios. These maps were developed to indicate three main zones with the following predicted maximum permanent ground deformations: (1) less than 6 in, (2) between 6 in and 12 in, and (3) over 12 in.

These evaluations were appropriate for an area wide water system vulnerability study but should not be used to make site-specific assessments. Detailed information about geotechnical conditions at the site, including groundwater locations, will determine the potential for and magnitude of ground displacements. Geotechnical explorations and laboratory testing are required to make these assessments.

6.3 Use of Permanent Ground Deformation Data in Vulnerability Analysis

The liquefaction induced lateral spreading and seismic slope displacements along the Bellevue water system is provided in ranges. The associated ground displacements should be implemented into the vulnerability analysis using a normal distribution with parameters summarized in Table 4.

Table 4: Lateral spreading and slope displacement parameters to be used in vulnerability study

Displacement, d (in)	*Mean (in)*	*Standard Deviation (in)*
$0 < d < 6$	3	2
$6 \leq d < 12$	9	3
$d \geq 12$	18	6

7. Summary

This TM summarized the earthquake scenarios considered for the Bellevue water systems vulnerability assessment, the associated ground shaking level (ground motion) within the service area, permanent ground displacements related to potential fault rupture, and liquefaction and landslides induced permanent ground displacements due the scenario ground motions.

Ground motion maps were developed for four earthquake scenarios: CSZ, SFZ Full, SFZ West, and SFZ East. Fault rupture based permanent ground displacement estimates were developed for SFZ Full and SFZ East scenarios. Liquefaction and seismic landslide induced permanent ground displacement maps were developed for CSZ and SFZ East Scenarios.

This geotechnical information will be incorporated into the seismic vulnerability study performed to predict the performance of the water system in seismic scenario events and develop restoration expectations and mitigation alternatives.

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Technical Memorandum

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Subject	**TM 1A: Bellevue Seismic Vulnerability Assessment Scenario Selection**
Project Name	Bellevue Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs Shannon & Wilson
Date	October 7th, 2022

1. Executive Summary

For use in the City of Bellevue Water System Seismic Vulnerability Analysis, four earthquake scenarios were considered. The Cascadia Subduction Zone (CSZ) event was included to provide consistency among peer utilities conducting similar studies. The second even to be considered will be the Seattle Fault Zone East (SFZE) event developed specifically for this project. This event was selected because it has a similar level of ground shaking to the full Seattle Fault event, incorporates a higher likelihood of surface fault rupture in Bellevue, and has a lower return period than the full Seattle Fault Zone event.

2. Background

As part of the City of Bellevue water system seismic vulnerability analysis, four initial earthquake scenarios were identified, and potential ground motion estimates were developed for each. Two of these scenarios will be selected to be carried forward for further analysis in subsequent evaluations. This document describes the approach and rationale used to select earthquake scenarios.

The four initial earthquake scenarios are as follows and are described in more detail in TM 1: Geotechnical Data Refinement.

1. CSZ - Cascadia Subduction Zone (CSZ) interface, M_W 9.0, ~500-year recurrence interval.
2. SFZ West - Seattle Fault Zone (SFZ) partial rupture west of Puget Sound, M_W 6.6, ~800-year recurrence interval, assumed 100% probability of occurrence.
3. SFZ East - SFZ partial rupture through Bellevue, M_W 6.6, ~800-year recurrence interval, assumed 50% probability of occurrence in the eastern reaches of the fault, relative to probability of a SFZ West event.
4. SFZ Full – Full rupture of the SFZ, M_W 7.2, ~6,000-year recurrence interval.

Another earthquake scenario used by nearby utilities but not included in this analysis is a Deep Benioff Zone (DBZ) earthquake on the Nisqually Fault. This event would be similar to the 2001 Nisqually event (Mw 6.8) but with a higher magnitude. USGS published ground motions show similar PGAs in the Bellevue water system as are predicted by the Mw 9.0 CSZ scenario included in this evaluation. While including a DBZ scenario would potentially result in calculation of higher risk than the CSZ due to shorter return periods (~100 years) in the DBZ, the similar ground motions make it somewhat redundant with the more prominent and frequently evaluated CSZ event. Additionally, the 2001 Nisqually earthquake produced no known impacts on the Bellevue water system according to Bellevue staff working in the water department at the time.

The selection of scenarios to be used for further analysis in this study was based on the following input variables:

- Earthquake scenario ground motion
- Probability of scenario occurrence (return period x probability of occurrence based on paleo-seismic evidence)
- Potential impact on Bellevue water system facilities (based on Hazus fragility curves)

3. Scenario Ground Motions

Peak ground acceleration (PGA) and peak ground velocity (PGV) maps for the CSZ, SFZ East, and SFZ West scenarios were developed by Shannon & Wilson and are further defined in TM 1: Geotechnical Data Refinement. The PGA map for the SFZ Full scenario was obtained from the USGS online database. Figures 2 through 5 show the PGA maps for each scenario. Figure 1 provides the legend for Figures 2 through 5.

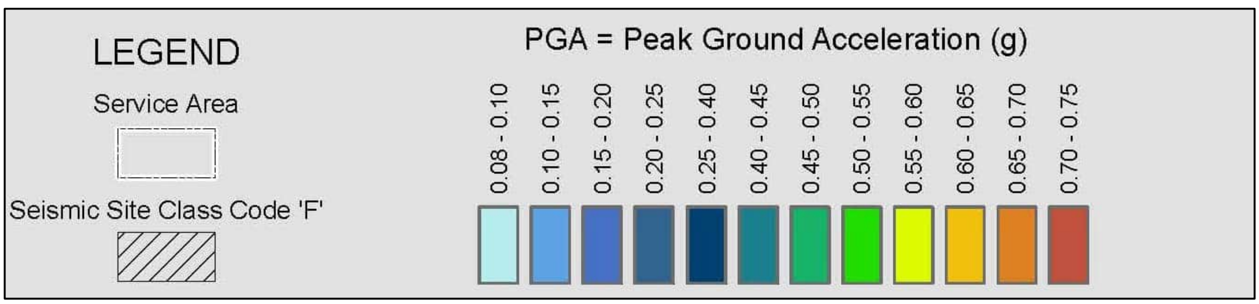

Figure 1. Enlarged PGA Legend for Figures 2 through 5

As shown in Figures 2 and 3, the CSZ and SFZ West scenarios result in similar ground motions, though slightly higher for the CSZ Scenario. Additionally, the CSZ is predicted to occur more frequently (recurrence interval of ~500 years) and has a longer duration of shaking than the SFZ West (~800-year recurrence interval) scenario.

Similarly, as shown in Figures 4 and 5, the SFZ East and the SFZ Full scenarios result in similar ground motions north of I-90 with slightly lower intensity south of I-90. While the ground motions are similar, the SFZ East is predicted to occur more frequently (~800 years) than the latter (~6,000 years). With similar ground motion that is higher across the Bellevue Water System, and with more frequent return periods, the SFZ East scenario is expected to result in higher risk (Consequence x Likelihood) to the Bellevue water system.

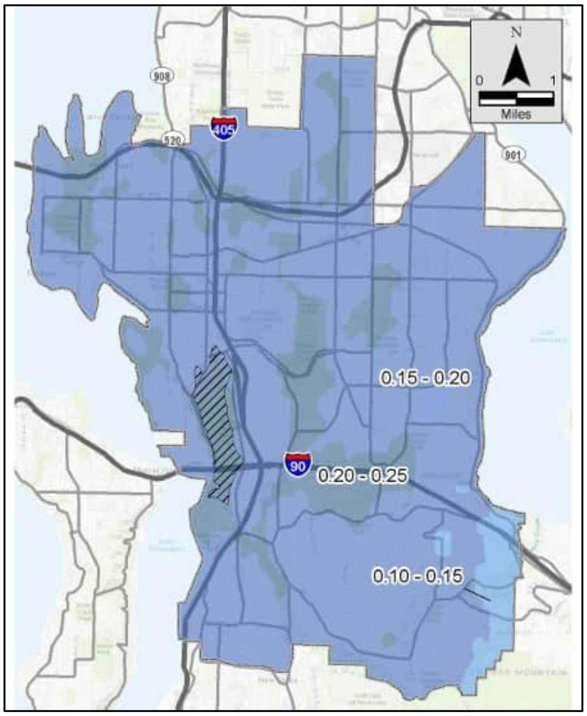

Figure 2. CSZ Scenario PGA (M_W 9.0 Cascadia Subduction Zone)

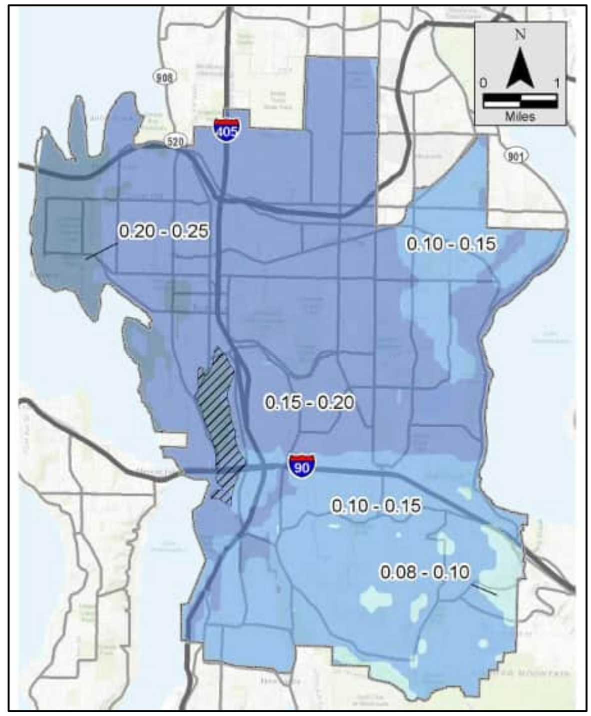

Figure 3. SFZ West Scenario PGA (M_W 6.6 SFZ partial rupture west of Puget Sound)

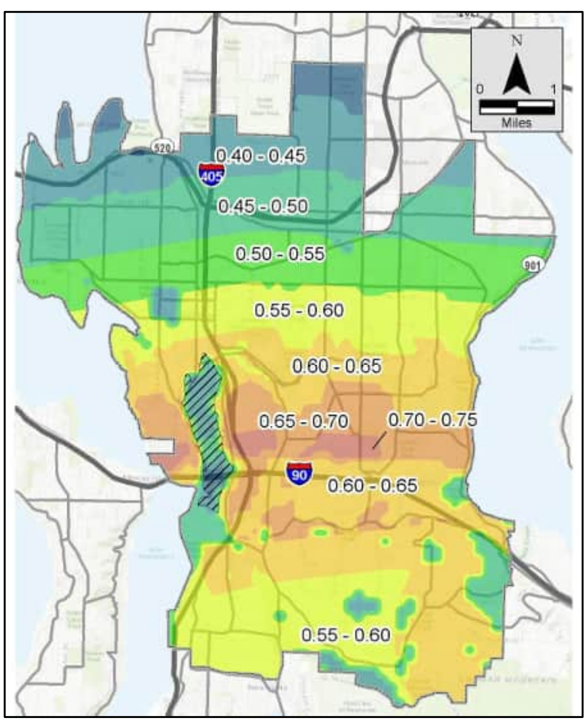

Figure 4. SFZ East Scenario PGA (M_W 6.6 partial rupture through Bellevue)

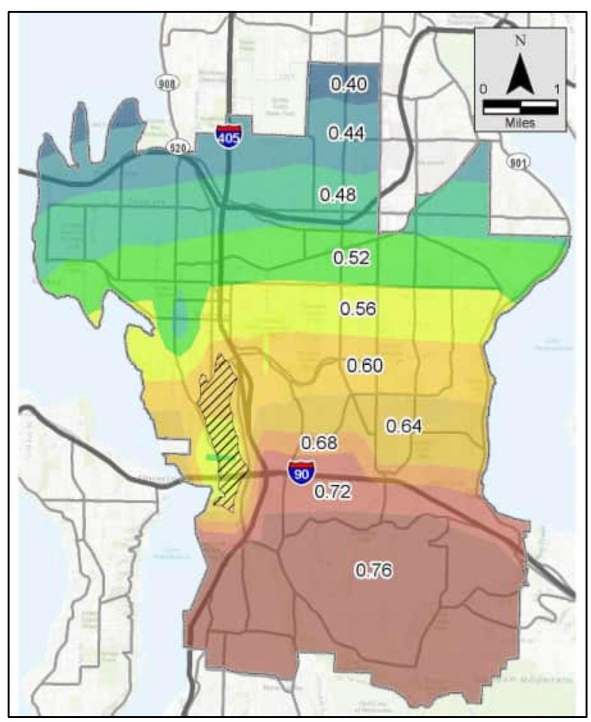

Figure 5. SFZ Full Scenario PGA (M_W 7.2 full rupture of the SFZ)

4. Facility Assessment and Fragility Curves

TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment describes the proposed approach for assessing the potential seismic fragility of water system facilities and pipelines, including the methodology for analysis of facilities using the Hazus fragility curve methodology. In order to aid in the selection of earthquake scenarios, the estimated ground motions from each of the four initial earthquake scenarios were applied to fragility curves developed for Bellevue water system facilities to assess the likelihood that each facility would be offline following an earthquake.

Figure 6 shows a color-coded table that indicates the probability that a given facility would be offline for each of the four initial earthquake scenarios considered. This can be used as a means to compare the expected relative consequence for each of the four initial scenarios. Based on this analysis, the implication is that the CSZ and SFZ West scenarios could be expected to have similar overall consequences, as would the SFZ East and SFZ Full scenarios.

Reservoirs	CSZ M9	SFZ East	SFZ West	Full SFZ
Cherry Crest	0.34%	12.37%	0.19%	12.81%
Clyde Hill 465	0.19%	6.40%	0.20%	7.04%
Clyde Hill 390	0.38%	11.87%	0.38%	12.81%
Clyde Hill 335 Rd	4.46%	33.40%	4.52%	32.11%
Clyde Hill 335 Sq	0.38%	8.12%	0.15%	7.47%
Cougar Mt. 1	0.19%	22.84%	0.02%	35.58%
Cougar Mt. 2	0.13%	23.17%	0.02%	35.58%
Cougar Mt. 3	2.08%	44.67%	0.81%	55.89%
Cougar Mt. 3A	2.08%	44.15%	0.76%	55.89%
Factoria	5.51%	45.69%	2.10%	53.03%
Forest Hills	0.37%	21.10%	0.04%	35.58%
Horizon View 1 - NEW	0.18%	13.25%	0.02%	22.18%
Horizon View 2	4.26%	42.58%	1.16%	55.89%
Horizon View 3	0.13%	13.43%	0.01%	24.95%
Horizon View 3A	0.34%	21.92%	0.03%	35.58%
Lake Hills North	0.18%	10.27%	0.05%	10.83%
Lake Hills South	0.17%	10.37%	0.05%	10.83%
Meydenbauer N	0.39%	21.51%	0.41%	18.98%
Meydenbauer S	0.39%	21.51%	0.41%	18.98%
N.E. 40th	0.36%	8.16%	0.11%	10.02%
Newport	0.17%	21.84%	0.02%	35.58%
Parksite	4.66%	46.94%	1.26%	55.89%
Pikes Peak				28.08%
Sammamish				35.58%
Somerset 2	0.04%	21.93%	0.00%	38.19%
Woodridge	0.20%	17.32%	0.10%	15.14%
Kirkland 545 - South				23.96%
Kirkland 545 - North				1.80%
CCUD 580 East				55.89%
CCUD 580 West				55.89%
CCUD 440				55.89%

Inlets	CSZ M9	SFZ East	SFZ West	Full SFZ
161st Inlet	0.03%	25.08%	0.00%	12.64%
Bel Red Inlet	0.05%	12.90%	0.02%	12.64%
Cherry Crest Inlet	0.03%	9.31%	0.01%	9.31%
Eastgate Inlet	0.05%	24.75%	0.00%	38.19%
Enatai	0.03%	25.41%	0.01%	24.75%
Inlet #11	0.03%	26.85%	0.00%	33.70%
Inlet #6	0.04%	17.77%	0.00%	38.19%
Inlet #8	0.02%	15.99%	0.00%	38.19%
NE 40th Inlet	0.05%	5.51%	0.01%	6.49%
NE 8th Inlet	0.06%	14.46%	0.01%	12.64%
Richards Road	0.07%	27.30%	0.02%	29.20%
SE 28th Inlet	0.04%	32.58%	0.01%	24.75%

Pump Stations	CSZ M9	SFZ East	SFZ West	Full SFZ
Cherry Crest	6.36%	54.67%	6.36%	55.32%
Clyde Hill	23.99%	75.50%	24.25%	76.83%
Cougar Mt. 1	4.24%	61.90%	1.12%	74.35%
Cougar Mt. 2	3.44%	62.29%	1.04%	74.35%
Cougar Mt. 3	2.79%	62.09%	0.90%	74.35%
Forest Hills	6.94%	61.00%	1.74%	75.35%
Horizon View 1 - NEW	0.63%	25.11%	0.09%	37.65%
Horizon View 2	20.06%	83.11%	6.92%	91.17%
Horizon View 3	0.03%	19.92%	0.00%	38.19%
Lake Hills (Crossroads)	6.22%	55.80%	2.65%	57.02%
Meydenbauer	0.82%	25.55%	0.82%	22.92%
NE 8th Inlet	0.06%	14.46%	0.01%	12.64%
NE 40th	6.42%	37.96%	3.07%	42.08%
Newport	4.27%	62.30%	1.05%	75.35%
Parksite	21.70%	86.22%	7.43%	91.17%
Pikes Peak				72.49%
SE 28th Inlet	0.04%	32.80%	0.01%	24.75%
Somerset Inlet	0.03%	25.85%	0.00%	38.19%
Somerset 2	0.04%	21.93%	0.00%	38.19%
Woodridge	6.75%	68.28%	0.01%	65.01%
161st Ave Inlet	0.03%	25.08%	0.00%	33.70%
670/NE 40th	23.37%	66.85%	15.03%	69.05%
CCUD 475/580				

Wells	CSZ M9	SFZ East	SFZ West	Full SFZ
WD97 Well No. 3	1.68%	41.29%	1.09%	38.95%
WD97 Well No. 5	1.90%	33.83%	0.68%	34.95%
WD97 Well No. 6	1.90%	33.83%	0.68%	34.95%
WD97 Well No. 7	1.90%	33.83%	0.68%	34.95%

Figure 6. Facility Comparison – Probability of Extensive or Complete Damage Relative to Initial Earthquake Scenarios

5. Scenario Selection

The evaluation described above suggests that the CSZ (M_W 9.0) and the SFZ East (M_W 6.6) scenarios are appropriate as representative scenarios for the remainder of the seismic vulnerability analysis of the Bellevue Water System. The primary rationale behind the selection of these scenarios are as follows.

- CSZ is a commonly used scenario for evaluation of expected performance of lifelines in the Pacific Northwest
- CSZ and SFZ West have similar ground motions and resulting consequence expectations, but the CSZ has a more frequent return period and is expected to result in a higher overall risk contribution when considerations relative to event likelihood and expected consequence are compounded.
- SFZ Full and SFZ East have similar ground motions and resulting consequence expectations, but the SFZ East has a higher probability of occurrence and is expected to result in a higher overall risk contribution when considerations relative to event likelihood and expected consequence are compounded. While the SFZ full produces the highest ground motions currently projected in the Bellevue water system, its low likelihood of occurrence make the slightly smaller SFZ East scenario more valuable for this evaluation.

As a result the project team selected the following earthquakes for detailed analysis as part of this project:

1) Cascadia Subduction Zone (CSZ) M9 scenario
2) Seattle Fault Zone East (SFZE) M6.6 scenario

Appendix B. Seismic Analysis Methodology

B.1 TM2: Seismic Analysis Methodology for Pipeline and Facilities Assessment

B.2 TM2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data

Technical Memorandum

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Subject	**TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment**
Project Name	Bellevue Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs
Date	October 7th, 2022

1. Background

The City of Bellevue water system seismic vulnerability assessment (SVA) will incorporate vulnerabilities of Bellevue water system pipelines and facilities into a comprehensive modeling analysis to predict the performance of the water system in seismic events and develop restoration expectations and mitigation alternatives. The facilities will be evaluated using Hazus facility fragility curves and the pipelines will be evaluated using the American Lifelines Alliance (ALA) fragility equations, modified to incorporate data from more recent earthquakes, as described in the American Lifelines Alliance 2001 Guideline titled *Seismic Fragility Formulations for Water Systems.*

2. Seismic Hazards

The seismic hazards that will be used for the Bellevue SVA are described in *TM 1: Geotechnical Data Refinement*. In summary, the seismic hazards have been developed based on publicly available data from the United States Geological Survey (USGS) and the State of Washington that was then refined to provide more precise predicted ground motions for the areas inside the Bellevue water system area.

Ground motions used to evaluate water system vulnerability were developed from two earthquake scenarios. These are the Mw 9.0 Cascadia Subduction Zone interface event (CSZ) and the Mw 6.6 Seattle Fault, East Side Rupture (~800 years). More details about seismic hazards are included in TM 1: Geotechnical Data Refinement and TM 1A: Earthquake Scenario Selection.

Technical Memo 1 also summarizes the development of permanent ground deformation (PGD) estimates for each of the above-mentioned earthquakes. This includes deformation from fault rupture, liquefaction, and landslides. This ground deformation data is used as described below to predict the performance of the pipelines.

3. Pipeline Fragility Analysis

A pipeline fragility analysis will be completed to determine the expected performance of the Bellevue water system pipelines. The goal is to determine the likelihood that pipelines would fail during a seismic event. The improvement analysis, which will be conducted later in the project, will evaluate proposed mitigation options, including the relative benefit of strengthening the pipelines with the greatest seismic risk.

3.1 Process and Parameters

The ALA seismic fragility equations for buried pipe express the repair rate per unit of length of pipe as a function of ground shaking or ground displacement. Peak ground velocity (PGV) is a measure of the speed of ground movement, while PGD measures the displacement of liquefaction settlement or lateral spread (in cm) and the displacement of landslide movement. PGD is also used to quantify ground rupture displacement in the fault zone.

The ALA equations are as follows:

Wave Propagation (PGV Equation): $RR = K_1 \times 0.00187 \times PGV$

Permanent Ground Deformation (PGD Equation): $RR = K_2 \times 1.06 \times PGD^{0.319}$

Where:

RR = repairs per 1,000 feet of pipe

K_1 = Coefficient specific to each pipe material for Wave Propagation Equation

K_2 = Coefficient specific to each pipe material for Permanent Ground Deformation Equation

PGV = peak ground velocity in inches/second

PGD = permanent ground deformation in inches

Repairs per 1,000 feet of pipe (RR) due to PGD and due to wave propagation are estimated using the appropriate equation for each hazard. The “K” values in the equations are a constant representing the relative fragility of the pipe, based on the ALA empirical data.

The results of the pipeline vulnerability analysis have been provided to the City in two electronic excel files (one for each earthquake scenario).

3.2 Data Source for ALA Empirical Equations

The ALA pipeline fragility equations are based on empirical evidence from the following earthquakes and water systems. The expected performance of various pipe materials is based on this data collected during post-earthquake response and restoration. As such the equations are only as good as the data set used to develop the empirical equations.

Table 1. Data Sources Used for ALA Empirical Equations

Earthquakes in Screened PGV Database	Earthquakes in PGD Database
1995 Hyogoken-nanbu (Kobe), Japan	1989 Loma Prieta, California
1994 Northridge, California	1983 Nihonkai-Chubu, Japan
1989 Loma Prieta, California	1971 San Fernando, California
1971 San Fernando, California	1906 San Francisco, California
1989 Mexico City, Mexico	
1983 Coalinga, California	
1979 Imperial Valley, California	
1965 Puget Sound, Washington	
1964 Niigata, Japan	
1949 Puget Sound, Washington	
1933 Long Beach, California	
1923 Kanto, Japan	

3.2.1 ALA Data for Asbestos Cement Pipe

As shown in Figure 1, the Bellevue water system comprises approximately 40 percent AC pipe (please refer to Table 4 for a complete list of pipe material abbreviations). Additionally, most pipelines in the Bellevue water system are not in liquefiable soil, thus PGV repair estimation equations will have a greater significance than PGD for the Bellevue water system.

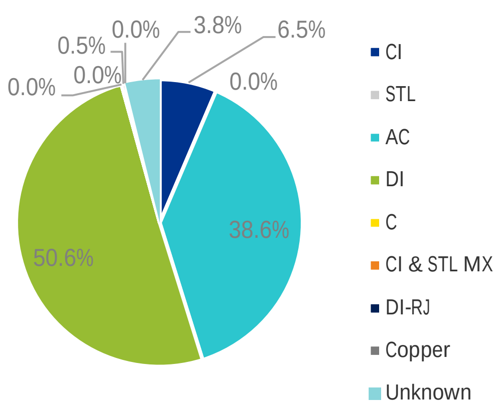
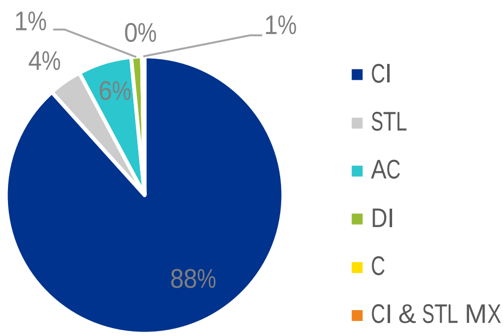


Figure 1. Pipe materials in Bellevue water system

In contrast, as shown in Figures 2 and 3, approximately 40 percent of data points used for the ALA PGD database were for AC pipe, but only 14 percent of the data points used for the ALA PGV database were for Asbestos Cement (AC) pipe. This limited data on AC pipe used for the empirical ALA equations alone introduces some uncertainty surrounding the accuracy of the ALA equations for use on the Bellevue water system which has a high percentage of AC pipe. To improve the accuracy of the pipeline fragility analysis for the Bellevue SVA project additional earthquake data was reviewed and compared with the ALA equations as described below.



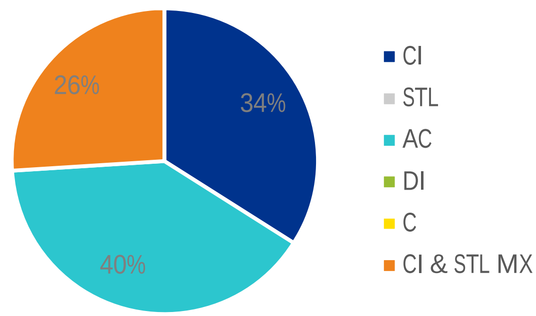


Figure 2. Pipe materials in ALA PGV Database based on length

Figure 3. Pipe Materials in ALA PGD Database based on number of data points

The vulnerability of AC pipe is thought to be associated with the brittle nature of the AC material. The pipe is joined with couplings, a short section of larger diameter "pipe" with elastomeric gaskets in each end. These are used to couple the pipe. Older AC pipe couplings, prior to approximately 1950 are sealed with mortar rather than gaskets. It is not believed that the BWS has any of this older pipe. The gasketed couplings appear to provide additional flexibility compared to, for example cast iron pipe leaded joints.

3.2.2 Comparison of ALA empirical equations vs. earthquakes in Christchurch, New Zealand

TM 2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data describes in detail the analysis completed to identify AC pipe repair coefficients for use in the Bellevue water system SVA. The result of this analysis was a recommendation to use the following coefficients with the ALA equations.

AC Pipe $K_1 = 4.0$

AC Pipe (6"-8") $K_2 = 1.0$

AC Pipe (>8") $K_2 = 0.8$

3.3 Equations and Coefficients for Pipe Analysis

"K" values use for analysis of the Bellevue water system were primarily taken from the ALA guidance document. Table 4 shows the pipe materials and the associated "K" values used for each material, including notes describing where the values used originated from. For some materials, not K values were available and the values used were derived based on engineering judgement based on relative comparisons or interpolation between similar materials.

Table 4. PIPE MATERIALS AND ASSOCIATED "K" VALUES FOR EACH MATERIAL[1]

Pipe Material Abbreviation	Pipe Material	Joint Type	PGV "K_1" Value	PGD "K_2" Value
AC (>8")	Asbestos Cement	Rubber Gasket	4.0[2]	0.8[1]
AC (6 – 8")			4.0[2]	1.0[2]
BRASS	Brass		0.15[3]	0.15[3]
BWC	Bar Wrapped Concrete		1.1[3]	1.0[3]
CI	Cast Iron	Leaded	3.5[2]	1.0[1]
DI (DI-RJ)	Ductile Iron	Rubber Gasket	0.5[1]	0.5[1]
ERDIP	Earthquake Resistant Ductile Iron Pipe		0.1[3]	0.1[3]
GLV (G, GST, GLV, Galvanized)	Galvanized Steel	Screwed	1.3[3]	1.3[3]
HDPE (PE)	High Density Polyethylene	Fused	0.2[3]	0.2[3]
PVC (POLY)	Polyvinyl Chloride	Rubber Gasket	0.5[1]	0.8[1]
STEEL (STL)	Steel		0.15[3]	0.15[3]
UNK (Unknown, Blank, N/A)	Unknown		1.1[3]	1.0[3]

[1] "K" value from ALA Guideline "Seismic Fragility Formulations for Water Systems"

[2] "K" value developed based on evaluation of AC pipe performance in Christchurch 2011 earthquake in consideration of data available from ALA "Seismic Fragility Formulations for Water Systems"

[3] "K" value estimated based on expected relative pipe performance in comparison to other pipes with published data

3.4 Application of ALA Equations to Bellevue water system

Pipes that are assumed to be subjected to PGD based on the geotechnical information developed as a part of TM 1 are analyzed using the ground deformation equation and the rest of the pipe is analyzed using the wave propagation equation. As described in TM 1, both probability and magnitude of landslide or liquefaction was developed for the designated hazard areas. This probability is used to calculate the percentage of the linear footage of pipe in the hazard area that is expected to be subjected to the described ground deformation. Then, pipe damage is calculated for wave propagation for all including areas not in liquefaction or steep slope areas and those subject to PGD.

The resulting number of leaks and breaks is an estimate with a large range of uncertainty that is useful and appropriate for planning level analysis only

For the probabilistic modeling described in TM 3, Modelling Methodology Development, each pipe is assigned a probability of failure based on the ALA equations. To do this a Poisson distribution is used with k=0 (number of breaks or leaks in the pipe) because only one break or leak is required to cause a pipe need repair. The equations for probability of leaks and breaks are as follows.

Probability of at least one pipe break:

$$P_{Break} = 1 - e^{\left(-\frac{K1 \times 0.00187 \times PGV \times L \times 0.2}{1{,}000} - \frac{K2 \times 1.068 \times PGD^{0.319} \times P_{PGD} \times L \times 0.8}{1{,}000}\right)}$$

[1] American Lifelines Alliance (ALA). 2001. *Seismic Fragility Formulations for Water Systems 2001 Report*, April.

Probability of at least one pipe leak:

$$P_{Leak} = 1 - e^{\left(-\frac{K1 \times 0.00187 \times PGV \times L \times 0.8}{1{,}000} - \frac{K2 \times 1.068 \times PGD^{0.319} \times P_{PGD} \times L \times 0.2}{1{,}000}\right)}$$

Where:

K_1 = PGV equation pipe material coefficient as defined in Table 4

K_2 = PGD equation pipe material coefficient as defined in Table 4

PGV = Average estimated scenario peak ground velocity for the pipe in inches per second (See TM1: Geotechnical Data Refinement)

PGD = Average estimated scenario permanent ground deformation in inches (See TM1: Geotechnical Data Refinement)

P_{PGD} = Probability that estimated scenario PGD affects a particular pipe (See TM1: Geotechnical Data Refinement)

L = Length of pipe or pipe segment in feet (ft)

The application of the resulting damage state probabilities from the facility fragility analysis to the modeling analysis for the Bellevue SVA is described in TM 3: Modeling Methodology Development.

4. Facility Fragility Analysis

For the purposes of this evaluation, the system was categorized into facilities and water distribution pipelines (described above). Facilities include all components that are not buried distribution pipelines, such as supply inlet stations, pressure reducing valve (PRV) vaults, emergency wells, pump stations, and reservoirs.

4.1 Process and Parameters

Expected facility performance was evaluated for each earthquake scenario in terms of its post-earthquake functionality. This process is based on the multi-hazard loss estimation methodology outlined in the Hazus technical manual. Each facility was assigned a building classification which groups similar performing buildings based on their expected damage and loss characteristics. Above-grade buildings were also assigned a code level based on when the facility was built and its condition. Parameters used to develop damage functions (fragility curves) for each facility are based on the building classification and code level. The damage functions for each facility were evaluated and adjusted as necessary based on site visits, review of previous seismic evaluations, fragility relationships included in HAZUS, and engineering judgement. For facilities that do not have a building type specifically described in HAZUS, a building fragility curve was determined using a combination of engineering judgement and comparing HAZUS data for similar standard structures. A summary of the building classification, code level, and damage function parameters for each facility is included in Attachment A.

The peak ground acceleration (PGA) for each facility was selected from the earthquake scenarios described in Section 2 above and TM 1, Geotechnical Data Refinement.

4.2 Damage States for Seismic Scenarios

The damage states used in the seismic scenarios are as follows:

- Slight/Minor – operable following the event.

- Moderate – sustained damage but safe and operable during repair.
- Extensive – inoperable but repairable. May be yellow or red tagged limiting access for an extended duration.
- Complete – not repairable. Replacement required.

4.3 Probability of Damage

The HAZUS fragility curves are in the form of a cumulative lognormal distribution. The shape of each curve is defined by the mean PGA (μ) and the standard deviation of the PGA values (β^2). The cumulative lognormal distribution is calculated with:

$$HAZUS = \frac{1}{2} + \frac{1}{2} * ERF\left(\frac{\ln(PGA) - \mu}{\beta * \sqrt{2}}\right)$$

In the equation above, ERF is the “error function” that is used when integrating the normal and lognormal distributions. The ERF is defined as:

$$ERF(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt$$

The fragility curves describe the probability of reaching or exceeding different damage states for a given PGA. This can be used to indicate a facility’s operability and/or extent of damage after a given seismic event. These equations were used to develop the probability of each damage state following a specific earthquake. The PGA was based on values from scenarios as described in section 2. The resulting probabilities of damage for each of the 4 earthquake scenarios are included in Attachment A.

These probabilities will be used in the Modelling as described in TM 3: Modelling Methodology to develop post-earthquake damage scenarios and associated water availability.

4.4 Valve and PRV Vaults

Buried Valve and PRV vaults fragilities have been estimated by applying the most applicable Hazus fragility formula to the pipes that come in and out of the vault. This allows the model to incorporate the slightly higher probability of failure that is associated with a rigid connection to a buried concrete structure, but also allows the damage to be modeled as a break or leak in the multi-break modeling scenario. This is more representative than listing these as a facility, since the repairs of these are likely to be of the same level of effort as a broken pipe and repair times would be measured in hours and not days, as would be expected from significant damage to a facility like a pump station.

5. Seattle Public Utilities Supply System Vulnerability

Seattle Public Utilities (SPU) recently completed a detailed seismic assessment of their entire water system, including the regional supply facilities and transmission pipelines that provide water to Bellevue. The City, Jacobs, Cascade Water Alliance, and SPU representatives met to discuss a preferred approach to developing outage probabilities and restoration times for the SPU Cedar Eastside Supply Line (CESSL) and Tolt Eastside Supply Line (TESSL). The result was a conclusion that due to the sensitive nature of the details of the SPU analysis and the lack of probability data specific to the ESSLs, it would be appropriate for the Jacobs team to prepare estimates of the probability of failure for each of the two supply lines for each earthquake scenario. To do this, the probability of failure of each segment of the TESSL and the CESSL was independently estimated and then the combined probability of failure was calculated. Hazards considered when estimating the probabilities for each segment included consideration of pipe vulnerability as identified in Figure 6-1 from the SPU Water System Seismic Study Summary Report, river crossings, steep slope/landslide prone areas, liquefaction hazard areas, and pipe material. The resulting probability values are based on the team's understanding of the SPU supply system, the vulnerabilities identified in the public version of the SPU Seismic VA report, experience with more detailed analysis of similar systems, and engineering judgement.

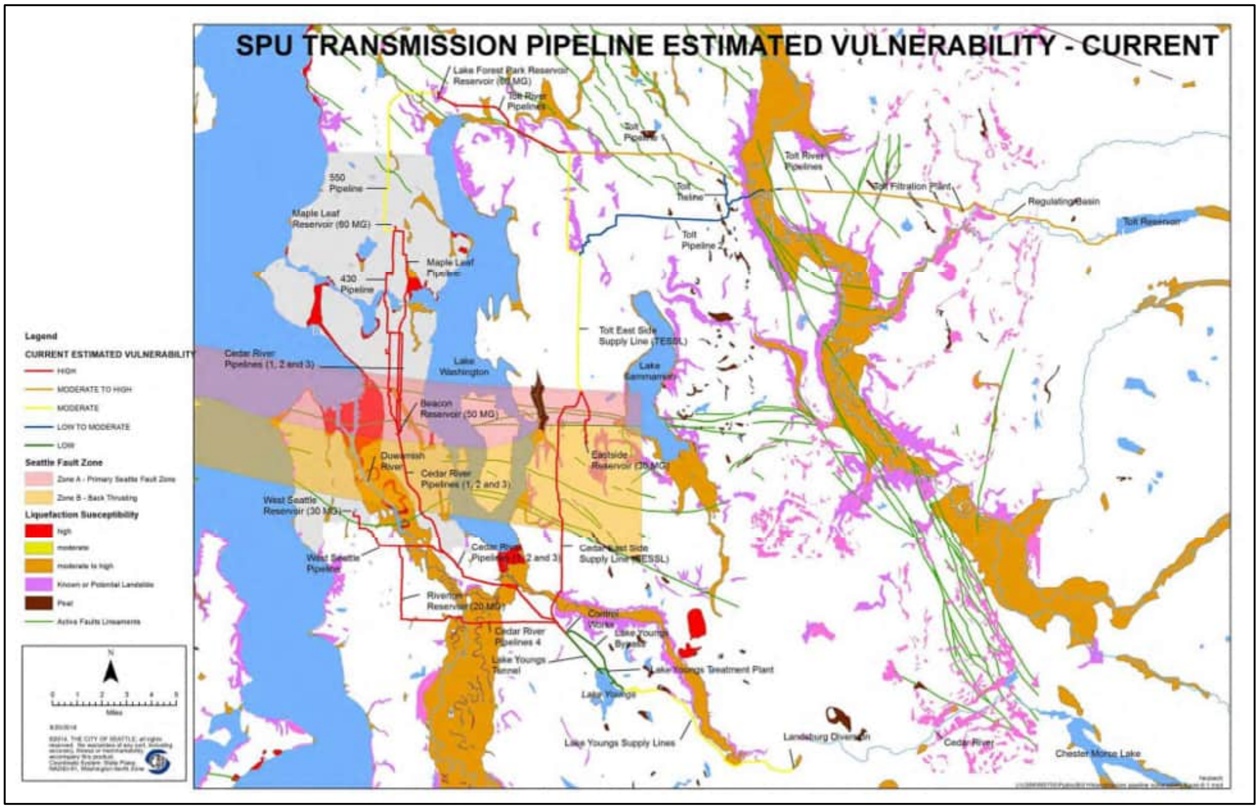


Figure 4. SPU Transmision System Current Vulnerability (Reprinted from Seattle Public Utilities Water System Seismic Study Summary Report, 2018)

Table 5 shows the assumed probabilities of pipeline supplies remaining in-service and the expected restoration times for each of the two seismic events being analyzed as a part of this project. Note that the in-service probability values are assumed to include the supply lines and facilities feeding into the TESSL or CESSL as well as the TESSL and CESSL themselves.

Table 5. SPU Supply System In-Service Probability and Expected Restoration Time

Supply	Probability In-Service (SFZ East)	Probability In-Service (CSZ)	Assumed Restoration Time (SFZ East), days	Assumed Restoration Time (CSZ), days
TESSL	65%	69%	14	14
CESSL	13%	19%	90	30

6. Critical Customer and Customer Group Identification

To collect more detailed water supply and restoration availability on specific customers and customer groups, the output data from the modeling exercise described in TM 3: Modeling Methodology Development will be presented for critical customers and certain customer groups. These subsets of the Bellevue water system customers are described below.

6.1 Critical Customers

Critical customers have been identified for this evaluation based on the priority of maintaining or restoring water service as soon as possible after an earthquake. ***NOTE: This list is not intended to establish an operational or policy priority, but rather serves as a boundary condition to help identify impacts to critical customers after an earthquake for the sake of this evaluation. Level of Service goals will be considered later in this project and will begin to consider restoration priorities and goals for restoring water service to various customers and customer groups.***

Potential critical customers were grouped into categories 1 through 3. Customers in category 1 (highest priority of customers) will be included as individual locations in the multi-break hydraulic analysis so that the probability of water availability to these points after an earthquake can be tracked. The critical infrastructure that could impact delivering supply to category 1 customers if a failure occurs will also be identified. Categories 2 and 3 are also considered to be critical customers, however the need to provide water to these locations does not have the same importance as providing service to those customers category 1 and adding these locations to the analysis would dilute the importance of the critical customers in category 1. Category 2 customers are important, but water supply is not critical to their operation or they are not as well suited as emergency shelters. Category 3 customers are important, but too numerous and widespread to be tracked individually or do not require water service for functionality.

Category 1 Critical Customers:

- Overlake Hospital Campus
- Kaiser Permanente Bellevue Medical Center
- Seattle Children's Bellevue Clinic and Surgery Center
- High Schools (Emergency Shelter Locations)
  - Newport High School
  - Bellevue High School
  - Sammamish High School
  - Interlake High School
- Community Centers (Emergency Shelter Locations)
  - North Bellevue Community Center
  - South Bellevue Community Center
  - Crossroads Community Center
- Washington State DOT EOC and Road Maintenance Facility
- Washington State DOT Bridge Maintenance Facility
- Bellevue City Hall

Category 2 Critical Customers:

- Bellevue Fire Stations 1 through 9
- Washington State Patrol Bellevue – Emergency Response Center
- Bellevue School District Elementary and Middle Schools
- Bellevue College Campus
- Bellevue Service Center – Emergency Management Center
- Bellevue Utilities - Eastgate Yard

Category 3 Critical Customers:

- Local Medical and Urgent Care Clinics
- Malls and Shopping Centers
- Assisted Living Centers
- 520 Reservoir and Pump Station – Utilities Maintenance District Assembly Point
- Clyde Hill Reservoir – Utilities Maintenance District Assembly Point

6.2 Customer Grouping

In addition to tracking water availability to the critical customers listed above, the modeling will also track water available to customer groups. Typically, customer grouping will start with distribution zones. In some cases, the distribution zones are discrete enough to allow tracking at the zone level. However, other zones are too large to be used to group customers and the zones have been subdivided into smaller subzones for tracking of water availability to customers. These smaller subareas consist of zones that have been divided along section and quarter section lines to keep things simple. Figure 5 shows the customer grouping with zones and subzones that will be used for the modeling analysis.

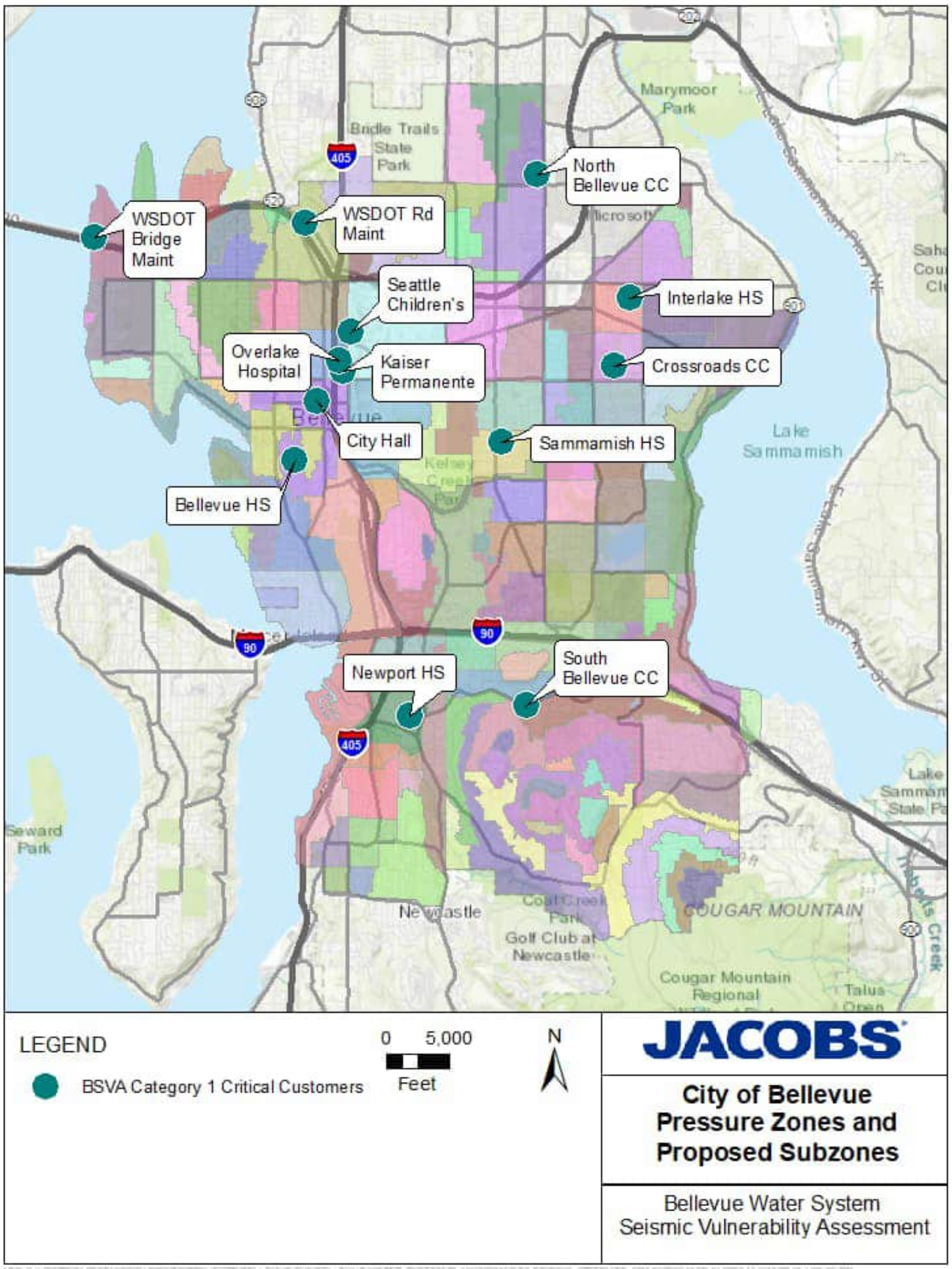


Figure 5. Bellevue Water System Category 1 Critical Customers and SVA Subareas

JACOBS

Technical Memorandum

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Subject	**TM 2A: Comparison of ALA Equations to Christchurch Earthquake Repair Data**
Project Name	Bellevue Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs
Date	October 7th, 2022

1. Background

The City of Bellevue water system seismic vulnerability assessment (SVA) will incorporate vulnerabilities of Bellevue water system pipelines and facilities into a comprehensive modeling analysis to predict the performance of the water system in seismic events and develop restoration expectations and mitigation alternatives. Elements of the water system will be evaluated using Hazus fragility curves for major facilities and modified American Lifelines Alliance (ALA) fragility equations for pipelines (See TM2 for further detail on the analysis methodology).

Approximately 40 percent of the pipe in the Bellevue water system is Asbestos Cement (AC) and the data used for the ALA empirical equation development contained limited information for AC pipe. In order to provide more certainty regarding the application of fragility curves to the Bellevue water system, the following analysis of available information from the Christchurch water system following the 2010–-2011 earthquakes was completed.

2. ALA Equations

The American Lifelines Alliance (ALA) was created in 1998 by the American Society of Civil Engineers (ASCE) and the Federal Emergency Management Agency (FEMA). In 1999, ALA commissioned a group of experts to prepare methods that describe the potential for damage to water transmission system components from earthquake hazards.[1] The resulting damage algorithms can be used to perform earthquake loss estimates.

The ALA seismic fragility equations for buried pipe express the repair rate per unit length of pipe as a function of ground shaking or ground displacement. Peak ground velocity (PGV) is a measure of the speed of ground movement, while PGD measures the displacement of liquefaction settlement or lateral spread (in cm) and the displacement of landslide movement. PGD is also used to quantify ground rupture displacement in the fault zone.

The ALA equations are as follows:

Wave Propagation (PGV Equation): $RR = K_1 \times 0.00187 \times PGV$

Permanent Ground Deformation (PGD Equation): $RR = K_2 \times 1.06 \times PGD^{0.319}$

Where:

[1] American Lifelines Alliance (ALA). 2001. *Seismic Fragility Formulations for Water Systems 2001 Report*, April.

RR = repairs per 1,000 feet of pipe

K_1 = Coefficient specific to each pipe material for Wave Propagation Equation

K_2 = Coefficient specific to each pipe material for Permanent Ground Deformation Equation

PGV = peak ground velocity in inches/second

PGD = permanent ground deformation in inches

Repairs per 1,000 feet of pipe (RR) due to PGD and due to wave propagation are estimated using the appropriate equation for each hazard. The total number of leaks and total number of breaks are then estimated by adding results from both equations (due to PGD and due to wave propagation). The "K" values in the equations are a constant representing the relative fragility of the pipe, based on the ALA empirical data. The original coefficients relied on limited empirical data available at the time. In their 2001 report, the ALA acknowledges the limitations of their method and that "a complete empirical database for all pipe materials under all levels of shaking still does not exist.[2]

3. Comparison of ALA equations to earthquakes in Christchurch, New Zealand

Given the lack of significant data used to create the ALA fragilities for wave propagation (PGV) impacts on AC, more recent data with significant quantities of AC pipe was reviewed to compare to the ALA fragilities. The watermains in Christchurch, NZ are 52.7 percent AC pipes[3] and between September 2010 and December 2011 Christchurch was affected by several earthquakes now referred to as the Canterbury Earthquake Sequence (CES). These included the Mw 7.1 September 2010 (south of Christchurch) and M_W 6.2 February 2011 earthquakes. The February 2011 event resulted in the most significant damage to infrastructure in the City of Christchurch as its epicenter was in the heart of the City. The Christchurch earthquakes were shallow crustal events with high shaking intensity and low duration. Thus, there are some limitations to this analysis when applied to other types of earthquakes that are likely to impact the City of Bellevue. For example, while the South Whidbey Island Fault and the Seattle fault zone are shallow, the CSZ is a crustal interface fault that would have a longer duration but lower shaking intensity in Bellevue when compared to the CES. The actual impact on the pipes will depend on the type of earthquake and related variables such as duration of shaking. However, the analysis for this project is based only on PGD and PGV as defined by the ALA fragility equations.

Significant research has been completed on the CES by the University of Canterbury and the University of Delaware. The combination of significant proportions of AC pipe and the detailed data collected following the earthquakes made Christchurch a good candidate for analysis to compare the ALA fragilities to systems constructed with significant quantities of AC pipe. AC pipe products in Christchurch followed a similar progression of composition and construction changes as AC pipe in the United States. This includes the conversion from concrete collars to rubber gasketed joints during the time when AC pipe was primarily used. Specific data on exactly when product transitions occurred in each water system is not well documented, so this level of detail has not been included in the analysis. Given lack of original manufacturing specifications, for the purposes of this assessment it is assumed that AC pipe in Christchurch at the time of the earthquakes were comparable to AC pipe in the Bellevue water system.

The analysis of the AC pipe failure rates and repair data form the Christchurch earthquake was completed in two phases. The first phase was focused on the ground deformation equation (PGD) and the on the ground shaking (PGV) equation. The second phase was more in depth analysis of ground

[2] American Lifelines Alliance (ALA). 2001. *Seismic Fragility Formulations for Water Systems 2001 Report*, April.

[3] Cubrinovski, MIsko, Matthew Hughes, Brendon Bradley,Ian McCahon, Yvonne McDonald, Howard Simpson, Rod Cameron, Mark Christison, Bruce Henderson, Rolando Orense, and Thomas O'Rourke. 2011. Liquefaction Impacts on Pipe Networks: Short Term Recovery Project No. 6 Natural Hazards Research Platform. Dec 2011. University of Canterbury.

shaking (PGV) repair data described in *Earthquake Response of Underground Pipeline Networks in Christchurch, NZ*[4] by O'Rourke et al.

3.1 Permanent Ground Deformation Repairs

The first phase included a cursory review of the overall repair rate data from two studies - *Liquefaction Impacts on Pipe Networks*[3] and *Performance of Horizontal Infrastructure in Christchurch City through the 2010 – 2011 Canterbury Earthquake Sequence*[5] (Cubrinovski et al. 2014) to consider the relative difference between the expected performance based on the ALA equations and the actual performance in the Christchurch earthquake. The former study classified land in Christchurch City into five main zones, from 0 - areas of most ground displacement and lowest Liquefaction Resistance Index (LRI), to 4 - areas of least ground displacement (Zone 4) and highest LRIs. The remaining zones where no observations were taken, were classified as "No Liquefaction Observations". This study also recorded the total pipes in each zone, classified by material and diameter.

This analysis was completed by using the ALA equations to calculate the estimated repair rate for pipe in Christchurch using the actual length of pipe in Christchurch. This was then compared to the empirical data representing the number of repairs that occurred after the Christchurch earthquake. The estimated and actual repairs were compared to determine how accurate the ALA equations were at predicting repairs for this earthquake. Additionally, the ALA report provides different K_1 and K_2 values for AC pipe depending on the joint type (rubber gasket or cement). Thus, estimates were calculated for both joint types.

3.1.1 Review of Ground Deformation Repair Data

Ranges of PGD values for each LRI zone were recorded in the 2011 report, so these were used for the comparison based on the PGD equation for pipes in LRI zones 0, 1, 2 and 3.[2] Zones designated as 4 or No Liquefaction Observations were not analyzed with the PGD equation because, based on how they are defined, most damage in these areas is assumed to not be due to liquefaction.

Figure 4 shows that the actual damage experienced in the February 2011 Christchurch earthquake from pipe sizes greater than 4 inches compared to the ALA equation estimations with the ALA K_2 value of 0.8 (for rubber gasketed joints), as well as two other potential K_2 value alternatives (1.2 and 0.5). The ALA equations tend to overpredict the number of repairs for lower liquefaction magnitudes (LRI zones 3 and 2) and underpredict the number of repairs for higher liquefaction magnitudes (LRI zones 1 and 0).

[4] O'Rourke, et al., Earthquake Response of Underground Pipeline Networks in Christchurch, NZ

[5] Cubrinovski, MIsko, Matthew Hughes, Brendon Bradley, John Noonan, Rex Hopkins, Steve McNeill, and Geoff English. 2014. Performance of Horizontal Infrastructure in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence, March 2014. University of Canterbury.

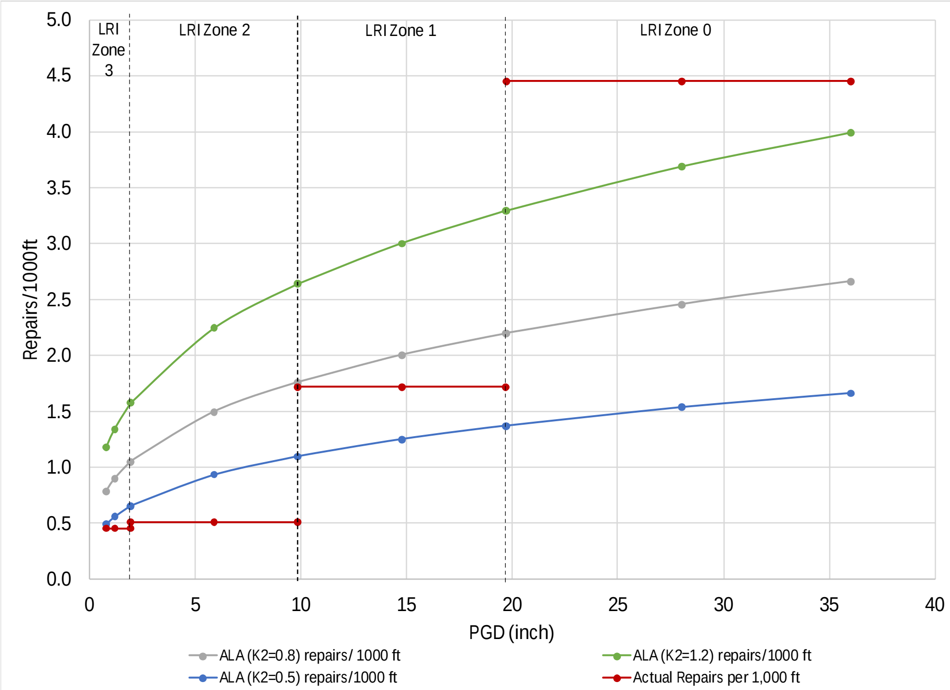

Figure 4. Actual 2011 Christchurch Repairs in Liquefaction Zones Compared to ALA

Figure 5 shows the same data, but with the actual repairs categorized between smaller pipe (6 and 8 inch diameter) and larger pipe (greater than 8 inch diameter).

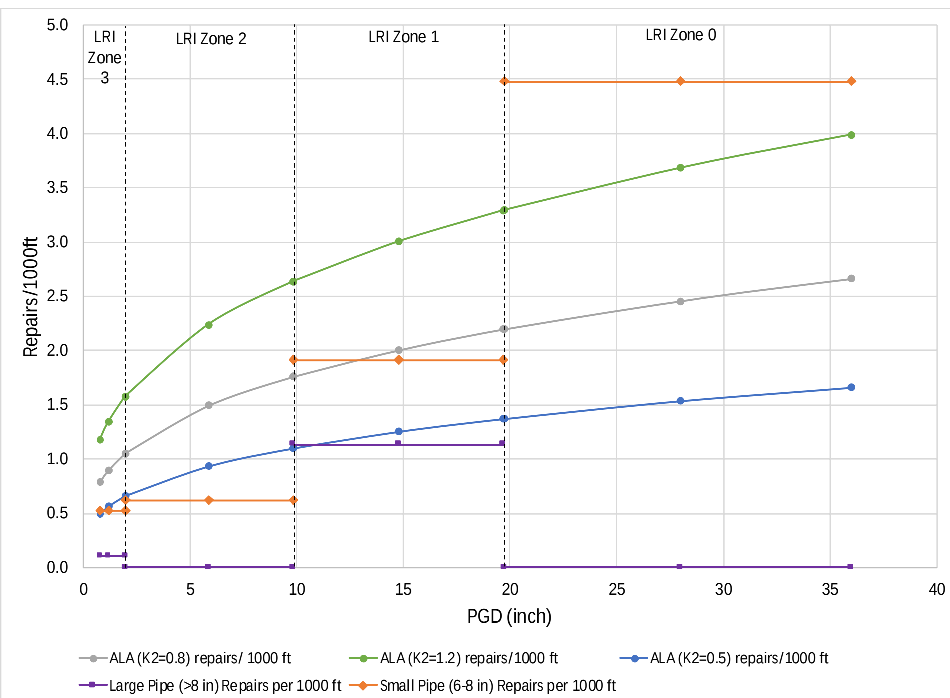

Figure 5. Actual 2011 Christchurch Repairs in Liquefaction Zones by Pipe Size Compared to ALA

3.1.2 Recommendations for Ground Deformation (PGD) Repair Equations

Based on the evaluation of pipe repairs in liquefactions zones, compared to ALA estimates for repairs due to PGD, the ALA equations appear to be on the same order of magnitude as the actual repairs from

Christchurch. The recommend modification to the K_2 values for use in the Bellevue water system analysis is to increase the K_2 value to 1.0 for AC pipe less than or equal to 8 inches in diameter.

3.1.3 Review of Ground Shaking (PGV) Repair Data

Phase 1 also included a review of the Cubrinovski data related to PGV. The PGV values for each LRI zone were obtained from USGS Shake map GIS data for the 2011 Mw 6.2 Christchurch earthquake. This earthquake was chosen because it resulted in higher ground motions and more damage to the Christchurch water system than the Mw 7.1 earthquake. Representative low, medium, and high PGV values for each zone were obtained from the Shake map and tabulated. This data review did not result in meaningful results and so determination of analysis for PGV was placed on hold until the phase 2 analysis.

3.2 Christchurch PGV repair data compared to ALA equations

Phase 2 of the comparison of ALA equations to the Christchurch earthquakes looked at a more in-depth analysis of ground shaking (PGV) repair data described in *Earthquake Response of Underground Pipeline Networks in Christchurch, NZ*[6] (O'Rourke et al. 2014) The data collected from the Christchurch earthquakes showed substantially greater repair rates at high PGVs than had been observed in the data set use for development of the ALA equations. The original empirical data originally used to develop the ALA equations was shown to significantly underpredict the actual failures in Christchurch. Additionally, the expected PGVs in the Bellevue water system during the Seattle Fault Zone earthquake scenario are greater than the highest recorded in the Christchurch earthquake. As such any repair rates in that area are extrapolations from all available data. An additional challenge in comparing the repair data from Christchurch to the ALA equations is that the Christchurch data appears to follow a distinct exponential curve, where the ALA curves for PGV are linear.

To compare this data and develop a revised empirical relationship for use on AC pipe in the Bellevue water system, the exponential curve developed by O'Rourke et al. was compared to the ALA linear curve for AC pipe. The actual data points for both Christchurch and the ALA dataset were also combined to determine what K_1 value for the ALA equations would provide the best fit for the combined data.

The final step of the analysis was to develop a "modified" exponential curve, based on the curve provided by O'Rourke et al., which is capped at a maximum repair rate of 0.7 repairs per 1000 ft of pipe, corresponding to the highest repair rates observed in post-earthquake reconnaissance.

The total number of repairs predicted for the Bellevue water system were compared for each of the two earthquake scenarios of the original exponential curve from O'Rourke et al., the modified exponential curve, the ALA linear curve with K_1=1.0 and the ALA linear curve with K_1=4.0. These are shown compared to the actual data used in the ALA equations and the actual 2011 Christchurch data in Figure 6.

Table 1 shows the comparison of the total repairs for each earthquake scenario and the combination of the two earthquake scenarios. As shown, the ALA linear equation with a K_1=4.0 provides a similar number of repairs as the modified exponential equation for the combination of the two scenarios. Additionally, it only slightly overpredicts repairs for the Cascadia Subduction Zone scenario and only slightly underpredicts the Seattle Fault Zone repairs

[6] O'Rourke, et al. 2014. "Earthquake Response of Underground Pipeline Networks in Christchurch, NZ" Earthquake Spectra. Vol. 30, No. 1 Feb 2014. pp. 183-204

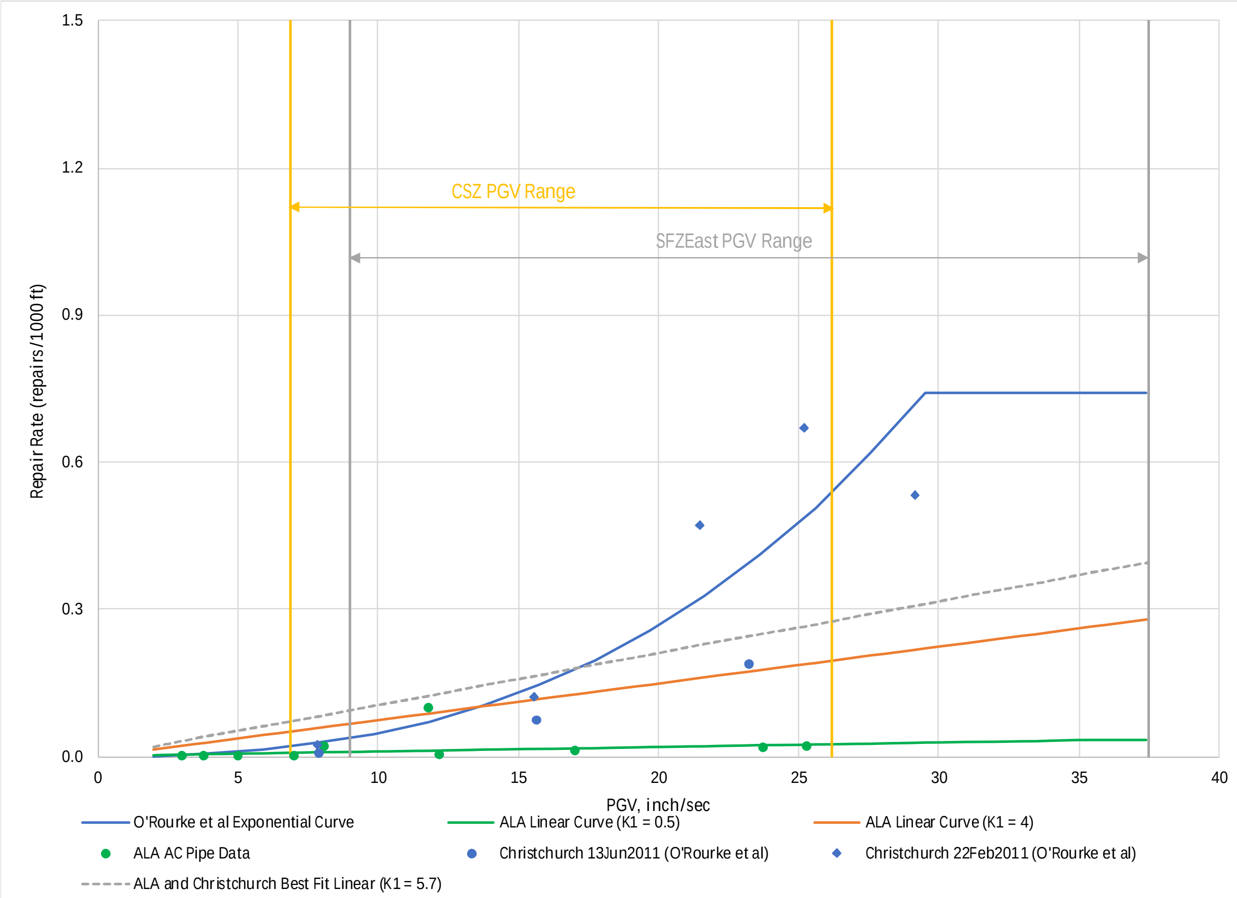

Figure 6. ALA and O'Rourke PGV equations compared to data from ALA development and 2011 Christchurch Earthquakes

Table 1. EARTHQUAKE SCENARIOS AND PREDICTED REPAIRS

Earthquake Scenario	ALA Linear Equation Predicted Repairs (K_1 = 1.0)	ALA Linear Equation (K_1 = 4.0)	Modified Exponential Equation	Exponential Equation
Cascadia Subduction Zone	30	137	82	83
Seattle Fault Zone East	56	224	288	482
Total	86	361	371	565

4. Recommendations for AC Pipe Repair Estimations

Based on the review of the AC pipe repair data available from the Christchurch earthquakes, it is recommended that the ALA fragility equations be used with the following coefficients for AC pipe.

Table 2. ALA AND BELLEVUE SVA "K" VALUES FOR AC PIPE

Pipe Material Abbreviation	ALA PGV "K_1" Value	ALA PGD "K_2" Value	SVA PGV "K_1" Value	SVA PGD "K_2" Value
AC, Rubber Gasketed (>8")	0.5	0.8[1]	4.0[2]	0.8[1]
AC, Rubber Gasketed (6 – 8")	0.5	0.8[1]	4.0[2]	1.0[2]

[1] "K" value from ALA Guideline "Seismic Fragility Formulations for Water Systems"

[2] "K" value developed based on evaluation of AC pipe performance in Christchurch 2011 earthquake in consideration of data available from ALA "Seismic Fragility Formulations for Water Systems"

These K values are based on available empirical data and analysis. As available data may change over time, the City could also keep up to date on other major studies and additional earthquake data that better characterize K values.

Appendix C. System Modeling Methodology

C.1 TM3: Modeling Methodology

JACOBS

Technical Memorandum

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Subject	**TM3: Modeling Methodology**
Project Name	Bellevue Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs
Date	October 7th, 2022

1. Background

As part of the City of Bellevue (City) Water System Seismic Vulnerability Assessment (SVA), Jacobs will be completing hydraulic and failure probability modeling of the Bellevue water system under selected earthquake scenarios. This modeling will estimate the potential damage to the system, customer service impacts, the probable restoration times following a seismic scenario event, and improvement alternatives to address system resiliency needs. To support the analysis, assumed likelihood and expected duration of outage for the Seattle Public Utilities (SPU) Tolt Eastside Supply Line (TESSL) and Cedar Eastside Supply Line (CESSL) will be incorporated to the model at the point where the TESSL and CESSL enter the Bellevue water service area.

2. Modeling Approach and Tools

The approach for the hydraulic modeling is outlined below in Figure 1. The matrix shows the phases of the analysis and the specific tools that are applied in each phase of the analysis. The approach is founded on leveraging the City's existing hydraulic model to assess hydraulic performance and water supply throughout the distribution system and includes an overlay of spatial geotechnical information to develop vulnerability parameters for pipelines and facilities in the City's system. The approach identifies each phase of the modeling process and how information from one phase informs the next phase of the modeling with the outcomes from the prior phase. This step-wise approach to modeling allows for focus of analysis on areas of the system that supply assumed critical customers (described in TM2) and those that impact large areas of the system if damaged. The inputs for each phase are listed and are described in detail in the next section (Modeling Inputs), and the information gained from each phase of the modeling analysis (Modeling Goals and Expected Outcomes) are also described in a later section.

2.1 Hydraulic Modeling

The tools used in the modeling analysis start with the City's existing hydraulic model in InfoWater. This hydraulic model is exported to EPANet for use with OptiCritical and Optimizer by Optimatics. OptiCritical is used to perform a hydraulic consequence of failure analysis and identifies the most critical pipes within the pipe network based upon the areas impacted both during a break event and then also during the repair period when the break is isolated. Optimizer is used to develop the optimal approach for restoration of the distribution system and evaluate improvement alternatives. To incorporate the probability of breaks and/or leaks into the OptiCritical analysis, a shapefile of the pipes in the hydraulic model will be exported from the InfoWater model to use with overlays of the geotechnical information and with the isolation valves from the City's geodatabase.

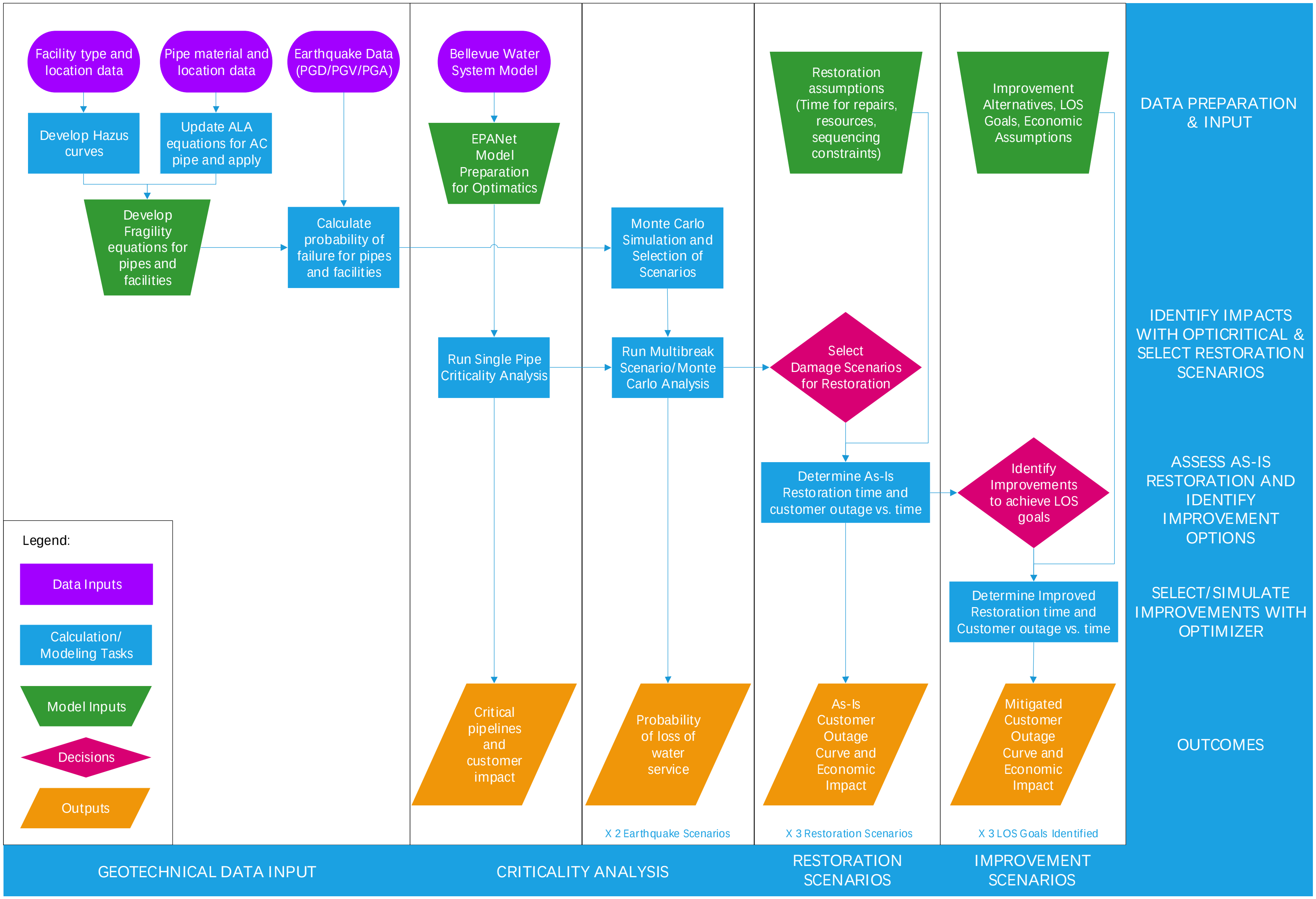

Figure 1. Modeling Approach

The City's existing hydraulic model include all pipelines within the City's distribution system, relevant (simplified) pipelines in adjacent inter-connected distribution systems (e.g. CCUD, Redmond), and pipelines of the SPU transmission systems that are within the City's boundaries. The SPU pipelines inside the Bellevue water service area will be incorporated into the overlays with the geotechnical information and will be incorporated into the system-wide analysis. The nodes where the SPU transmission pipelines enter the system will be represented as reservoirs (or similar) with water available based on the probability and expected restoration duration for each supply line for each earthquake.

The distribution of pipe segment length within the City's hydraulic model was assessed to determine if there was a minimum pipe length that should be excluded from the analysis or if skeletonization of the model based upon pipe diameter, material, and roughness would be beneficial for the analysis. Skeletonization joins pipes in series if a specified set of parameters (like pipe diameter, material, and roughness) are the same. Since the hydraulic model is an "all pipes" model derived from the City's GIS, there are many pipe segments for pipes in series that share the same physical attributes. For the Bellevue model, skeletonization was performed based upon the pipe diameter, material, and roughness parameters, and this reduced the total number of pipes in the Bellevue model by approximately fifty percent. The same pipe length remained in the model, but the number of pipe segments was reduced. The hydraulic model performance of the skeletonized model was confirmed to provide the same results as the full-pipe model.

The SPU supply operability will be considered. The control settings of inlet valves to the City's system from the SPU supplies were reviewed. After discussions with City staff, it was decided that all inlet valves would be set to operate in PRV mode (none in flow control mode), so that inlets would open if an adjacent inlet was isolated and could not supply water. This verification was performed so that supply from SPU is maintained from inlets that may not be impacted during a break scenario. If inlets were forced to be closed based upon a previous operational scheme, the criticality of some locations in the City's distribution system may be overstated.

After skeletonization of the model, the model is exported to EPANET for use with OptiCritical. To validate the performance of the exported EPANet model with the InfoWater model, the selected scenario will be run in EPANet and compared to the model output in InfoWater. InfoWater uses EPANet as the hydraulic engine, so it is anticipated that results from the InfoWater model, and the EPANet file will be similar. Tank level variation, supply from inlets, pump station flows, and overall system pressure will be compared to confirm that the EPANet file is comparably simulating the City's system as is observed with the InfoWater model. Valve types that are not available in EPANet such as altitude valves will be modified to a throttle control valve for simulation in the EPANet model. A final step to prepare the model in OptiCritical is to link the City's valves to the model network. After an initial review of the City's valves GIS and spatial alignment with the model network, the City updated locations of valves in areas where pipe replacements had been made. These adjustments by the City staff improved the linkage of the valves to the correct pipe segment in the hydraulic model. In addition, the City's hydraulic model is managed in a projection that is different than the projection used for the City's GIS. To improve the valve alignment of the valves from the City's geodatabase with the model pipes, the valves will be reprojected in ArcGIS to the projection used with the City's hydraulic model.

Excel will be used to track information that is passed to the Optimatics software, including the generation of the fragility and probability data, development of cost profiles, and development of the objective function for optimization. Excel is an efficient option to manage data for use with Optimatics software as the data updates can be streamlined based upon changing input factors and can be quickly updated and changed to support sensitivity analyses of parameters.

2.2 Multi-break Scenario Generation

The input for the multi-break scenarios will be generated with a Monte Carlo style approach that will randomly assign facility damage states and pipe breaks or leaks based on the probability of failure developed for each earthquake scenario in the vulnerability analysis described in TM 2.

Multi-break scenarios will be created using a custom python script that assigns facility damage states and pipe break and leak conditions to individual assets based upon the probability of the event occurring for that asset. Since failure is defined randomly for each scenario in accordance with the probability of failure, each scenario will have a unique combination of facility damage states or pipe breaks and leaks occurring. The overall distribution of damage, across all scenarios generated, will be consistent with the underlying probability of failure of the individual assets (for instance, assets with a higher probability of failure will fail in more multi-break failure scenarios).

For each earthquake scenario, up to ten thousand simulations will be generated using a custom python programming script run to provide a representative simulation set for hydraulic criticality analysis. Simulations will be based on a normal distribution and the mean probability of occurrence of failure for each system element modeled.

3. Modeling Inputs

A summary of the information developed and provided to the modeling team to be used in each phase of the modeling is described below. Many of the inputs will be defined spatially in GIS and assigned to the pipes within the hydraulic model and imported into the Optimatics modeling software.

3.1 Geotechnical and Vulnerability Data Input

Seismic hazard mapping for two earthquake scenarios (described in TM 1A) will be developed in GIS format. The data will include peak ground acceleration (PGA) and peak ground velocity (PGV), as well as expected permanent ground deformation magnitude and probability. This hazard mapping data will be overlaid with the facilities and pipe network to identify the simulation parameters for probability of failure for the multiple break scenarios by applying the ALA and HAZUS equations in a probabilistic manner. See TM 2 for more details on this methodology.

The probability of damage for pipes and facilities will be input into the Monte-Carlo simulation process for use in creating the multi-break simulations. This will result in a listing of specific facilities and pipes with their respective status for each selected earthquake scenario.

3.2 Criticality Analysis Input

The initial hydraulic modeling will be to perform a criticality analysis for the water system. To complete this analysis, the following data sources will be provided:

- City’s water system hydraulic model: provides water system connectivity and hydraulic details, water demand distribution, and operational information for the distribution system.
- GIS Shapefiles of system valves, water mains and laterals, and facilities within the distribution system: Valves are used to provide isolation during pipe and facility failure events. Supplemental shapefiles provide guidance for valve alignment in areas where the valves are not physically close to the model pipes.
- Damage state scenarios with pipe and facility status for each of the multi-break scenarios
- Availability of TESSL and CESSL supplies for each scenario
- Critical customer types and locations: provides spatial assignment of assumed critical customers (as described in TM2) to junctions so that the delivery of water for consumption and fire protection can be assessed during criticality assessment.

- Water system population spatial distribution: provides basis for estimating the extent of the distribution system population likely to be affected under criticality and pipe failure scenarios.

3.3 Restoration Scenarios Input

In developing the initial restoration timeline for the selected system restoration scenarios, an objective function will be developed to guide analysis of prioritization of activities for restoration. The objective function is a mathematical representation of the activities to be optimized given defined constraints and with variables (time, cost, customers impacted, economic impacts) that are to be minimized or maximized. The input will include the following:

- Expected restoration time for each of the SPU transmission lines (CESSL and TESSL) for each scenario as estimated based on available information from SPU seismic study.
- Tabular summary of restoration resources (number of crews) and repair durations (crew allocation) required to repair pipe leaks, pipe breaks, and extensively damaged (non-functional) facilities.
- An optimization objective function for analysis within Optimizer that prioritizes restoration activities and actions within the distribution system that supports prioritization of restoring service to assumed critical customers and large population groups.

3.4 Improvement Scenarios Input

As shown above in Figure 1, three improvement scenarios that are varied by the Level of Service (LOS) goal will be developed for each of the three restoration scenarios. The improvement scenarios as shown in Figure 1 will build upon the data compiled during the single and multi-pipe break analysis that identify the most efficient valve closure plan for isolation. The improvement scenarios will also consider the information developed for the restoration scenarios and identification of both temporary solutions for restoring service and the potential areas where permanent hardening or looping the system could improve the initial state of the system after a seismic event. Depending upon the number of improvement options that are identified to support hardening of the system with the goal of attaining an improved initial state after a seismic event, the opportunity for applying optimization to compare and phase improvement options will be reviewed.

With optimization, the development of an objective function to use for identification of the optimal set of improvements to meet each of the level of service (LOS) goals will be developed. The level of investment of improvements for each LOS goal will allow for comparison of the cost-benefit for improving the initial state of the system and decreasing the restoration time. To generate the optimized cost profile using Optimizer for each LOS goal, the following information will be provided:

- Identification of improvement options for each improvement scenario assessed. These will include mitigation alternatives such as pipe replacement and facility hardening, as well as operational and managerial changes such as increasing pipe stockpiles and purchasing more equipment or temporary repair materials.
- Tabular summary of cost functions for seismic improvements including pipe replacement cost and order of magnitude costs for improvements to facilities. Pipe replacement costs will be summarized and assigned based upon the type of land/right of way (ROW) where the pipe is installed and will include both traditional restrained ductile iron pipe (DIP) and earthquake resistant ductile iron pipe (ERDIP).
- Tabular summary of LOS goals.
- Definition of objective function for optimizing improvement scenarios based upon LOS goals.

4. Modeling Goals and Expected Outcomes

The expected outcome for each phase of the modeling analysis is described below. As noted above, the analysis will be conducted in phases, and information generated in each phase is structured to achieve the modeling goals for that phase and provide input and information for the next phase.

4.1 Vulnerability Phase Output

The result of the vulnerability phase modeling will be used as inputs for the criticality phase and include visual representations to allow for checking of results prior to the next phase. These include:

- Damage state scenarios identifying the state of each pipe or facility for use in the multi-break analysis
- A spatial representation that shows the recurrence of failure for specific pipe segments being identified for the multi-break analysis will be generated that displays the recurrence of damage to various pipes in each of the simulations.

4.2 Criticality Phase Output

The output from the criticality phase, including both the single pipe criticality and the multiple break criticality that incorporates the geotechnical data input and includes the following:

- Probability of outage for each assumed critical customer for the single pipe break analysis
- Identification of critical facilities and pipes based upon the population (demand) disconnection during a break event and after break isolation for the single pipe break analysis
- Identification of critical facilities and pipes based upon model predicted low pressure during a break event and after break isolation for the single pipe break analysis
- Probability of outage for each assumed critical customer and each customer group for each seismic scenario from the multi-break analysis
- Damage state for three selected damage scenarios (25th, 50th and 75^{th} percentile probability states from Monte Carlo analysis) for each of the two seismic scenarios.
    - Summary of individual pipe segments and system areas that are offline or damaged
    - Summary of facilities that are offline or damaged

4.3 Restoration Phase Output

The output from the restoration phase provides information that is used to develop improvements for system hardening and to set the time baseline and operational response assumptions for restoring service to customers. The output includes the following information on facilities:

- As-is customer outage curves and economic impact
- Optimized list of prioritized activities for restoring service to customers

4.4 Improvement Phase Output

As shown in Figure 1, the output from the improvement phase includes analysis results of system performance with improvements to mitigate the “as-is” water system damage state and a restoration analysis to develop the phasing of activities still needed to restore service to customers. The assessment of improvements and consideration of optimization will be driven by the type and number of improvements to consider. Analysis of the multi-break scenarios will be repeated with a revised break scenario, incorporating system improvements that are identified and incrementally assessed for their performance in the multi-pipe break analysis. Like the restoration phase evaluation, activities that are required to restore service for the improved system state will be optimized and prioritized. The optimization problem statement driving the improvement implementation during the restoration period (or before) is to restore service to maximize the service restored based on population (demand) served. A summary of the output from the improvement phase includes:

- Summary of restoration analysis with seismic improvements incorporated (improved system state), demonstrating the benefit that the seismic improvements make
- Identification of seismic improvements that reduce the initial outage probability and allow for efficient restoration of service to customers
- Optimized list of prioritized activities to restore service to customers from the improved state
    - Identification of improvements/restoration actions that restore service to assumed critical customers
    - Identification of improvements/restoration actions to incrementally restore service to the broad customer base.

Appendix D. Existing System Performance

D.1 TM4: Existing System Vulnerability and Customer Outage Probability

Subject	**TM4: Existing System Vulnerability and Customer Outage Probability**
Project Name	Bellevue Water System Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs
Date	October 7, 2022

1. Background

The City of Bellevue Water System Seismic Vulnerability Assessment (SVA) includes criticality and Monte Carlo modeling of the water distribution system to identify system components that present the highest risk for customer outages. The development of the methodology used and the determination of the vulnerability of existing system components can be found in TM 2: Seismic Vulnerability Assessment for Pipelines and Facilities and TM 3: Modeling Methodology. This document describes the results of the two phases of vulnerability modeling described in TM 3. The analysis presented in this document also identifies, based on single pipe criticality analysis, the most “vulnerable” system components. The system components that are considered the most “vulnerable” are those that would be likely to have the highest impact on the number of customers without water service or with significantly curtailed service immediately following an earthquake should they fail or be damaged as a result of seismic events.

The results presented in this document include the following items:

- Pipe Vulnerability Analysis: Identification of the relative vulnerability of the pipes within the distribution system as identified by the probability of failure during an earthquake event
- Single Pipe Criticality Analysis: Identification of the individual pipe segments within the distribution system that are the most vulnerable and have potential to impact the greatest number of customers
- Monte Carlo Simulation: Development of the leak and break distribution with a randomized, Monte Carlo approach based upon the probability of pipe and facility failure to use in performing the multi-break criticality analysis
- Multi-Break Criticality Analysis: Development of the distribution of the impact of water system failures on water service interruption

2. Pipe Vulnerability Analysis

The pipe vulnerability analysis methodology and approach are described in TM 2: Seismic Vulnerability Assessment for Pipelines and Facilities. The end result of this analysis can be found in two tables titled “Pipe Vulnerability Data_CSZ.xlsx” and “Pipe Vulnerability Data_SFZE.xlsx”. The vulnerability was calculated to estimate the probability of failure of each pipe in the water system as well as the expected number of leaks and breaks in each “subarea” of the system as defined in TM 2. Generally, subareas were developed based on subdividing areas around quarter sections, with the goal of keeping the total length of pipe in each subarea within a reasonable range of each other. The following figures show the results of this pipe vulnerability analysis summarized by the entire system for each earthquake scenario, and then geospatially to provide perspective on the areas of the system most impacted by each earthquake scenario.

Figure 1 shows the total number of water pipe breaks and leaks expected for each of the two earthquake scenarios evaluated as a part of this study. The Seattle Fault Zone East (SFZE) event has substantially more leaks and breaks expected than the Cascadia Subduction Zone (CSZ) event due to the more intense localized shaking associated with the SFZE event. The fault rupture from the SFZE event is likely to impact multiple pipes in the southern portion of the system as compared to the CSZ event where potential damage is more likely to be more evenly distributed throughout the system and would involve substantially lower numbers of pipe repairs of leaks and breaks in total.

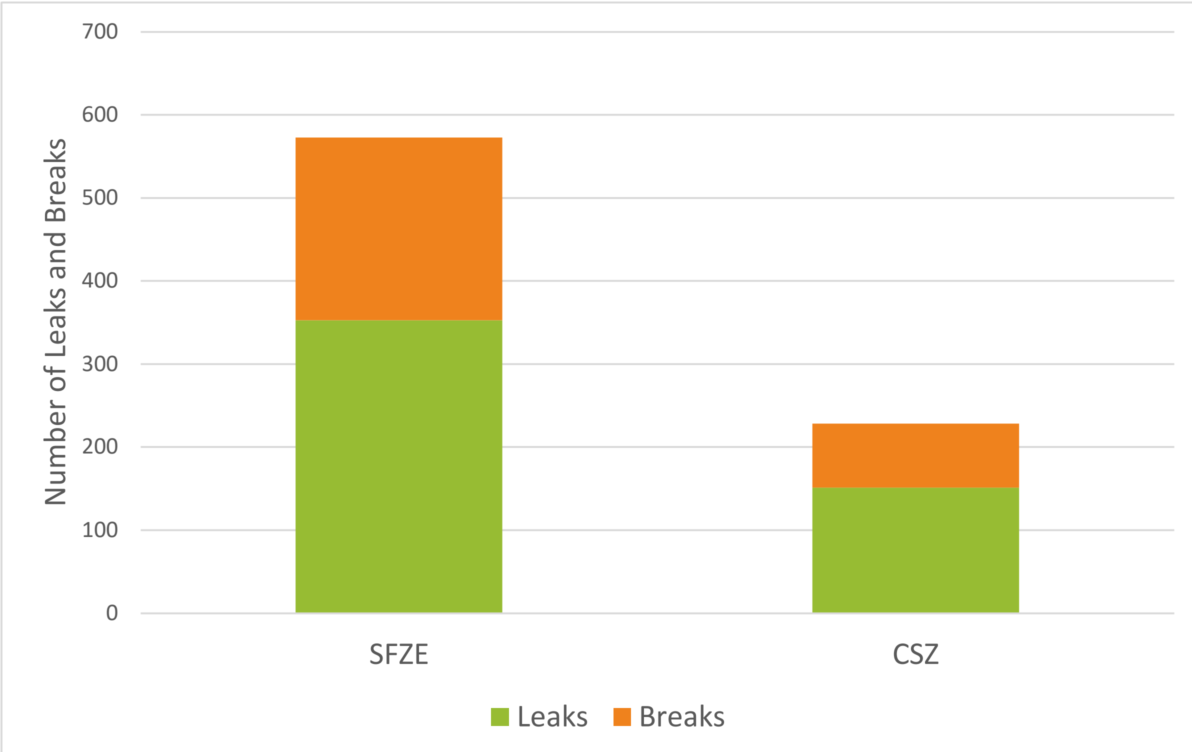

Figure 1. Pipeline ALA Vulnerability Analysis Summary

2.1 Probability of Pipe Repairs

Figures 2 and 3 show the water system pipe network with the pipes color coded by their probability of leaks in the SFZE and CSZ events, respectively. The highest probability of leaks is driven by areas where significant permanent ground deformation (liquefaction or landslide) is likely. However, because the data is shown on a per pipe basis, and the probability of leaks is based on the length of the pipe, the data is heavily influenced by the length of each pipe segment in the system.

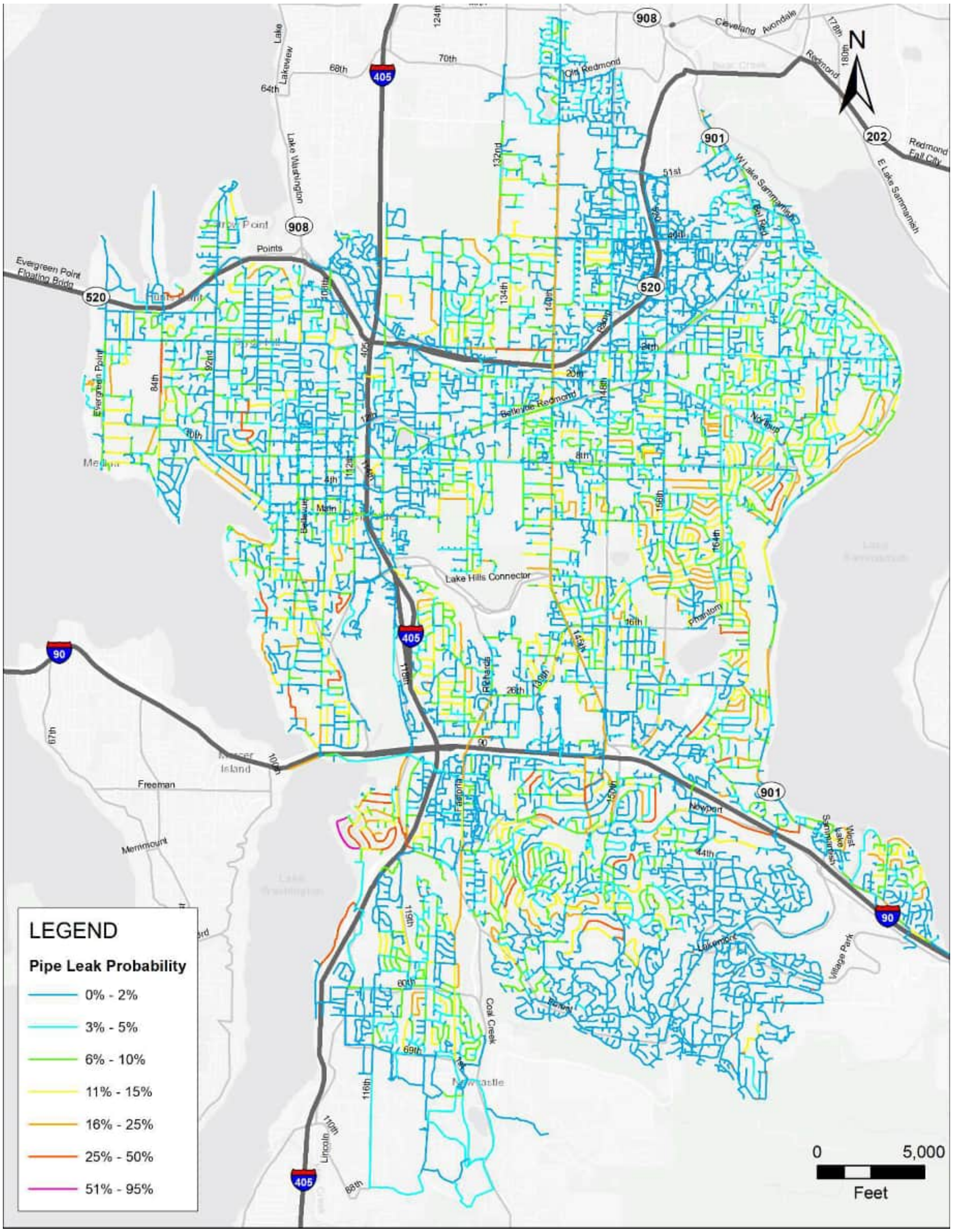

Figure 2. Seattle Fault Zone East – Pipe Leak Probabilities

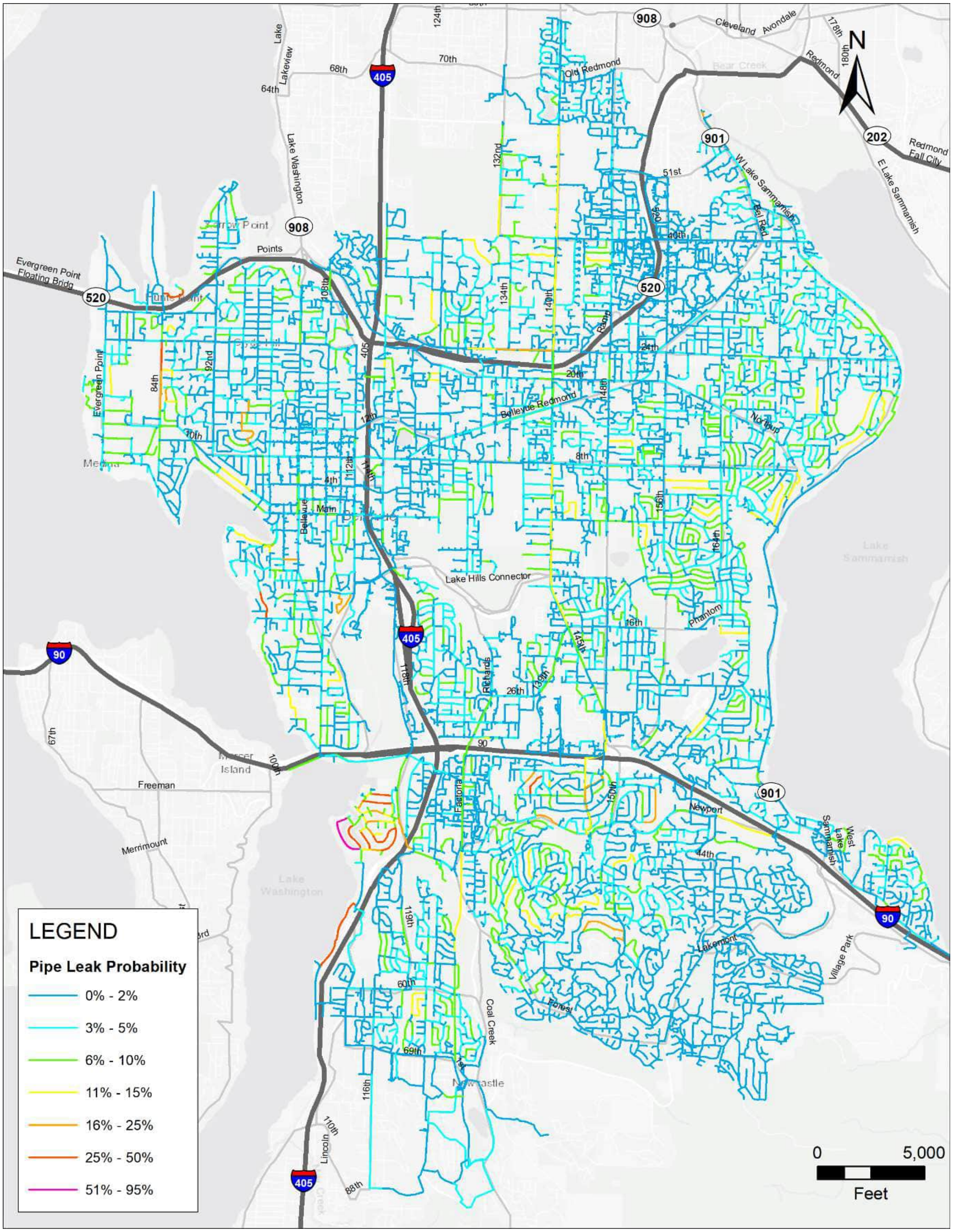

Figure 3. Cascadia Subduction Zone – Pipe Leak Probabilities

Figures 4 and 5 show the water system pipes color coded by the probability of breaks in each pipe segment for the SFZE and CSZ events, respectively. For the SFZE event, the probability of breaks is highest right along the potential fault line, followed by areas where liquefaction is likely to occur.

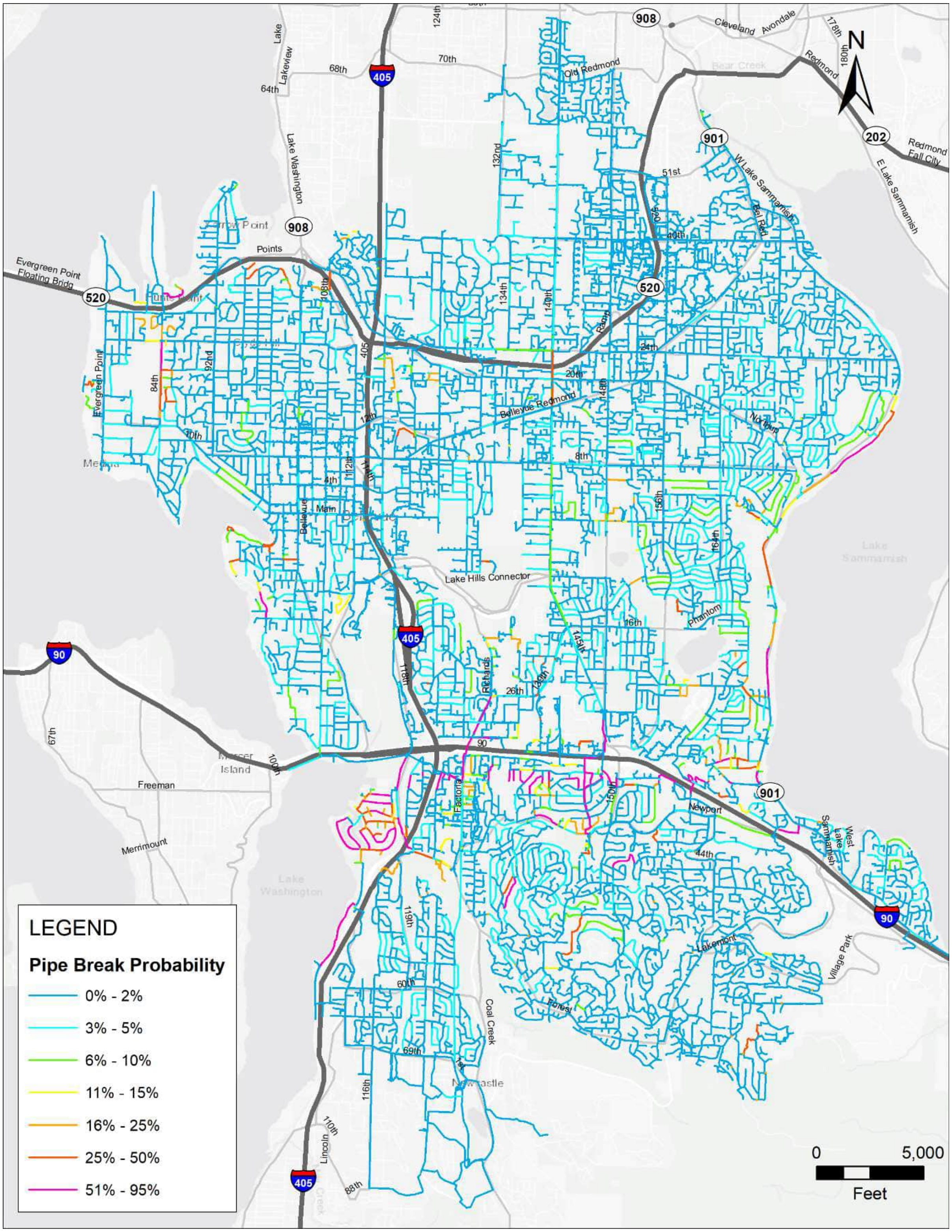

Figure 4. Seattle Fault Zone East – Pipe Break Probabilities

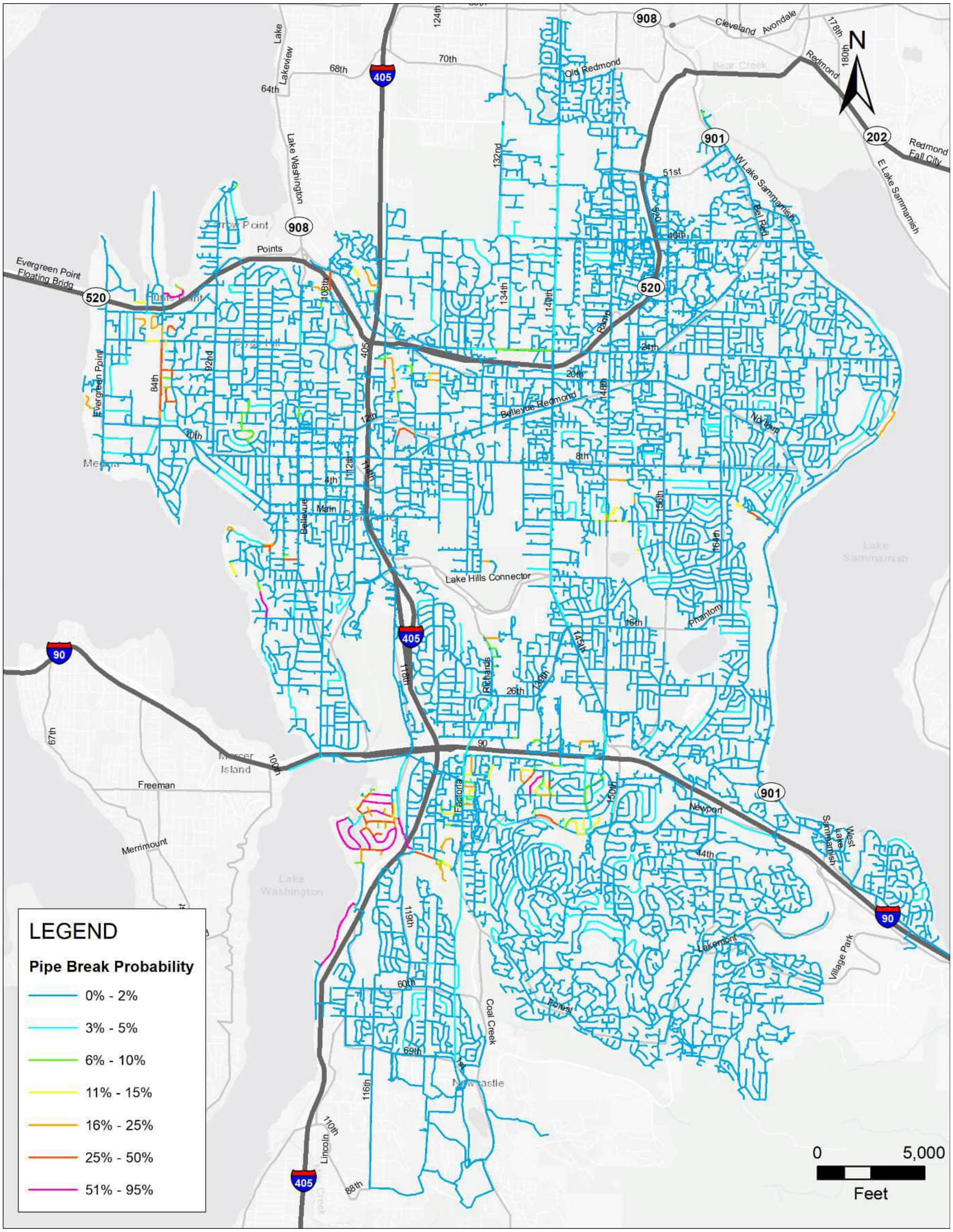

Figure 5. Cascadia Subduction Zone – Pipe Break Probabilities

2.2 Expected Number of Pipe Repairs

Figures 6 and 7 show the total probable number of repairs (breaks and leaks) for the water system in the SFZE and CSZ events, respectively. The graphic shows repairs based on the total counts of repairs likely for each subarea. Similar to the pipe probability maps above, the subareas with more repairs are typically a result of liquefiable soils as the repair rate substantially increases in liquefiable soils.

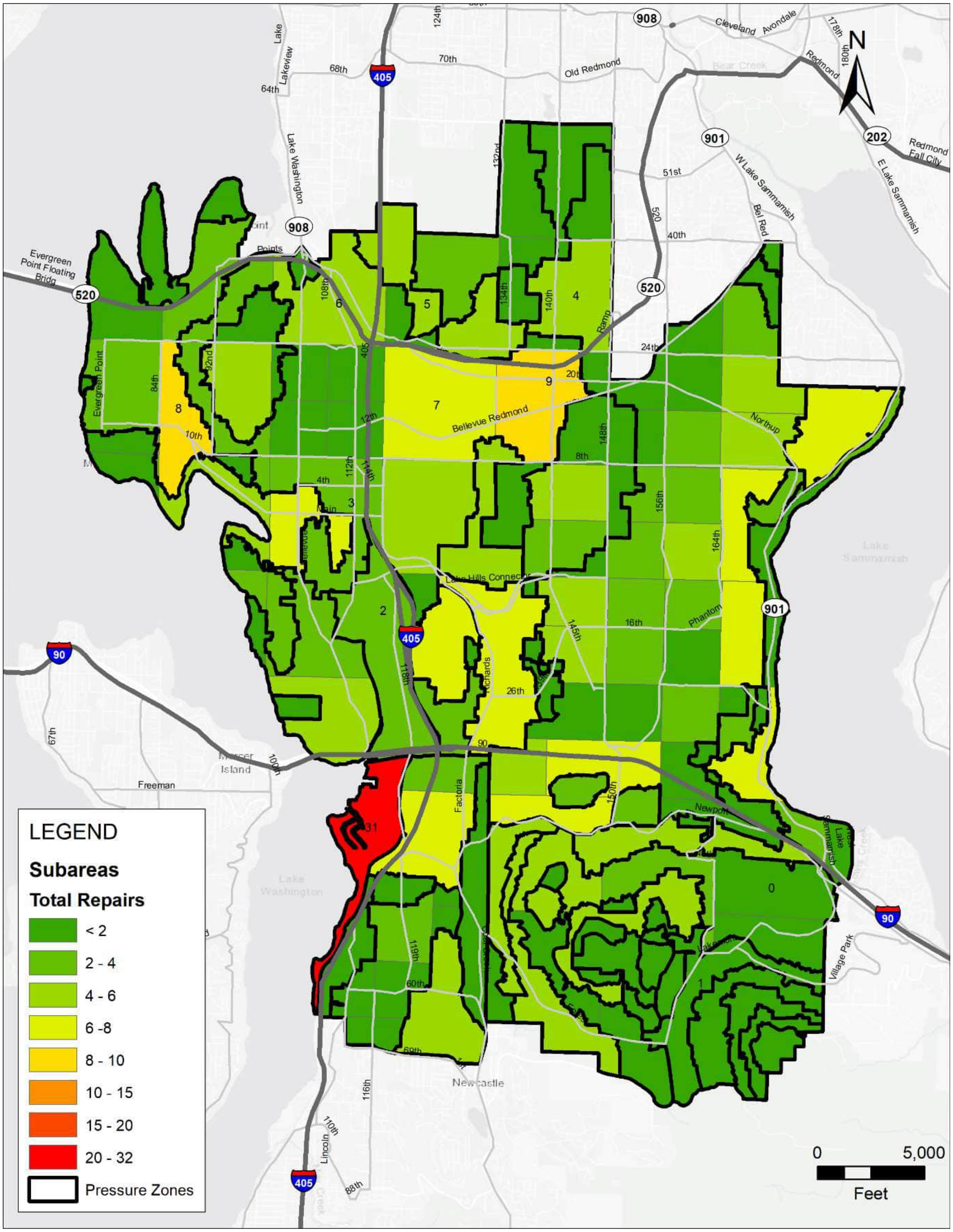

Figure 6. Seattle Fault Zone East – Pipe Failure Distribution. Combined Probable Pipe Breaks and Leak Counts by Analysis Area

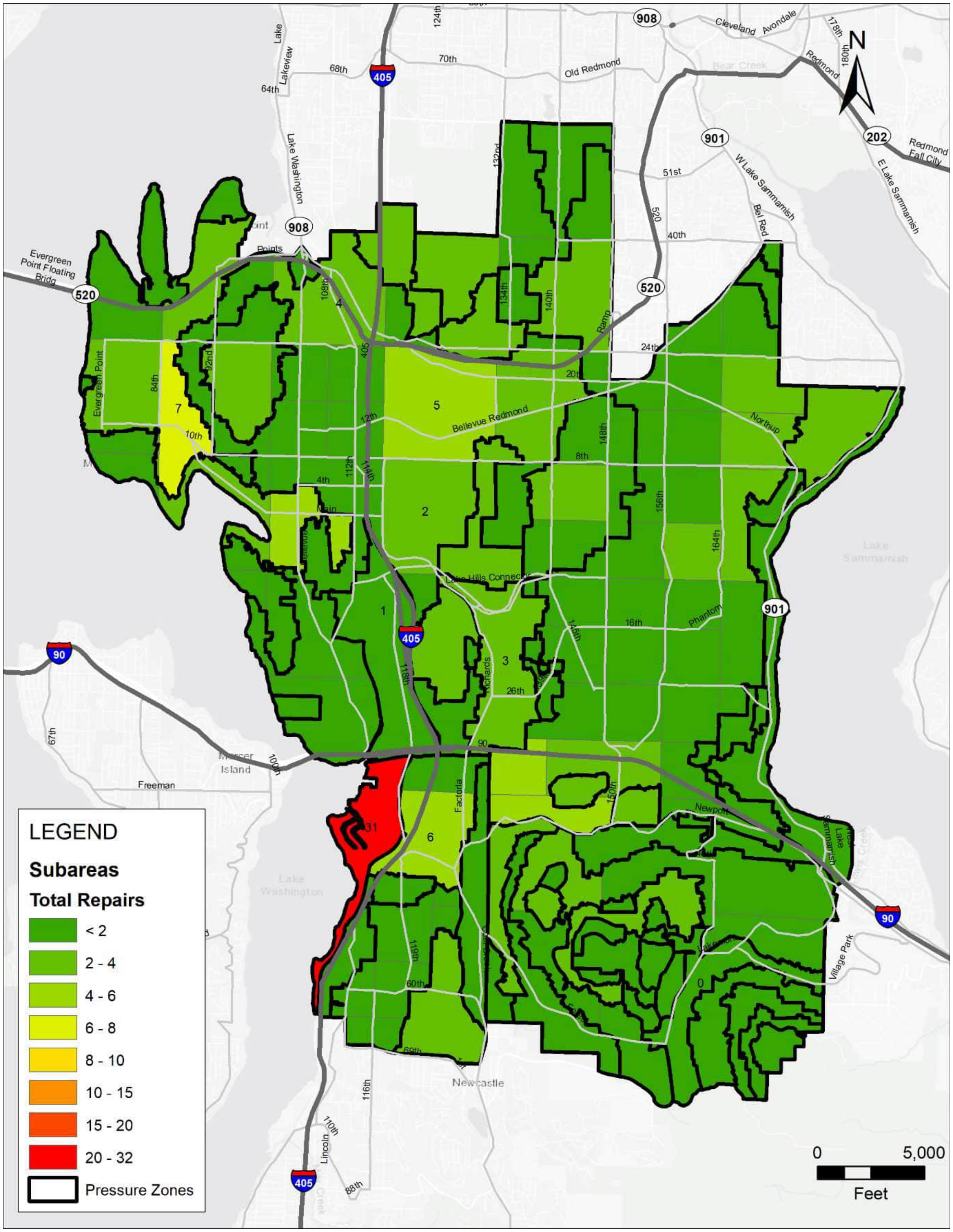

Figure 7. Cascadia Subduction Zone – Pipe Failure Distribution. Combined Probable Pipe Breaks and Leak Counts by Analysis Area

Figures 8 and 9 show the expected number of breaks only by subarea for the SFZE and CSZ events, respectively. Looking at only breaks further accentuates the impact of liquefiable soils because it is expected that 80% of the repairs in liquefiable soils will result from pipe breaks.

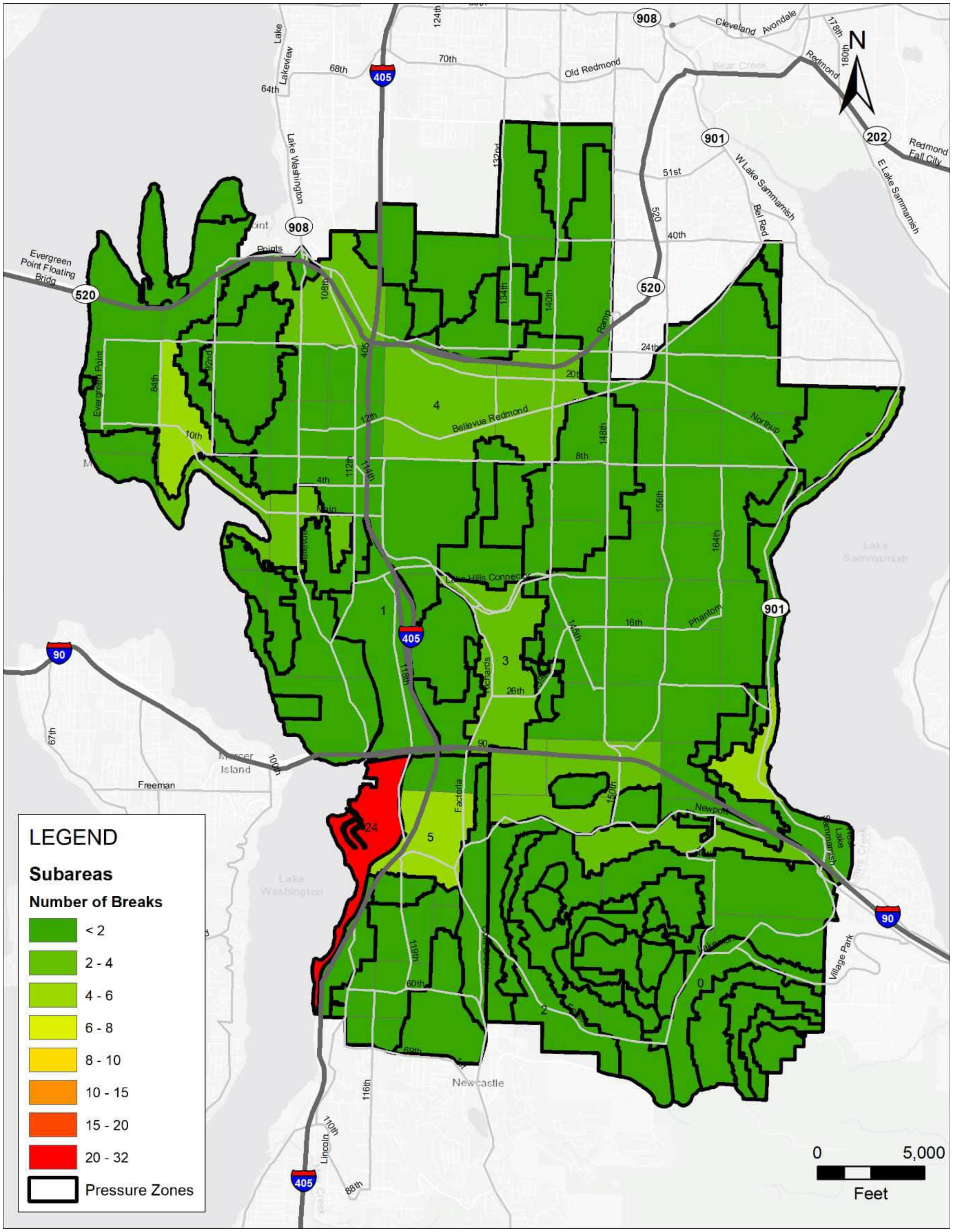

Figure 8. Seattle Fault Zone East – Pipe Failure Distribution. Probable Pipe Break Counts by Analysis Area

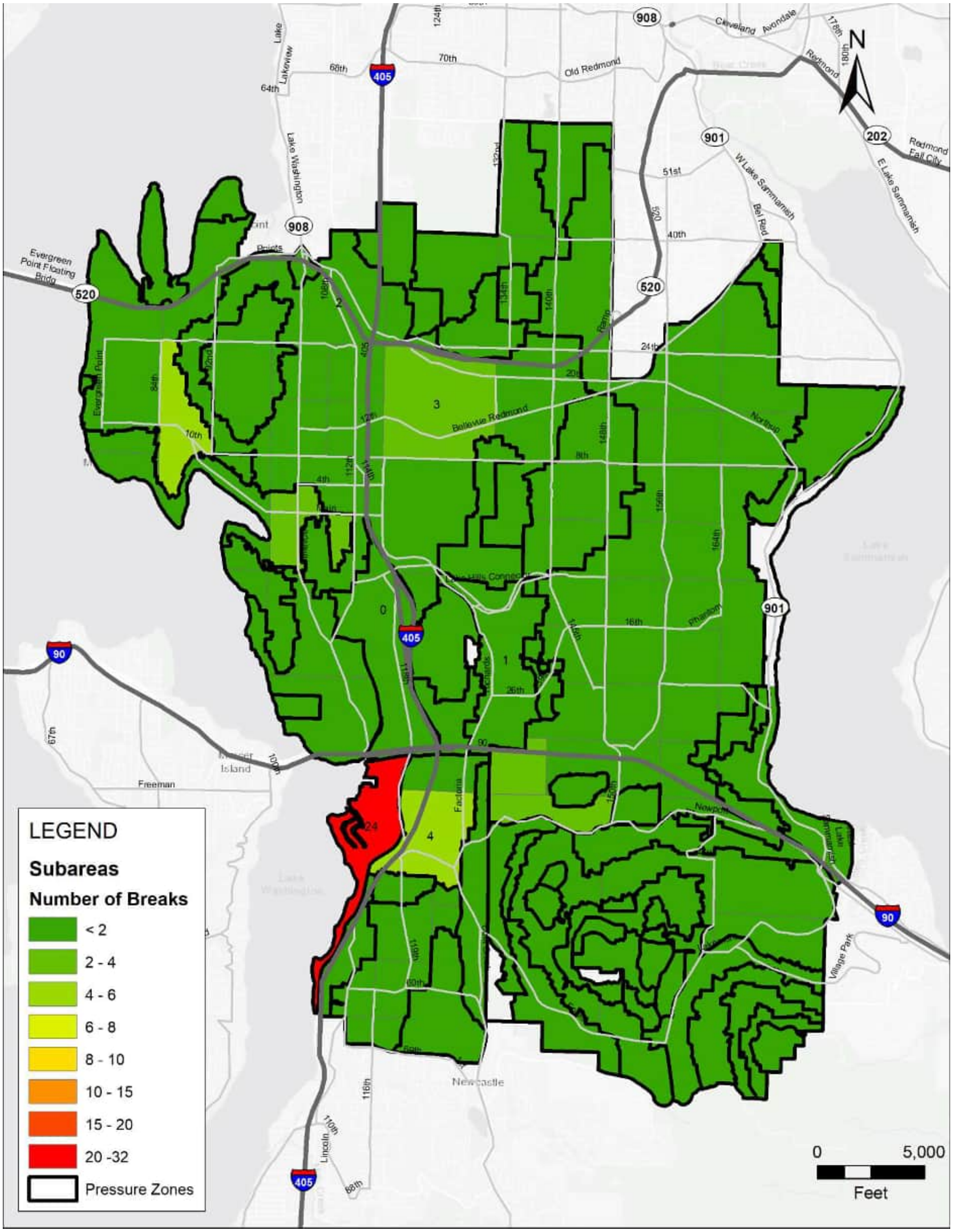

Figure 9. Cascadia Subduction Zone – Pipe Failure Distribution. Probable Pipe Break Counts by Analysis Area

As demonstrated by the information in this section, the majority of the pipe in the Bellevue Water System is in competent soils and has a relatively low probability of failure for the potential seismic events considered. Due to the nature of the analysis, the pipe segments with longer individual sections resulted in the highest probability of repairs, as probability of repairs is linearly proportional to the length of the pipe segment. Even considering this nuance, the primary driver for high repair probability is the presence of potential permanent ground deformation as a result of seismically induced liquefaction or landslides.

3. Single Pipe Criticality Analysis

The single pipe criticality analysis was conducted to identify specific pipe sections within the Bellevue system that have potential for the greatest impacts during pipe break events. Each pipe within the system was simulated as experiencing a break, and the impact to the system was quantified based upon the following criteria:

- Number of valves that need to be closed to isolate the pipe break
- The demand (in gpm) that was impacted with pressures of less than 30 psi during the initial pipe break
- The demand (in gpm) that was impacted with pressures of less than 30 psi after the pipe break is isolated for repair

The single pipe criticality results are summarized below in a series of figures that show a distribution for each of the criteria above both in a system-wide evaluation followed by a spatial presentation of the results.

3.1 Valve Closures required for Pipe Break Isolation

The results of the criticality analysis for valve closure are shown in Figure 10a and 10b. The number of valve closures to isolate individual pipe breaks throughout the Bellevue water system ranged from 1 valve to a maximum of 10 valves. For nearly 90 percent of the pipes in the Bellevue system, no more than three valves are needed to provide isolation for repair of a pipe break. This distribution of required valve closures demonstrates that the Bellevue system has a good distribution of valves throughout the system to allow for efficient isolation and repair of single pipe incidents without significant impact to large areas of the system.

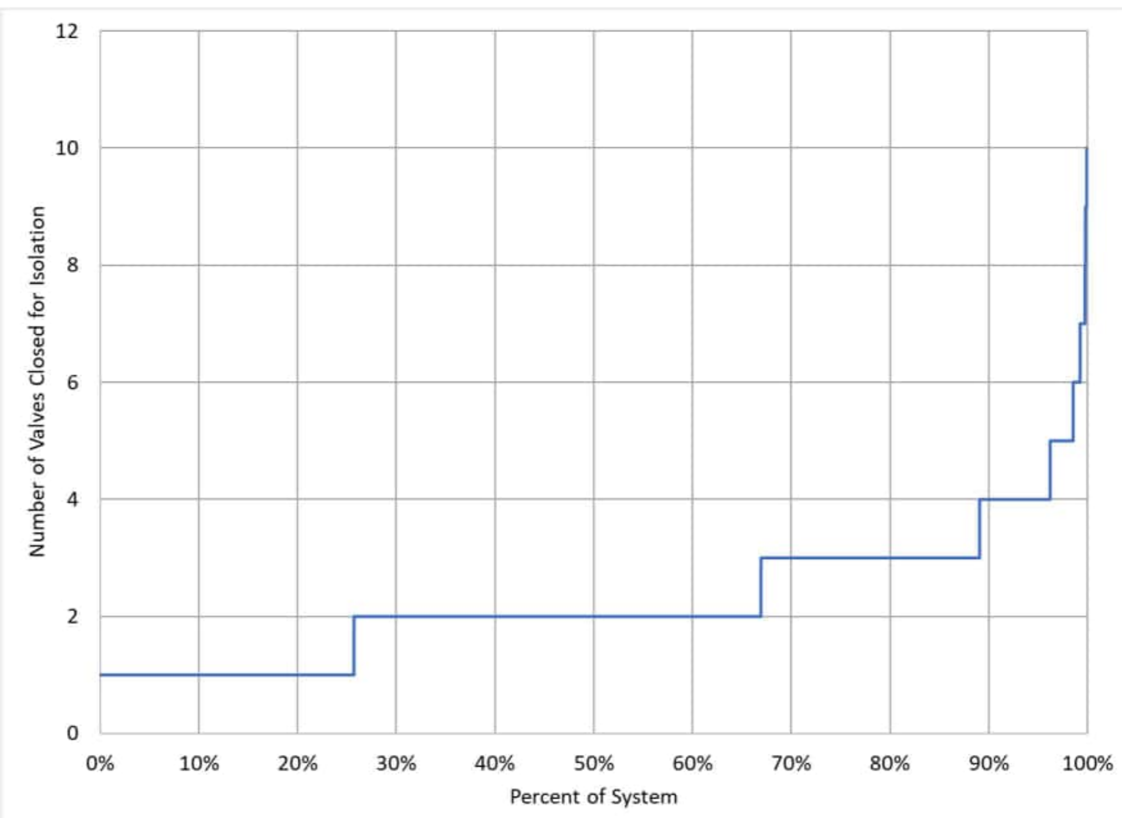

Figure 10a. Number of Valve Closures Required for Pipe Failure Isolation by Percent of Pipes

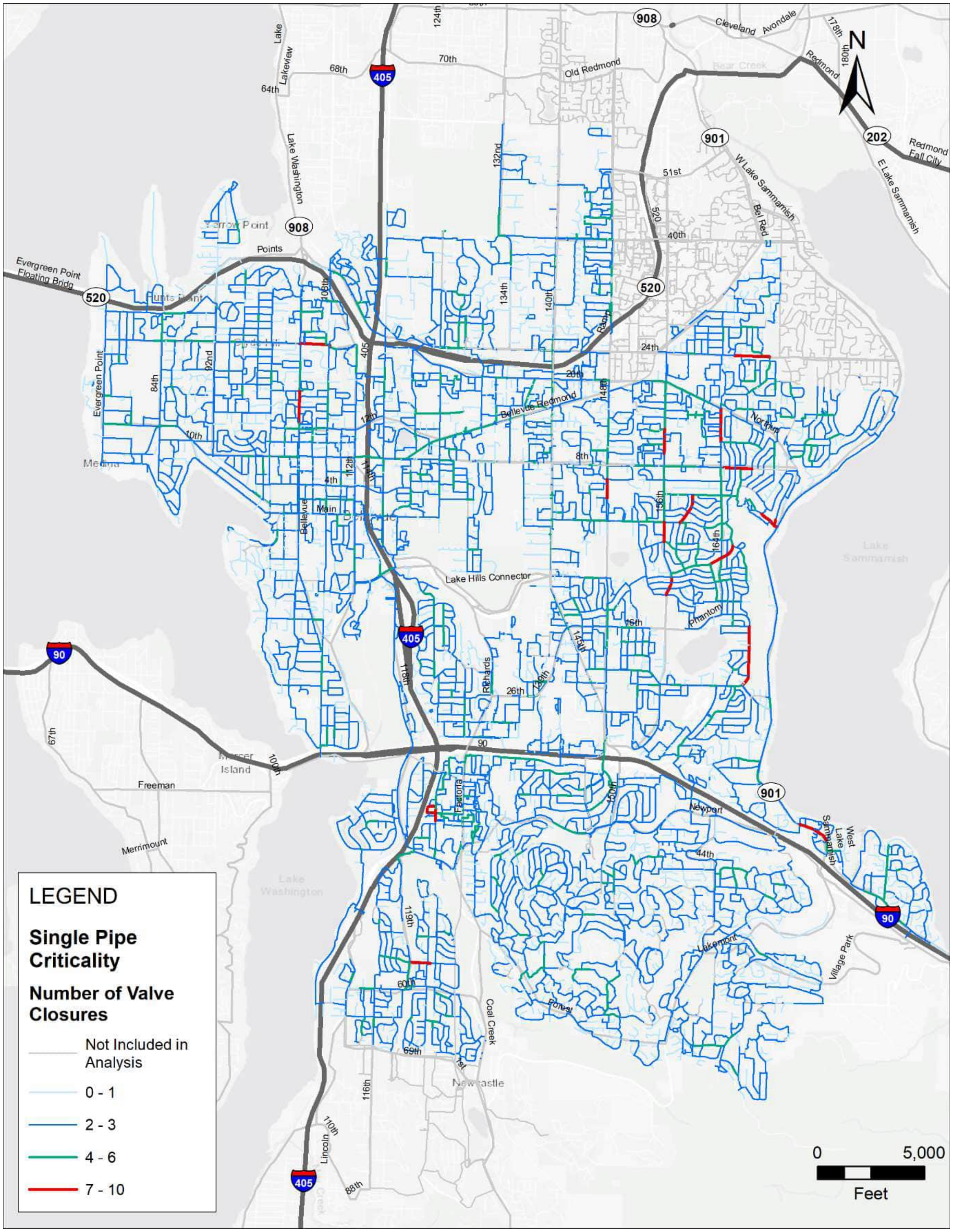

Figure 10b. Number of Valve Closures Required for Pipe Failure Isolation Map

3.2 Demand below 30 psi during the Initial Pipe Break

The results of the quantity of demand in the Bellevue system that experiences modeled pressures less than 30 psi during a single pipe break are shown in Figure 11a and 11b. From a review of Figure 11a, approximately 18 gpm in the Bellevue system is shown to be impacted for up to about 65 percent of the system. This flat distribution is most likely due to a few locations in the system that are predicted to be below 30 psi under the simulated condition, and the 18 gpm is always calculated as being lower than 30 psi. The amount of demand impacted increases somewhat linearly to 21 gpm for 90 percent of the system. For the remaining 10 percent of the system, the amount of demand impacted increases to a maximum of 78 gpm. The location of the pipes that have the most impact on delivering demand during a break are shown in Figure 11b. The pipes that are shown to have the most impact are pipes that are at the highest elevations of the system and pipes that are at the ends of pressure zones and are the only source of supply to isolated areas.

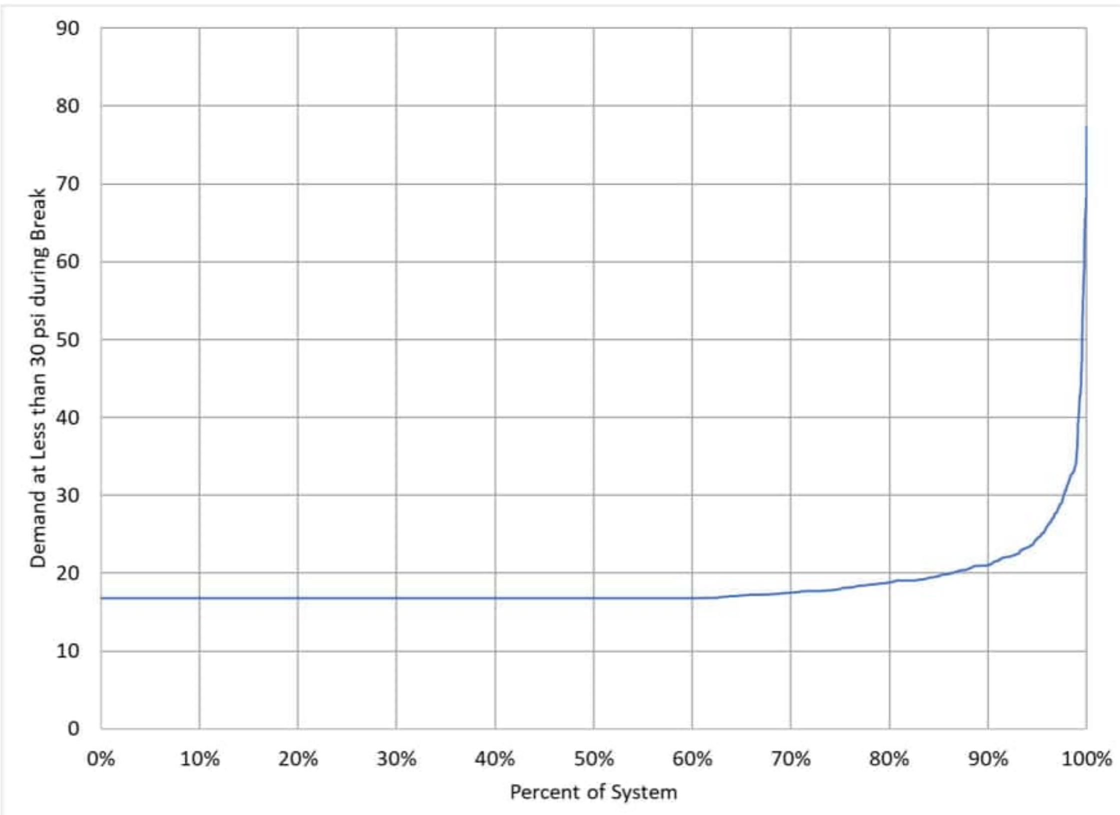

Figure 11a. Demands with pressure below 30 psi during Pipe Breaks Events by Percent of Pipes

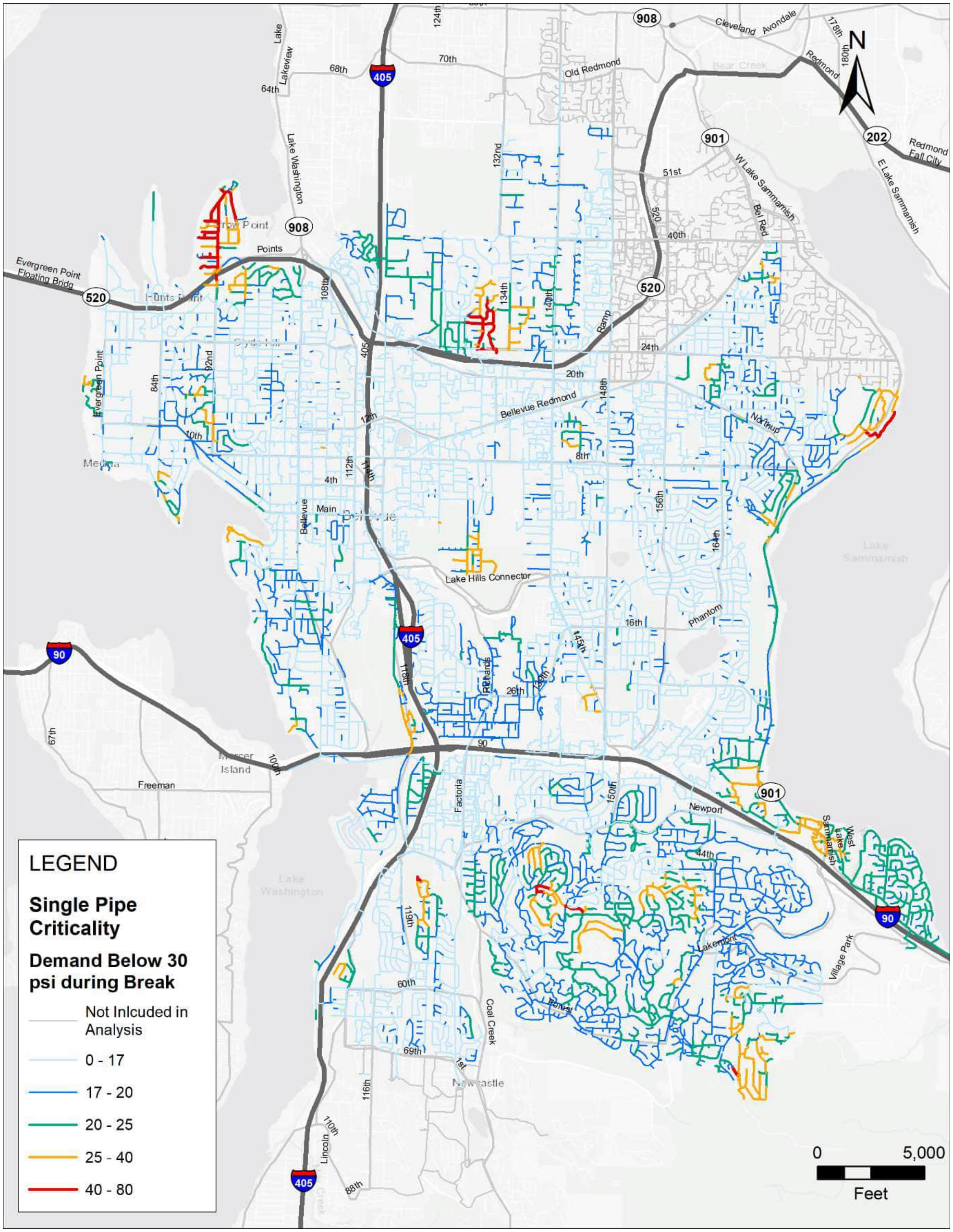

Figure 11b. Demands with pressure below 30 psi during Pipe Breaks Events Map

3.3 Demand below 30 psi after Break Isolation

The analysis of quantifying the demand that is delivered at pressures below 30 psi after isolation of a single pipe break is presented in Figures 12a and 12b. In comparing these results to the results for low pressure areas during a break, there is less impact across the system. Approximately 16 gpm is impacted up to the 97 percent level. From that point, the level of demand impacted increases to 1,600 gpm. This elevated demand value is due to the delivery point for CWA and can be excluded from the analysis. The pipes that isolate this demand are also shown in red in Figure 12b. The other pipes that isolate higher demand levels when a break is isolated are shown in Figure 12b.

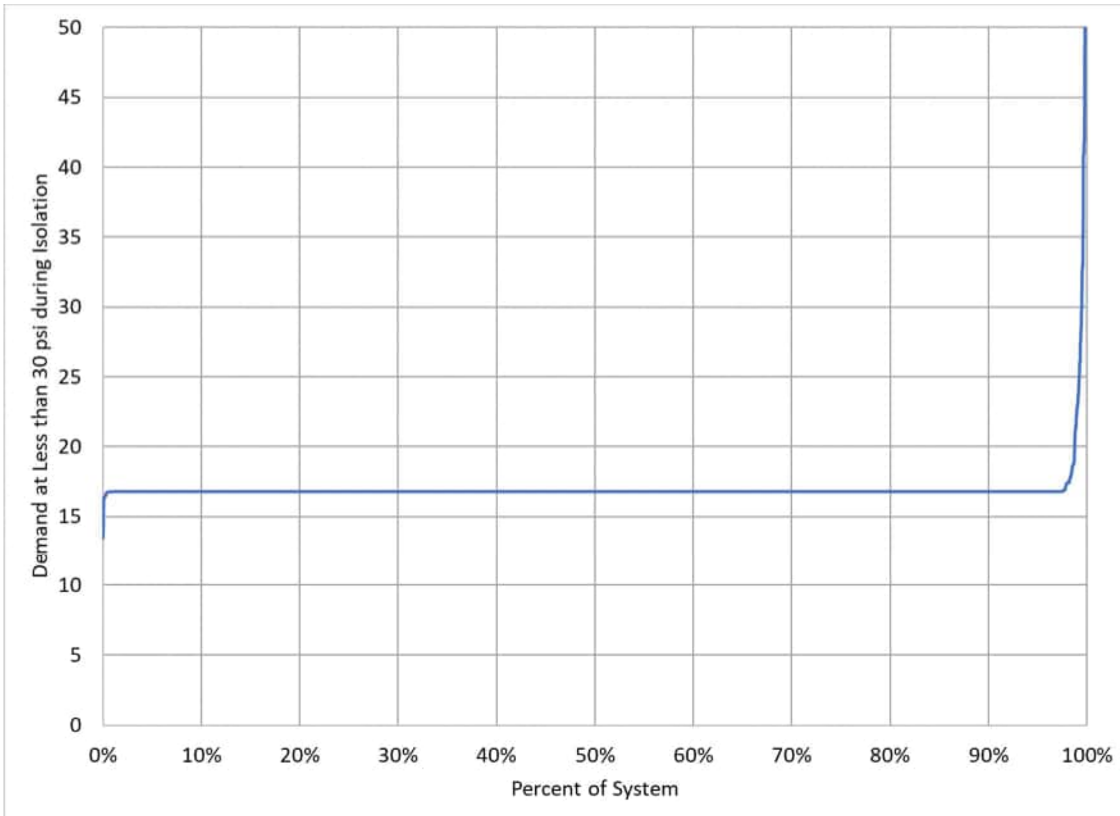

Figure 12a. Demands with pressure below 30 psi during Pipe Break Isolation by Percent of Pipes

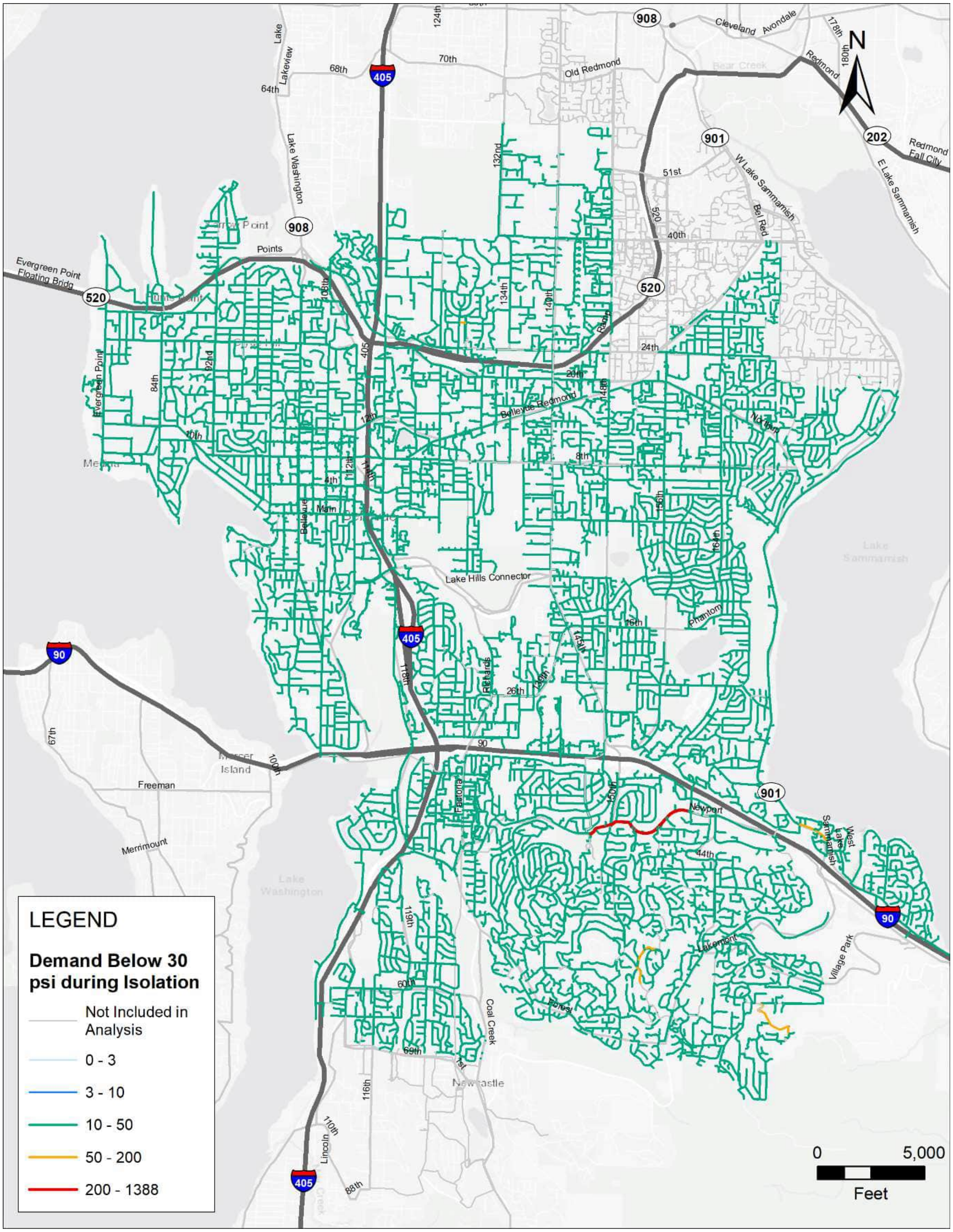

Figure 12b. Demands with pressure below 30 psi during Pipe Break Isolation Map

4. Monte Carlo Simulations

In order to determine the probability that a given customer or subarea of the system will have water service after either of the two earthquake events, Monte Carlo based simulations were performed to develop scenarios that represent the distribution of probably damage to the water system as a result of an earthquake. The simulations were performed using a custom Python script that generated an individual random variable between 0 and 1 based on a normal distribution for each water system pipe segment and facility and compared that random value to the probability of a specific damage state for the element. For pipes, the damage states were “leak” or “break”, and for facilities the damage states were “extensive damage” or “collapsed”. These terms are defined in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment.

Determination of whether an element was likely to experience a leak or break, or extensive damage or collapsed state, were determined independently. If an element had both possible damage states, the higher (break or collapsed) was applied to the element. If the element had only leak or extensive damage, that state was applied. If neither damage state occurred for the facility, then it was considered to be online.

After the damage states were determined for each facility (i.e., Cougar Mountain PS # 1) in each simulation, the damage states were applied to all the hydraulic model elements associated with that facility (i.e., Cougar Mountain PS #1, Pumps 1, 2, and 3). This allows the hydraulic model to deactivate each element in the hydraulic model necessary to represent the entire facility being offline.

4.1 Number of Simulations and Simulation Results

To determine the normality of the resulting Monte Carlo simulations and confirm an adequate and statistically significant number of simulations were being used, histograms were reviewed to look at the distribution of pipe or facility damage across all the simulations. Initial trial runs using only 1,000 Monte Carlo simulations resulted in noticeably inconsistent distribution of pipe repairs as shown in Figure 13. Final runs used for the multi-break analysis used 10,000 simulations, which produced a substantially cleaner normal distribution as shown in Figure 14.

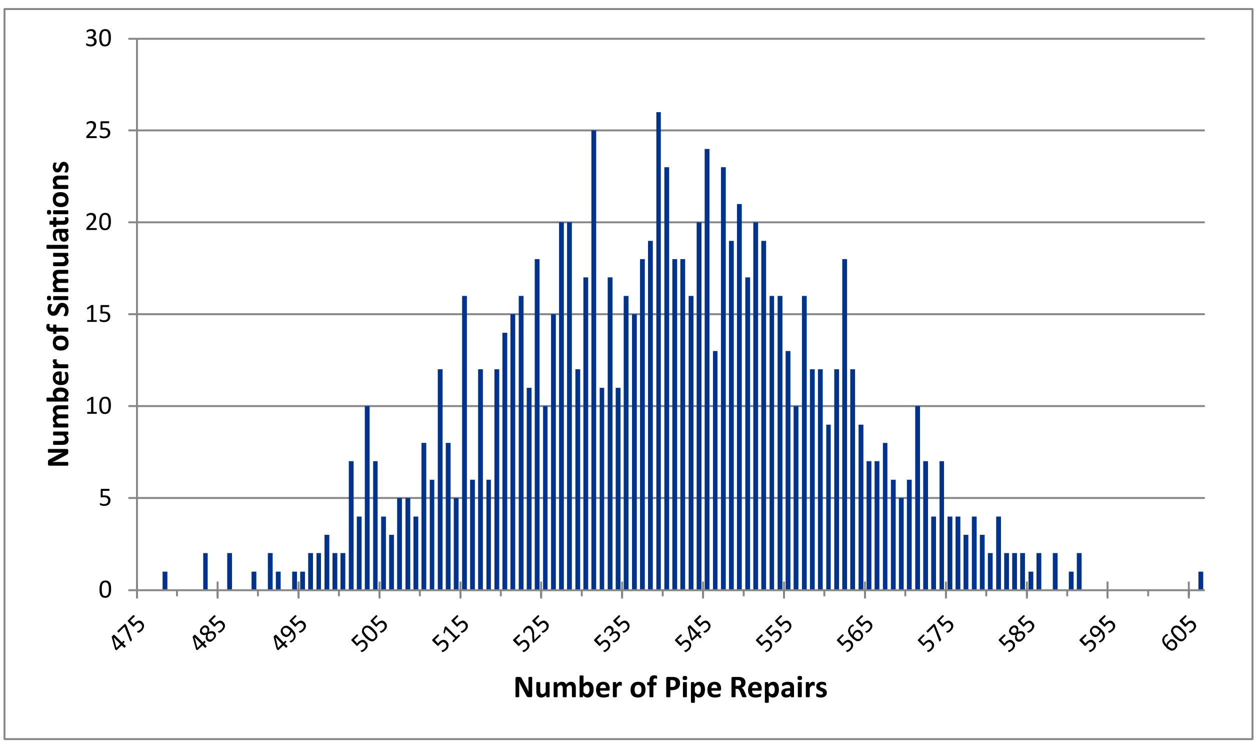

Figure 13. SFZE Pipe Repair Histogram based on 1,000 Monte Carlo Simulations during Testing

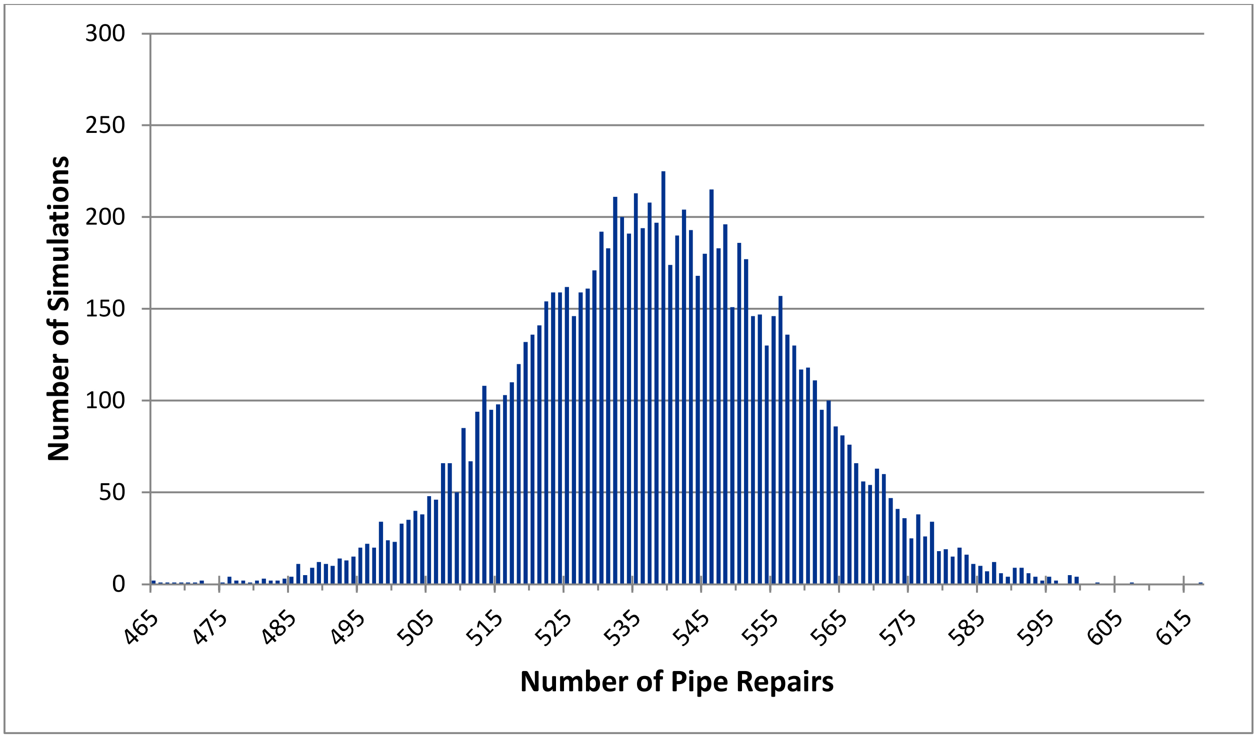

Figure 14. 10,000 Monte Carlo simulation histogram of pipe repairs developed through Multi-break Analysis for SFZE Event

4.2 Simulation Outputs

The output from the Monte Carlo simulation process was reviewed to confirm that the results matched the expected distribution and probabilities of damage for water system pipes and facilities. Figures 15 and 16 show the distribution of pipe repairs for the SFZE and CSZ events.

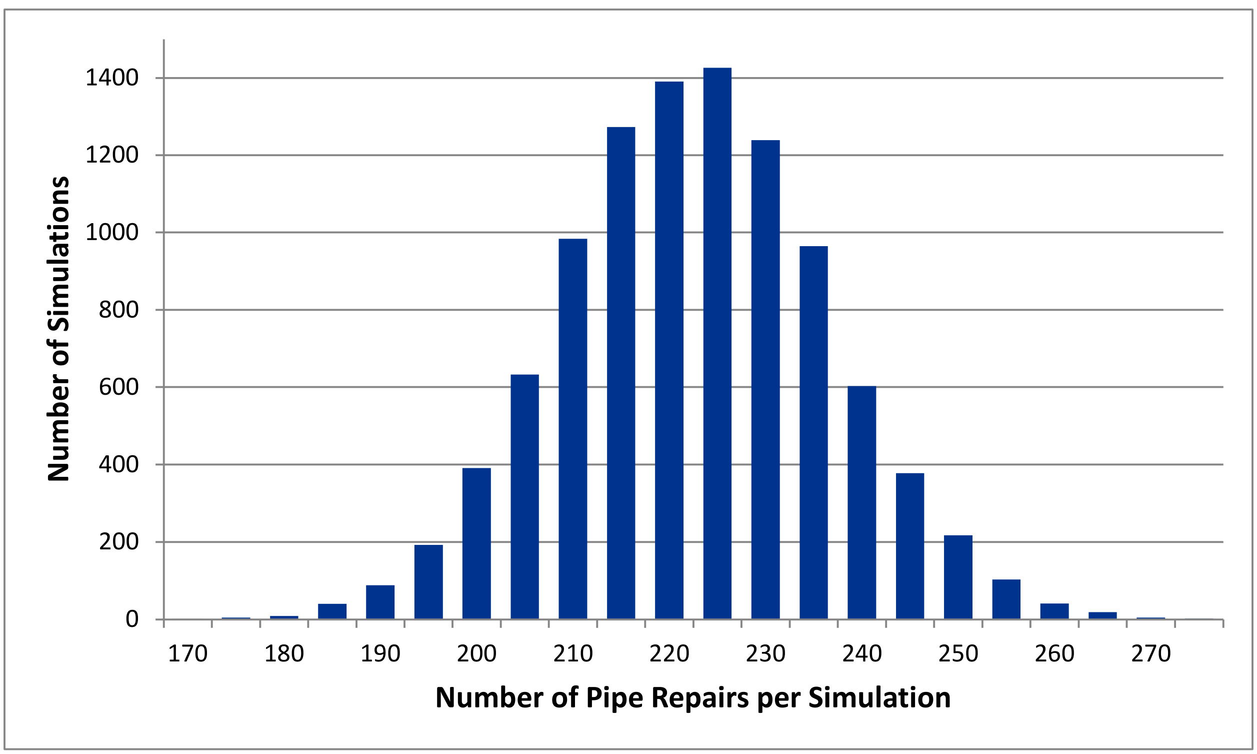

Figure 15. CSZ Monte Carlo Simulation Pipe Repair Histogram

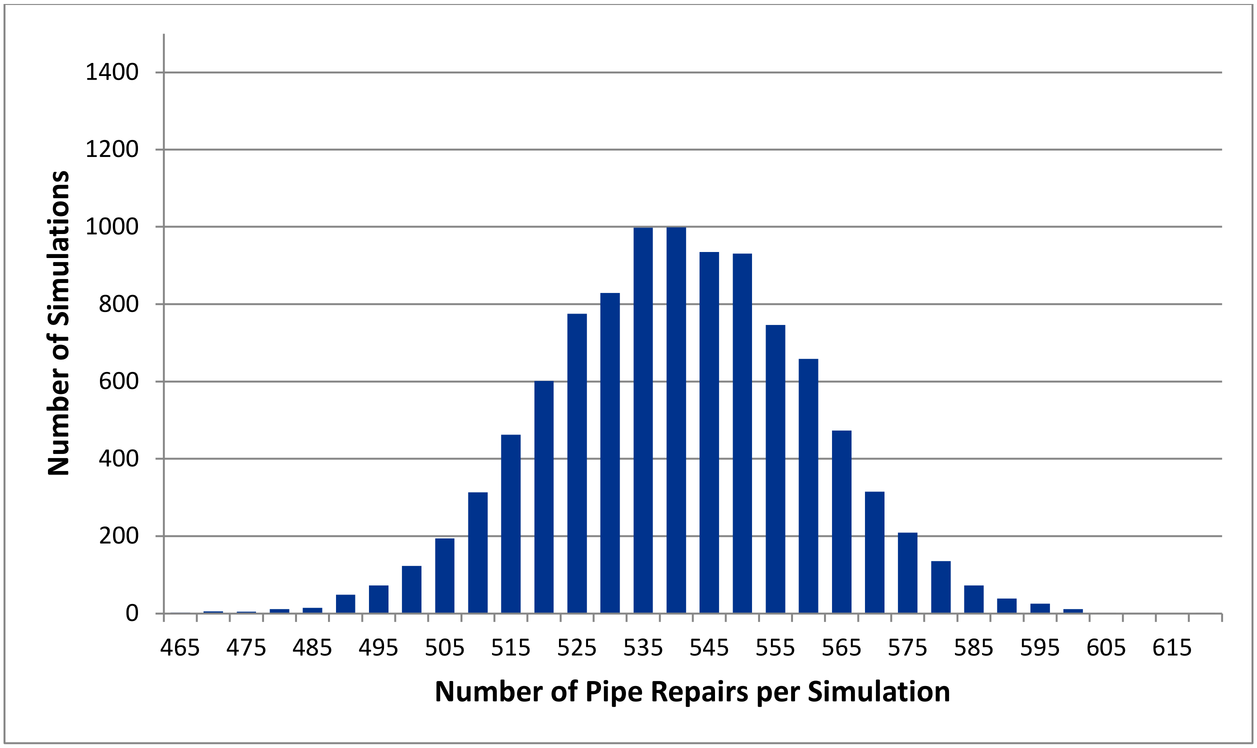

Figure 16. SFZE Monte Carlo Simulation Pipe Repair Histogram

Table 1 shows a comparison of the total number of facilities expected to be online based on estimated probabilities compared against the results of the Monte Carlo simulations. These results show that the average number of facilities online for each type of facility is almost identical to the probabilities input into the simulation.

Table 1. Comparison of Facility Damage Probabilities to Monte Carlo Simulation Results

Facility Type	Total Number of Facilities in Simulation	SFZE Average Number of Facilities Online		CSZ Average Number of Facilities Online	
		Expected	Monte Carlo Results	Expected	Monte Carlo Results
Pump Stations	24	13.5	13.5	22.1	22.1
Reservoirs	32	24.1	24.1	30.9	30.8
Inlets	13	8.5	8.5	13.0	13.0
SPU Supplies	2	0.8	0.8	0.9	0.9

The simulation results information provided above demonstrates that the Monte Carlo simulations conducted to generate the multi break scenarios for water system performance were successful in producing 1) an adequate number of simulations to result in a normal statistical distribution for pipes and facilities failures, 2) the expected average number of pipe repairs for all simulations, and 3) the expected number of facilities online for each event over all the simulations. These results indicate that the Monte Carlo simulation results are statistically consistent with the estimated probabilities of failure for pipe and facilities within the water system.

5. Multi-Break Hydraulic Analysis

The multi-break criticality analysis was conducted to identify the impact of multiple pipe breaks and leaks on the capability of the Bellevue system to deliver water supply to customers following the evaluated seismic events. For both the SFZE and the CSZ scenarios, a set of 10,000 simulations with varied broken pipes and leaks, select facilities out of service, and variation of water supply sources from SPU out of service were developed. The broken pipes, facility status, and water supply status was established for each simulation based upon probability of failure and was derived through the Monte Carlo approach described above. The status of broken pipes as well as facilities and supplies identified to be offline for each simulation were set in the Bellevue hydraulic model, and then each simulation was run to identify the areas most likely to be impacted across each set of simulations. Impact was quantified through a tabulation of the demand within each subarea of the Bellevue water system not being delivered at 30 psi. The total demand impact was also summarized for each simulation. The results for the multi-break hydraulic simulation are summarized in the following sections and figures.

This analysis assumes that all reservoirs are at their normal operating state when the earthquake occurs, and the resulting hydraulic conditions does not account for drain down of the reservoirs due to excessive water loss from leaks and breaks in the system. The analysis does account for reservoirs which are damaged in each simulation. With this regard, the results are representative of the state of the system immediately (within the first 30 minutes to an hour) after a seismic event, such that the situation will get worse as time goes on as water continues to exit the system via pipe and facility failures.

5.1 Seattle Fault Zone East Multi-Break Results

The demand impacts for the SFZE simulations were compiled by subarea, and Figure 17 and Figure 18 show the quantity and percent of demand by subarea that cannot be met with pressures above 30 psi for the SFZE. The data presented in Figure 17 and Figure 18 is a compilation (average) of all of the 10,000 simulations developed for the SFZE event. The information presented in Figure 18 is particularly striking given that the results predict that the majority of the water system has more than 60 percent demand not being met on an average basis across the 10,000 simulations. Figure 19 shows the distribution of demand impacts for all of the SFZE simulations. As shown in Figure 19, the median demand impact for the entire system including supplies to other systems like CCUD, Mercer Island, and the BIP is between 8,500 and 9,000 gpm (12.2 mgd – 13.0 mgd), which is greater than one-half of the total demand of the water system (14,800 gpm) for the average day demand condition used in the analysis. The distribution of demand in Figure 19 aligns with the spatial distribution of demand impacts shown in Figure 18.

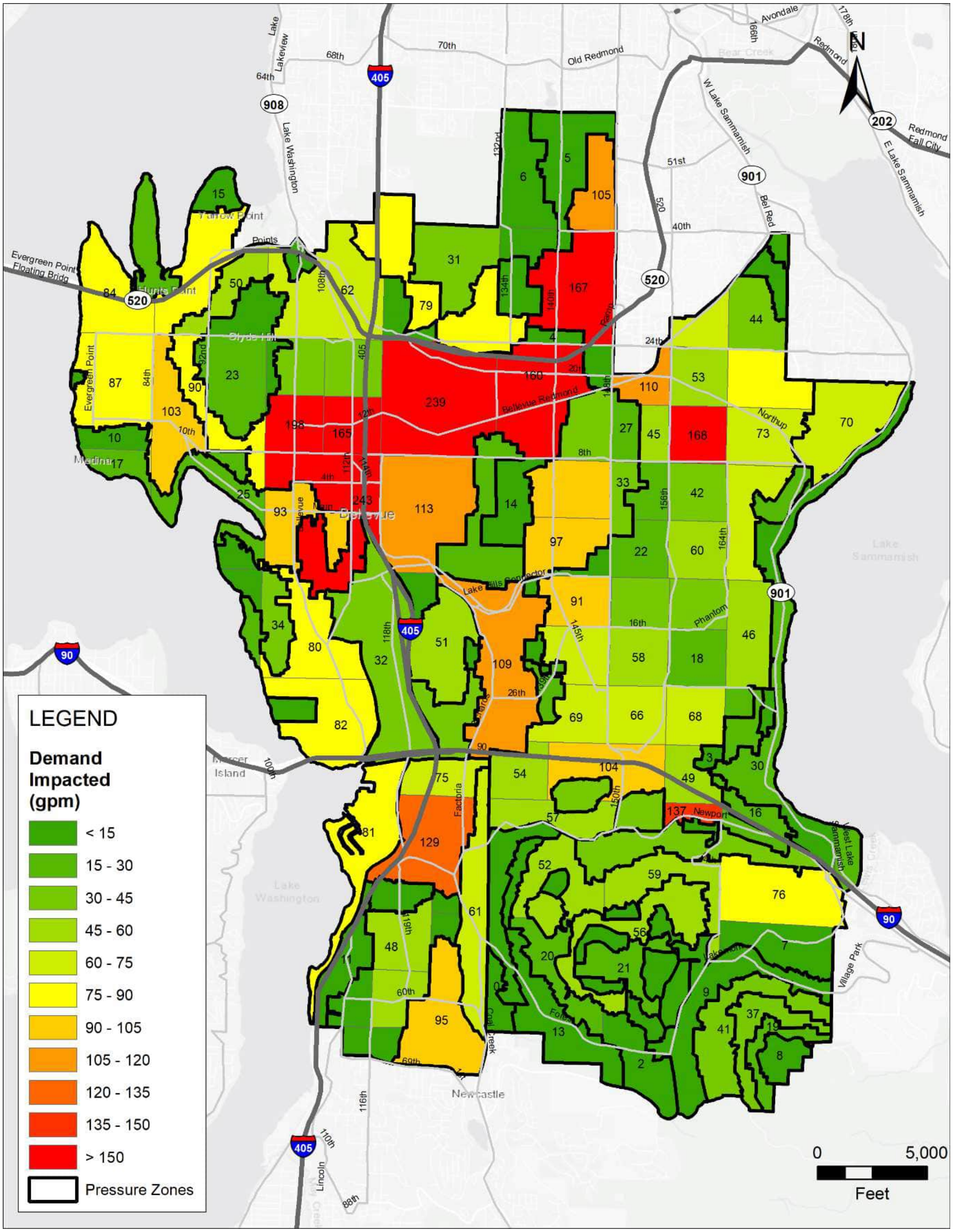

Figure 17. Predicted Demand Impacts in gpm by Subarea immediately following SFZE

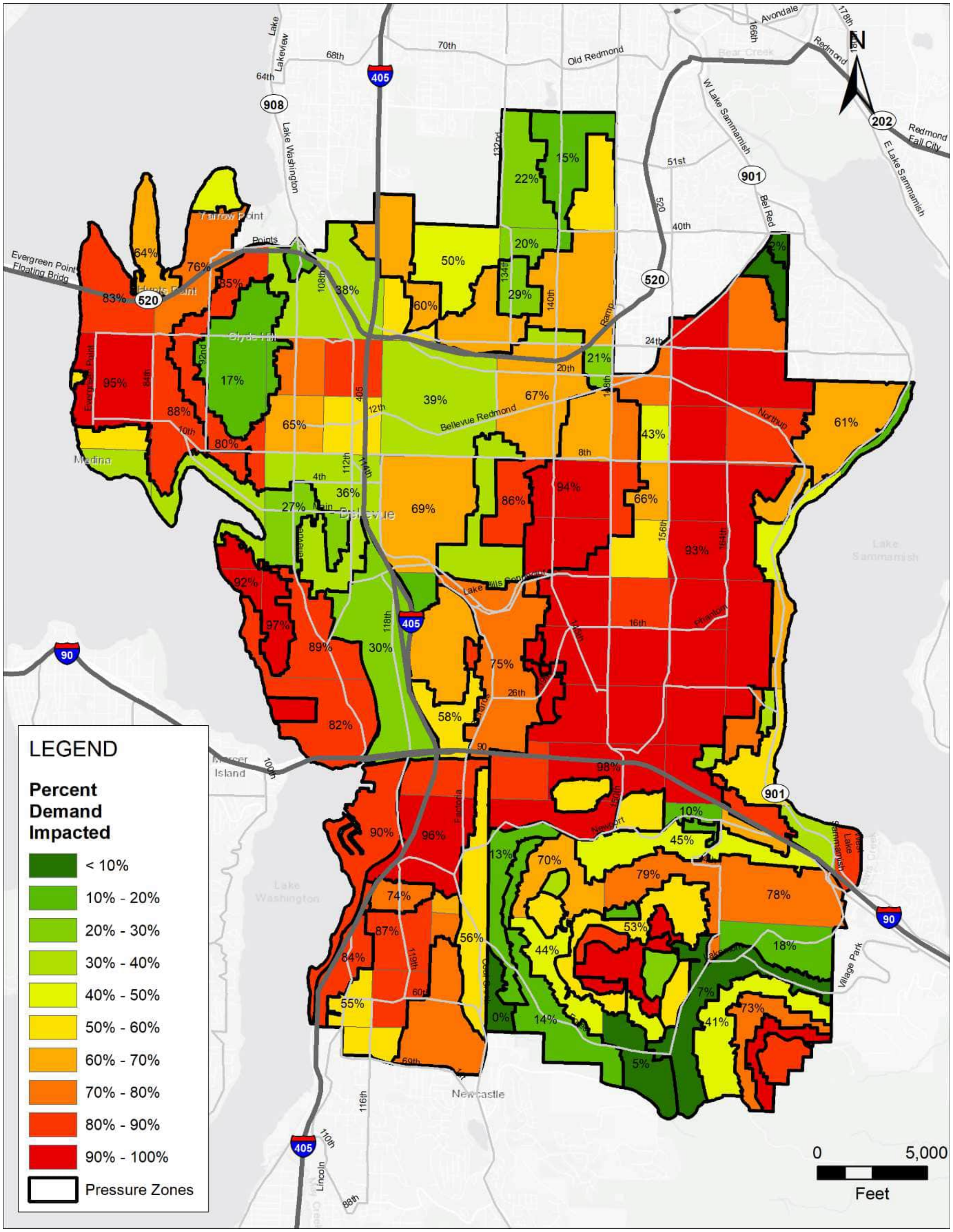

Figure 18. Predicted Demand Impacts by Percent of Subarea Demand immediately following SFZE

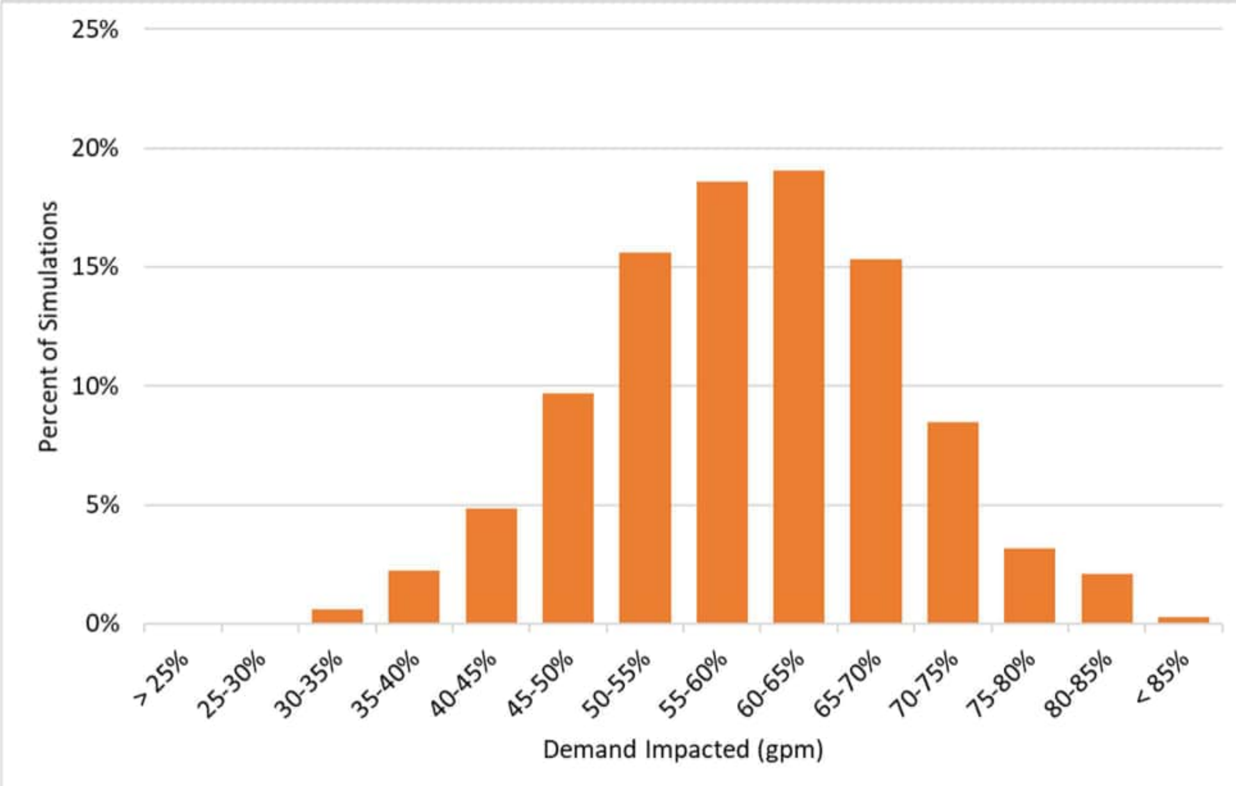

Figure 19. Distribution of System-wide Demand Impacts for all SFZE Multi-Break Monte Carlo Simulations

5.2 Cascadia Subduction Zone Multi-Break Results

The approach applied for the SFZE simulations was also applied for the CSZ simulations to quantify the demand impacts by subarea. Figure 20 and Figure 21 show the quantity and percent of demand by subarea that cannot be met with pressures above 30 psi for the CSZ. As noted previously, the SFZE is likely to be a more significant and impactful event given the more intense localized shaking expected, and the magnitude and extent of demand impacts is much greater than shown for the CSZ event. For example, there is a much lower percentage of the system that cannot meet 60% of the demand in a subarea for the CSZ event (Figure 21) as compared to the SFZE event (Figure 18).

For the CSZ, Figure 22 shows the distribution of demand impacts for all demands in the water system, including consecutive systems for all of the CSZ simulations. The SFZE event (Figure 19) showed a normal distribution with a median of approximately 8,750 gpm (12.6 mgd). For the CSZ event, the distribution of the demand impacts shows two “peaks”. The two peaks are due to the conditions when a specific supply is likely to be out of service due to damage. The median demand impact of the first peak is around 1,500 gpm (2.2 mgd), and the median demand impact of the second peak is around 3,250 gpm (4.7 mgd). This is compared to approximately 14,800 gpm total demand in the water system.

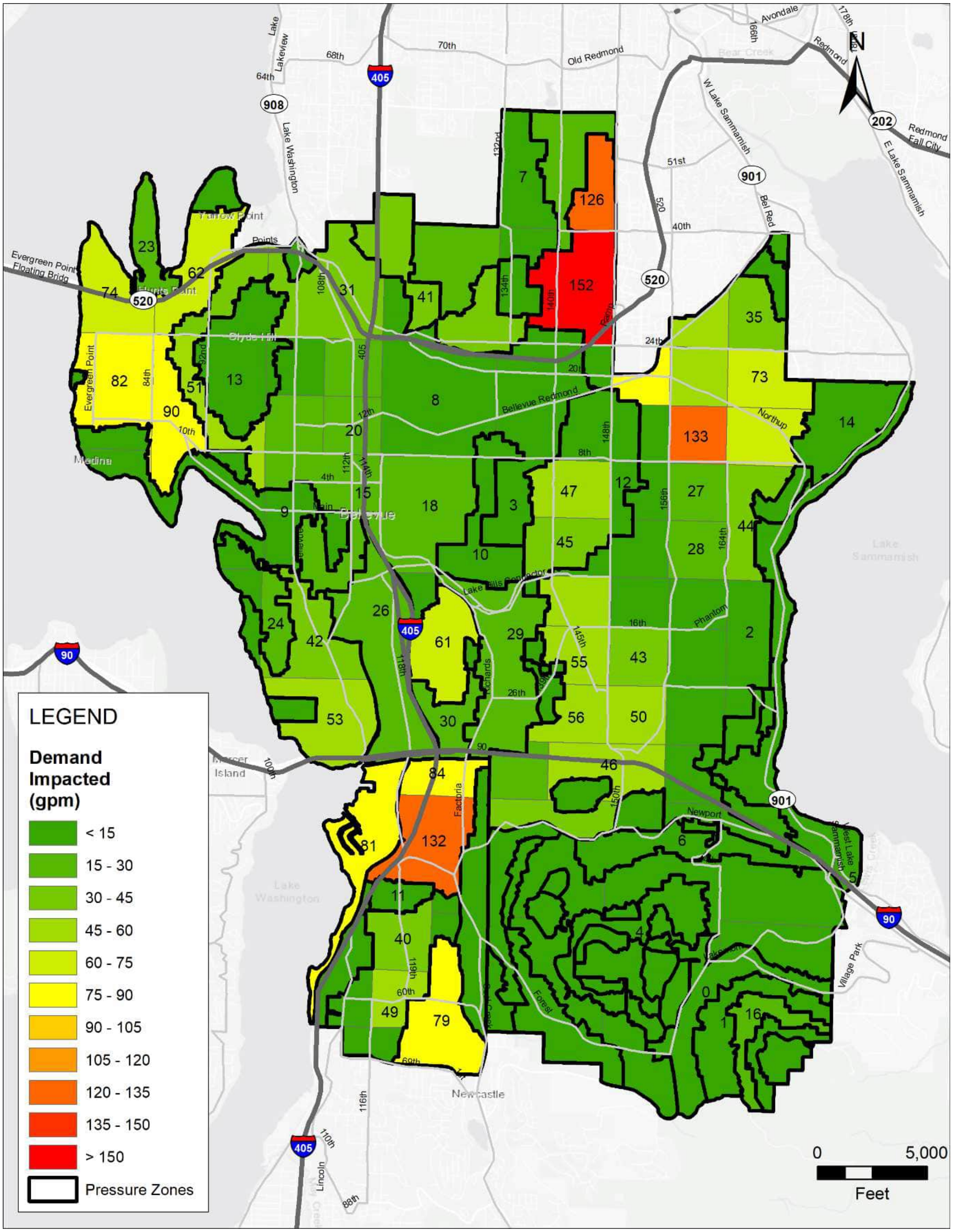

Figure 20. Summary of Predicted Demand Impacts in gpm by Subarea for CSZ

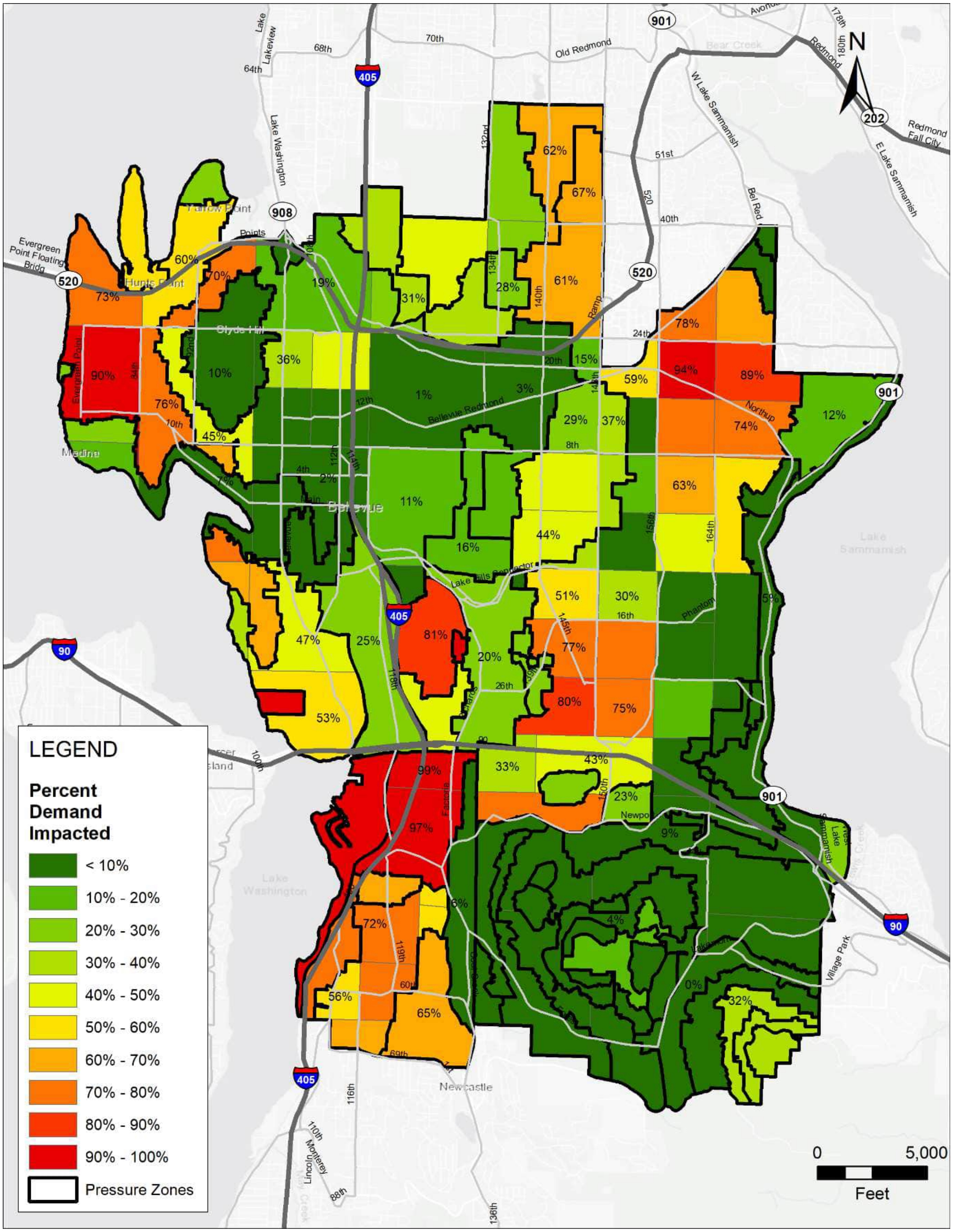

Figure 21. Summary of Predicted Demand Impacts by Percent of Subarea Demand for CSZ

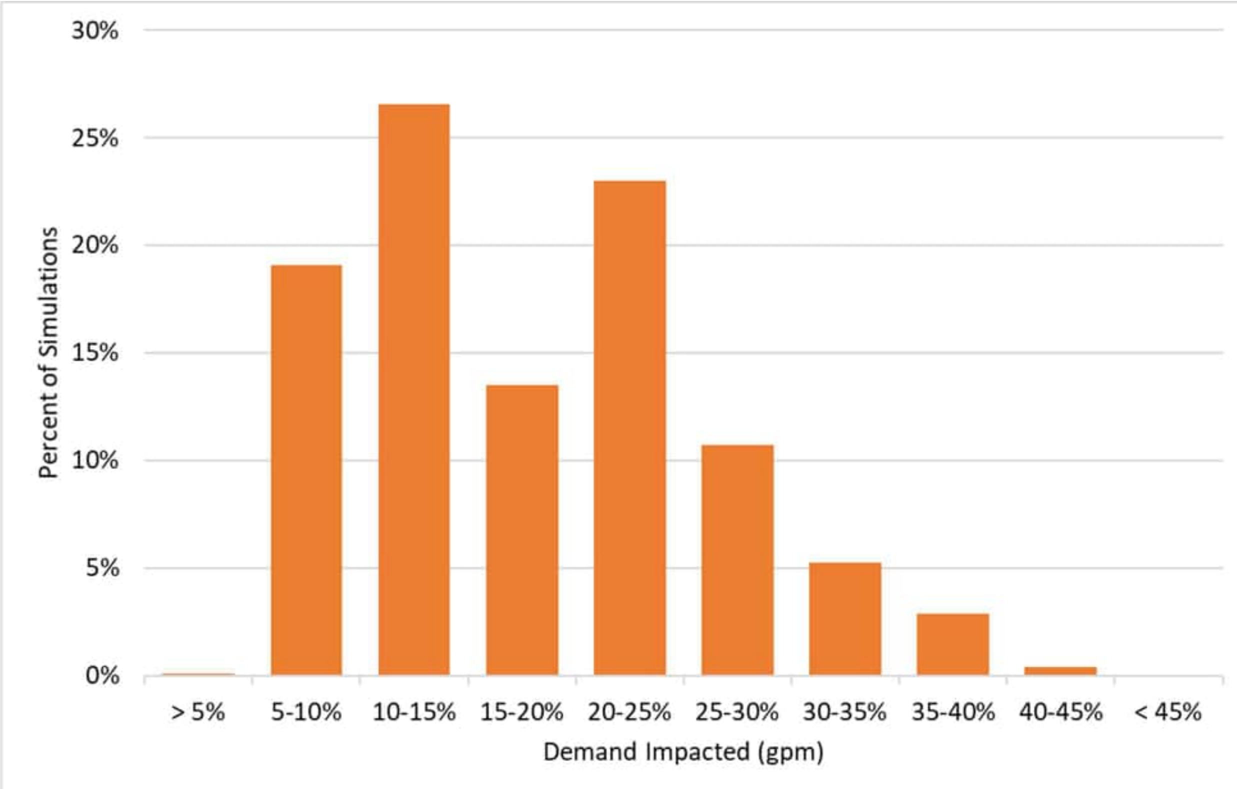

Figure 22. Distribution of System-wide Demand Impacts for all CSZ Multi-Break Simulations

5.3 Critical Customer Outage Probabilities

In addition to looking at overall impacts to the ability of the water system to maintain supply to customers in specific subareas, the multi-break results were also analyzed to determine the impact on individual Category 1 Critical Customers as described in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment. Table 2 shows the Category 1 Critical Customers as well as the probability that they are expected to have water above 30 psi following each of the two earthquake events.

Table 2. Category 1 Critical Customer Water Service Probabilities

Critical Customer	Junction ID	Probability of Water Service in SFZE Event	Probability of Water Service in CSZ Event
Overlake Hospital	COB1027757	71%	100%
	COB1004597	58%	100%
	COB1004596	60%	100%
	COB1027172	Included Above	
	COB1026642		
Kaiser Permanente Bellevue Medical Center	COB1026457	91%	100%
Seattle Children's Bellevue Clinic and Surgery Center	COB1028033	16%	98%
Bellevue High School	COB1102138	2%	78%
Interlake High School	COB1026027	2%	3%
Newport High School	COB1026048	2%	25%
Sammamish High School	COB1023715	2%	76%
	COB1110362	2%	80%
	COB2010386	Included Above	
City Hall	COB1025906	75%	100%
North Bellevue Community Center	COB1012549	29%	69%
South Bellevue Community Center	COB1024791	59%	100%
Crossroads Community Center	COB1017051	11%	93%
Washington State DOT EOC and Road Maintenance Facility	COB1003963	100%	100%

5.4 Multi-Break Analysis Results Summary

The multi-break analysis shows that the majority of the Bellevue water system is not likely to have water immediately following a Seattle Fault Zone East (SFZE) event and that situation will only worsen as water drains out of system water storage tanks as a result of leaks and breaks distributed across the system. The most frequent water outages are predicted for areas near water bodies where significant liquefaction potential exists, as well as in a wide area of the Lake Hills 520 zone. The primary reason for the significant impacts to the Lake Hills 520 zone are 1) frequent loss of the SPU supplies (at least one SPU is offline in 90% of the simulations), 2) the size of the Lake Hills 520 zone results in significant water loss due to broken or leaking pipes, and 3) the zone is at a high elevation and even small dips in pressure gradient result in reduced pressure for much of the zone. For the Cascadia Subduction Zone event the outages are less widespread and much less likely. The primary areas with high probabilities of outages are the areas near water bodies where there is higher liquefaction expected.

The information presented above as determined by this analysis provides a picture of the likely state of the water system following an earthquake and identifies the magnitude of the problem.

The results of this analysis will be used moving forward in the project, with 3 individual simulations for each earthquake event being selected to determine the amount of time it will take to restore water service following the earthquakes as well as to develop and evaluate mitigation alternatives that could reduce the amount of time that water outages may extend after a major earthquake.

Appendix E. Economic Impacts Characterization

E.1 TM5: Economic Impact Parameters

Jacobs

Technical Memorandum

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www.jacobs.com

Subject	**TM5: Economic Impact Parameters**
Project Name	Bellevue Water System Seismic Vulnerability Assessment
Attention	Doug Lane, City of Bellevue
From	Jacobs
Date	October 7, 2022

1. Background

The City of Bellevue Water System Seismic Vulnerability Assessment (SVA) includes detailed assessment of potential impacts to the Bellevue water system, and system customers, as a result of a major earthquake. In order to provide a basis to compare the cost of water system improvements targeted at improving system seismic resiliency against the benefits and value such increased system resiliency may provide, the SVA seeks to assess and estimate the economic impacts that could result from loss of service to Bellevue water system customers as a result of major seismic events.

This technical memorandum summarizes the methodologies used and resulting economic impact parameters assessed as part of the SVA. The economic impact parameters considered evaluate four components that are combined to represent potential overall impacts to the local economy resulting from potential loss of water service following a major seismic event:

1) Impacts to residential water customers resulting from loss of water service

2) Decrease in economic activity resulting from business disruption resulting from loss of water service

3) Economic impacts from loss of life resulting from an inability to effectively operate hospitals and major healthcare facilities if water service is unavailable

4) Economic impacts resulting from loss of water required to support fire suppression.

For each of these economic components, the impacts stemming from loss of water service cannot be isolated from other factors that may adversely impact economic activity such as loss of electricity, impact to transportation infrastructure, employees lost to injury or death, or direct earthquake damage to buildings or homes. Because this evaluation is focused only on benefits stemming from increased water system seismic resiliency, the water service impacts are evaluated independent of these other factors. The primary goal is to improve water system seismic resiliency and reduce the likelihood that water system failures are the cause of in significant impacts to customers and economics.

This analysis does not include economic impacts of collateral infrastructure damage such as damage to streets and public/private property resulting from system water main breaks, failures, and related flooding, the cost of repairing the water system related to seismic damage, or injuries/loss of life due that could result directly from water system infrastructure or facility failures.

2. Economic Impact Parameter Methodology and Results

The methodology and results for evaluating the potential economic impacts relating to a loss of water supply after an earthquake for each of the four categories identified above are described in the following sections.

2.1 Impacts to residential customers resulting from loss of water service

The dollar impacts to residential customers are estimated based on an estimated loss of service cost per household, the number of households without water after an earthquake, and the duration of water service outages. In equation form, this calculation is:

$$Loss\ of\ service\ cost = \frac{\$231}{household\ x\ day} * Number\ of\ households\ without\ water * days\ without\ water$$

The loss of service cost per household was estimated in 2018 to be $231 per household per day based on consumer surplus calculations completed previously for the City of Bellevue (BIS Engineering, 2018). This analysis represents a higher cost of living in the City of Bellevue compared to the Impact on Residential Customers of $60.00 per capita per day (2010 dollars) (Federal, 2011),

The number of households was estimated for each Bellevue SVA (SVA) subarea using the following steps:

1. Spatial Join population GIS data provided by the City (parcels_2018_0313_ORandPPH_yrbuilt.lyr[1]) with SVA Subareas.

2. Aggregate number of households per parcel within each SVA

2.2 Decrease in economic activity resulting from business disruption resulting from loss of water service

To determine the economic impact of loss of water service to businesses, a complex and spatially distributed analysis of business activity, value added effect, and potential impact from loss of water service was conducted.

The foundation for the business economic impact is Value Added as provided by IMPLAN (www.implan.com), which is a software and data package frequently used by economists to conduct input-output (I-O) analysis that quantifies the economic value or impact of changes to industry sectors within a local economy. From their website "IMPLAN is a platform that combines a set of extensive databases, economic factors, multipliers, and demographic statistics with a highly refined modeling system that is fully customizable." The SVA uses the term Value Added Effect (VAE) to refer to impacts specifically related to a loss of water service, more specifically, the VAE is an estimate of what the impact to the local economy would be if a particular proportion of the revenue from a given economic sector were lost because of a loss of water service.

According to IMPLAN, Value Added is defined as follows:

> "Value Added represents the difference between Output and the cost of Intermediate Inputs within a region in a given period of time. It equals Gross Output (sales or receipts and other operating income, plus inventory change) minus intermediate inputs (consumption of goods and services purchased from other

[1] Calculations based on King County Assessor (March 2018) and U.S. Census Bureau's 2012-2016 American Community Survey (ACS) data.

industries or imported). Value Added is equivalent to the industry's contribution to GDP.".

Value Added is calculated using SAM multipliers which represent the change in total gross domestic product resulting from a change in business activity within a particular sector of the economy. SAM multipliers account for both the indirect and induced effects of a change in demand from an economic sector, which are defined as follows.

- Indirect Effects. If a business ceases operation because of a water outage, the indirect multipliers account for losses for businesses in Bellevue that supply goods or services to that business, i.e. in addition to the business affected by the water outage, its local suppliers also lose sales for supplying them with goods or services.

- Induced Effects. Induced effects account for lost household income from employees at affected businesses that is no longer spent on goods and services such as food, beverages, and clothing purchased from businesses in Bellevue.

It should be noted that using I-O multipliers to calculate VAE may somewhat overstate the immediate economic impacts from the early stages of water outage because the methodology assumes annual effects can be divided by 365 to calculate daily effects and the multiplier effects do not take place instantaneously. I-O models are typically silent about how long that process takes, but full multiplier effects will take more than a matter of days to be realized. The time lag of multiplier effects should be considered when evaluating the estimates provided in the SVA.

VAE is then tailored to specific industry sectors using water resiliency factors that estimate the proportion of that business's economic impact that would likely be lost during a water service interruption. For example, some businesses like restaurants and food processing are highly dependent on water service, and an extended disruption in water service can be expected to result in a significant reduction in production from the business. However, real estate and construction have only minor dependency on water supply, so the proportion of the VAE lost due to lack of water service from construction or real estate is much lower than the proportion for manufacturing or food processing.

In order to use the VAE for the geospatial modeling being completed as part of the SVA, the following process was used.

1. As summarized in Table 1, delineate North American Industry Classification System (NAICS) sectors for use in the SVA by using the first 2 digits of the NAICS code, except Sector 51-Information which uses the first 4 digits of the NAICS code to separate dissimilar industries that are included within Sector 51. Sector 51 represents 46% of the total VAE for the City of Bellevue, with 44% of total VAE coming from two of the 9 subsectors included in Sector 51.

2. Calculate total annual VAE for the City of Bellevue by NAICS Sector using economic data purchased from IMPLAN. Total annual VAE is calculated by multiplying IMPLAN value added for each sector times that sector's Value Added "SAM Multiplier".

3. Obtain Bellevue B&O Tax Data by business. Tax data was provided by the City of Bellevue for each individual business. Data included business name, NAICS code, physical address, 2018 Gross Receipts (Net, Gross and Tax Due), 2018 Utility Revenue (Net, Gross and Tax Due), 2018 Other Revenue (Net, Gross and Tax Due), and 2018 Taxable Square Footage and Square Footage Tax Due.

4. Map physical business addresses geospatially and then join them with the SVA subareas to allow for spatial distribution during the subsequent vulnerability analysis modeling (see step 10).

Table 1. NAICS Codes and Sector Description for SVA Business Economic Impact Analysis

NAICS Code (First 2 or 4 digits)	Sector Description
11	Agriculture, Forestry, Fishing and Hunting
22	Utilities
23	Construction
31	Manufacturing
32	Manufacturing
33	Manufacturing
42	Wholesale Trade
44	Retail Trade
45	Retail Trade
48	Transportation and Warehousing
49	Transportation and Warehousing
51	Information ***(Not Used, See Breakout Below)***
5111	All Publishers Except Software
5112	Software Publishers
5121	Motion Picture and Video Industry
5122	Sound Recording Industry
5151	Radio and Television Broadcasting
5173	Wired and Wireless Telecommunications Carriers
5174	Satellite and Other Telecommunications
5182	Data Processing, Hosting and Related Services
5191	Other Information Services
52	Finance and Insurance
53	Real Estate and Rental and Leasing
54	Professional, Scientific, and Technical Services
55	Management of Companies and Enterprises
56	Administrative and Support and Waste Management and Remediation Services
61	Educational Services
62	Health Care and Social Assistance
71	Arts, Entertainment, and Recreation
72	Accommodation and Food Services
81	Other Services (except Public Administration)
92	Public Administration

5. Calculate the Total "Effective Tax Due" for each business by adding Gross Receipts and Square Footage "Actual Tax Due" to ([Utility Tax "Net Revenue"] + [Other "Net Revenue"]) x 2018 Gross Receipts Tax Rate (0.001496). This method of estimating utility tax and other tax moderates observed extreme variations in tax rate for the Utility Tax and Other categories resulting in taxable revenue from those categories that is consistent with Gross Receipts. Table 2 below includes a hypothetical example of how this calculation would work for a business that reported revenue in all three categories, as well as taxable square footage. Note, that this example is not representative of any actual business. The example in Table 2 shows how this method "smoothed" the estimated taxes for a business that has unusually high reported Actual Utility Tax and Other Tax Due. The actual Utility Tax Due and Other Tax Due is $600,000 and $300,000, respectively. The Effective Utility Tax Due and Effective Other Tax Due, used in this methodology is $14,960 for each of the two tax categories, and the Total Effective Tax Due is $435,082.

Table 2. Example calculations of effective tax due for a hypothetical business

Category	Gross Revenue[1]	Net Revenue[2]	Taxable Square Footage	Actual Tax Due[3]	Effective Tax Rate	Effective Tax Due[4]
Gross Receipts	$150,000,000	$100,000,000		$149,600	0.001496[5]	$149,600
Square Footage			1,000,000	$255,562	0.2555618[5]	$255,562
Utility Tax	$25,000,000	$10,000,000		$600,000	0.001496[6]	$14,960
Other	$25,000,000	$10,000,000		$300,000	0.001496[6]	$14,960
Total	$200,000,000	$120,000,000	1,000,000	$1,305,162		$435,082

Notes;

[1] Gross Revenue represents Gross Gross Receipts, and Gross Revenue in Utility Tax and Other categories

[2] Net Revenue represents Net (Taxable) Gross Receipts, and Net (Taxable) Revenue in Utility Tax and Other categories

[3] Actual Tax Due is the actual tax paid by the business. For Gross Receipts, this is the Net Gross Receipts x 0.001496, for the Utility Tax and Other categories, the rate varies depending on the type of revenue generated, and for the Square Footage Tax, the rate is $0.2555618/taxable square foot.

[4] Effective Tax Due is equal to Actual Tax Due for Gross Receipts and Square Footage categories. For Utility Tax and Other categories, Effective Tax Due is the Net Revenue for the category multiplied by the gross receipts tax rate of 0.001496

[5] Effective Tax Rate is the same as actual tax rate

[6] Effective Tax Rate is lower than actual tax rate

6. For each SVA NAICS Sector, proportion the total VAE for the sector to businesses based on each businesses' Effective Total Tax Due. The Equation below shows how each sector's VAE is proportioned to individual businesses based on effective tax due.

$$Business\ A's\ VAE\ = \frac{Business\ A's\ Effective\ Tax\ Due}{\sum Effective\ Tax\ Due\ for\ Business\ A's\ Sector} \times \sum VAE\ for\ Business\ A's\ Sector$$

7. Compare the VAE in each SVA NAICS Sector to the businesses revenue to identify any potential disproportional attribution of VAE.

   Two sectors, Sector 11 (Agriculture) and Sector 31 (Manufacturing) both had significant and apparently unrealistic discrepancies between effective total tax due and revenue, primarily due to a small number of large businesses that pay little or no tax. For these two sectors, VAE was proportioned based on the total reported revenue of the businesses, instead of effective tax due. Note that this method does not account for businesses that report and are taxed on square footage in lieu of revenue, but in these two sectors, square footage was minimal and can be considered negligible as it would not significantly alter the distribution of VAE.

The Equation below shows how the VAE for Sector 11 and 31 is proportioned to individual businesses.

$$Business\ A's\ VAE\ =\ \frac{Business\ A's\ Total\ Gross\ Revenue}{\sum Total\ Gross\ Revue\ for\ Business\ A's\ Sector} \times \sum VAE\ for\ Business\ A's\ Sector$$

8. Review the top 25 business by VAE (representing almost half of the total VAE in the water service area) to verify that their locations correspond to the location where they conduct the majority of their business. In one case, the Subarea assigned to the business was manually adjusted to correct for a discrepancy between locations where the business conducts the majority of their business and where their revenue was reported.

9. Apply water resiliency factors to each SVA NAICS Sector based on values developed by Chang, et al. Calculated Economic Loss Factor (ELF) = (1 – Water Resiliency Factor). Water Resiliency Factors account for the relative ability of a business to keep operating during a water outage[2] (Chang et al. 2002).

   Table 3 shows how the NAICS codes used in the SVA have been aligned to the corresponding Standard Industrial Classification (SIC)[3] Divisions and Sectors from Chang, et al., as well as the resiliency factors which were used to calculate the economic loss factor for each sector as described above.

10. Calculate Daily Economic Loss for each business by dividing Annual VAE from # 6 or 7 above by 365 days per year, and then multiplying by the business' sector's ELF.

$$Business\ A\ daily\ VAE\ lost\ from\ water\ outage\ =\ \frac{Business\ A\ Annual\ VAE}{365\,\frac{days}{year}} \times Business\ A's\ Sector's\ ELF$$

11. Calculate the total Daily Economic Loss for each SVA subarea to be used in modeling by summing the individual daily economic loss for each business in a subarea to obtain the total economic loss due to water outage for that subarea.

    Note: Because the tax data for many businesses with multiple locations are reported at only one location, it is not appropriate or accurate to distribute potential economic loss on a business by business basis. In order to distribute Daily Economic Loss spatially, it is recommended that Daily Economic Loss for a SVA subarea be proportioned based on water demand by subarea.

[2] Note that the recent Bellevue Water System Emergency Supply study used an unpublished value for outages between 0 and 3 days. However, for this analysis the published resiliency factors were used without modification.

[3] SIC Codes are part of the old U.S. business sector classification system that was replaced by NAICS in 1997.

Table 3. NAICS Sector to SIC Division Reference and Water Resiliency Factors

NAICS Code for SVA	NAICS Sector Description	SIC Division	SIC Economic Sector	Chang, Et, al. Resiliency Factor		
				Less than 1 Week	1 to 2 Weeks	Greater than 2 Weeks
11	Agriculture, Forestry, Fishing and Hunting	A	Agriculture	0.53	0.35	0.3
22	Utilities	E (46, 48, 49)	Communications/Utilities	0.65	0.49	0.43
23	Construction	C	Construction	0.68	0.47	0.43
31	Manufacturing	D	Nondurable and Durable Manufacturing	0.42	0.34	0.28
32	Manufacturing	D	Nondurable and Durable Manufacturing	0.42	0.34	0.28
33	Manufacturing	D	Nondurable and Durable Manufacturing	0.42	0.34	0.28
42	Wholesale Trade	F	Wholesale Trade	0.51	0.36	0.3
44	Retail Trade	G	Retail Trade	0.46	0.32	0.28
45	Retail Trade	G	Retail Trade	0.46	0.32	0.28
48	Transportation and Warehousing	E (40-45)	Transportation	0.65	0.49	0.43
49	Transportation and Warehousing	E (40-45)	Transportation	0.65	0.49	0.43
51	Information					
5111	All Publishers Except Software	D	Nondurable and Durable Manufacturing	0.42	0.34	0.28
5112	Software Publishers	I	All Services Except Health	0.45	0.33	0.27
5121	Motion Picture and Video Industry	I	All Services Except Health	0.45	0.33	0.27
5122	Sound Recording Industry	I	All Services Except Health	0.45	0.33	0.27
5151	Radio and Television Broadcasting	E (46, 48, 49)	Communications/Utilities	0.65	0.49	0.43

Table 3. NAICS Sector to SIC Division Reference and Water Resiliency Factors

NAICS Code for SVA	NAICS Sector Description	SIC Division	SIC Economic Sector	Chang, Et, al. Resiliency Factor		
				Less than 1 Week	1 to 2 Weeks	Greater than 2 Weeks
5173	Wired and Wireless Telecommunications Carriers	E (46, 48, 49)	Communications/Utilities	0.65	0.49	0.43
5174	Satellite and Other Telecommunications	E	Communications/Utilities	0.65	0.49	0.43
5182	Data Processing, Hosting and Related Services	I	All Services Except Health	0.45	0.33	0.27
5191	Other Information Services	I	All Services Except Health	0.45	0.33	0.27
52	Finance and Insurance	H	Finance, Insurance, and Real Estate	0.44	0.27	0.24
53	Real Estate and Rental and Leasing	H	Finance, Insurance, and Real Estate	0.44	0.27	0.24
54	Professional, Scientific, and Technical Services	I	All Services Except Health	0.45	0.33	0.27
55	Management of Companies and Enterprises	H	Finance, Insurance, and Real Estate	0.44	0.27	0.24
56	Administrative and Support and Waste Management and Remediation Services	I	All Services Except Health	0.45	0.33	0.27
61	Educational Services	I	All Services Except Health	0.45	0.33	0.27
62	Health Care and Social Assistance	I (80)	Health Services	0.27	0.21	0.19
71	Arts, Entertainment, and Recreation	I	All Services Except Health	0.45	0.33	0.27
72	Accommodation and Food Services	I	All Services Except Health	0.45	0.33	0.27
81	Other Services (except Public Administration)	I	All Services Except Health	0.45	0.33	0.27
92	Public Administration	I	All Services Except Health	0.45	0.33	0.27

2.3 Economic impacts from loss of life resulting from an inability to effectively operate hospitals and major healthcare facilities if water service is unavailable

Water is an essential resource for hospitals and major healthcare facilities. In the event of a major earthquake, a sharp increase in life-threatening injuries and high demand for treatment can be anticipated. This increases the importance of maintaining an adequate water supply to hospitals as it can become the difference between losing or saving lives. To estimate the economic impact of water outage in these scenarios, the value of a statistical life (VSL) and estimated number of deaths due to water service loss are used to quantify the total impact.

The environmental protection agency (EPA) defines the VSL as "a summary for the dollar value of small changes in mortality risk experienced by a large number of people" and recommends a default VSL of $7.9 million in 2008 dollars (EPA 2014). The default VSL is $9.4 million in 2019 dollars using a 19.3% cumulative increase in inflation between 2008 and 2019 based on the October 2019 Consumer Price Index (CPI-U). This is the value of reducing mortality by one statistical death based on what people are willing to pay to reduce the risk.

There are three major medical facilities within the Bellevue WSA: Seattle Children's, Overlake Hospital, and Kaiser Permanente. Staff from each hospital were interviewed to understand the potential impact of not having water service after an earthquake, and the status of their onsite emergency water supply reserves. Following any major seismic event, Children's and Kaiser currently plan to triage and treat simple, urgent cases while sending complicated cases to Overlake Hospital. Both facilities have emergency water, but noted that they would likely not remain open, and are not required to, if adequate water could not be available.

Overlake Hospital is the designated Disaster Medical Coordination Center back up for King County, with Harborview in Seattle serving as the primary facility for both the County and Washington State. If either the Cascadia Subduction Zone (CSZ) or Seattle Fault Zone Event (SZFE) earthquakes occurred, overland and roadway routes to Harborview and other facilities could likely be cut off based on fault lines and known liquefaction hazard areas. Therefore, Overlake is likely to see a significant number of cases after an event. The hospital has 340 beds and could see up to 10,000 people seeking treatment after an earthquake occurs. In terms of emergency water supply, Overlake is required by the Joint Hospital Association to have enough resources to operate for ninety-six hours (four days). Hospital staff have estimated they currently have approximately three days' worth of bottled/stored water on hand (Axtell, pers. Comm. 2019). Following a major seismic event, water supply service to Overlake Hospital is likely to quickly become a critical issue.

Based on this information, the economic analysis uses the following assumptions to estimate loss of life due to loss of water service to the hospital:

- 5% of the 10,000 cases seen are considered life-threatening (500 cases)
- Of the life-threatening cases, a portion will result in death even with water service.[4] An additional 5% of the life-threatening cases will result in loss of life without access to a hospital as a result of loss of water (25 cases)
- 5% of the 340 occupied beds would be life-threatening cases that will result in loss of life without water (17 cases). This assumes the worst case scenario that the hospital is operating at capacity before the event occurs.

[4] The 1989 Loma Prieta earthquake in the Bay Area, California resulted in 63 deaths out of 3,757 injuries. The 1994 Northridge earthquake in Los Angeles, California resulted in 72 deaths out of 9,000 injuries.

- Emergency onsite reserves of potable water and non-potable water for sanitation are exhausted by the end of day three after a significant event, causing the hospital to shut down and begin relocating patients
- Lives lost without water would occur between days four and seven after an initial seismic event

These assumptions estimate 42 deaths due to water outage (25 + 17 = 42). If these deaths were prevented, it would equate to $394.8 million (42 * $9.4 million VSL).

Note that it is assumed that there would be significant loss of life resulting from either of the major earthquakes considered in the SVA. The deaths and economic impacts described above are only those that would be directly attributed to loss of hospital service due to loss of water service at Overlake Hospital.

2.4 Economic impacts resulting from loss of water required to support fire suppression

Fires after an earthquake can result in tremendous damage which can be exacerbated without a functioning water system to support fire suppression. John M Eidinger developed a model to study these impacts by iterating scenarios based on historic data, fire spread physics, and water system damage (Eidinger 2004). This analysis uses the general principals presented in Eidinger's paper using simplifying assumptions suited to the Bellevue WSA.

Three variables are important for estimating the extent of fire damage: number of ignitions, fire spread, and fire suppression.

1. Number of ignitions is calculated using an ignition rate (IR) and total building floor area. Based on historic data, IR can be calculated using the following equation $IR = -0.025 + (0.59 * PGA) - (0.29 * PGA^2)$ where the IR is per 1,000,000 sf of building floor area and PGA stands for peak ground acceleration of an earthquake. Table 4 summarizes the number of ignitions estimated for each earthquake scenario.

Table 4. Total Number of Ignitions After Earthquake

Earthquake Scenario	Average Peak Ground Acceleration	Ignition Rate (IR/1,000,000 sf)	Total building floor area in Service Area (sf)	Number of Ignitions
Cascadia Subduction Zone Event[1]	0.145	0.055	381,870,000	21
Seattle Fault Zone East Event[2]	0.547	0.211	381,870,000	81

[1]Aligns with estimated 155 ignitions in the Lower Mainland, British Columbia for the CSZ scenario if scaled proportionately to a city the size of Bellevue (Scawthorn and Waisman 2001).

[2] The 1989 Loma Prieta Earthquake (7.1 magnitude event comparable to SFZE scenario) recorded 67 ignitions (Eichman 2004).

sf = square feet

2. The Hamada and TOSHO models have historically been used to simulate fire spread within community blocks. Both models assume that fires do not spread across firebreaks such as streets while additional modeling suggests that the probability of fire spreading across firebreaks depends heavily on wind (Eichman 2004). Bellevue typically has low wind conditions ranging from two to four miles per hour on average (CLV 2019) therefore, if an ignition is not extinguished, it is assumed to burn all of the buildings within one side of the street on a single block but does not cross the street or cross to another block.

3. Fire suppression depends on the condition of the water system after an event and the planned emergency response by the fire department and other emergency responders. Complex models such as the HAZUS model (developed by the National Institute for Building Sciences), System Earthquake Risk Assessment (SERA) and RiskLink simulate fire ignitions, spread and suppression to estimate the damage caused by fires following earthquakes. Case studies with hundreds of simulations suggest that the most sensitive parameters for estimating damage include the number of ignitions, wind conditions, and location of fires (Eichman 2004). The Bellevue fire department has 9 fire stations staffed 24 hours per day with at least 48 fire suppression personnel on hand at all times within the Bellevue WSA. Based on conversations with the fire department, emergency response after an earthquake will be focused primarily on saving lives and assessing damage for prioritization. Therefore, this analysis assumes that fire department response could contain about 10 ignitions with a fully functioning water system and about 5 ignitions absent water service availability to fire hydrants and building sprinkler and fire suppression systems.

Based on historical data, most ignitions occur in residential areas because of their prevalence of ignitable building materials (such as wood) and vulnerable natural gas service lines. For example, in the 1994 California Northridge earthquake, more than 70% of earthquake related ignitions occurred in residential areas (Eidinger, 2004). Additionally, historic ignition data suggests that 75% of ignitions occur in wood structures (more typical for residential areas) and mobile homes (Elhami et. Al. 2017). Therefore, the probability of a fire occurring in a particular block in a particular SVA subarea, was estimate separately for both residential and non-residential areas according to the following equation:

$$Probability\ of\ residential\ fire\ loss = total\ ignitions * probability\ of\ ignition\ being\ extinguished * \frac{number\ of\ residential\ blocks\ in\ BSVA\ subarea}{Total\ number\ of\ blocks\ in\ WSA}$$

This equation assumes that each ignition that is not extinguished results in one block of loss. It also assumes that the probability of fire loss is proportional to the number of blocks in each SVA subarea.

Fire loss (economic impact due to fire damage) includes both direct loss (structures burned) and indirect loss (revenue loss due to burned business being closed). This analysis assumes

1. Direct loss based on 2018 King County Assessor data for improvements. Values are averaged across the Bellevue WSA on a per house basis for single family residential to provide the same direct loss value for each home; regardless of location, size, or appraised value.
2. Indirect loss using the same methodology described in the section 2, and assuming that the total indirect loss is the annual VAE multiplied by the number of years required to rebuild commercial structures (estimated at two years).

Direct loss is applied to both burned residential buildings and burned non-residential buildings, but indirect loss is only applied to non-residential buildings. In order to isolate the economic impact of water outages, the fire loss for each SVA subarea is calculated as the delta between the estimated fire loss with water and the estimated fire loss without water. The delta depends on the estimated number of contained ignitions with water service active (10) versus without water service (5). In equation form,

$$\begin{aligned}
&Fire\ loss\ due\ to\ water\ outage \\
&\qquad = [(direct\ residential\ loss) \\
&\qquad * (probability\ of\ residential\ fire\ loss\ with\ water \\
&\qquad - probability\ of\ residential\ fire\ loss\ without\ water)] \\
&\qquad + [(direct + indirect\ nonresidential\ loss) \\
&\qquad * (probability\ of\ nonresidential\ fire\ loss\ with\ water \\
&\qquad - probability\ of\ nonresidential\ fire\ loss\ without\ water)]
\end{aligned}$$

Based on case studies simulating number of fires burning over time, the majority of ignitions are anticipated to be contained, or run out of fuel or self-extinguish within the first 24 hours following a major seismic event (Eidinger 2004). Therefore, this analysis assumes that 70% of the economic loss related to fires can be attributed to day 1 after an earthquake event, followed by 20% for day 2 and 10% on day 3.

3. Summary of results

The following observations are made based on the results of this analysis;

- Of the four economic parameters, Loss of Value Added Effect due to potential loss of business activity is the primary driver for post seismic event economic impact related to potential loss of water service. For example, if water service were interrupted across the entire Bellevue WSA and not restored after fourteen days, business loss could likely account for 75% of the $3.76 billion cumulative economic impact.

- Economic impact due to loss of life and fire loss are likely to be realized within the first seven days following a major seismic event.

- There is no significant difference in economic impact between the CSZ and SFZE events. The only difference is a minor difference in fire loss.

Figures 1 through 5 illustrate the cumulative economic impact to each SVA Subarea of having no water at 3, 7, 14, 30 and 60 days following the CSZ event. These figures are also representative of the SFZE event, which has only inconsequential differences due to the variation in impact on fire suppression.

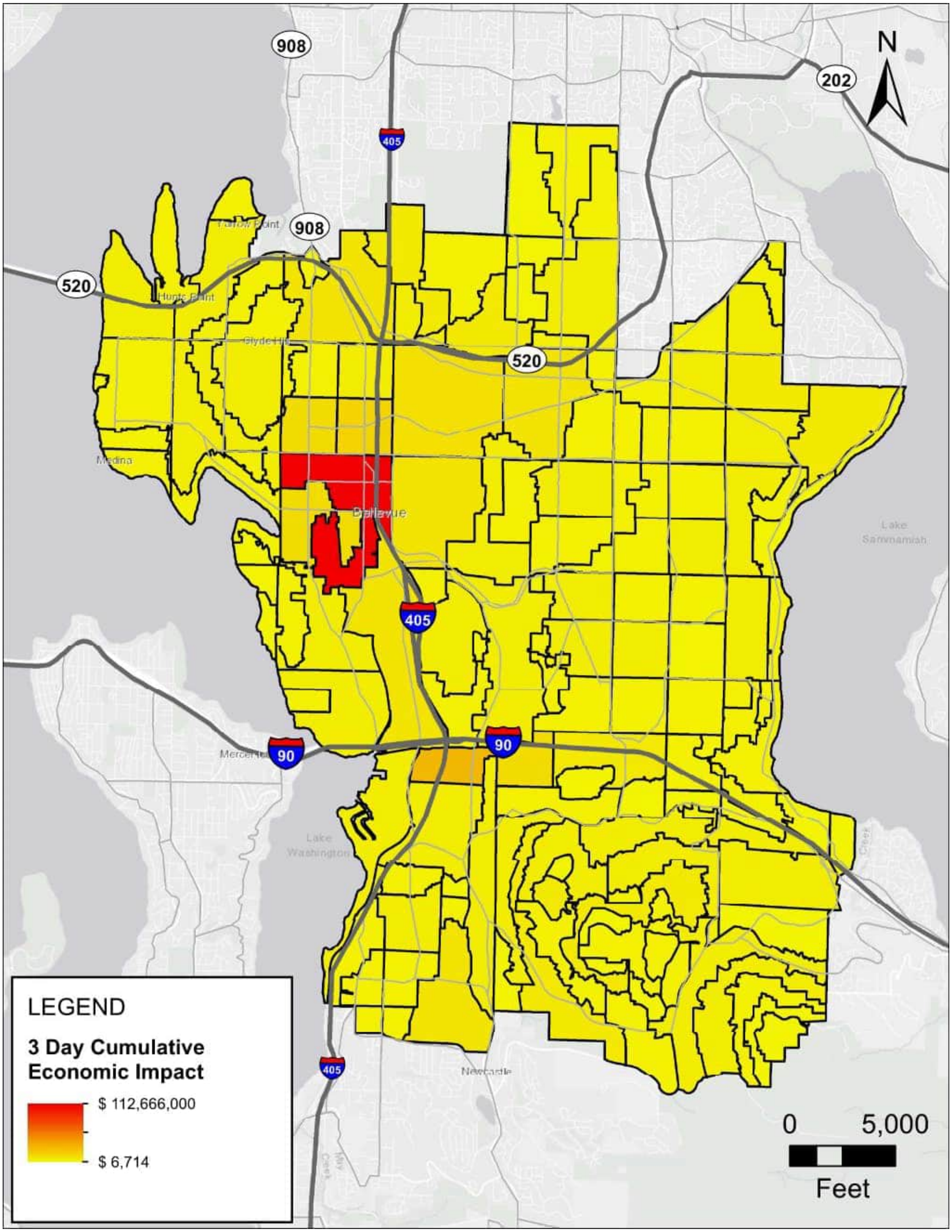

Figure 1. 3 Day Cumulative Economic Impact

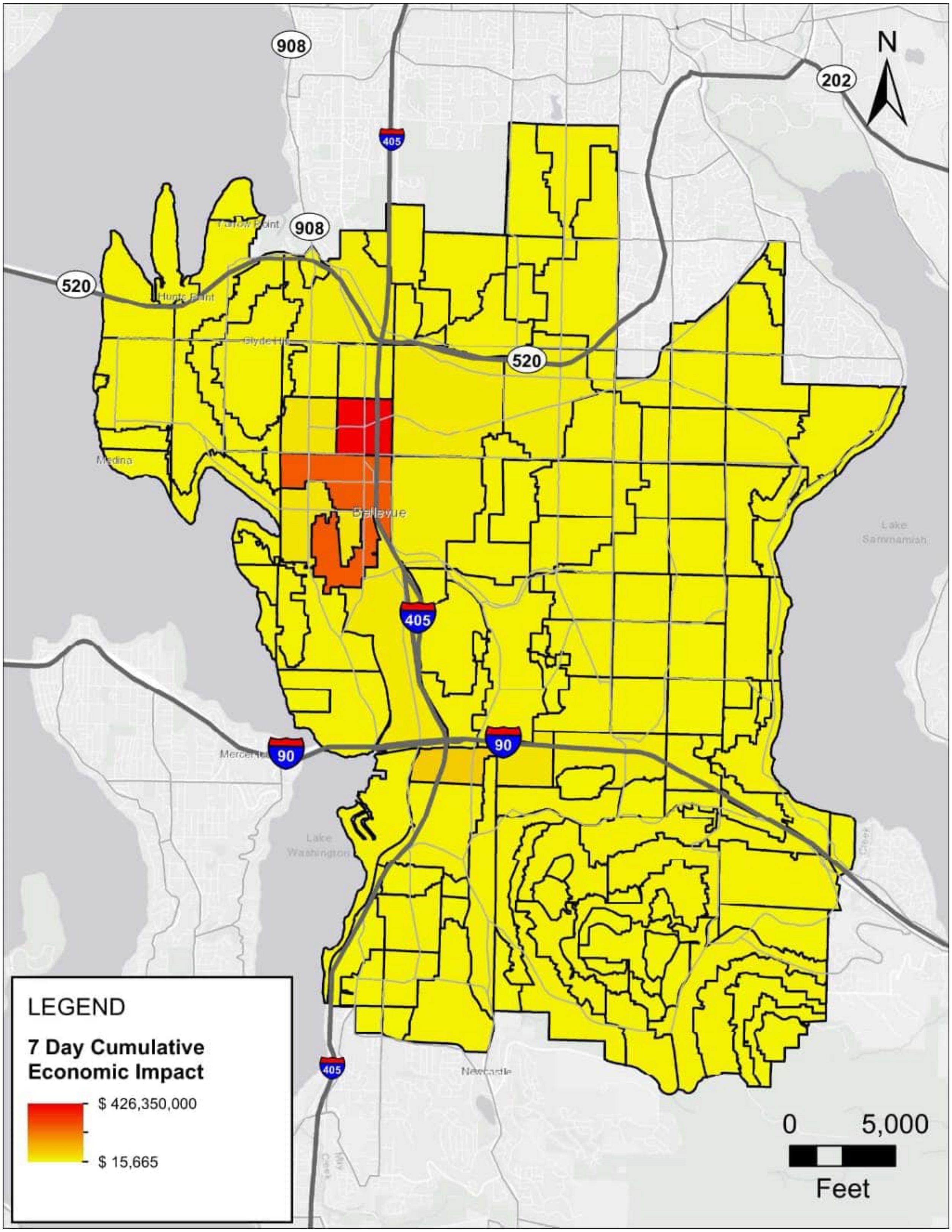

Figure 2. 7 Day Cumulative Economic Impact

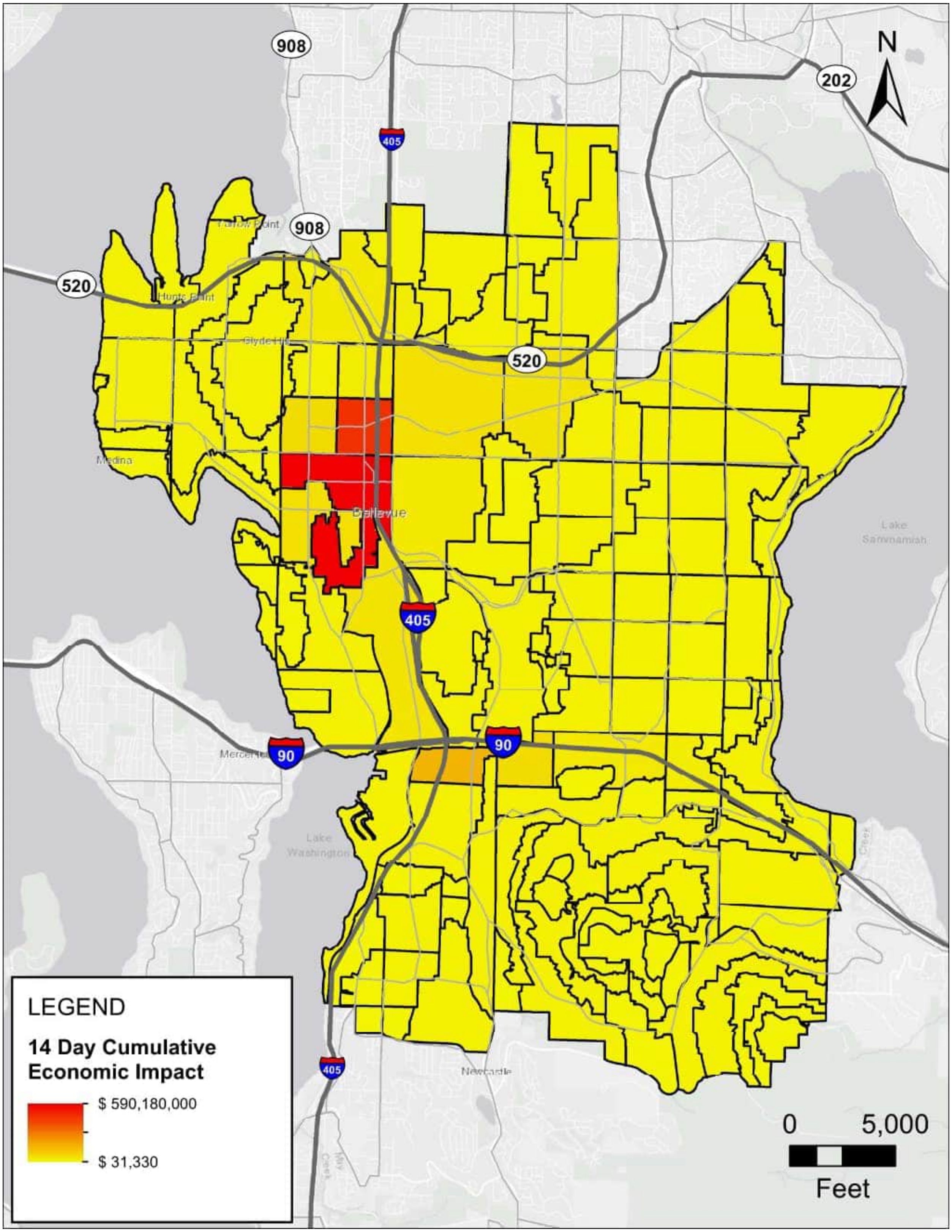

Figure 3. 14 Day Cumulative Economic Impact

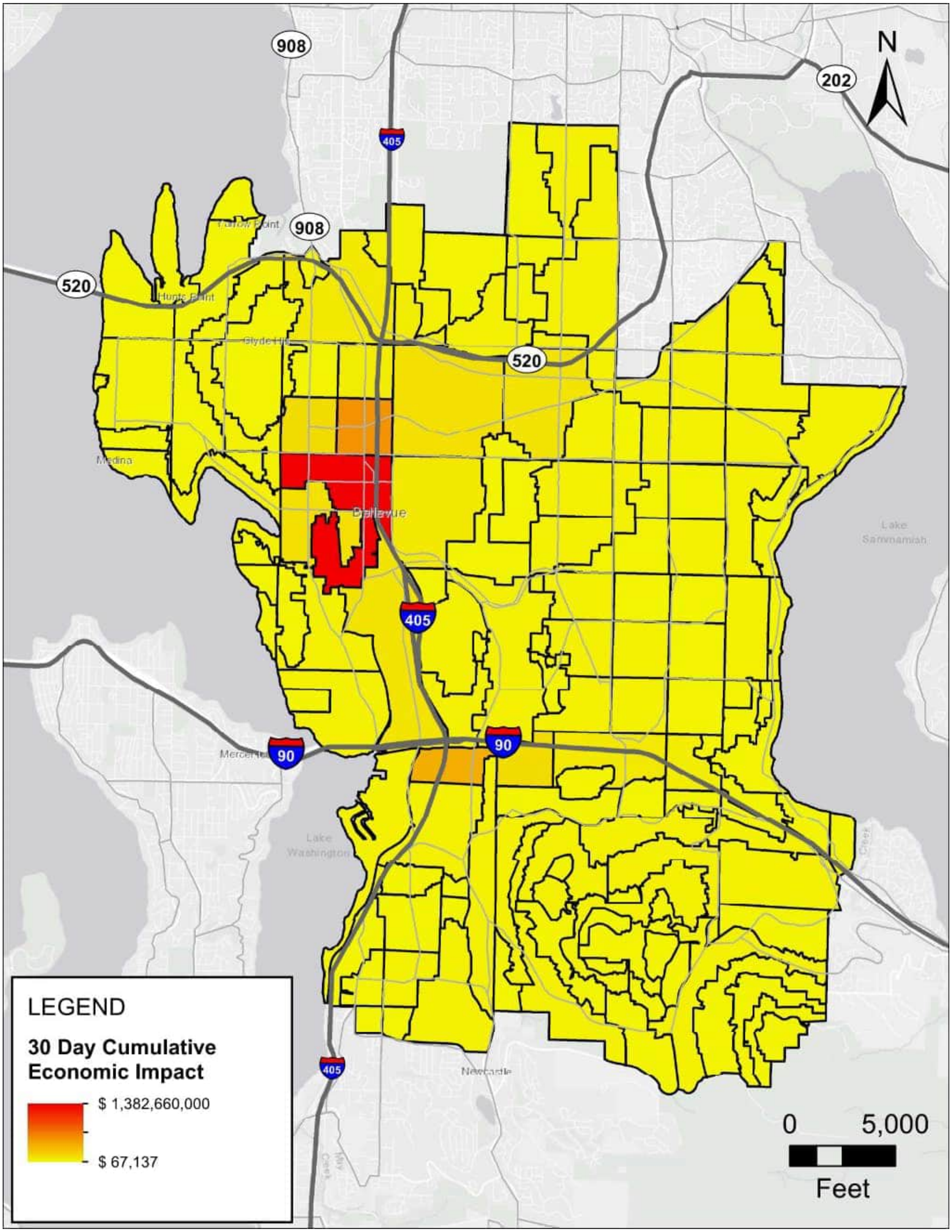

Figure 4. 30 Day Cumulative Economic Impact

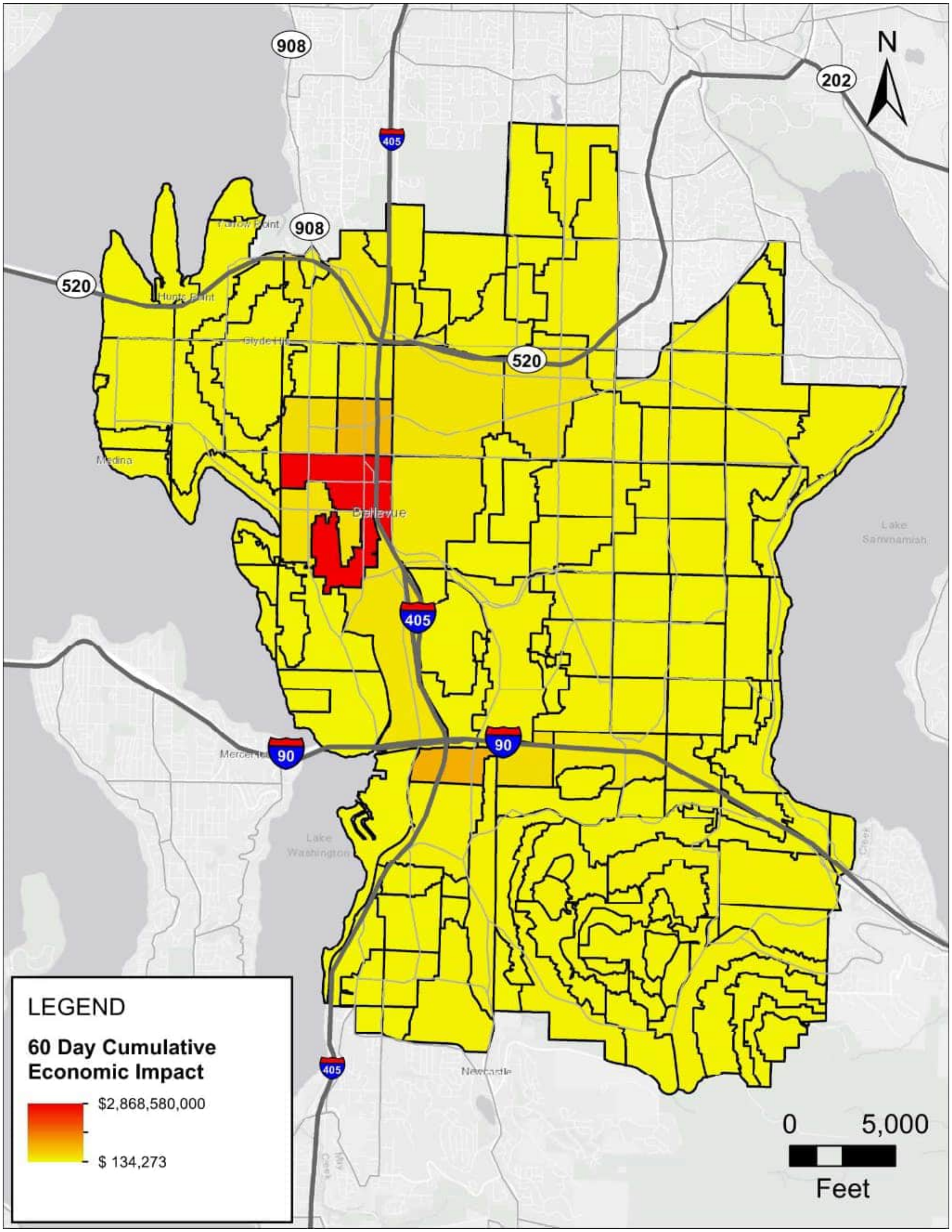

Figure 5. 60 Day Cumulative Economic Impact

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Appendix F. Existing System Seismic Vulnerability and Potential Service Outage Severity

F.1 TM6: As-Is Service Outage, Restoration Times, and Economic Impacts

Jacobs

Technical Memorandum

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Subject	TM6: As-Is Service Outage, Restoration Times, and Customer Impacts
Project Name	Bellevue Water System Seismic Vulnerability Assessment
From	Jacobs
Date	October 7th, 2022

1. Background

The City of Bellevue Water System Seismic Vulnerability Assessment (SVA) includes identification of the as-is service outage for different seismic scenarios, developing an approach for returning service to customers to identify restoration times for customers for the as-is condition, and then identifying the economic impacts of post-earthquake water outage for the as-is condition. This as-is condition provides the baseline for comparing the benefit that system improvements provide by reducing the restoration time and the overall economic impact in the City.

The development of the methodology used and the determination of the vulnerability of existing system components can be found in TM 2[1] and TM 3[2], and the modeling results for customer outage probability in TM4[3]. The restoration assumptions were developed jointly with the City during the Outage and Restoration Assumptions workshop, and the economic assumptions applied to develop the economic impact curves is summarized in TM 5: Economic Impact Parameters.

This document describes the results of the restoration scenario modeling described in TM 3, and then uses the modeling results to identify customer and economic impacts. The results presented in this document include the following items:

- Restoration Methodology: Summary of methodology for restoration scenario development.
- Restoration Assumptions: Identification of the assumptions for repair times, resource availability, available materials, and availability of mutual aid
- Damage Scenarios and Restoration Curves: Identification of the restoration time for each seismic scenario by applying the restoration assumptions to the simulated system restoration.
- Potential Economic Impact: Identification of the potential economic impact by applying the economic assumptions to the simulated system restoration.

[1] TM2: Seismic Vulnerability Assessment for Pipelines and Facilities
[2] TM3: Modeling Methodology
[3] TM4: Existing System Vulnerability and Customer Outage Probability

2. Methodology

As outlined in TM 3: Modeling Methodology, modeling was performed to estimate the potential damage to the system, customer service impacts, and the probable restoration times following a seismic scenario event. The modeling that was completed for the restoration evaluation was completed using Optimizer by Optimatics on each of four selected multi-break scenarios. As described in TM 3, an objective function was developed to identify the preferred order of system improvements that would return service most efficiently to the City’s system. The objective function applied in Optimizer combined meeting minimum pressure criteria with a pressure penalty that was a function of the economic impact for each subarea as defined in TM 5. This approach to the restoration simulations focused efforts on the areas for initial improvements that had the most benefit both for large population groups and for critical economic centers.

Once the order of improvements was defined, the assumptions for restoration resources and repair durations was assigned to formulate the timeline for repairs. The tiered structure of the City’s system was also considered, and water supply to receiving pressure zones could not be provided until the supplying pressure zone was repaired. For some zones, this meant that up to 5 pressure zones must be repaired and returned to service before water supply could be restored.

3. Restoration Assumptions

A summary of the restoration assumptions developed with the City to repair facility and asset damage after an earthquake is provided in Table 1. These are shown separately for the Cascadia Subduction Zone event (CSZ) and the Seattle Fault Zone East (SFZE) event. The primary difference in the CSZ and SFZE restoration assumptions is in the number of crews available to support repairs over time. This difference in crew availability is due to the difference of the extent and anticipated damage between the CSZ and SFZE events on a regional basis, in considering the likely availability of mutual aid. For the CSZ event, less damage is anticipated, but the damage is anticipated to be more widespread, causing more nearby utilities to be unable to provide mutual aid as well as requesting mutual aid from more distance water systems. As a result, the rate of additional crews to support repairs is less than the projected number of crews available for the SFZE event. The restoration assumptions for the repair to the SPU system is based upon information provided in the SPU seismic system assessment public report and discussions with SPU staff.

Table 1: Restoration Assumption Summary

	SFZE	CSZ
Pipe Repair Crews		
Time from Seismic Event	Crews Available	
0-3 days	2	2
4-7 days	5	2
8-14 days	10	5
14-21 days	20	10
21+ days	20	20
Pipe Repair Rate		
Time from Seismic Event	Repair Rate (number of repairs per crew day)	
AC and DI Pipe Break	1	1
All other Pipe Break	1.5	1.5
AC Pipe Leak	1	1
All other Pipe Leak	2	3
Facility Repair Rate		
Pump Stations and Reservoirs	Number of Facilities Repaired per Week	
First 30 days	0	0
After 30 days	2	1
Inlet Stations	Use pipe repair crews and repair rates for AC pipe	
PRVs	Use pipe repair crews and repair rates for AC pipe, these should already be coded as pipes with leaks and breaks.	
SPU Repair Time		
CESSL and TESSL (if offline)	21 days	21 days

4. Results

A summary of the selected damage scenarios and the restoration curves and economic impacts are summarized in the following sections.

4.1 Damage Scenarios

Seismic damage scenarios for restoration analysis were selected from the multi-break Monte Carlo analysis. The seismic scenarios selected for restoration analysis included the following scenarios:

- CSZ: 50% Scenario, Simulation C2213
- SFZE: 25% Scenario, Simulation S9496
- SFZE: 50% Scenario, Simulation S8938
- SFZE: 75% Scenario, Simulation S2301

The percentage values shown to describe the scenarios (e.g., 25%, 50%, or 75%) are indications of the relative probability of each occurring. These scenarios were selected from a set that was narrowed by looking for scenarios in which the number of facilities offline and the number of pipes offline represented approximately the 25th, 50th, or 75th percentile of values from all 10,000 multibreak scenario iterations for each of the two events (CSZ and SFZE). These scenarios were selected to cover the range of scenarios in the multi-break analysis. Table 2 summarizes the number of pipe repairs (leaks+breaks), and facility outages for each selected damage scenario. As described in the methodology section, each as-is damage scenario was modeled and evaluated to determine the preferred order or repairs to return service to the distribution system customers most efficiently.

Table 2: Restoration Scenario Summary

Item	C2213 (CSZ 50%)	S9496 (SFZE 25%)	S8938 (SFZE 50%)	S2301 (SFZE 75%)
SPU Supplies Online[1]	1	1	1	0
Number of Inlets Online	13	9	10	9
Pump Stations Online	22	11	12	15
Reservoirs Online	31	27	26	21
Total Pipe Repairs	220	523	537	552
[1]CESSL is offline in all selected scenarios				

4.2 Restoration Curves

Using the selected order of repairs identified in the restoration modeling and the restoration assumptions presented above, system outage times were calculated and restoration curves that present the customer impact over time were developed for each of the selected seismic scenarios.

System outage times were also calculated for each pressure zone and sub area for each scenario. The outage times were based on the expected damage, and the estimated restoration times of critical components required to restore service. Table 3 summarizes the benchmark restoration times for each seismic scenario, and Figure 1 shows the entire restoration period for each seismic scenario by percent of customers with water, and Figure 2 summarizes the restoration time by number of customers without water for each seismic scenario.

Table 3: Restoration Time Summary by Earthquake Scenario

	Days after Earthquake Event			
Percent of Customers Restored with Service	C2213 (CSZ 50%)	S9496 (SFZE 25%)	S8938 (SFZE 50%)	S2301 (SFZE 75%)
50%	38	59	65	60
75%	47	74	77	72
90%	58	83	85	83
99%	70	90	96	94

Figure 1: Restoration Time Summary by Earthquake Scenario

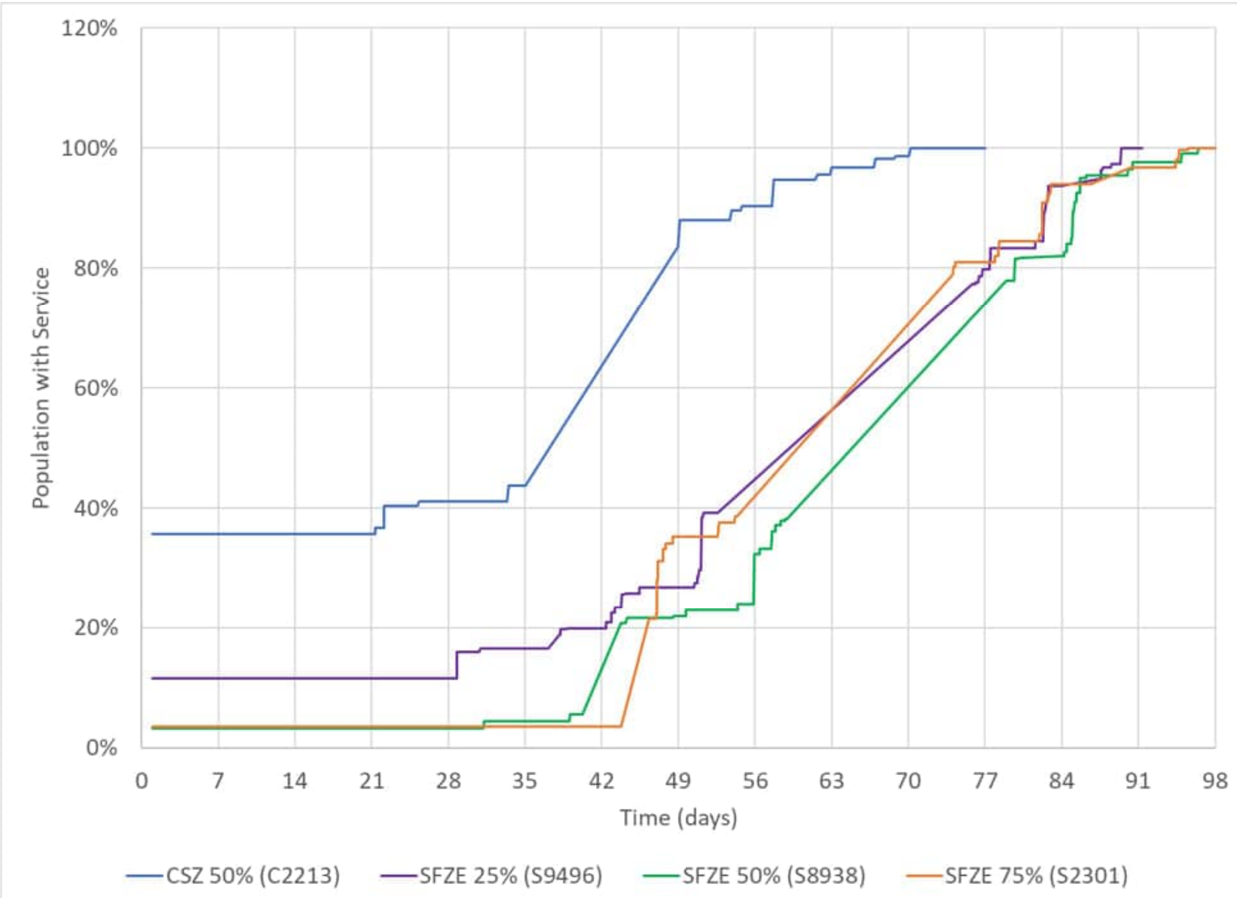
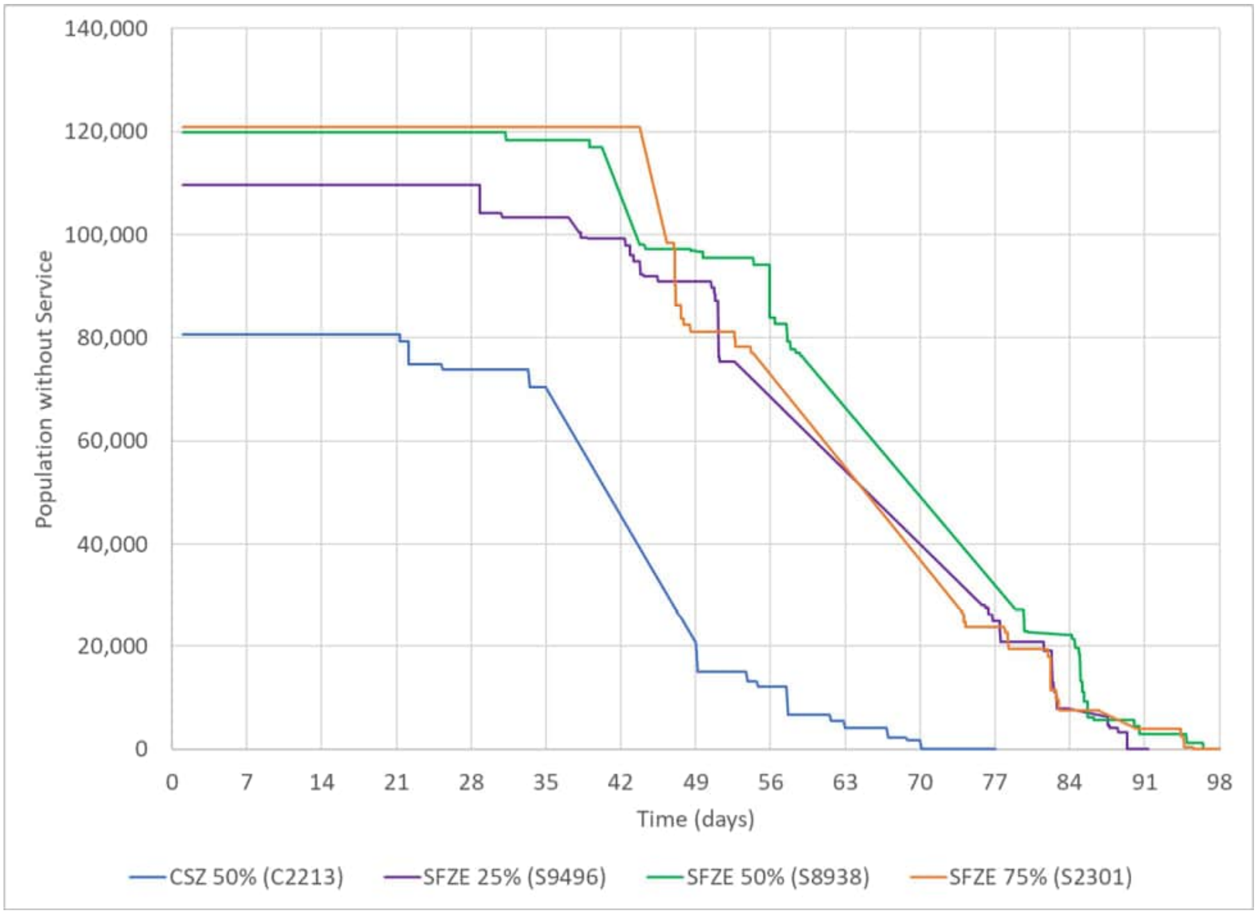


Figure 2: Customer Outage Summary by Earthquake Scenario



In addition to the system-wide assessment of outages, geographic assessment of restoration was also completed. Due to the tiered nature of the City's distribution system, supply is introduced in pressure zones that are in the middle of the HGL range of the system. Therefore, pressure zones that are higher in the system or served from PRVs from the City's primary supply zones (BV0400 and LH0520) continue to be out of water service until water supply is returned to each subsequent supply zone. The areas of the system that show the most potential for damage from an earthquake are also located in the lower pressure zones based upon the geology. Once repairs in the supplying pressure zones are made, supply can be returned to the receiving pressure zones and reservoirs to sustain water pressure.

Figure 3 through Figure 6 show the geographic restoration times for the four selected seismic scenarios. Table 5 summarizes the restoration times for critical facilities and essential facilities/distribution centers within the system, and Figure 7 shows the time series distribution of the restoration time for critical facilities. Figure 8 shows the time series distribution of the restoration time essential businesses. The information for the critical facilities will provide the baseline for assessing improvements and supporting LOS goals.

For the purposes of this analysis, critical facilities are those defined as “Category 1 Critical Customers” in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment. These include Hospitals, High Schools, Community Centers, and Washington State DOT facilities and Bellevue City Hall. Essential businesses for this analysis have been defined as based on the following NAICS codes shown in Table 4, which were informed by the official Washington State essential business declarations made during the COVID-19 emergency.

Table 4: Essential Business NAICS categories

NAICS Code	NCAIS Description
4441	Building Material and Supplies Dealers
444110	Home Centers
444120	Paint and Wallpaper Stores
444130	Hardware Stores
444190	Other Building Material Dealers
4442	Lawn and Garden Equipment and Supplies Stores
444210	Outdoor Power Equipment Stores
444220	Nursery, Garden Center, and Farm Supply Stores
4451	Grocery Stores
445110	Supermarkets and Other Grocery (except Convenience) Stores
445120	Convenience Stores
4452	Specialty Food Stores
445210	Meat Markets
445220	Fish and Seafood Markets
445230	Fruit and Vegetable Markets
445291	Baked Goods Stores
445292	Confectionery and Nut Stores
445299	All Other Specialty Food Stores
4453	Beer, Wine, and Liquor Stores
445310	Beer, Wine, and Liquor Stores
4461	Health and Personal Care Stores
446110	Pharmacies and Drug Stores

Table 5: Restoration Time Summary for Key Restoration Percentages of Critical Facilities and Essential Businesses for Earthquake Scenarios

	Days after Earthquake Event		
Earthquake Scenario	25% Restoration	50% Restoration	90% Restoration
Critical Facilities			
CSZ 50% (C2213)	21%	49%	68%
SFZE 25% (S9496)	45%	77%	84%
SFZE 50% (S8938)	48%	80%	86%
SFZE 75% (S2301)	48%	75%	95%
Essential Facilities			
CSZ 50% (C2213)	23%	49%	68%
SFZE 25% (S9496)	44%	77%	85%
SFZE 50% (S8938)	57%	80%	86%
SFZE 75% (S2301)	48%	75%	91%

Figure 3: Subarea Restoration for C2213 (CSZ 50%) Earthquake Scenario

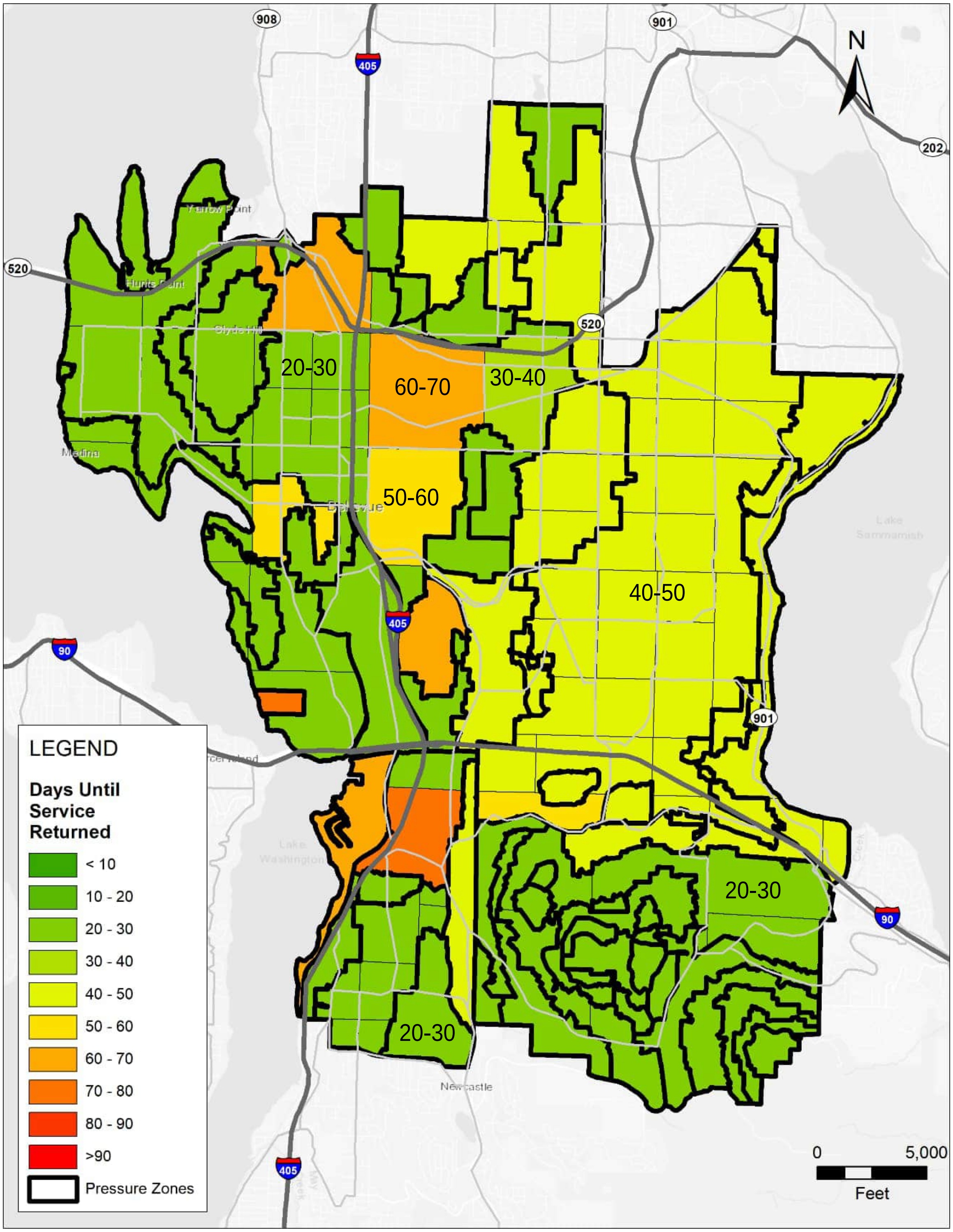


Figure 4: Subarea Restoration for S9496 (SFZE 25%) Earthquake Scenario

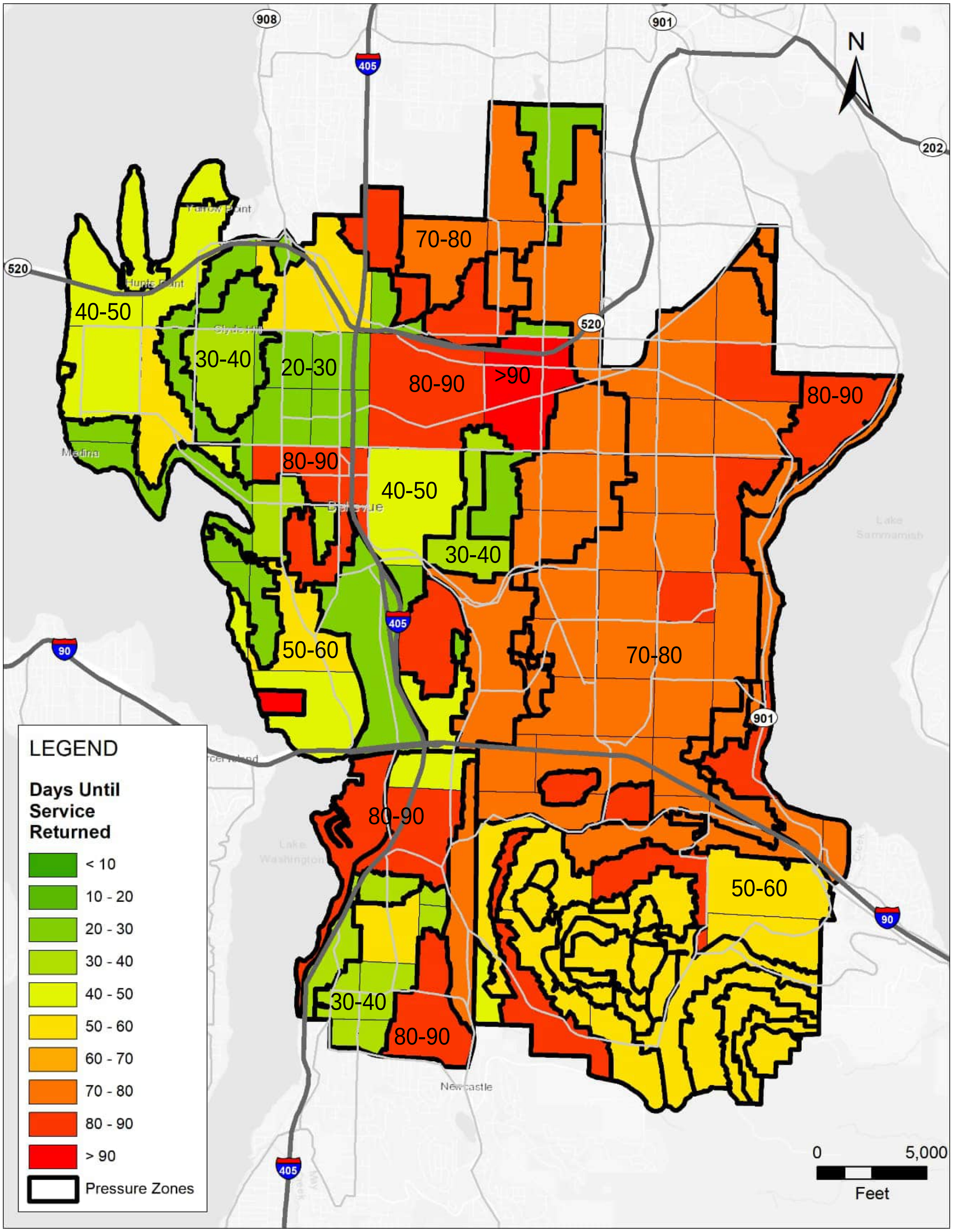


Figure 5: Subarea Restoration for S8938 (SFZE 50%) Earthquake Scenario

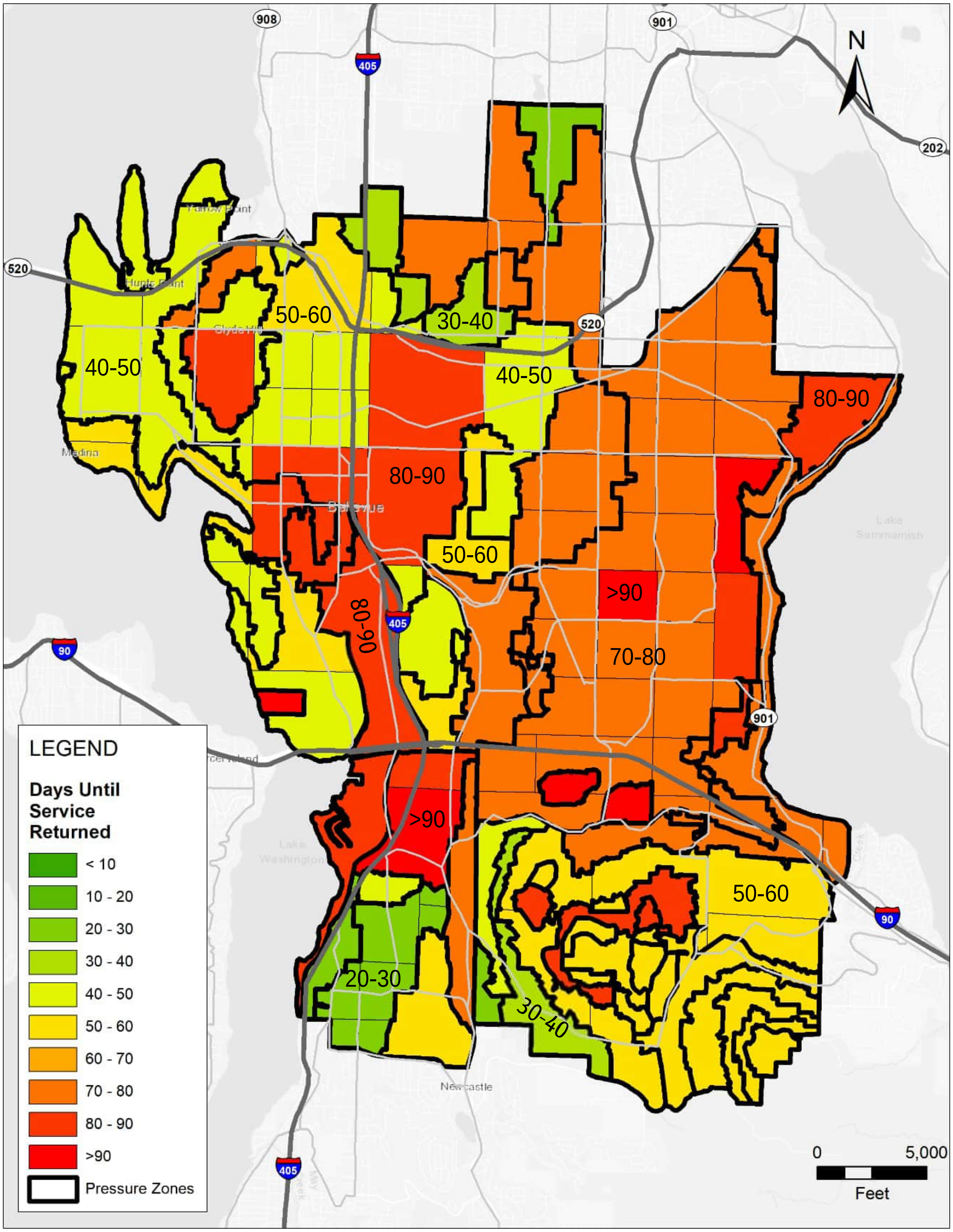


Figure 6: Subarea Restoration for S2301 (SFZE 75%) Earthquake Scenario

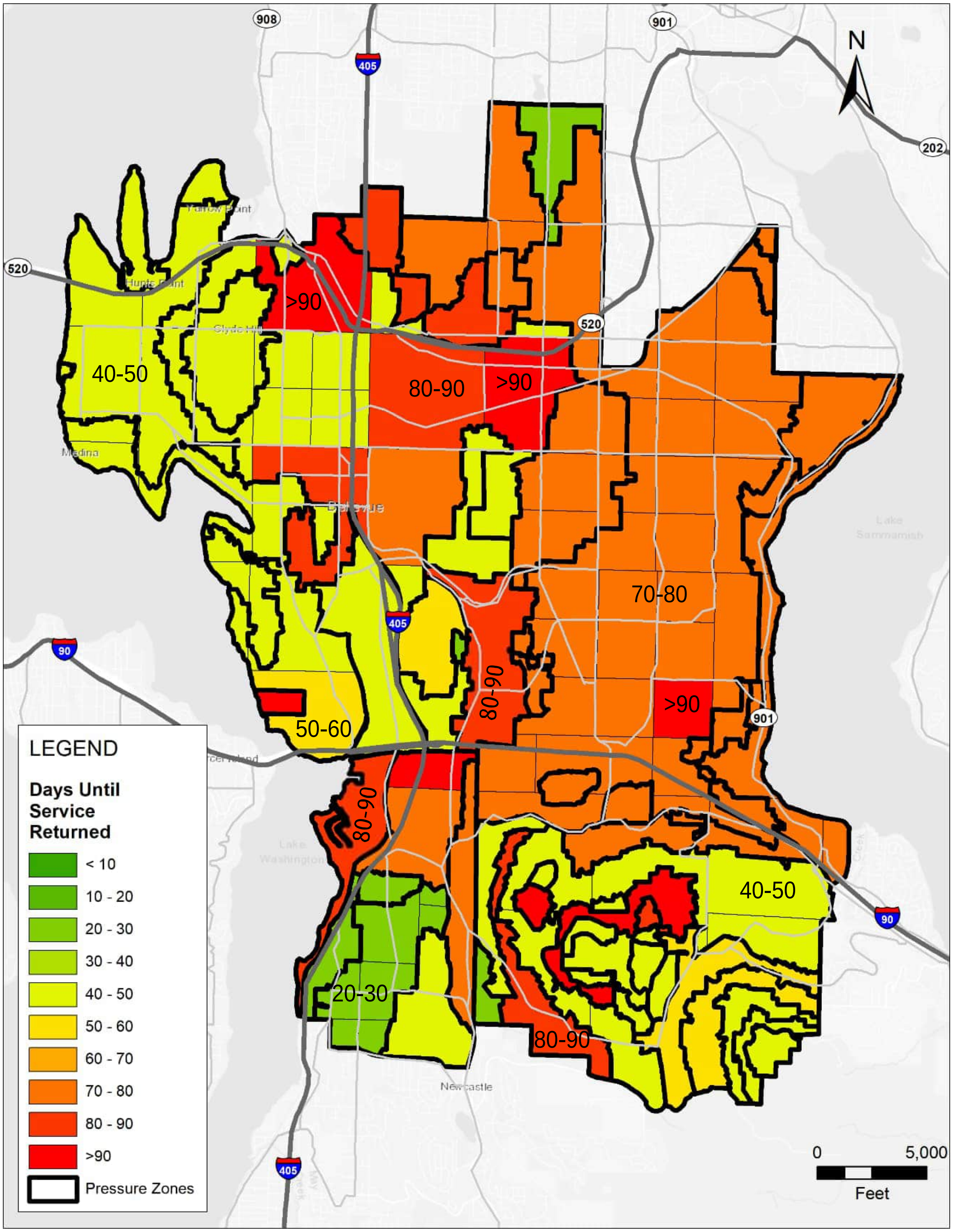


Figure 7: Critical Facilities Restoration Times for Earthquake Scenarios

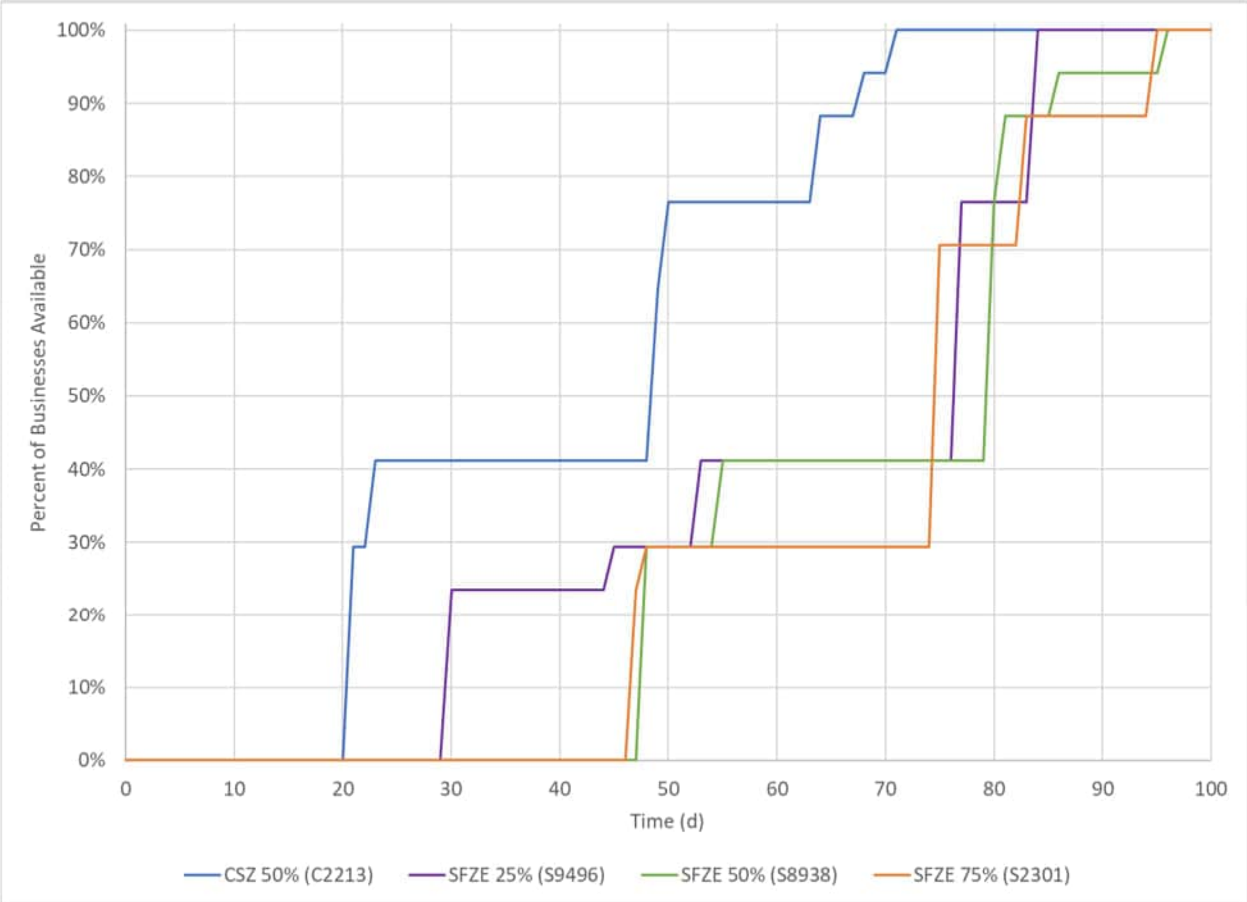
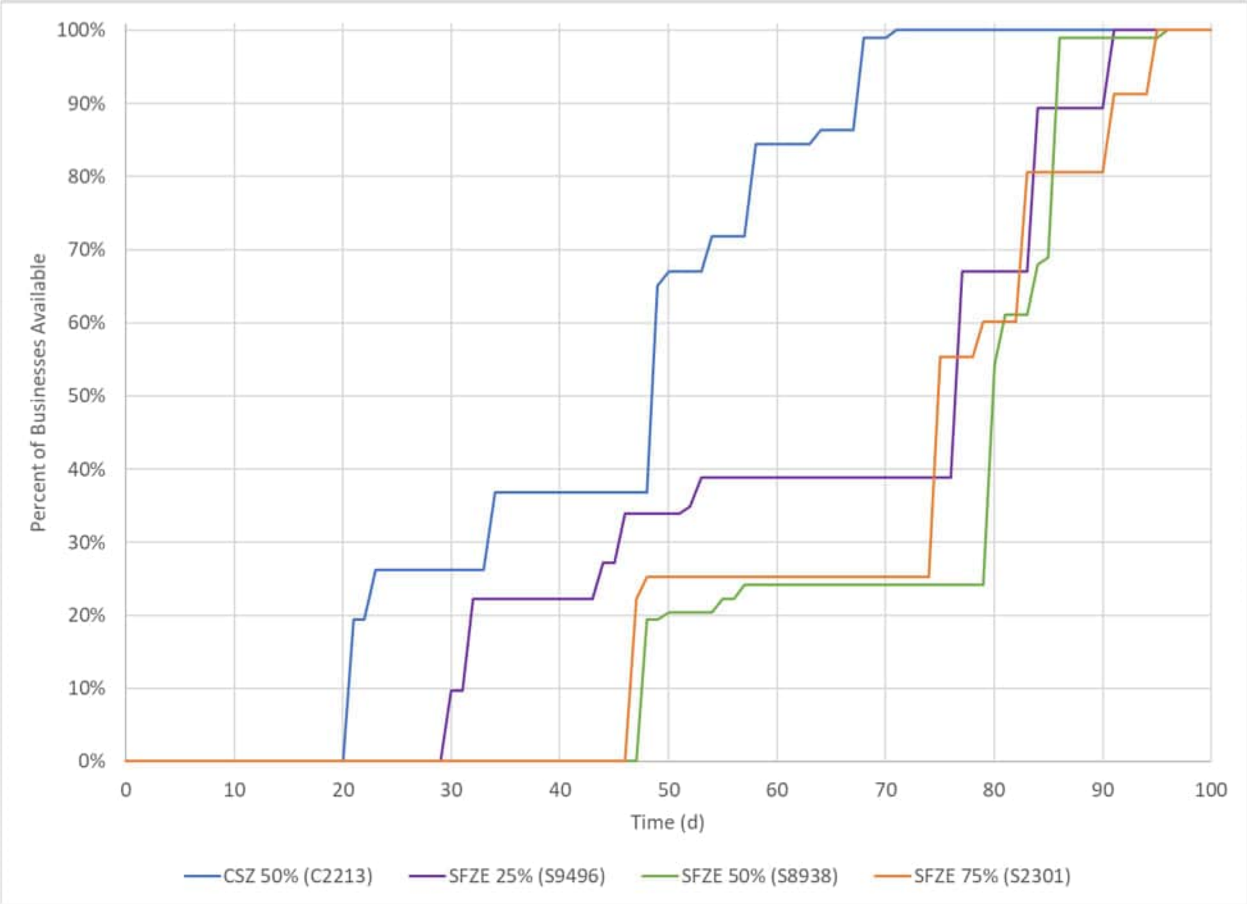


Figure 8: Essential Business Restoration Times for Earthquake Scenarios



5. Potential Economic Impact

Using the restoration results presented above and the economic assumptions presented in TM 5, economic impact curves were developed for each selected seismic scenario. Table 6 summarizes the total economic impact due to water outage as well as the annual risk for each seismic event. The annual risk for the CSZ event was calculated based upon a 500-year return period (0.2% probability of occurrence each year), and the annual risk for the SFZE event was calculated based upon an 800-year return frequency with a 50% probability of occurrence (0.0625% probability of occurrence per year).

Figure 9: Water Outage Economic Impact for As-Is Restoration for Selected Earthquake Scenarios

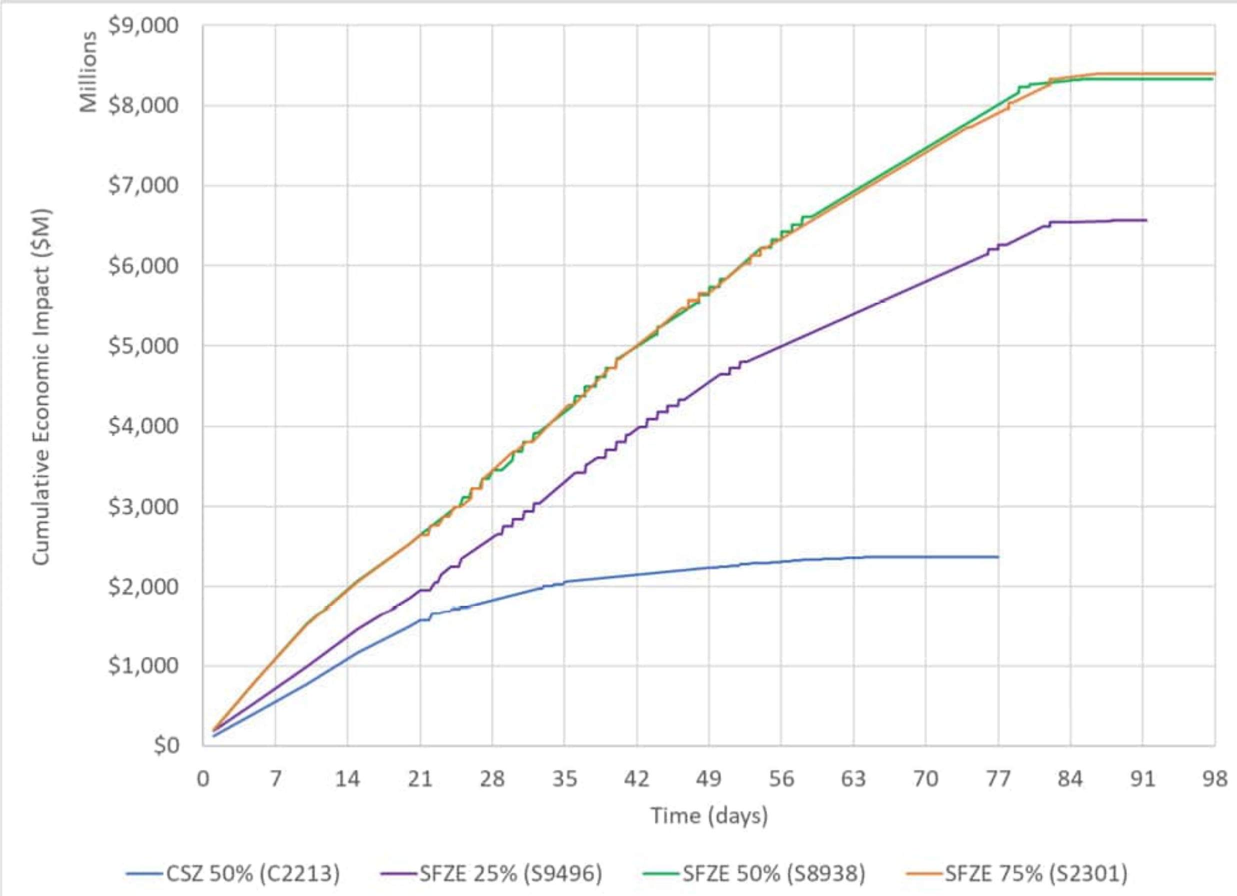


Table 6: Total Economic Impact of Water Outage by Earthquake Scenario

	Total Economic Impact ($M)	Annual Risk ($M/Year)
CSZ 50% (C2213)	2,375	4.7
SFZE 25% (S9496)	6,564	4.1
SFZE 50% (S8938)	8,326	5.2
SFZE 75% (S2301)	8,398	5.2

6. Summary

The restoration analysis of the as-is system shows that the restoration times for residential service range from 55 to 75 days across the selected scenarios. Based upon the order of preference for restoration activities, the most beneficial system repairs that improved system performance were to pipe in the primary supply zones of BV0400 and LH0520 and repairs to facilities.

The restoration analysis showed that due to the geographical diversity of the Critical facilities and essential businesses, the restoration of these facilities is similar to the restoration of residential service.

Based upon the results of the As-Is Restoration analysis, improvements will be developed and evaluated to assess their benefit in reducing the number of days that service is returned to customers and essential facilities are able to operate. The initial restoration analysis provides the benchmark by which to assess the benefits of improvements implemented in the City's system. Table 7 and Table 8 show the current state of the Bellevue Water System based on the categories and timeframes developed for the City of Bellevue water system post-earthquake level of service goals. Note that the goals for each of these categories will be developed as part of the next steps of the seismic vulnerability analysis.

Table 7: As-Is Water System Post-Earthquake Performance for CSZ 50% Earthquake Scenario

	Event	1-Day	3-Days	7-Days	14-Days	21-Days	1-Month	2-Month	3-Months	6-Months
Emergency Room Hospitals						🟢				
Hydrants at Designated Resilient Supply Points[1]										
Community Recovery Facilities[2]						🔴		🟠	🟢	
Essential Businesses[3]						🔴		🟠	🟢	
Basic Domestic Service to All Customers			🔴				🟠		🟢	
Existing Service Restored to All Hydrants[4]										

🔴 = 20%-30% Operational 🟠 = 50%-60% Operational 🟢 = 80%-90% Operational

Notes:
[1]Designated Resilient Supply Points have not yet been defined.
[2]Community Recovery Facilities are Critical Facilities, excluding Hospitals as defined in Section 4.2
[3]Essential Businesses are as defined in Section 4.2
[4]Analysis does not include evaluation of fire flow conditions.

Table 8: As-Is Water System Post-Earthquake Performance for SFZE 50% Earthquake Scenario

	Event	1-Day	3-Days	7-Days	14-Days	21-Days	1-Month	2-Months	3-Months	6-Months
Emergency Room Hospitals								🟢		
Hydrants at Designated Resilient Supply Points[1]										
Community Recovery Facilities[2]								🔴	🟢	
Essential Businesses[3]								🔴	🟢	
Basic Domestic Service to All Customers								🟠	🟢	
Existing Service Restored to All Hydrants[4]										

🔴 = 20%-30% Operational 🟠 = 50%-60% Operational 🟢 = 80%-90% Operational

Notes:
[1]Designated Resilient Supply Points have not yet been defined.
[2]Community Recovery Facilities are Critical Facilities, excluding Hospitals as defined in Section 4.2
[3]Essential Businesses are as defined in Section 4.2
[4]Analysis does not include evaluation of fire flow conditions.

Appendix G. Post-Earthquake Level of Service Goals

G.1 TM7: PE-LOS Goals

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Technical Memorandum

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Subject	TM7: PE-LOS Goals
Project Name	Bellevue Water System Seismic Vulnerability Assessment
From	Jacobs
Date	October 7th, 2022

1. Background

This document describes the development of target Post-Earthquake (PE) Level of Service (LOS) Goals used to identify potential performance measures for water system seismic resilience improvements alternatives evaluated as part of the SVA.

Anticipated "as-is" performance of the existing system and subsequent water service outage duration restoration times were estimated for the Seattle Fault Zone East (SFZE) and Cascadia Subduction Zone (CSZ) seismic event scenarios. The as-is performance was then compared to target PE-LOS goals to identify upgrades that will improve system seismic performance to levels that are acceptable to the City. The estimated as-is system restoration durations and economic impacts to the City due to damage from both events are described in TM 6: Restoration and Economic Impacts (TM6).

2. PE-LOS Goal Framework

As awareness of the magnitude of seismic risks to water systems has become more widely recognized, utilities and local governments have begun implementing a practice of creating Post-Earthquake/Event Level of Service (PE-LOS) goals. PE-LOS goals start with the assumption that having a water system that can supply water to all customers immediately after a major seismic event is either impossible or impractical. As such, the PE-LOS goals focus on which parts of the system should be upgraded to provide the necessary water to people in reasonable durations and additionally focus on where restoration efforts and system improvements should be prioritized to most effectively reduce and mitigate adverse impacts following a major seismic event.

When creating PE-LOS goals, there are four key components to consider:

1. Water quantity (flow rates and volumes available)
2. Water quality (suitability for use)
3. Duration to restore service (time involved in recovering system water supply and returning to "normal")
4. Priority locations for service restoration

Each of the above components forms the basis of the PE-LOS goals presented in the following sections.

3. PE-LOS Goal Regulations and Standards

There are no regulations or fully adopted industry standards that govern or define the establishment of specific PE-LOS goals for water supply and utility systems. However, there are several references that are helpful to use as a comparison while developing PE-LOS goals for the City. The following outlines the approaches to developing or recommending PE-LOS goals taken by other utilities and states, as well as the differentiation between building codes and PE-LOS goals.

3.1 State and Other Utility PE-LOS Goals

The Washington State Seismic Safety Committee's Emergency Management Council (WSSC) published *Resilient Washington State* in 2012. *Resilient Washington State* provides some guidance for PE-LOS goals for water systems, but the guidance is high level and does not take into account the severity of the earthquake or account for the different types of customers served by a typical water system. It also does not account for locational specific seismic hazards such as those evaluated for Bellevue, and as a result the requirements are not consistent with other guidelines from neighboring states or other utilities in Washington and is not directly applicable to the City of Bellevue.

The Oregon Seismic Policy Advisory Committee (OSSPAC) published the *Oregon Resilience Plan* (ORP) in 2013. As the ORP was developed with significantly more detail than *Resilient Washington State*, the ORP will be used as a reference for the remainder of this TM. Both the Oregon and Washington resiliency guidance documents were prepared with broad involvement from the respective states' community stakeholders, and both developed earthquake performance goals after an evaluation of their respective existing infrastructure systems.

A key feature of the ORP is developing phased PE-LOS goals that align water system restoration priorities for different types and groups of customers. The ORP's main objective when developing the phased PE-LOS goals was to generally meet a two-week recovery period and return to a resilient level of service after a 500-year Cascadia Subduction Zone (CSZ) event. The timeline of the phased approach was based off general recommendations created by the OSSPAC.

The PE-LOS goals that the ORP proposes include target percentages for the operational level for various functions of the water system on a timeline. The operational level percentages are suggested to meet average winter demands with potable water that has been disinfected and tested. The PE-LOS goals developed by the ORP for a 500-year event are shown in Table 1.

Various local utilities have also developed their own PE-LOS goals, while others have seismic projects in the works, with the intent of developing their own LOS goals. They are listed below by geographic location from north to south. In all of these cases, the goals are generally in alignment with the basic concepts of the ORP, with minor variations in the way levels of service are defined and whether water must be potable or not. However, given that the ORP is the most comprehensive set of goals that is applicable to a wide range of utilities, the framework from the ORP has been used as a basis for establishing goals for the City of Bellevue.

- City of Everett, Washington – From the *City of Everett Water Supply Risk Assessment Study* (Carollo, 2012), PE-LOS goals were proposed for a Probable Event (a 500-year event) and a Maximum Earthquake Event (a 2,500-year event). These goals are different that most in the industry, as they were developed before the ORP and other commonly used frameworks were established.
- Seattle Public Utilities (SPU), Washington – The *Seismic Study Summary* (SPU, 2019) investigated seismic hazards in the central Seattle district and holistically assessed existing system vulnerabilities. Findings were used to develop both short-term goals (within the next 15-20 years) and long-term goals (within the next 50+ years). SPU's PE-LOS goals were developed specifically for the SPU system, with goals associated with specific assets.
- Water Supply Forum, Washington – While not a utility, the Forum is a group of agencies that serve the Snohomish, King, and Pierce Counties with a utility perspective on current and future regional water supply and related water resources issues. The Forum began the Regional Water Supply Resiliency project in 2015 to identify key risks to water supply and to strategize how best to address and recover from them. See Table 2 below for the PE-LOS goals developed via the Forum. Note that these goals focus on only supply to water distribution systems and do not address restoration of/within the

distribution systems themselves. Water Supply Forum PE-LOS goals were developed based on the ORP. City of Bellevue staff represented Cascade Water Alliance as part of the Water Supply Forum.

- Tacoma Water – Tacoma Water developed PE-LOS goals as part of the *2015 All Hazards Vulnerability Assessment*, (CH2M HILL (now Jacobs), 2016). Tacoma Water's PE-LOS goals were developed based on the ORP.

Table 1: 500-Year Return Earthquake LOS Goals (ORP, OSSPAC, 2013)

System Function	Event	0-24 Hours	1-3 Days	3-7 Days	1-2 Weeks	2-4 Weeks
Potable water available at supply source		🔴	🟠		🟢	
Main transmission facilities, pipes, pump stations, and reservoirs operational		🟢				
Water supply to critical facilities available		🟠	🟢			
Water for fire suppression at key supply points		🟢				
Water for fire suppression at fire hydrants				🔴	🟠	🟢
Water available at community distribution centers/points			🟠	🟢		
Distribution system operational			🔴	🟠	🟢	

🔴 = Desired time to restore component to 20%-30% Operational

🟠 = Desired time to restore component to 50%-60% Operational

🟢 = Desired time to restore component to 80%-90% Operational

3.2 PE-LOS Goals compared to Building Codes

It is critical to understand that PE-LOS goals are different from building codes, and the two may not necessarily align. For water systems, building codes focus on the importance of the water system facility and do not govern the resiliency of buried piping. Buildings are categorized into one of four categories, ranging from Category I to Category IV. Category IV buildings are considered "essential" as those that need to have immediate occupancy after a major 2,475-year seismic event. For water systems, the code only requires this highest level of performance for facilities that are required to maintain and provide fire suppression. This fire suppression condition usually only applies to some reservoirs and to pump stations serving dead-end zones.

PE-LOS goals will often result in the determination that designs for water system facilities that are critical to the operation of the system need to be upgraded or replaced with facilities that are designed with higher levels of seismic resiliency than the code might require for a new facility. While there is an added cost to be paid for this additional seismic strengthening when incorporated as part of the initial construction, the added cost is usually relatively small in comparison to the total cost of a replacement facility. Seismic retrofits of facilities already constructed, however, can be significantly more costly, and may not be as effective, often making the added cost of seismic retrofit options less appealing.

Finally, it is necessary to make a distinction between classification of a facility as essential (Category IV according to the building code) and designing to the equivalent classification level. Designating a facility as a Category IV (essential) facility results in additional stringent requirements for all components of the facility. For facilities that are not designated as Category IV (essential) according to the building code, achieving the same level of resiliency design for the facility can be achieved by increasing the importance factor for the facility without designating the facility as a Category IV (essential) facility.

The result is that the PE-LOS goals that are established for the City of Bellevue water system will result in most water system facilities being designed to seismic standards that are greater than what is required by code.

4. PE-LOS Goal Customer Category Development

As noted above, identifying which locations in the water system to restore first is a primary component for developing PE-LOS goals. Determining the categories for which customers would be grouped was generally based off of the concepts presented in the ORP. To be more applicable to the needs of the City, the seven groupings from the ORP were adjusted to the six categories detailed below. The categories were primarily developed by City staff with input from Jacobs.

Emergency Room Hospitals: Hospitals are critical to the emergency response and support after a seismic event. The Joint Commission, a primary accreditation body for hospitals and health care organizations within the United States, requires accredited hospitals to maintain a minimum of 72 hours of emergency potable water supplies. Water is essential for the operation of a hospital and loss of water beyond this timeframe typically results in the hospital being required to close and evacuate.

Designated Resilient Supply Points: The City will be establishing designated resilient supply points throughout the water system that will provide access for water bottle filling stations and water for fire suppression. These locations have not been identified as the location is dependent upon ability to provide traffic management, expected availability of water, and community need. In general, these locations will include emergency well sites, water reservoirs with seismic valves (that automatically close to prevent loss of stored water to system leakage and pipe breaks as a result of a major seismic event), and locations along resilient piping routes that are expected to be able to sustain active water supply service after a seismic event.

Community Recovery Facilities: Community recovery facilities include water-sensitive customers that are critical to short-term emergency response and recovery, including emergency shelter sites, emergency operations centers, and key agencies such as WSDOT maintenance facilities. For evaluation purposes, these include Category 1 Critical Customers as defined in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment. While additional critical customers may be considered during implementation of the proposed improvements, the Category 2 Critical Customers from TM 2 are not included because while they are important, water supply is not critical to their operation or they are not well suited as emergency shelters.

Essential Businesses: Essential businesses include grocery stores, pharmacies, medical clinics, first-aid facilities, and other locations essential for non-emergency health, safety, and well-being. This category was developed based on observation of designated essential businesses as part of the COVID-19 pandemic.

Basic Domestic Service: Basic domestic service is water service that is not up to normal standards for pressure and capacity (may be reduced pressure or curtailed supply availability) supplied from residential services and taps.

Existing Service Restored: Restoration to existing service is the eventual goal after a seismic event and is full restoration of the level of service, with no restrictions in water availability or use.

Table 2: Water Supply Forum, PE-LOS Goals for a CSZ Earthquake Scenario (2018)

System Component	Service Provided		Immediately After	24 Hours	3 Days	7 Days	14 Days	1 Month
Water Supply	Supply transmission system, provide local distribution source (wells), fill tank trucks.	Quantity	Storage	Storage	50% AWD[1]	50% AWD[1]	50% AWD[1]	AAD
		Quality	Non-Potable[2]	Non-Potable[2]	Non-Potable[3]	Non-Potable[3]	Potable	Potable
Transmission to End Points[4]	Supply terminal reservoir, wholesale meters along transmission line, provide fire suppression along transmission lines. Includes critical facilities (pump stations, treatment etc.)		50% AWD[1]	50% AWD[1]	50% AWD[1]	50% AWD[1]	AWD	AAD
Transmission/Supply to Major Regional Essential Services[5]	Serve essential customers (e.g., hospitals).		50% AWD[1]	50% AWD[1]	50% AWD[1]	50% AWD[1]	50% AWD[1]	AWD
Backbone	Supply special seismic resistant lines to essential customers, service to community distribution points, provide fire suppression along backbone.		Individual utility decision					
System Storage	Support backbone and local distribution		Limited water from storage for fire, drinking			Individual utility decision		
Distribution	Service to individual customers - residential, business, industrial. Water to fire hydrants for fire suppression.		Individual utility decision					

(AWD = Average Winter Demand; AAD = Average Annual Demand)

Notes:

[1]Percentages represent the estimated percent of total delivery. Not all areas will be feasible to serve within the first month.

[2]Water supply and water held in terminal reservoir are expected to be potable immediately after the event. However, there could be short-term disruptions/damage to water treatment plants and/or transmission pipelines that could compromise potability of water in the terminal reservoir within 24 hours following the event.

[3]Disruptions/damage to the transmission pipelines could result in contamination of water coming from treatment plants or into terminal reservoirs until repairs can be made and normal operations are resumed.

[4]Transmission to End Points includes one or more transmission pipelines providing the noted level of service connecting the supplies to and including the first terminal reservoirs downstream from each supply. At the utility's discretion, additional transmission pipeline segments and reservoirs can be included in this criterion.

[5]Transmission/Supply to Major Regional Essential Services includes a supply, and transmission line supplying water to hospitals designated as essential by the utility. The supply and transmission may be dedicated to supply to essential services and be different than the supply and transmission system serving the overall utility service area. Additional facilities in addition to hospitals such as nursing homes, may be designated by the utility.

Potable water at the supply source/treatment source and at the transmission system were not included as categories as City of Bellevue water supply and transmission is provided, owned, and managed by SPU under contract with the Cascade Water Alliance, of which Bellevue is a member utility. Careful coordination with the Cascade Water Alliance to influence SPU investment in regional water supply and transmission system seismic resiliency should be a priority for the City.

5. PE-LOS Goal Implementation Timeframe and Adoption

Most PE-LOS goals are established with a target implementation timeframe of approximately 50 years. These goals are typically adopted by the water utilities governing body as an established benchmark towards which the utility is committed to working. Some utilities have established additional, less challenging targets and shorter-term goals to work towards in the near-term with the long-term goals as the ultimate milestone.

To get stakeholder and governing body buy-in to adoption of PE-LOS goals, it is critical to have a clear understand of the costs and water rate impacts for achieving these goals. The Bellevue SVA project took the cost and rate impacts into consideration by establishing target PE-LOS goals, identifying improvements needed to achieve those goals, and determining the cost associated with those improvements. Once the suite of improvements needed to achieve the goals is defined, the cost and rate-payer impacts can be more clearly understood and communicated to stakeholders to help facilitate the adoption and implementation process.

To aid the development of a clear roadmap to achieving seismic resiliency, the SVA PE-LOS goals were developed for Short-, Mid-, and Long-Term planning horizons. The duration of these planning horizons have not yet been finalized, as the timeline will be dependent on stakeholder feedback regarding the willingness to pay for the various improved levels of service.

6. Bellevue Water System PE-LOS Goal Targets

The following section defines the target PE-LOS goals developed as part of the SVA to aid in identifying the potential improvement alternatives available to achieve seismic resiliency. Once these PE-LOS goals were established, improvements relative to these target goals could be evaluated, and benefit-cost analysis applied to determine the optimal prioritization and grouping of improvement alternatives appropriate to realizing PE-LOS goals. Once the cost of improvements associated with achieving these goals is better understood, the PE-LOS goals will be formalized along with target implementation timeframes for each time period.

The framework for the PE-LOS goals is described in Section 2 and includes target timelines for each customer/supply category to return to service. The figures below that depict the PE-LOS framework show the duration that has elapsed after the seismic event across the top row and the customer/supply category down the left column. The hexagons show the target goals for the system restoration and the circles show the as-is state of the system. The colors (red, orange, and green) represent the percentage of the customer class connections/locations that are expected to be restored by the time shown.

For example, the orange hexagon in the Community Recovery Facilities category represents the timeframe for which 50 to 60 percent of the community recovery facilities would be expected to have water once improvements to reach that PE-LOS goal have been implemented.

Two sets of short-, mid-, and long-term “target” PE-LOS goals were developed for the SVA, one for the CSZ and one for the SFZE, as presented below in Figure 1 through Figure 6. A comparison of the six sets of target PE-LOS goals is provided at the end of this section.

Figure 1: SVA Target Short-Term PE-LOS for CSZ

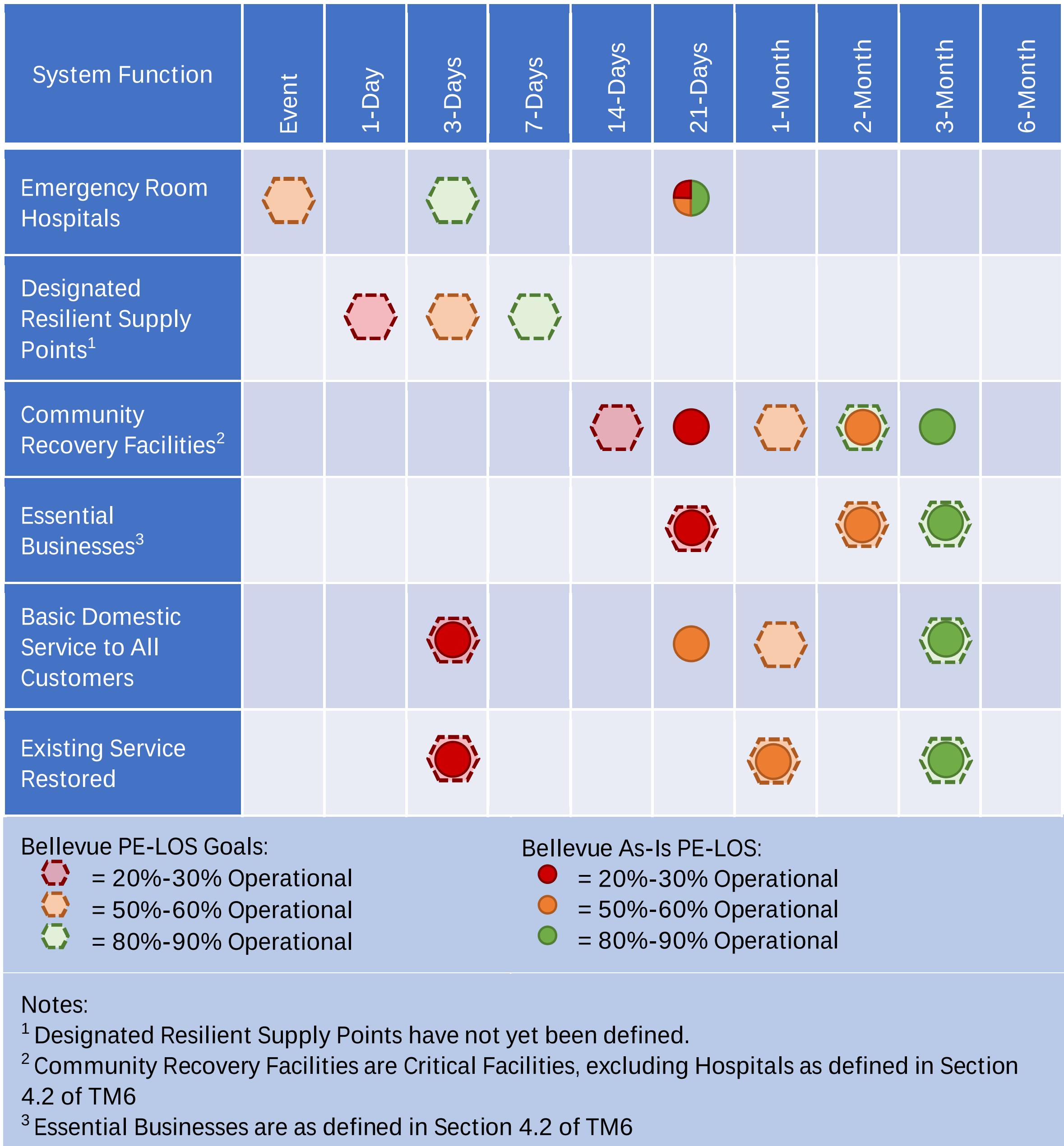


Figure 2: SVA Target Mid-Term PE-LOS for CSZ

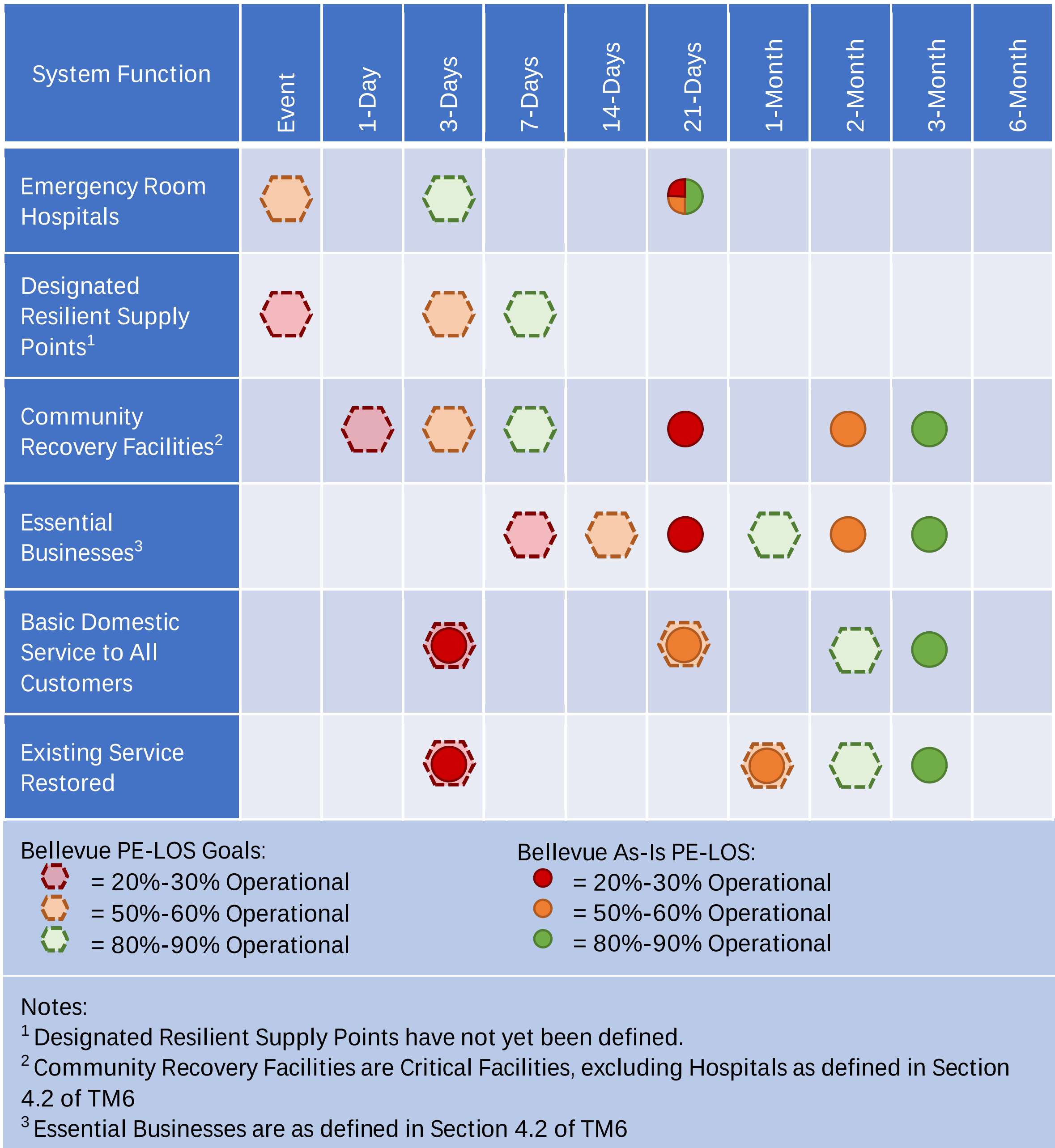


Figure 3: SVA Target Long-Term PE-LOS for CSZ

Notes:

[1] Designated Resilient Supply Points have not yet been defined.

[2] Community Recovery Facilities are Critical Facilities, excluding Hospitals as defined in Section 4.2 of TM6

[3] Essential Businesses are as defined in Section 4.2 of TM6

Figure 4: SVA Target Short-Term PE-LOS for SFZE

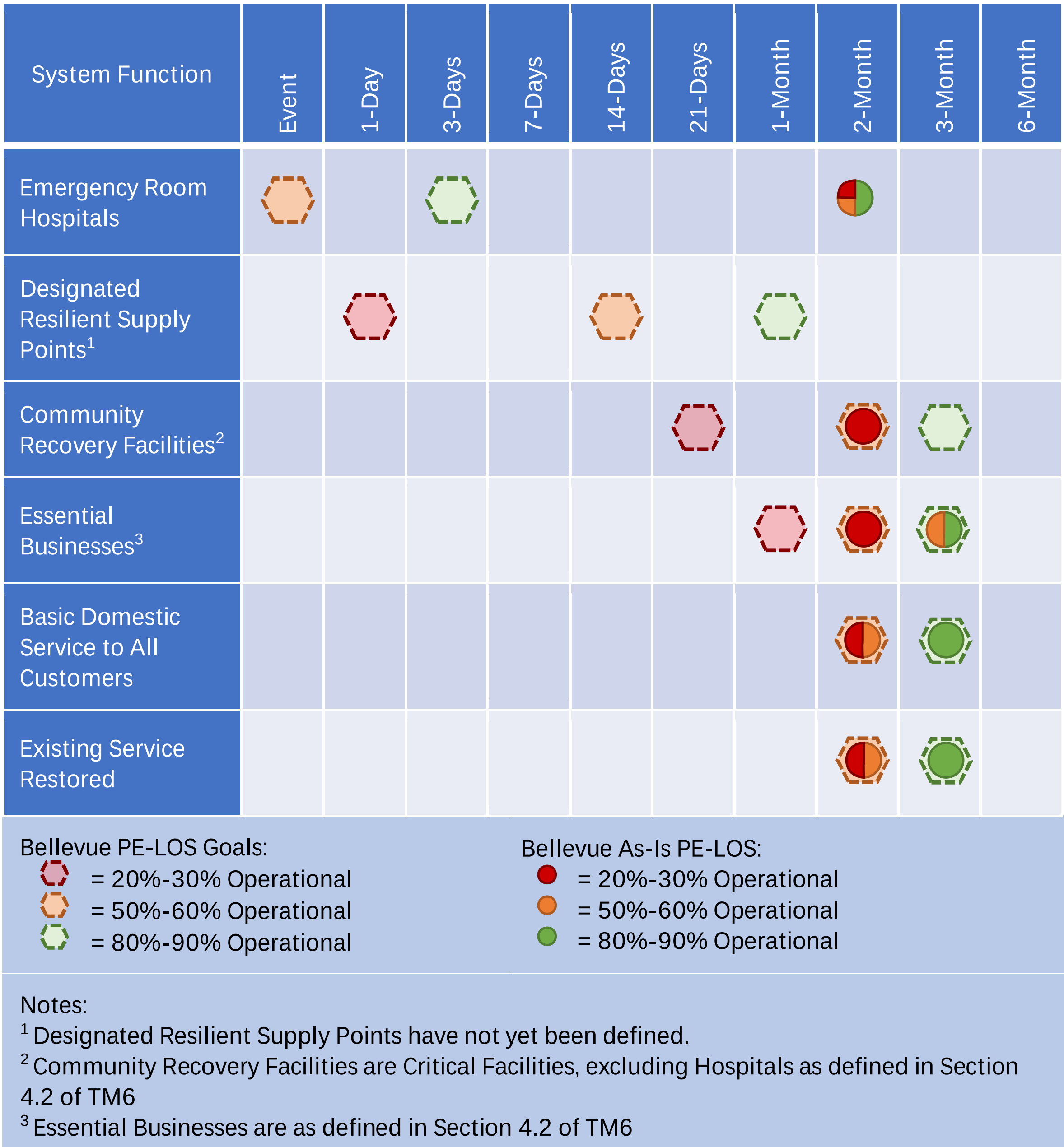


Figure 5: SVA Target Mid-Term PE-LOS for SFZE

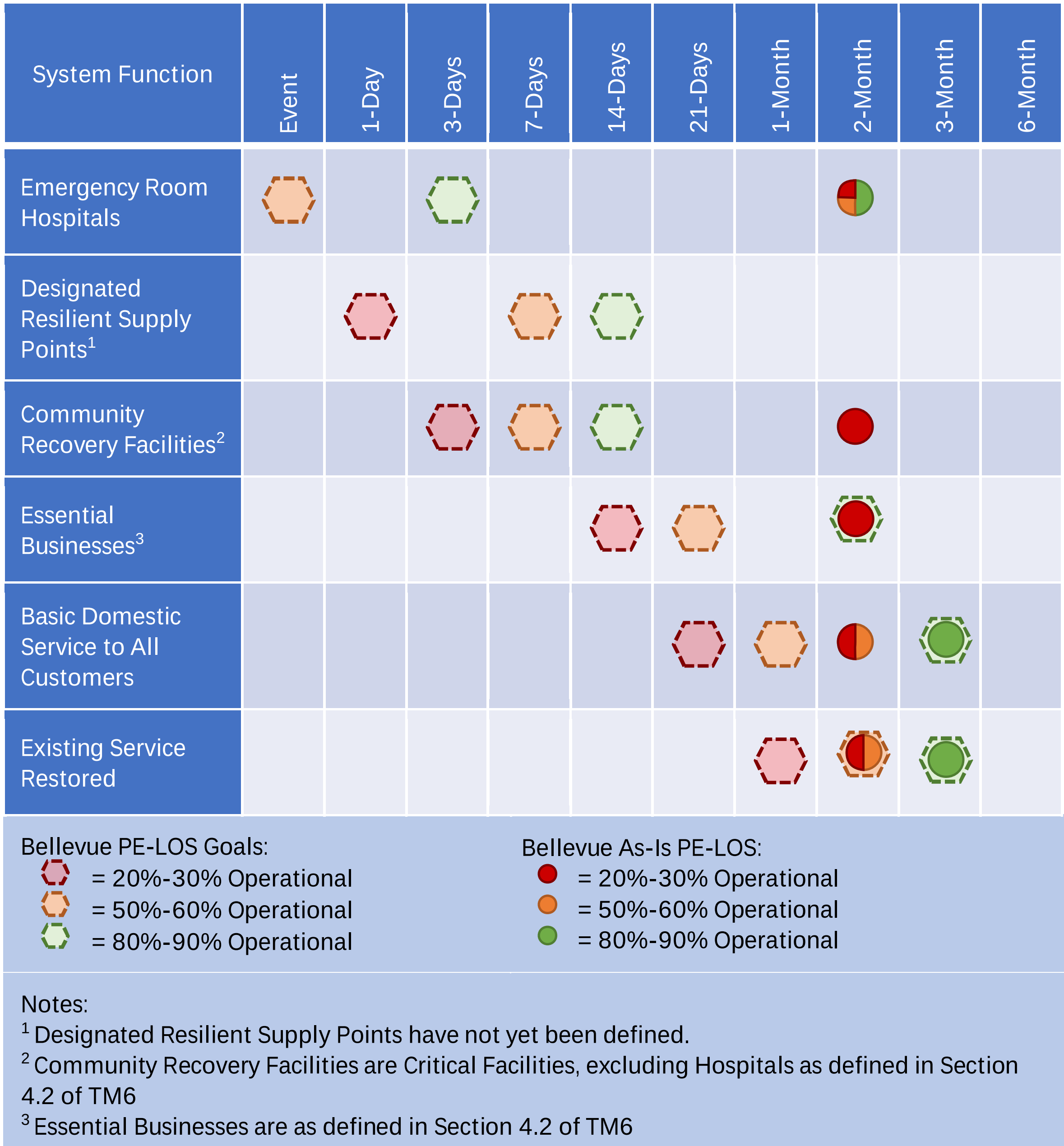
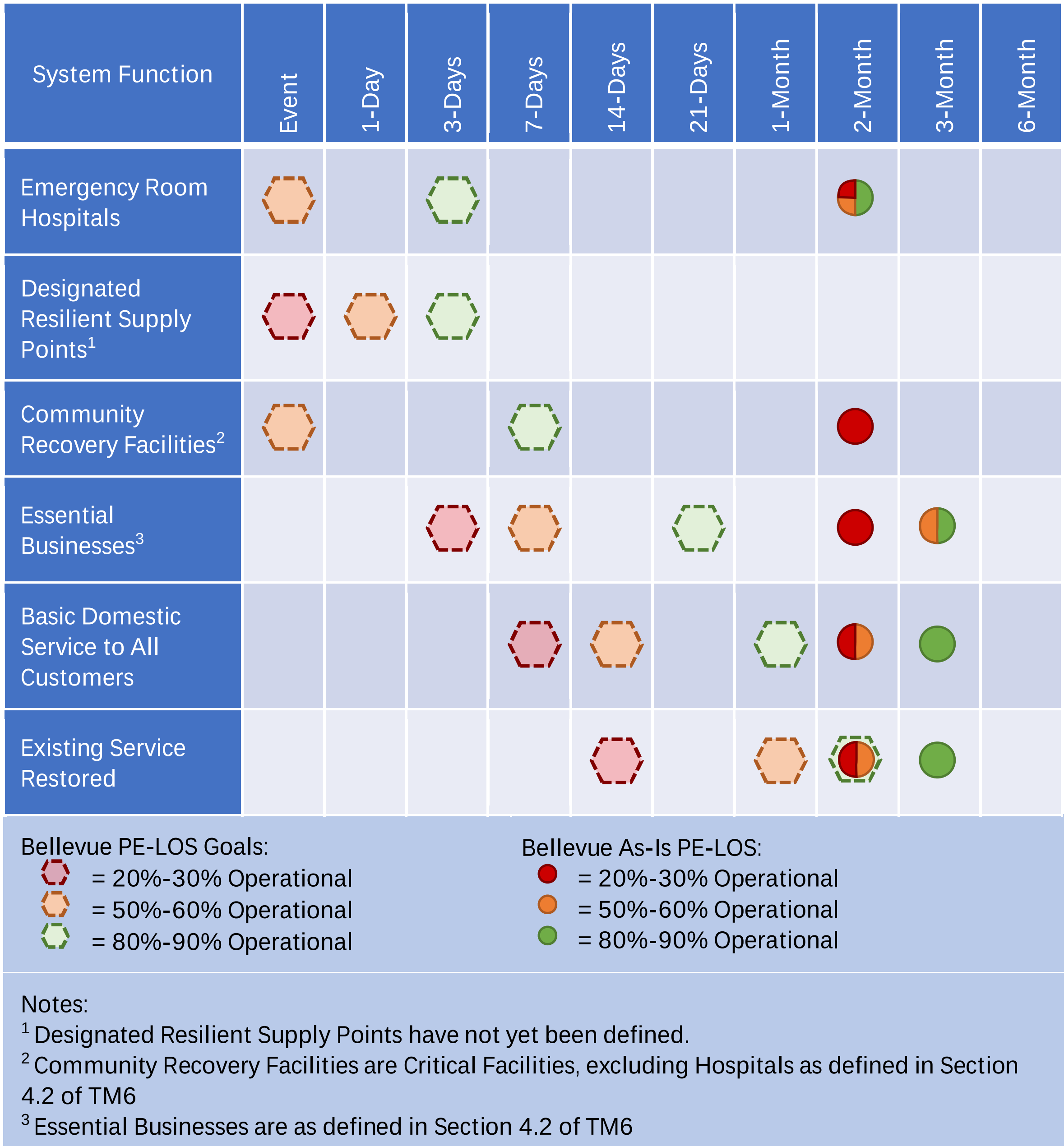


Figure 6: SVA Target Long-Term PE-LOS for SFZE



In general, the Long-Term goals were developed based on comparison with other utilities goals and the ORP. These represent the ultimate destination that would signify what a seismically resilient water system earthquake response should look like. The short-term goals are based on readily available improvements and critical needs, such as the need to improve water availability to emergency room hospitals. The mid-term goals serve as an intermediate guidepost between the long and short-term goals that helps to prioritize what should be improved after the initial improvements while the utility is along the path to the long-term PE-LOS goals.

When looking at the differences between the CSZ and SFZE goals, it is important to keep in mind the severity of the two earthquake events. As the SFZE fault is both shallow and the epicenter is estimated to be very near or even under the City, the impacts to water service (water system damage) will be much more severe. The PE-LOS goals reflect this difference by allowing for additional time to restore water service. This can be most easily noticed in the differences between the two's short-term goals: recovery efforts at the emergency room hospitals and designated resilient supply points are much more focused on for the SFZE event.

7. Summary

The target PE-LOS goals presented in this TM were developed in collaboration between City staff and Jacobs. The goals are based on and are comparable to goals developed by state committees and peer utilities and were modified to specifically meet the needs of the City. These goals will be used for the remainder of the SVA as a benchmark to compare and evaluate improvement alternatives with the intent that once the improvements required to achieve these goals are defined, the City will formally adopt them and implement improvements as required to meet the goals in a specified timeframe.

8. References

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Washington State Emergency Management Council's Seismic Safety Committee. 2012. *Resilient Washington State – A Framework for Minimizing Loss and Improving Statewide Recovery after an Earthquake: Final Report and Recommendations.* Washington. November

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Appendix H. Improvements Alternatives

H.1 TM8: Improvement Alternatives

Jacobs

Technical Memorandum

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Subject	TM8: Improvement Alternatives
Project Name	Bellevue Water System Seismic Vulnerability Assessment
From	Jacobs
Date	October 7th, 2022

1. Background

Potential improvement alternatives to increase the seismic resilience of the City of Bellevue (City) Water System have been developed as part of the City's Water Distribution System Seismic Vulnerability Assessment (SVA). These alternatives are based on the as-is restoration durations for water service after an earthquake, the economic impacts to the community, and the target Post-Earthquake Level of Service (PE-LOS) goals developed previously as part of the SVA.

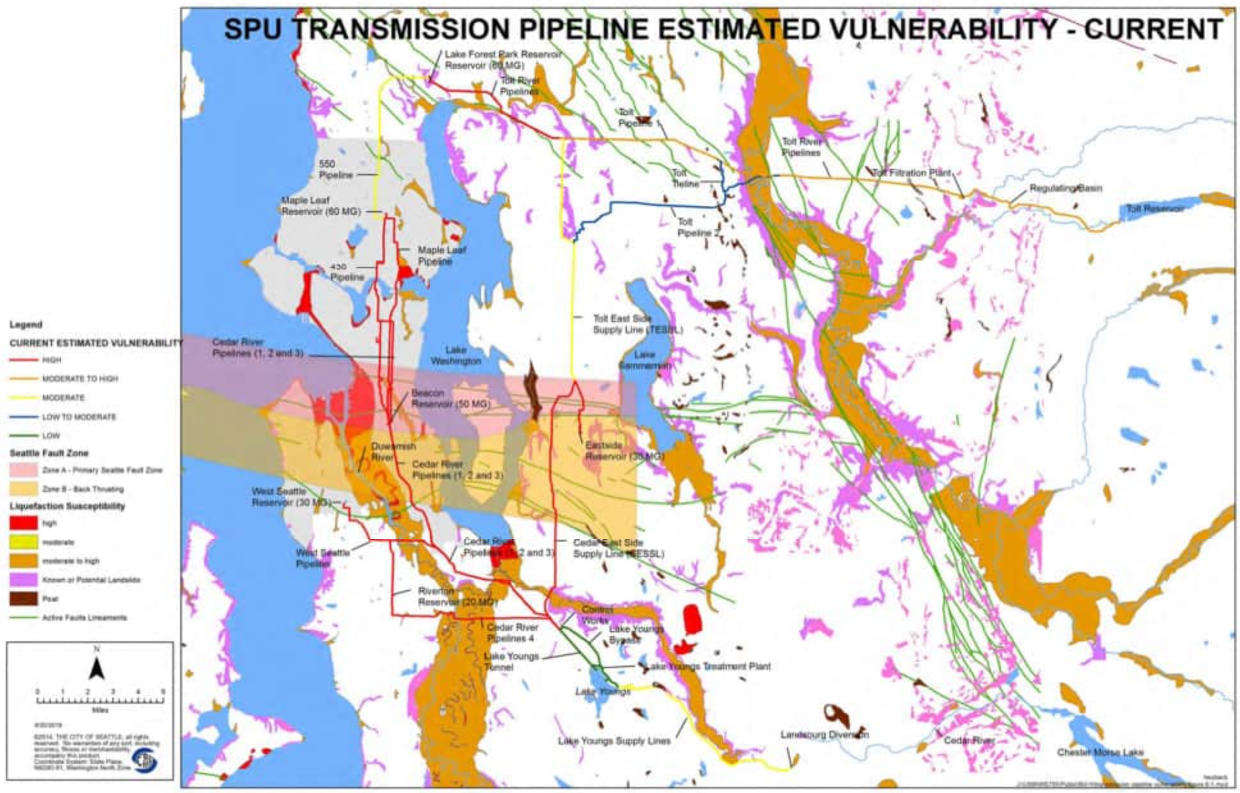
This document characterizes and describes the range of improvement alternatives developed to improve the City's water system seismic resilience and reduce the customer outage durations and economic impacts to the region resulting from loss of water service after a major earthquake. The improvement alternatives presented in this document are developed under the following five categories:

- Water Supply Improvements
- Resilient System Backbone Improvements
- Facility (Pump Station and Reservoir) Improvements
- Widespread Pipe Replacement
- Operational Improvements

2. Water Supply

The City of Bellevue purchases water from Seattle Public Utilities (SPU) as part of the Cascade Water Alliance (Cascade), of which Bellevue is a member utility. Water supply for Bellevue is supplied into the City water system from the Tolt Supply Line (TSL) from the north via the Tolt Eastside Supply Line (TESSL) and from the Cedar Supply Line (CSL) from the south via the Cedar Eastside Supply Line (CESSL). While the SPU 2018 Water System Seismic Study did not include analysis of the TESSL, CESSL or TSL, the overall estimates included detailing likely water service restoration timelines for the SPU direct water service area customers is informative. The study reports that expected service restoration time for direct service customers is up to 3 weeks, and it is further assumed that this would occur before restoration of water service via the CESSL and TESSL. Based on this, the SVA assumes 21 days as a minimum likely water service outage duration relative to SPU regional system water supply into the City of Bellevue following a major seismic event, consistent with the current state of the SPU system. A schematic of the SPU Supply System is provided in Figure 1.

Figure 1: SPU Supply System Schematic and Current Estimated Vulnerability
From 2018 Seattle Public Utilities Water System Seismic Study Summary Report



Alternatives to improve the seismic resilience of water supply delivery into Bellevue were evaluated and are described below.

2.1 Improve Resiliency of SPU Supply

The City of Bellevue does not have direct control over SPU regional water supply and transmission system operations, resilience, improvements, or capital investment, and this system is essential to the current and likely future operation of the Bellevue water system. Because the evaluation of the SPU transmission system is outside of the scope of the SVA, the improvement alternatives considered for this analysis are based on general knowledge of the SPU transmission system and limited published data available from the SPU 2018 Seismic Study.

Ultimately, it will be up to the City to work with Cascade and SPU to evaluate the SPU regional water supply system and identify improvements and opportunities that can allow the City to reduce water service outage risks, mitigate water supply outage impacts, and meet its own target PE-LOS goals.

Improvements to the SPU system were defined based on those that are likely needed to get the SPU system functional in just one day following a major seismic event, and those that could be necessary to restore SPU supply functionality for Bellevue within 7-days following a major earthquake. Table 1 shows these two categories of improvements as well as the assumed cost impact to City of Bellevue ratepayers, along with notes about the assumed improvements that would be required within the SPU system to achieve the indicated levels of performance. These alternatives and values serve only as placeholders until an in-depth analysis of the SPU system and necessary improvements is completed. The improvements are focused on the Tolt Supply and TESSL because this a more direct route to get SPU water supply into Bellevue following a major seismic event, and also because this supply routing is likely to be less vulnerable to SFZE impacts. Note that SPU's stated approach has been to focus improvement on the Cedar Supply system since it is capable of serving more of the SPU supply area than the Tolt. It is expected that the cost to reach the same level of service from the Cedar Supply would be higher than from the Tolt Supply; however, other factors may require that additional cost to be justified after more in-depth evaluation is completed.

Table 1: SPU Supply System Improvement Alternatives

Improvement Alternative	Rough-Order-of-Magnitude Cost Assumption (Bellevue Ratepayer Impact)	Notes
SPU Supply to Bellevue Available in 1 Day	$45M	Assumes nearly complete replacement of Tolt Supply Line (upstream of TESSL) and TESSL with seismically resilient steel or ductile iron pipe, of which approximately 25% would be indirectly paid by City of Bellevue ratepayers.
SPU Supply to Bellevue Available in 7 Days	$15M	Assumes targeted replacement of critical vulnerable (landslide and liquefaction prone) areas along Tolt Supply Line (upstream of TESSL) and TESSL with seismically resilient steel or ductile iron pipe, of which approximately 50% would be paid by City of Bellevue ratepayers.
Note: The values in the table above are placeholder values based on budgetary costs for similar types of projects at other utilities. These values were assumed in order to identify the relative potential cost of different alternatives for consideration during evaluation as part of the SVA. Actual budgetary costs cannot be determined until a more thorough evaluation of the TSL and TESSL is completed and required improvements are identified. Costs shown reflect assumed total project cost.		

2.2 Groundwater Supply in Bellevue

2.2.1 Preexisting Groundwater Wells for Emergency System Supply

In 2019, the City of Bellevue completed a planning study for emergency water supply which is summarized in the *Bellevue Emergency Water Supply Planning Report* (HDR & Stantec, 2020). This report identifies several different options and goals that could be addressed to provide emergency water supply to Bellevue. The City holds water rights for existing groundwater supply wells that are not currently equipped to supply potable water into the City's distribution system. Primary conclusions of the emergency supply report that are relevant to the improvement alternatives considered for the SVA are summarized below:

1) The City's current water rights may not be sufficient relative to the full water system demand following an earthquake.

2) The City could develop emergency groundwater supplies that would provide a baseline volume of supplemental water supply for use following a major seismic event, and it is likely feasible that emergency water rights could be legally secured to support such supply.

3) The City's four existing water supply wells and sites could be reconstructed and configured with community water distribution capability to support drive-up water bottle filling stations.

The *Emergency Water Supply Planning Report* recommends a minimum emergency water supply of 9 MGD, which is less than the average Bellevue winter water demand of 12 MGD. Most utilities plan for post-earthquake demands to be similar to average winter demands, given that there are some water demand savings and reductions that can be accomplished due to curtailment and conservation. However, a significant portion of the water supply after a major earthquake will likely be required for firefighting and water system restoration and repair, in addition to a significant amount of water loss due to pipe leaks and breaks, and other system seismic damage.

Permanent, full-time operational groundwater supply to the Bellevue water system at capacities that could meet the post-earthquake demands are not realistic or feasible in the planning horizon for this project, so the permanent groundwater supply option has been eliminated from consideration.

The *Emergency Water Supply Planning Report* identified a target alternative to develop up to 3.8 MGD of emergency well capacity that is connected to the system only during an earthquake. The estimated capital cost for this alternative was $7.5 million. In order to have a representative total project budget for 9 MGD of emergency water supply the groundwater supply alternative assumes a total project cost of $20 million for potential emergency well supplies.

If this alternative is implemented, the City will require additional operations staff to test, exercise, and maintain these wells so that they are available in the event of an emergency. For planning purposes, the City should assume that a two-person crew will spend 2 days per month at each well site. For example, if the emergency groundwater system includes 5 wells, the City should assume a two-person crew will spend 10 days per month on the wells, which is equivalent to 1 FTE. This assumption is based on approximately one day for pump, treatment system, and generator testing. The other day would be allotted for maintenance activities, which might require 1 day each at multiple wells or several days at one well in any given month.

2.2.2 Groundwater Wells for Emergency Local Water Distribution and Supply

In addition to the use of the preexisting wells for emergency system supply and/or as community distribution points, the *Emergency Water Supply Planning Report* identified the potential to develop other lower capacity emergency wells to be used as emergency neighborhood water distribution points. While this is alternative would provide significant value in making water available via fill stations while service from the water distribution system is being restored, it does not allow for the City to supply water to critical customers and have water available to begin locating and repairing water main breaks immediately after an event even if the SPU supply is not available.

Given the substantial benefits and relative ease of implementation, it is recommended that the City develop neighborhood distribution emergency wells as described in the *Emergency Water Supply Planning Report*.

2.3 Connection to Neighboring Groundwater Supplies

Three utilities (Issaquah, Redmond, and Sammamish Plateau Water) on the eastside of Lake Washington and adjacent to Bellevue own and operate permanent groundwater supplies. Of these, Redmond and Issaquah are already connected directly to the Bellevue Water System via interties between the two systems. Sammamish Plateau Water is not currently connected directly to the Bellevue Water System.

For the purposes of supply augmentation during a major seismic event such as the two considered as part of the SVA, none of these utilities have adequate groundwater supply to provide all of their normal demands from groundwater alone. Sammamish Plateau Water is the closest with 80% of their supply supported from their groundwater sources. Since none of these neighboring utilities have excess groundwater supply available, and because any such available supplies would be likely be dependent on additional pumping in order to supply the Bellevue system, the option of including emergency water supply from a neighboring utility was eliminated from the analysis as not feasible/desirable relative to other water supply and resilience options. The City should still pursue emergency interties with neighboring utilities where hydraulically feasible in order to provide localized benefits in reliability and service restoration.

3. Resilient System Backbone Routes

Water from the SPU regional supply system feeds primarily into the Bellevue 400 and Lake Hills 520 zones. These two zones are the largest zones in the Bellevue water system, and along with having the most pipe in the system, they also are expected to experience the most pipe damage during a major seismic event. After reviewing the as-is damage and restoration durations, it was apparent that resilient backbones to feed key parts of the system, connecting water supply to the customers in less vulnerable zones, had the potential to provide significant value with reduced cost compared to widespread pipe replacement in these large distribution zones.

The evaluation did not incorporate any additional resilience features for backbone piping compared to normal distribution system piping. See Section 5 for the evaluation and assumptions associated with pipe replacement alternatives. The evaluation showed that improvement to these levels provides a significant reduction in the number of pipe repairs required for these routes following a major earthquake, which would be adequate to allow the city to achieve the target level of service goals. This is true as long as the backbones themselves can be isolated in a timely manner, the details of which was outside of the scope of the study.

The City and Jacobs worked together to develop a collection of resilient backbone routes for consideration as part of the improvement prioritization evaluation. The backbones developed are shown in Table 2 and Figure 2. The table shows the primary function that each of the backbone routes serve, the length of the backbone segment, and a cost for replacing the pipe within the backbone. Note that cost assumptions for distribution pipe replacement are presented in Section 6. Critical customer categories 1, 2, and 3 are defined in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment. The functions of the backbone routes are defined as follows:

Community Recovery: These system backbones provide water to community recovery facilities such as community centers and high schools, emergency operations centers, and maintenance facilities. They also serve as critical transmission corridors to move water throughout the water system.

Supply to South Bellevue from TESSL/Wells: These system backbones convey water from the TESSL water supply inlet stations and emergency wells in the Crossroads area to the Eastgate and Factoria areas to provide water to customers in South Bellevue.

Serves Isolated Zone: These system backbones provide connections to zones that are isolated on the edges of the distribution system.

Critical Customer: These system backbones primarily function to serve critical customers.

Economic Impact: These system backbones serve the economic centers of the city as a means to maintain water supply in support of economic activity and post event recovery.

Supplies Southeast Hills: These system backbones are parallel pipes that serve the higher residential zones on Sunset hill, Somerset hill, and Cougar Mountain.

Connection to CESSL: These system backbones provide connections from the CESSL water supply inlet stations to other major supply corridors.

Connection to TESSL: These system backbones provide connections from the TESSL water supply inlet stations to other major supply corridors.

Figure 2: SVA Resilient System Backbone Routes

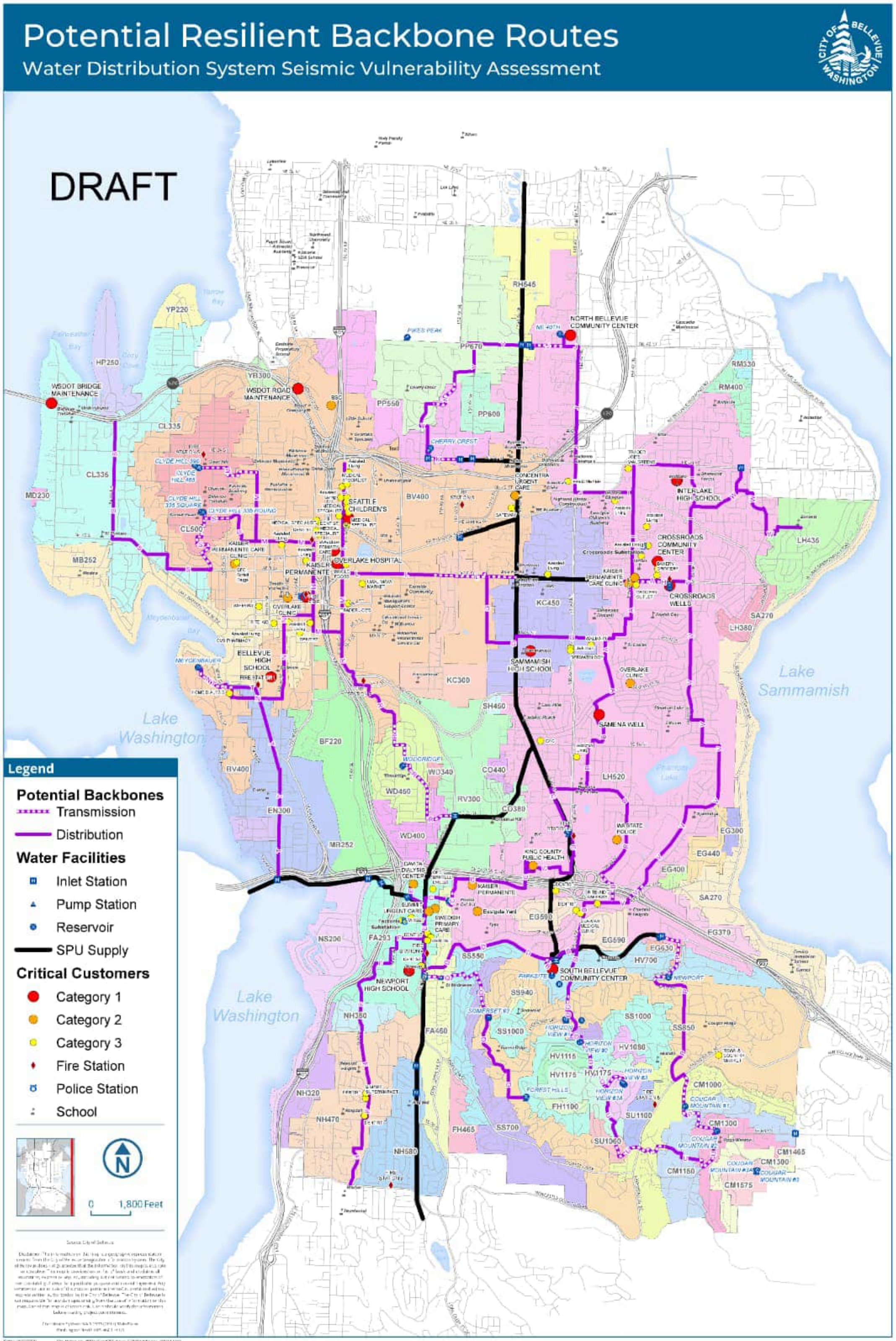


Table 2: SVA Resilient System Backbone Alternatives

ID	Route	Primary Function	Pipe Replaced in Improvement Alternative (ft)	Replacement Cost (2021 $)
A	Crossroads to Samena Well	Community Recovery	8,736	$4.3 M
B	Samena Well to Parksite/SBCC	Supplies South Bellevue from TESSL/Wells	13,659	$6.0 M
C	Lake Hills to Factoria	Supplies South Bellevue from TESSL/Wells	6,721	$5.2 M
D	Parksite to Factoria	Supplies South Bellevue from TESSL/Wells	5,315	$2.5 M
E	Inlet #11 to dialysis center & Factoria Blvd / Inlet #11	Community Recovery	2,292	$1.9 M
F	Newport Hills to Factoria	Serves Isolated Zone	10,280	$4.4 M
G	LH520 to BV400	Community Recovery	7,526	$4.1 M
H	NE 8th Inlet to Crossroads	Community Recovery	1,525	$1.5 M
I	Crossroads to Interlake HS	Community Recovery	13,674	$5.9 M
J	NE 40th Inlet to Bel-Red*	Community Recovery	8,082	$4.3 M
K	Cherry Crest Inlet and Pump Station	Community Recovery	1,070	$0.6 M
L	136th Ave Inlet to Hospitals	Critical Customers	10,338	$5.6 M
M	Bel-Red/Downtown/Clyde Hill	Economic Impact	13,421	$7.2 M
N	Downtown to Meydenbauer	Serves Isolated Zone	7,689	$3.7 M
O	Horizon View Pump Supply	Supplies Southeast Hills	8,801	$4.8 M
P	Cougar Mountain Pump Supply	Supplies Southeast Hills	97	<$0.1 M
Q	Somerset/Forest Hills Pump Supply	Connection to CESSL	4,848	$2.6 M
R	Richards/Woodridge to Downtown	Connection to CESSL	9,459	$4.6 M
S	Clyde Hill to Medina	Serves Isolated Zone	20,700	$11.1 M
T	Enatai to Meydenbauer	Connection to CESSL	12,501	$5.9 M
U	Horizon View to Cougar Mountain	Supplies Southeast Hills	40	<$0.1 M
V	Crossroads to Eastgate	Supplies South Bellevue from TESSL/Emergency Wells	14,158	$6.7 M
W	Lake Hills Spur	Community Recovery	7,354	$3.3 M
Y	NE 40th to Cherry Crest	Connection to TESSL	9,254	$4.1 M

4. Facility Improvements

Facility Improvements focus on improving the seismic resiliency of pump stations, reservoirs, pressure reducing valve (PRV) stations, and water supply inlet stations from SPU supply corridors. Because most PRVs and inlets are in buried vaults and structures, they tend to have reasonable inherent seismically resiliency and did not receive significant focus in this analysis. Reservoirs are helpful for pressure equalization and redundancy for short-term localized emergencies or planned pipeline shutdowns, but cannot feasibly store enough water to mitigate or maintain service through a regional supply outage. The City's operators have confirmed that almost all pressure zones can be operated (some at reduced pressure) without a reservoir online in an emergency scenario. As such, the majority of the focus for the SVA is on the seismic resilience of pump stations, as they are critical to moving water from the lower supply fed zones up to customers located at higher elevations.

The facility improvements are divided into categories as follows:

- Required for backbone routes: Facilities located at the start or end of resilient backbone routes or are integral to the backbone routes
- Required to supply zones not on backbone routes: Facilities that are the primary or only source of supply to zones, but are not a part of a backbone route
- Backup or redundant facilities: Facilities that are not the primary or most direct feed to a zone and can easily be bypassed and still provide water to customers

Ultimately, facilities are the hardest element of the system to bring back online after an earthquake due to the potential for damage to the structure and the interior components, long lead times to replace equipment, resource limitations for repair, and need to get red-tags removed prior to re-entry. Given this, the City should develop a plan to eventually upgrade all pump stations to be seismically resilient in order to allow for full system restoration in the target timeframes described by the target PE-LOS goals.

Costs for improvement or replacement of each pump station were developed to be incorporated into the improvement prioritization analysis. The costs shown are based on data extracted from the City of Bellevue Water System Capital Project Planning Budget Tool, which uses a unit cost value of $900,000 per MGD of pump station capacity (as 2021 dollars). This unit cost value of $900M/MGD was used for all pump station replacement cost calculations except for Forest Hills because Forest Hills has significant geotechnical concerns that may require significant additional work or relocation to include construction of a new pump station and reservoir.

Figure 3 and Figure 4 show City water system facilities and their expected probability of failure for the CSZ and SFZE events overlayed on the water system hydraulic profile (taken from the *2016 City of Bellevue Water System Plan*). Probability of failure is defined as the estimated likelihood of extensive or complete damage (resulting in the facility being offline) following the seismic event, as defined in TM 2: Seismic Analysis Methodology for Pipeline and Facilities Assessment. The areas of the system that are served by the highest risk facilities can be observed from the information shown in Figure 3 and Figure 4. The capacity, anticipated replacement cost, associated system backbone route (if applicable) and probability of failure in each of the considered earthquake events is shown in Table 3 for each of the pump stations. Enhanced risk categories have been noted for facilities that are required for defined backbone routes. Future upgrades or replacement of these facilities should be in accordance with the Enhanced Performance Criteria defined in Table 4.

Table 3: Pump Station Improvements Summary

Pump Station	Capacity (MGD)	Assumed Replacement Cost (2021 $)	Backbone Route	SFZE Failure Prob.	CSZ Failure Prob.	Notes (See below)	Risk Category (See Table 4)
Cherry Crest	New PS, Not Evaluated					2	
Clyde Hill	3.1	$2,800,000		76%	24%	1	
Cougar Mountain 1	3.1	$2,800,000	P	62%	4%		IV
Cougar Mountain 2	2.9	$2,600,000	P	62%	3%	1	IV
Cougar Mountain 3	3.6	$3,200,000		62%	3%		
Forest Hills	3.9	$10,000,000		61%	7%	3	
Horizon View 1	5.2	$4,700,000	O	25%	1%	2	IV
Horizon View 2	3.2	$2,900,000	O	83%	20%	1	IV
Horizon View 3	3.8	$3,400,000		20%	<1%		
Lake Hills (Crossroads)	5.1	$4,600,000		56%	6%	4	
Meydenbauer	1.2	$1,100,000		26%	1%		
NE 8th Inlet 1	13.6	$12,200,000		15%	<1%		IV
NE 40th Reservoir	14.4	$13,000,000		38%	6%	4	
Newport	3.7	$3,300,000	P	62%	4%		IV
Parksite	5.7	$5,100,000	O	86%	22%	1	IV
Pikes Peak	Decommissioned and Incorporated into new Cherry Crest PS					1	
SE 28th Inlet	11.6	$10,400,000		33%	<1%		
Somerset Inlet	5.2	$4,700,000	Q	26%	<1%		
Somerset 2	4.1	$3,700,000	Q	22%	<1%		
Woodridge	9.8	$8,800,000		68%	7%	5	
161st Ave Inlet	10.1	$9,100,000		25%	<1%		
670	6.9	$6,200,000		67%	23%		IV
CCUD 475/580	7.8	$7,000,000		No Structural Data			

Notes (See Notes Column in Table):

1- Already Programmed or Budgeted for Replacement
2- Recently Replaced or Upgraded
3- Requires significant geotechnical improvements or relocation
4- Repumps into storage facility, emergency bypass possible
5- Pumps to zone also fed by PRV from above

Figure 3: CSZ Facility Outage Probability

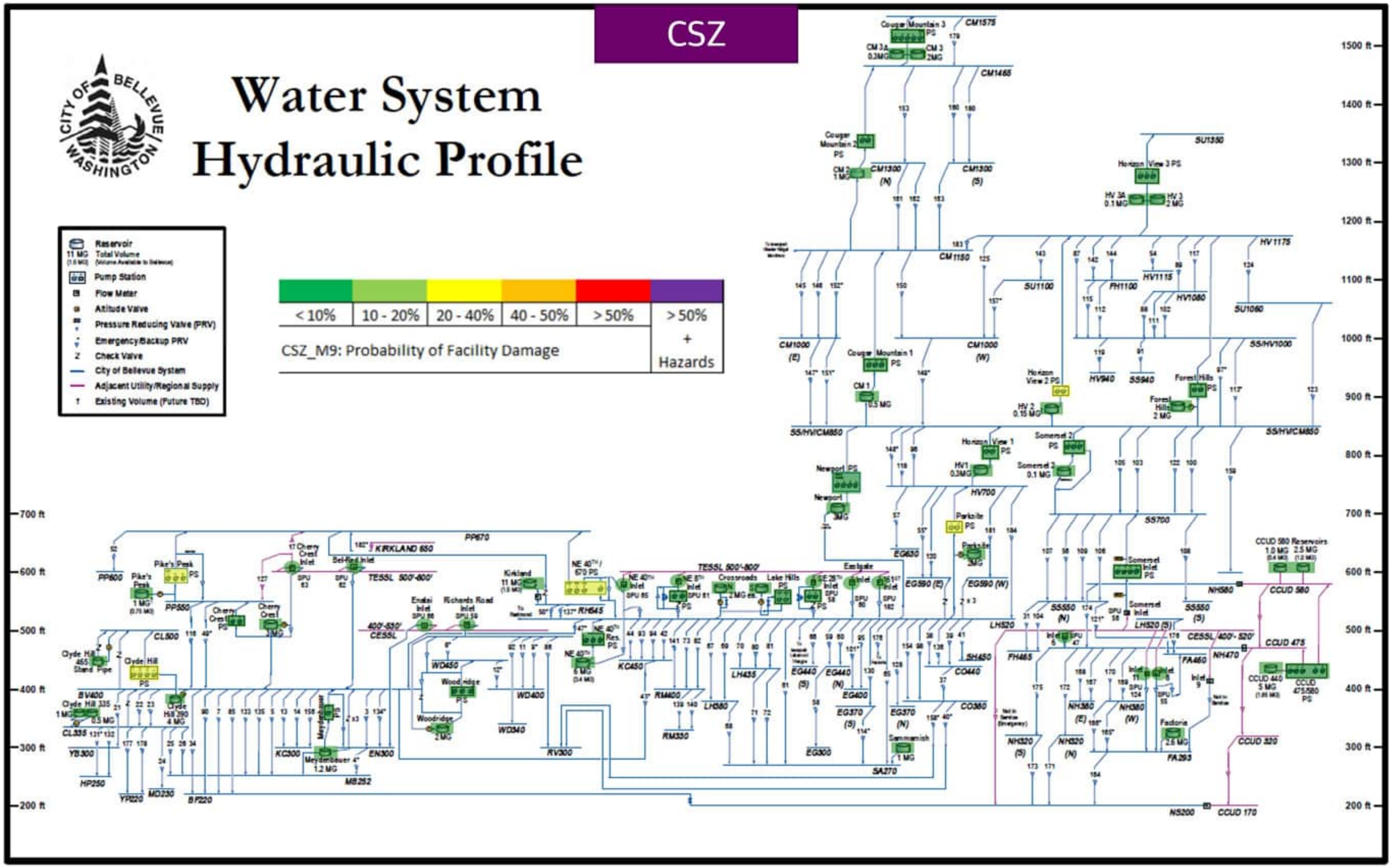
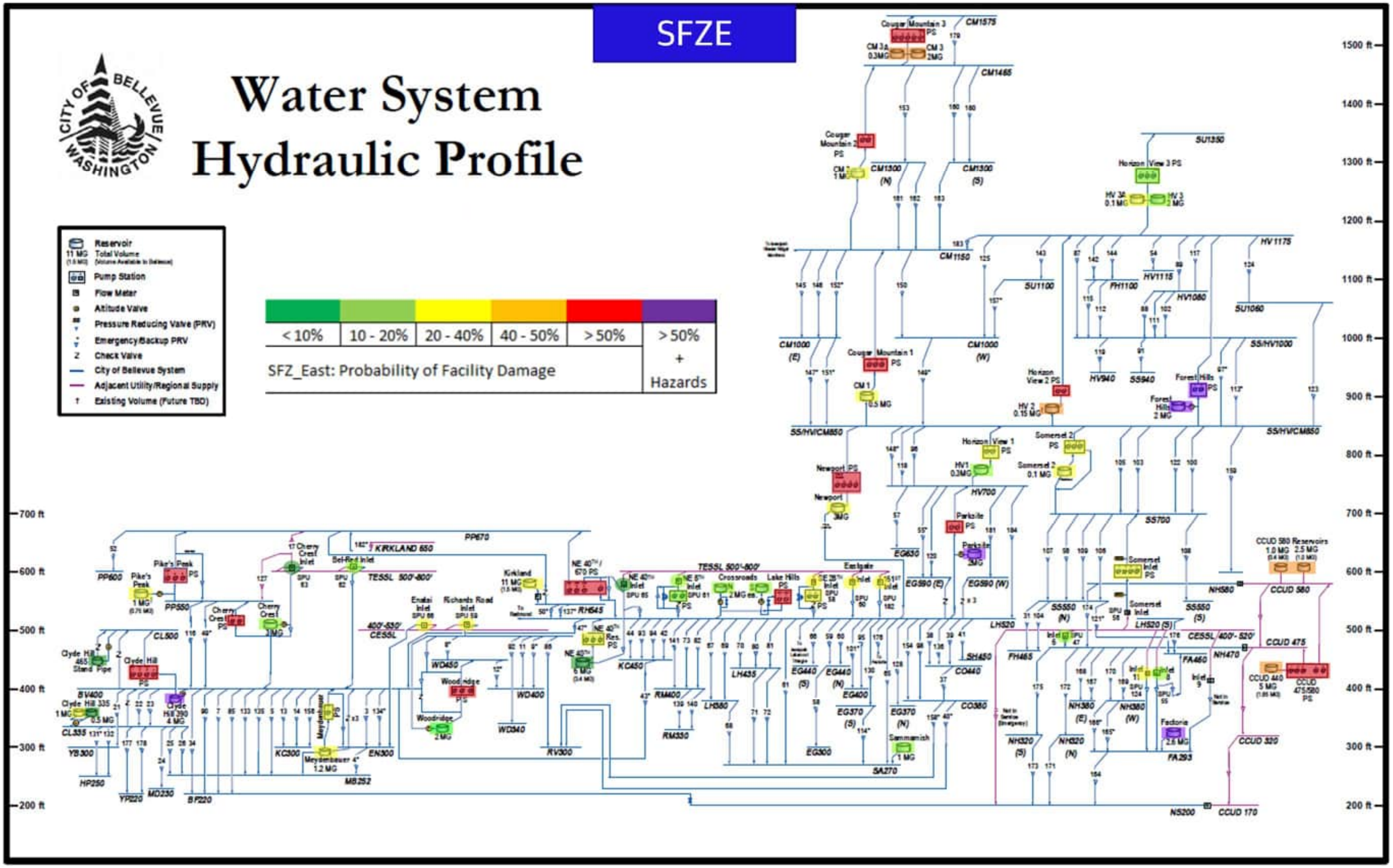


Figure 4: SFZE Facility Outage Probability



4.1 Facility Improvement Design Criteria Recommendations

As explained in Section 3.2 of TM 7: PE-LOS Goals, designing facilities (primarily pump stations) according to the International Building Code is likely not adequate to meet the Post-Earthquake Level of Service Goals targeted as part of a broader seismic resilience program. As such, the improvements assumed as part of the evaluation incorporate a higher level of seismic evaluation and design than would be required by code for most facilities.

Table 4 provides proposed enhanced performance criteria that should be adopted by the City to bring the pump stations up to a level that is consistent with the seismic events considered as part of the seismic vulnerability assessment. Following these criteria will be critical to allowing the City to improve the system to the point that the post-earthquake level of service goals developed as part of the SVA are achievable. This table should supplement other code based seismic design criteria during the evaluation and design of pump station improvements or replacement projects. Anytime that the code requires a higher performance level than this table, the code should take precedence. The Table is organized and formatted consistent to allow for extraction and use independent of this TM for ease of application and review by building code officials, design engineers, and architects.

Table 4: Bellevue Pump Station Enhanced Performance Criteria

	Enhanced Performance Criteria as Defined by ASCE 41			
	Lower Level Earthquake (BSE-1)		Higher Level Earthquake (BSE-2)	
	ASCE 41 Structure Performance	ASCE 41 Non-Structural Performance	ASCE 41 Structure Performance	ASCE 41 Non-Structural Performance
New Facility				
Design Earthquake	BSE-1N		BSE-2N	
Risk Category IV[1]	Immediate Occupancy[2]	Operational[2,3]	Immediate Occupancy	Position Retention, Ip=1.5[4]
Risk Category III	Immediate Occupancy	Operational[5]	Damage Control[6]	Position Retention
Existing Facility being Upgraded				
Design Earthquake	BSE-1N[7]		BSE-2N[7]	
Risk Category IV[1]	Immediate Occupancy[2,8]	Position Retention, Ip=1.5[2,4,9]	Immediate Occupancy[8]	Position Retention, Ip=1.5[4,9]
Risk Category III	Immediate Occupancy[8]	Position Retention, Ip=1.5[4,9]	Damage Control[6]	Position Retention

Table Notes:

1) Includes Bellevue Water System facilities required to provide water to Emergency Room Hospitals, designated resilient supply points, backbone routes, and community recovery facilities; in addition to Essential Buildings as defined by IBC Table 1604.5. Refer to categorization of Bellevue Water System facilities included in 2021 Water System Seismic Vulnerability Assessment project documentation.

2) Due to enhanced performance requirements for BSE-2N, the BSE-1N requirements for Category IV structures will not control evaluation or design.

3) Special Certification not required for active mechanical and electrical equipment unless building is categorized as essential as defined by IBC Table 1604.5. Certification is still required for facilities if required by IBC and ASCE 7.

4) Non-structural performance shall be designed for position retention, but with the importance factor increased to 1.5.

5) Special Certification not required for active mechanical and electrical equipment.

6) Structures designed for damage control shall target occupancy within 14 days after the BSE-2N earthquake, in the opinion of a registered design professional.

7) In order to achieve the City of Bellevue Water System Level of Service Goals, Existing facilities must have the same performance as new facilities and shall be evaluated based on the same seismic events used to design new facilities.

8) Destructive testing not required unless recommended by registered design professional or building is categorized as essential as defined by IBC Table 1604.5.

9) Existing facilities' non-structural components should be designed for position retention. If existing active mechanical or electrical equipment is to be replaced as part of or after a structural facility upgrade, the non-structural performance shall be designed in accordance with a new facility as defined in this table.

5. Widespread Pipe Replacement

Widespread distribution system pipe replacement will be considered to determine the potential to reduce the overall number of leaks and breaks that would need to be repaired after a seismic event. This includes evaluation of widespread improvements to the entire system, or just to specific parts of the water system.

The primary focus of this evaluation is to consider the benefits of replacing existing seismically vulnerable asbestos cement (AC) and cast iron (CI) pipe with more seismically resilient materials and pipe joint configurations. As described in TM2: Vulnerability Analysis Methodology and TM2A: Comparison of ALA (American Lifelines Alliance) Equations to Christchurch Earthquake Repair Data, the expected number of repairs for AC or CI pipe is approximately 12 times greater than for unrestrained ductile iron (DI) pipe installed in the same location.

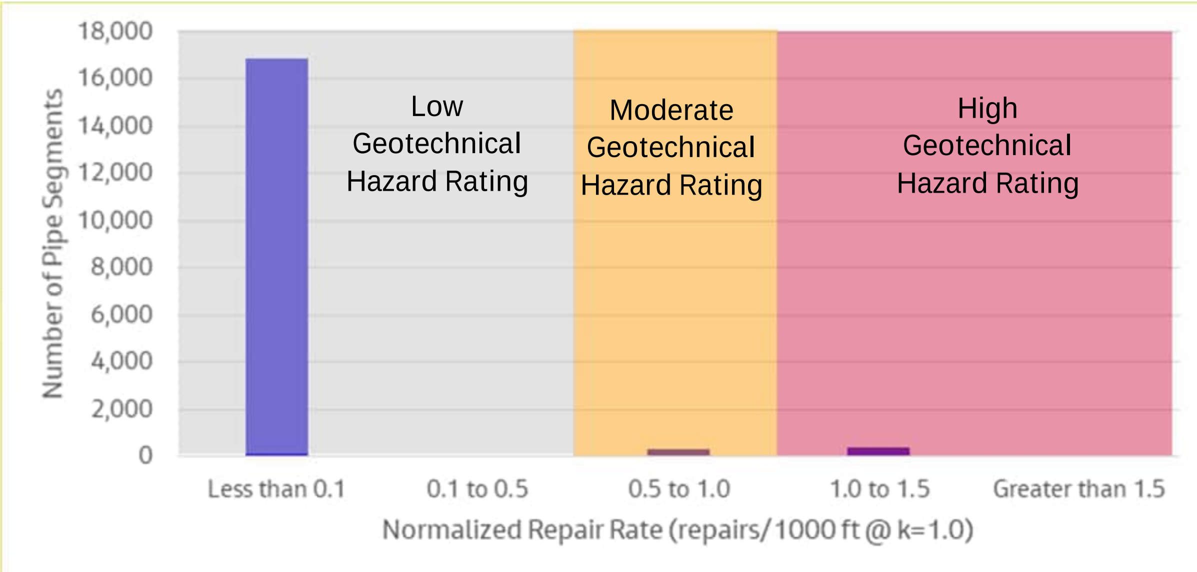
Additionally, this alternative considers the potential benefit of replacing pipe in geologically vulnerable areas (areas with higher potential for liquefaction or earthquake induced landslides) with more resilient piping such as restrained DI or earthquake resistant ductile iron pipe (ERDIP), consistent with the associated ISO 16134 standard. Note that high-density polyethylene (HDPE) fusion welded pipe could also potentially be another seismically resilient piping alternative to consider for vulnerable area installation, but that HDPE was not specifically evaluated because it is a significant departure from the current piping standards for the City, where DI piping is already in common use.

5.1 Pipe Location Vulnerability Rating

In order to identify the relative vulnerability of pipe locations in the water system, a geotechnical hazard rating was developed based on the pipe material normalized repair rate for each pipe in the system. Normalized repair rate represents the expected repair rate in repairs per 1,000 lineal ft (LF) of pipe if the ALA equation pipe K1 and K2 coefficients (measures of pipe material fragility) were assumed equal to 1 for the Seattle Fault Zone East seismic event. This approach allows the vulnerability of every location in the system to be compared to the rest of the system, regardless of the pipe material.

Figure 5 shows a histogram of the normalized repair rate per 1,000 LF of pipe for all pipe locations in the Bellevue Water System. Based on this information, all pipes with a normalized repair rate less than 0.5 repairs/1,000 LF were categorized as low vulnerability. Pipes from 0.5 to 1.0 repairs/1,000 LF were categorized as moderate vulnerability and those with normalized repair rates greater than 1.0 were categorized as high vulnerability. The geotechnical hazard rating information shown in Figure 5 was used in the development of the Pipe Replacement Alternatives discussed in Section 5.3.

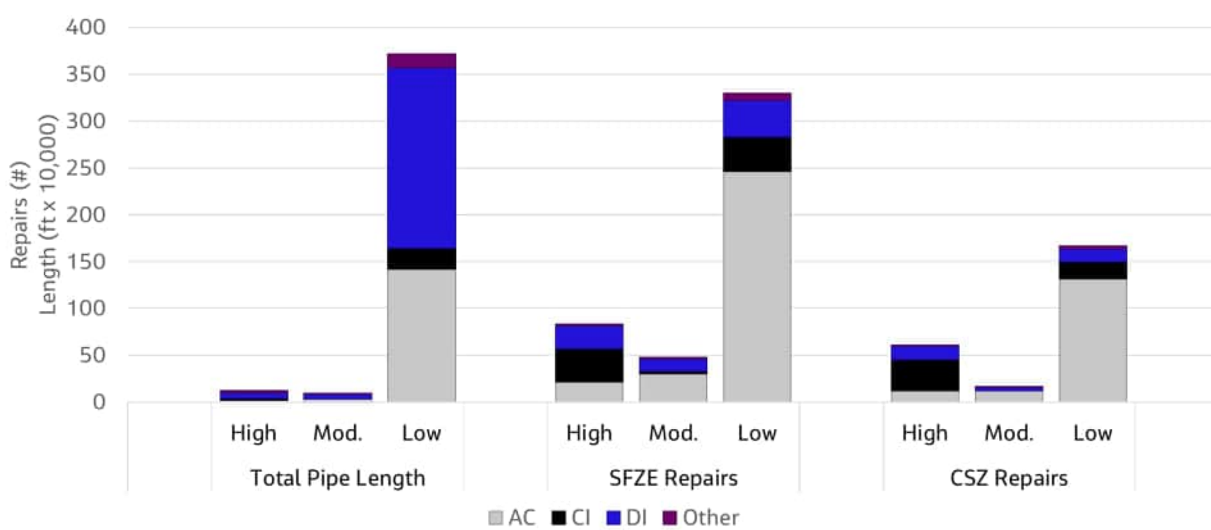
Figure 5: Water System Normalized Repair Rate Histogram



5.2 As-is Contribution of Repairs by Existing Pipe Material

Figure 6 shows the total length of each major pipe material in the water system in each vulnerability rating category as well as the number of expected post-earthquake repairs for each material and vulnerability. This shows that 65 percent of the post-earthquake repairs are expected to be in AC pipe which comprises only 30 percent of the water system by length. Similar to the geotechnical hazard rating information in Figure 5, the pipe repair information shown in Figure 6 was used in the development of the Pipe Replacement Alternatives discussed in Section 5.3.

Figure 6: Expected Repairs to Existing System by Pipe Material and Vulnerability Rating Category



5.3 Pipe Replacement Alternatives

Using the information shown in Figure 6, five pipe replacement alternatives were developed based on potential “design standards” that could be implemented as pipe is replaced and/or pipeline seismic resilience improvements are completed over the course of the next several decades. The alternatives are defined based on the minimum pipe material in terms of seismic resilience that would be installed in each of the three vulnerability rating categories. Table 5 shows the materials that are proposed under each of the alternatives considered for each geotechnical hazard rating category.

Table 5: Pipe Replacement Alternatives Summary

Geotechnical Hazard Rating	Pipe Material Standards				
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
High	Unrestrained DI	ERDIP	ERDIP	ERDIP	ERDIP
Moderate	Unrestrained DI	Restrained DI	ERDIP	ERDIP	Restrained DI
Low	Unrestrained DI	Unrestrained DI	Unrestrained DI	Restrained DI	Restrained DI

Figure 7 shows the total amount of pipe that would need to be replaced system-wide to achieve the pipe material combinations shown in Table 5. The primary differences between alternatives 1 through 3 are the amount of pipe to be replaced in high and moderate vulnerability areas, because of the need to essentially replace all pipe in those areas. However, the amount of pipe in such areas is relatively small, so the total replacement length to accomplish that is minimal. Alternatives 4 and 5 require significant additional replacement of pipe because all unrestrained DI pipe in all areas would need to be replaced. However, this has minimal actual increased cost if the replacement of this pipe occurs when the pipe is being replaced for other reasons (i.e., age or capacity) as the only added cost at that time is the cost increase to incorporate restraint at the pipe joints.

Figure 7: Pipe Replacement by Material for Each Alternative

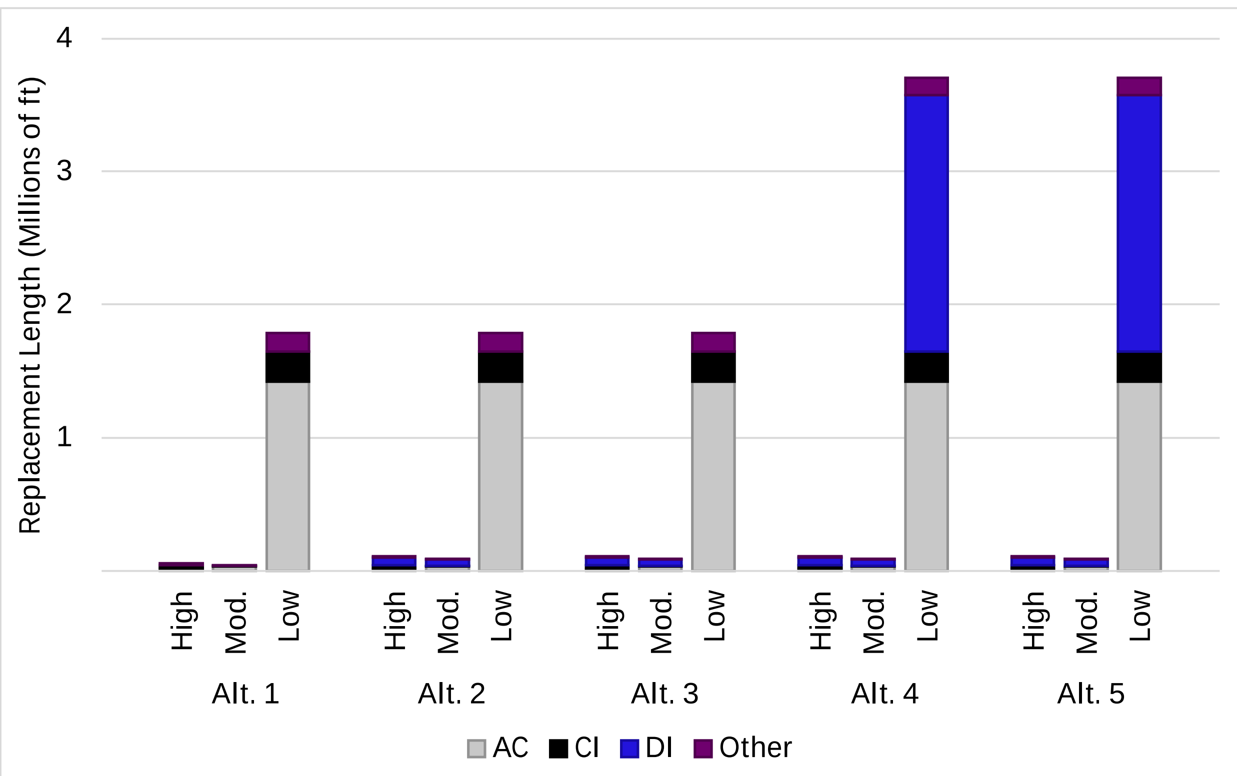


Figure 8 shows the expected number of repairs for pipe in each vulnerability category for the existing system based upon information in Figure 6 for each of the pipe replacement alternatives (assuming that all pipe in the system has been replaced to meet the standard described in the alternative). As illustrated by the repair comparison between the existing system and Alternative 1, the largest impact to the reduction in post-earthquake repairs results from replacing brittle pipe (AC and CI) in low vulnerability areas with DI pipe. Alternative 2 provides a substantial improvement over Alternative 1 in the high vulnerability areas through the implementation of ERDIP in these areas. By replacing existing pipes with ERDIP in moderate and high vulnerability areas under Alternatives 3 and 4, there is a further reduction in expected post-earthquake repairs. Alternatives 4 and 5 incorporate restrained DI pipe in low vulnerability areas, which can be expected to result in a small additional reduction in post-earthquake repairs.

Figure 8: Improvement Alternative Repair Comparison

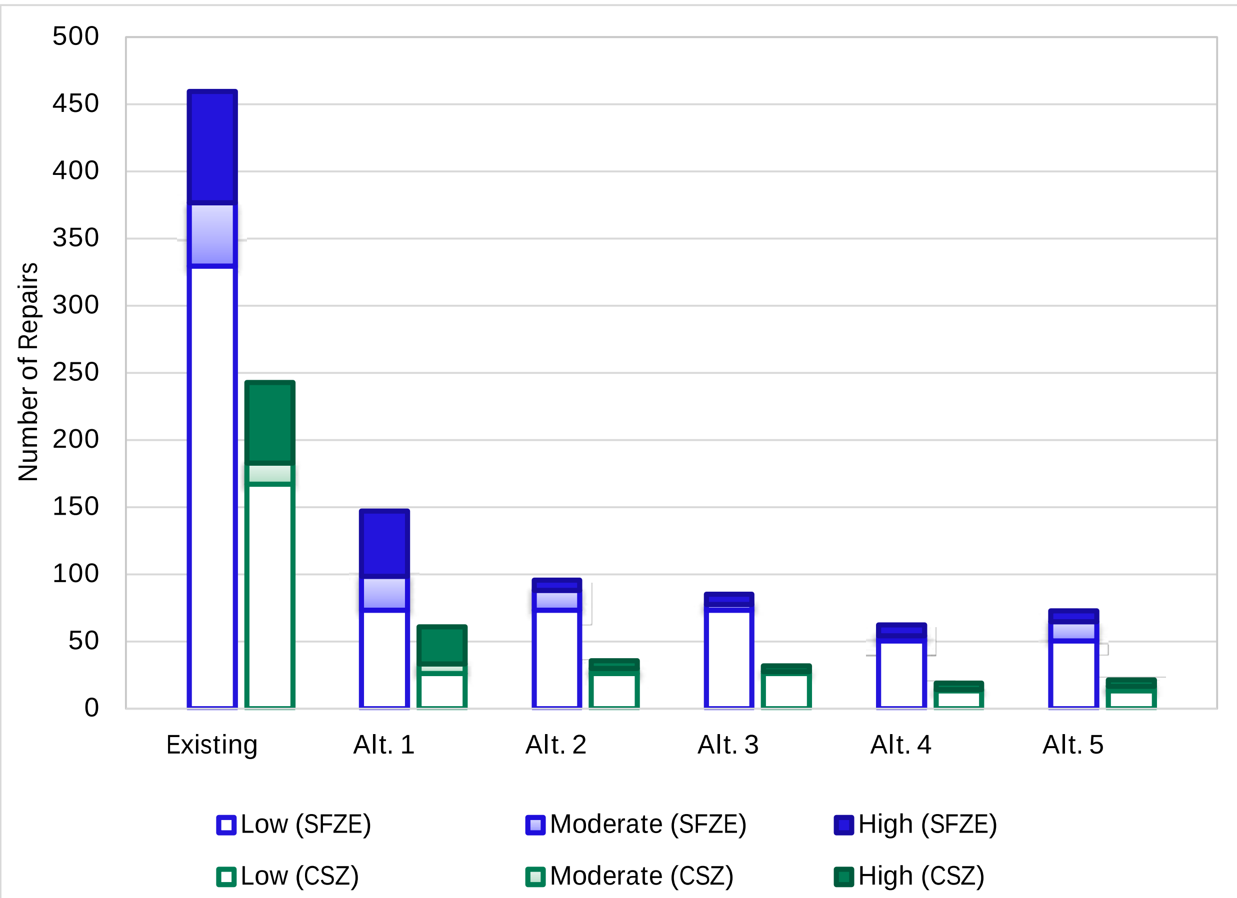


Figure 9 shows the length of pipe and total pipe replacement costs estimated for each of the 5 alternatives. The cost to replace AC pipe is shown separately for the cost to replace other types of pipe. Based on the assumption that the City will replace all of the AC pipe in the system in the next several decades, only the cost to replace other pipe would be considered additive costs over currently planned spending as long as the improvements are phased on a similar pipe replacement timeframe. Alternatives 4 and 5 show a significant jump in the length of pipe and quantity of non-AC pipe that would need to be replaced.

Figure 10 shows a comparison of the pipe replacement cost and the number of repair reductions for the SFZE earthquake scenario. The cost is broken up into the cost to replace pipe with unrestrained or restrained DI pipe. Alternatives 1 through 3 each have gradually increasing reductions in the number of post-earthquake pipe repairs with minimal increase in cost. Alternatives 4 and 5 have limited additional reduction in post-earthquake repairs, but over double the cost.

Because Alternative 3 has a significantly lower cost than alternatives 4 and 5, but similar benefit (reduced leaks and breaks), it was selected to use as the baseline for evaluation of the value of these improvement alternatives and the identification necessary improvements to achieve the target PE-LOS goals.

Figure 9: Pipe Replacement Alternatives Lengths and Costs

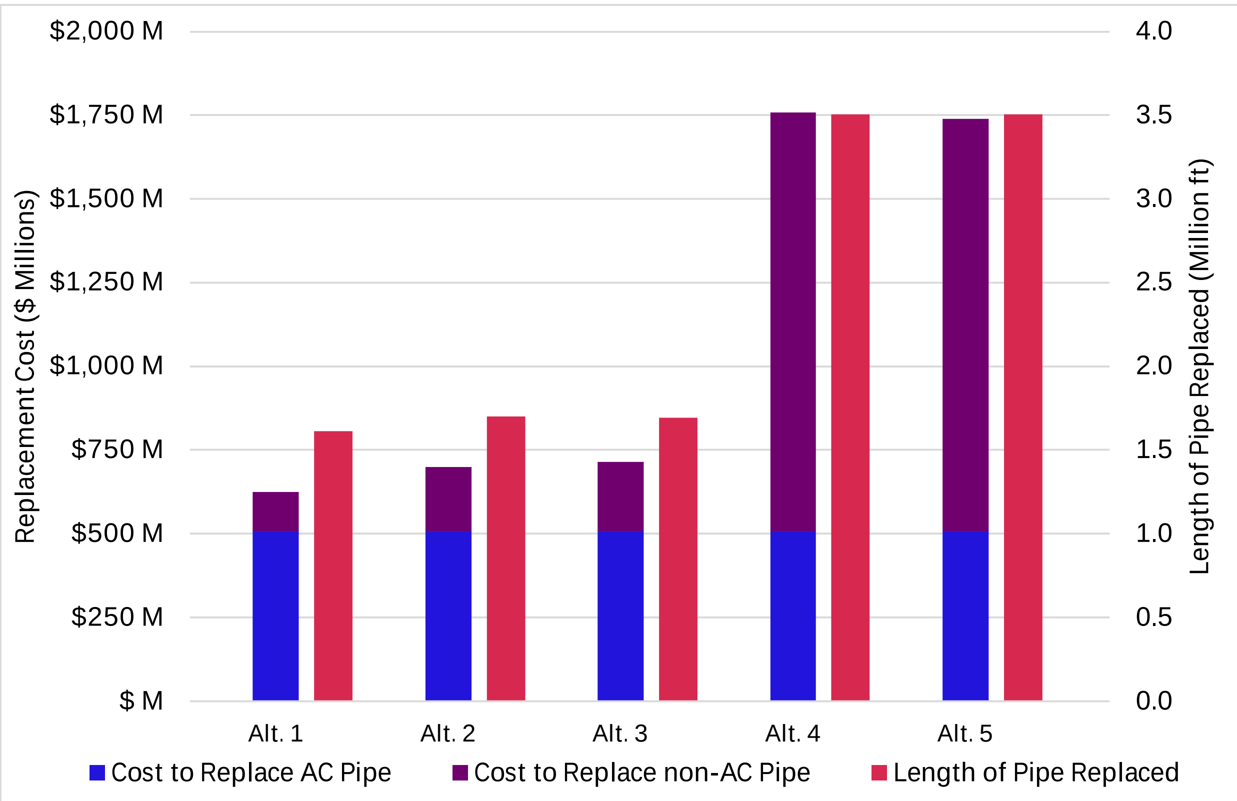
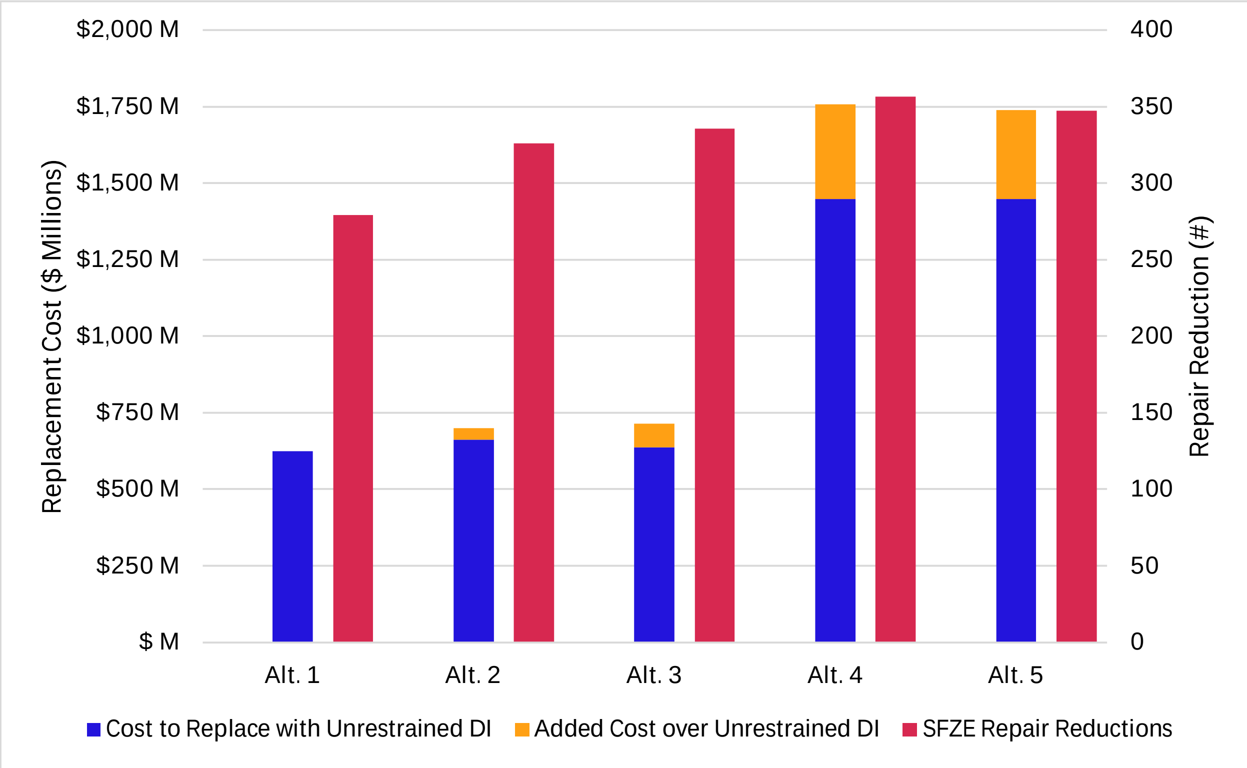


Figure 10: Pipe Replacement Cost and Repair Reduction Comparison



6. Improvement Alternative Cost Assumptions

The following section describes the cost assumptions used for development of improvement alternative costs presented in this TM and the rest of the SVA. For all alternatives, the following markups on recent construction contractor bid prices are included in the costs shown, which are indicative of expected total project costs.

- Sales Tax = 10.1%
- Inflation = 2.5% from 2019 to 2021.
  *All costs shown are in 2021 dollars based on escalation from 2019 budgetary cost information. Abnormal or unusual price escalation due to 2020-2021 market conditions are not included.
- Contingency = 40%
- Non-Construction Costs =total of 37.1%
  - Consultant Design = 15%
  - Services During Construction = 3%
  - City Labor (non-construction management) = 5%
  - Permitting = 1%
  - City Construction Manager = 3%
  - Non-Construction Cost Contingency = 40%

6.1 Facilities

As described in Section 4, facility costs were developed using the City of Bellevue Water System Capital Project Planning Budget Tool. This tool assumes a cost of $393,000/mgd of construction cost for water system pump stations. After applying the markups shown above in the City of Bellevue Water System Capital Project Planning Budget Tool, the total project cost per mgd for pump stations is estimated at $900,000/mgd.

6.2 Distribution Pipe Replacement

Distribution pipe replacement costs were developed using historical City of Bellevue bid prices and cross referenced with the City of Bellevue Water System Capital Project Planning Budget Tool. The budget tool assumes a constant unit cost per inch diameter linear foot value for each pipe material type. Due to the magnitude and extent of the pipe replacement considered in this analysis, it was beneficial to develop representative costs for each pipe size or size range. Table 6 shows the total project pipe replacement cost per linear foot for each size and pipe material considered as part of the alternatives evaluation. This includes all of the markups noted above.

Table 6: Total Project Cost per Linear Foot Used for Pipe Replacement

	Pipe Material		
Pipe Diameter (in)	Unrestrained Ductile Iron	Restrained Ductile Iron	Earthquake Resistant Ductile Iron
4	$250	$300	$440
6	$340	$410	$610
8	$410	$480	$730
10	$450	$520	$830
12	$500	$610	$880
14	$580	$710	$1,030
16	$660	$810	$1,170
18	$740	$910	$1,320
20	$830	$1,010	$1,470
24	$990	$1,210	$1,760
30	$1,240	$1,510	$2,200
36	$1,490	$1,820	$2,640
48	$1,980	$2,420	$3,520

6.3 Cost Assumptions

Planning level costs estimates were developed based on recent City of Bellevue construction contractor bid price history using generic cost curves as described above. These estimates can be considered accurate for a range of +100/-50 percent. These costs are suitable for comparison and evaluation among alternatives. Individual projects or even overall program budgets should be budgeted using more detailed cost estimating methodologies aligned to the specific improvement elements and market conditions anticipated when such improvements will be implemented. The estimated costs outlined herein and throughout the SVA are based on and consistent with information available at the time of development, and may not align with future conditions. The final cost of water system improvement projects will depend upon the actual labor and material costs, competitive market conditions, implementation schedule, and other variable factors.

The purpose of the cost estimates presented herein and throughout the SVA is to provide a basis to make optimized decisions regarding capital expenditures and to provide concept-level guidance for budgeting implementation of mitigation improvements. As a result, the final project costs for each alternative will vary from the estimates presented herein. Because of this variability, project feasibility and funding needs must be carefully reviewed prior to making specific financial decisions.

7. Operational Improvements

In addition to the physical improvement alternatives described above, the team also developed a list of operational improvements. While none of these operational improvements reduce time that it takes to get the system back to a fully restored operational state, they are beneficial and useful to help reduce the impact of water system outages after an earthquake event.

7.1 Surface Water Drafting for Fire Protection

The Bellevue Fire Department regularly practices surface water drafting as a means to supplement fire flow delivery in areas adjacent to surface water bodies and lacking sufficient/convenient potable water supply for fire suppression needs. While this provides the ability to get water supply for fire suppression in areas near surface water, this approach is capacity limited and does not typically provide all the water needed for fire suppression, especially in major fires such as those that may be expected after a major earthquake. This practice is valuable and should be continued, but does not replace the need for a resilient water system that can meet City fire suppression needs immediately after a seismic event.

Figure 11: Bellevue Fire Surface Water Drafting Practice

Figure 12: Bellevue Fire Department Surface Water Drafting Connections

7.2 Emergency Preparedness Education

While Emergency Preparedness Education does not address or reduce the amount of time that water service may not be available during/following water supply emergencies, it does lessen the impact to residents who are more proactively prepared for extended water outages. Previously, preparedness education had focused on a mantra of “3 days, 3 ways”. While current education no longer references 3 days, this is still ingrained in many residents’ minds. Current recommendations are to be prepared with 3 days of water for evacuation and 14 days of water for home survival. While water system outages may last longer than 14 days, this is a good starting point for initial survival before water replenishment can occur.

Emergency preparedness education should include training on how much water to store, how to properly store water, and how to find and appropriately treat water for consumption when stored water runs out.

7.3 Jumper Hoses

Many utilities have developed plans to use jumper hoses connected between fire hydrants or blowoffs as a means to bypass pipe leaks and breaks in water systems and restore/maintain water supply to critical customers. The use of jumper hoses is a valuable approach for times when a single break is causing the loss of water to a critical customer. However, the use of a jumper hose does not address a wide-spread issue when hundreds of water main breaks are causing loss of continuity and supply pressures in the water system.

Even though the use of jumper hoses may not provide the water supply connectivity needed during the earthquake event, having hoses on hand to bypass a handful of breaks and potentially be able to provide an isolated supply from a nearby tank to the emergency room hospital or other critical customers could be a valuable investment. Operations staff should be properly trained on the storage, transport, deployment, disinfection, and general use of the jumper hoses.

7.4 Community Distribution Points

The City should develop plans and specified locations for community distribution points as a means to provide water during system supply outages. These locations should be prepared with 1) traffic flow management plans, 2) water bottle fill station manifolds, and 3) staff trained in running the facilities.

The improvement prioritization process will determine the proposed approach to increasing the resiliency of the system. Specific locations that can be counted on to serve water will be developed after the improvement approach for the system is identified. In general, these should start with emergency supply well locations and tanks with seismic valves, and then expand to cover a geographically diverse representation of the water system. Figure 13 shows an example of a water distribution manifold developed by Tacoma Water and stored onsite at one of their water supply wells.

Figure 13: Tacoma Water Emergency Water Distribution Manifold

7.5 Blivets

Blivets are collapsible water tanks that can be transported in the back of a truck for emergency water transportation and distribution. The Bellevue Water department has two blivets currently. While blivets do not result in quicker restoration of water system service, they do allow for the city to provide emergency water supply in areas of the city that may not have active water system service. The City should reconsider the available blivets and their condition, and consider having enough blivets on hand to be able to supply the basic drinking water needs of customers in areas of the City that are furthest from the emergency wells and resilient water supply mains. Operations staff should be properly trained on the storage, transport, deployment, disinfection, and general use of the blivets, as well as regularly inspecting their condition and integrity of them.

While Blivets can be a helpful tool, FEMA and the National Guard also operate water trucks that can provide similar functions and would not require pulling Bellevue water system maintenance staff off of repair work to operate them.

7.6 Spare Repair Parts Inventory Management

The need for spare repair parts after an earthquake is driven by the available crews and equipment to repair damaged pipe, and the number of repairs that will need to be completed. While the expected number of repairs that will be needed greatly exceeds the available spare parts inventory for the City of Bellevue, the availability of crews to execute the repairs is expected to be the limiting factor on the restoration of water system service.

Additionally, repairs to water system piping cannot commence until water supply into the system is available to locate pipe leaks and breaks damage. Supply to the water system is not expected to be available for days or weeks after a major earthquake event, allowing time for emergency managers to begin to request additional spare parts be provided from other parts of the country.

Table 7 shows the available repair parts available (as of Summer 2019). Based on this inventory, it appears that the minimum expected duration after a major SFZE event before additional repair parts would be required is 3 weeks. This is likely adequate to procure additional parts from other areas of the country. The greatest level of uncertainty is repair parts for pipes 14-inches in diameter and larger, due to the limited number of repair parts on hand. Based on this, it is recommended that the City consider the availability and potential need for repair parts for the larger pipe sizes and considering keeping a minimum of 5 to 10 repair sets for each size of pipe on hand at all times.

Table 7: Bellevue Water System Repair Parts Inventory and Time until Additional Repair Parts are Required

Pipe Size	Repair Parts Available	Weeks until more spares needed for SFZE*
4”	51	
6”	70	5 weeks
8”	52	3 weeks
10”	19	
12”	31	3 weeks
14”	5	
16”	2	3 weeks
18”	3	
24”	3	
*Based on duration from when repairs begin, which is based on when water is available at a source to allow for locating and fixing breaks.		

8. Summary

The improvement alternatives defined in this TM will be evaluated based on their ability to help the City achieve the target PE-LOS goals defined as part of the SVA project. Selected improvement will then be prioritized to develop an implementation plan and define funding needs to achieve the target PE-LOS goals.

Appendix I. Recommended Seismic Resilience Improvements

I.1 TM9: Improvement Prioritization

Jacobs

Technical Memorandum

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Subject	TM9: Improvement Prioritization
Project Name	Bellevue Water System Seismic Vulnerability Assessment
From	Jacobs
Date	October 7th, 2022

1. Background

The City of Bellevue (City) Water System Seismic Vulnerability Assessment (SVA) includes identification of the as-is service outage for a selection of seismic scenarios, and then identifying and evaluating improvement alternatives to reduce the water service outage time expected after a seismic event.

This document describes the results of the improvement prioritization process in which the potential improvement alternatives were evaluated and the selected ones prioritized to provide the most cost-effective path towards short-, mid-, and long-term seismic resiliency goals.

The results presented in this document include the following items:

- Prioritization Methodology
- Summary of Post-Earthquake Level of Service (PE-LOS) Goal Targets and Improvement Alternatives
- Improvement Combinations evaluated to achieve the PE-LOS goals
- Selected Improvement Combinations and Prioritization

2. Methodology

The prioritization methodology applied for assessing improvements and combinations of improvements against the target PE-LOS goals is shown in Figure 1. The PE-LOS goals established and summarized in TM 7 and the improvement options for main replacement, facility upgrades/replacement, and backbone development summarized in TM 8 were used to assess system performance against the PE-LOS goals.

For each of the PE-LOS goal timeframes (Long-Term, Mid-Term, Short-Term), multiple improvement combinations were developed to meet the PE-LOS goals and allow for comparison of the improvement combination options. A benefit-cost ratio comparison of the improvement combinations was reviewed with the City, and an improvement combination was selected for prioritization of the improvements included in the set of alternatives.

Figure 1: Prioritization Methodology

3. Post-Earthquake Level of Service Goal Targets

The concept and development of the target Post-Earthquake Level of Service (PE-LOS) goals is detailed in TM 7: Post-Earthquake Level of Service goals. The target PE-LOS goals were developed to guide the evaluation of improvement alternatives, so that the improvement alternatives were focused on achieving the desired performance of the system in a seismic event and meeting utility and customer expectations for water service restoration and outage durations, as well as reducing the potential economic impacts. Refer to TM 7 for the specific goals used for evaluation and prioritization of system improvements.

4. Improvement Alternatives

Improvement alternatives were developed considering the expected damage to the water system due to either of the two seismic events, Cascadia Subduction Zone (CSZ) and Seattle Fault Zone East (SFZE), that were evaluated as part of the SVA. There are four improvement categories that are incorporated into the evaluation of potential options to strengthen the system to provide more seismic resiliency. These improvement categories include:

1) Supply Improvements: Coordination with Cascade Water Alliance and Seattle Public Utilities to increase the resilience of the SPU regional water supply system to Bellevue so that either the regional water supply can be available immediately or could be returned to service within 7 days following a major seismic event (depending on which alternative is being considered as described below)
2) Facility Improvements: Improvements to specified pump stations and facilities to achieve a goal of immediate occupancy and fully operational status following a major seismic event, as described in the facility enhanced performance criteria in TM8: Improvement Alternatives.
3) Widespread distribution system pipe replacement: Strengthening of all vulnerable pipe in specified distribution system zones in accordance with Alternative 3 defined in TM 8: Improvement Alternatives. This includes upgrade to a minimum seismic performance equivalent to unrestrained ductile iron pipe for all pipe in the zone, and earthquake resistant ductile iron pipe (or equivalent performance) for pipes in moderate or high geotechnical hazard areas (those with significant potential for landslide or liquefaction issues, primarily).
4) Development of seismically resilient backbone pipe routes: Strengthening of specific backbone pipe routes using the same criteria summarized above (Alternative 3 from TM8: Improvement Alternatives). Additional consideration could be given to restrained joint ductile iron pipe for backbone routes with low geotechnical hazards, especially for the most critical backbone routes.

Selected improvements are described in the following sections of this TM. For more details on these selected improvements or for details on improvements that were not selected for implementation, refer to TM 8: Improvement Alternatives.

5. Improvement Combinations to Achieve PE-LOS Goal Targets

A summary of the improvement combinations for the Long-Term, Mid-Term, and Short-Term horizons are presented in this section. The restoration curves for each improvement combination are presented with the as-is restoration curve, and the comparison of the reduction in the economic impact is also shown for each improvement combination. The cost is shown for each of the improvement combinations in each tabular summary and the reduction in the economic impact are used in the evaluation of the benefit-cost ratio presented in Section 6.

5.1 Long-Term Improvement Combinations

The improvement combinations to meet the Long-Term PE-LOS goals are summarized for the four improvement categories below in Table 1, and the restoration curves for the CSZ earthquake for each of the long-term combinations are shown in Figure 2 and Figure 3 for critical customers and system-wide, respectively, and in Figure 4 and Figure 5 for the SFZE earthquake. Figure 6 and Figure 7 show the Long-Term risk reduction for the CSZ and SFZE earthquakes in terms of the reduction of the projected economic impact if the improvements in each combination were implemented.

Table 1: Long-Term Improvement Combinations

Combination	Supply	Facility Improvements		Pipe Improvements	Backbone System	Cost (2021)
L1	Immediate SPU Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Forest Hills	Lake Hills NE 40^{th} Reservoir PS Newport Parksite Woodridge 670	Strengthening system-wide	No backbone	$847M
L2	Immediate SPU Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Forest Hills	Newport Parksite Woodridge 670	Strengthening key zones (BV 400, EG 300, FA 293, IH 520, SS 850)	Partial backbone[1]	$457M
L3A	Well Supply available immediately; SPU Supply available in 7 days	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Forest Hills	Newport Parksite Woodridge 670	Strengthening key zones (BV 400, EG 300, FA 293, LH 520, SS 850)	Expanded Partial backbone[2]	$447M
L3B	Well Supply available immediately; SPU Supply available in 7 days	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Forest Hills	Newport Parksite Woodridge 670	Strengthening key zones (EG 300, FA 293, LH 520, SS 850)	Full Backbone	$379M

[1]Segments included in L2 Partial Backbone: A, G, L

[2]Segments included in L3A Expanded Partial Backbone: A, B, G, L, M

Figure 2: CSZ Long-Term Critical Customer Restoration Curve

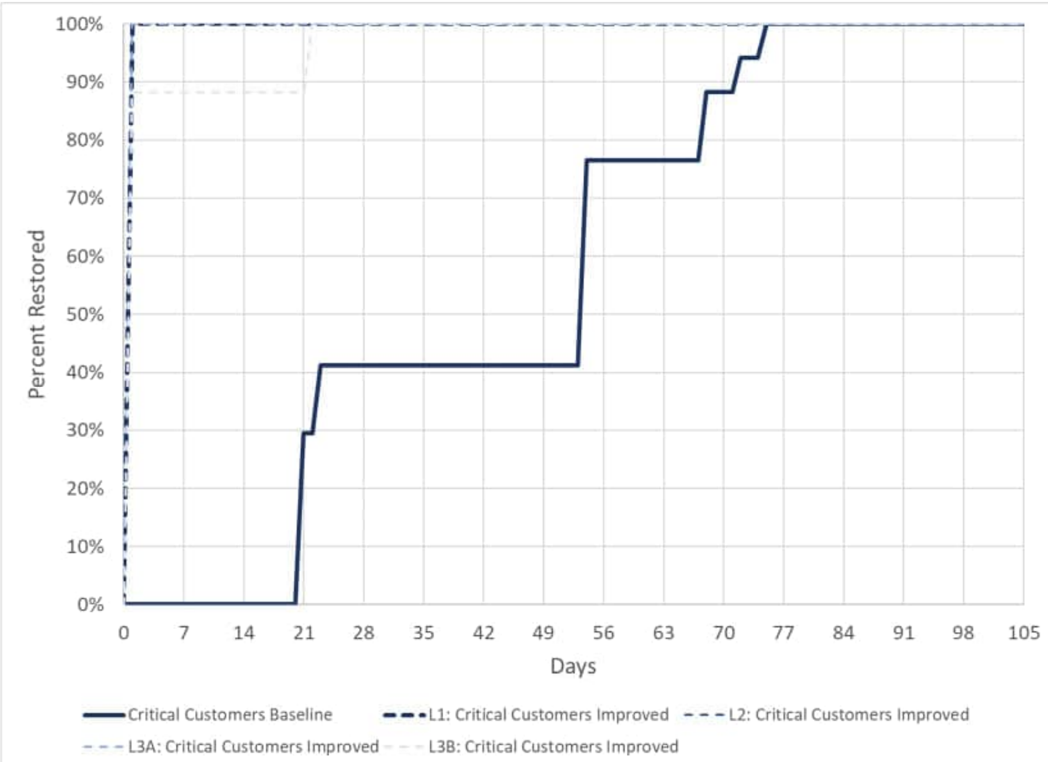


Figure 3: CSZ Long-Term System-Wide Restoration Curve

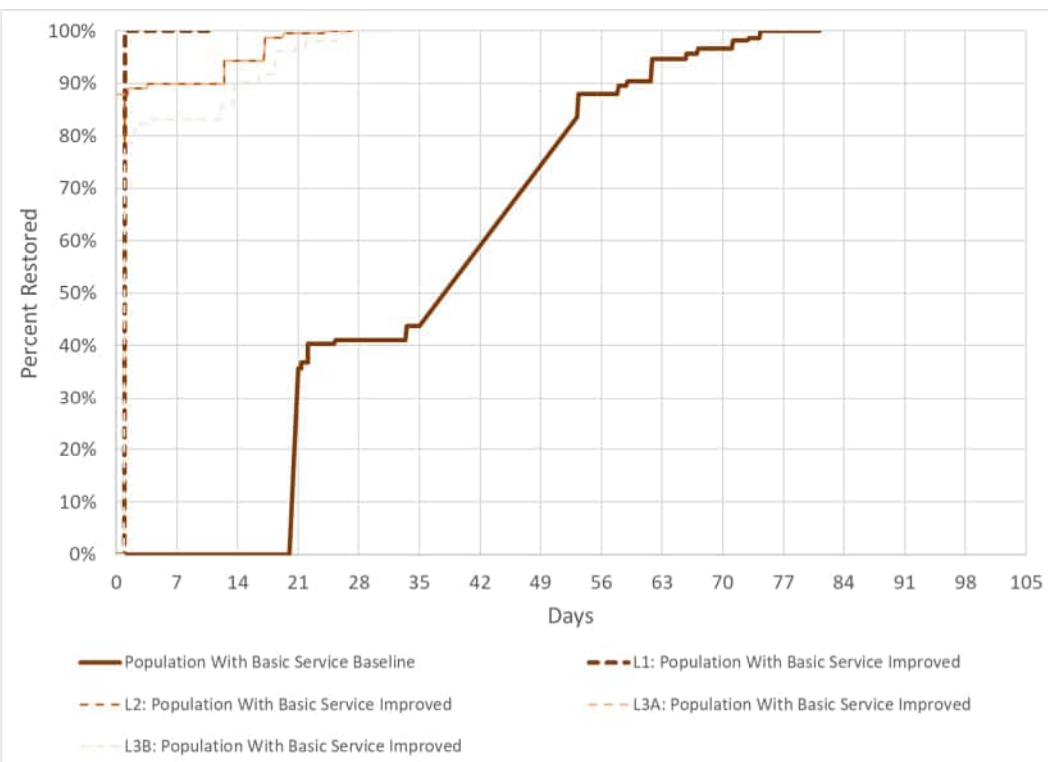


Figure 4: SFZE Long-Term Critical Customer Restoration Curve

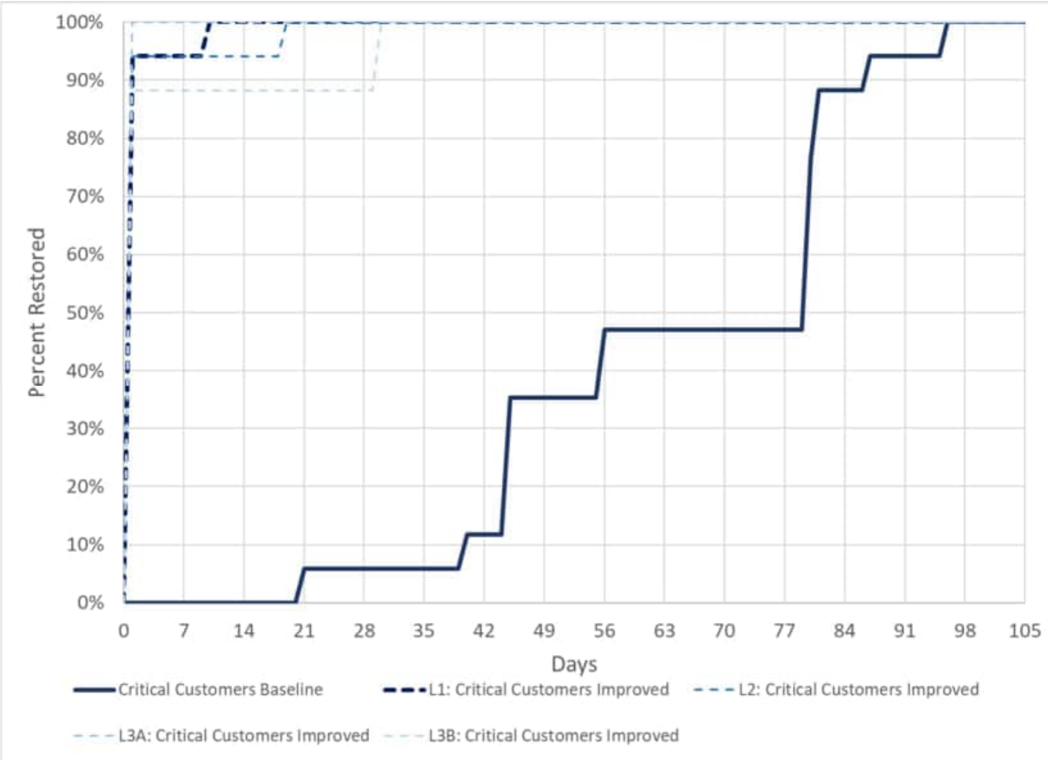


Figure 5: SFZE Long-Term System-Wide Restoration Curve

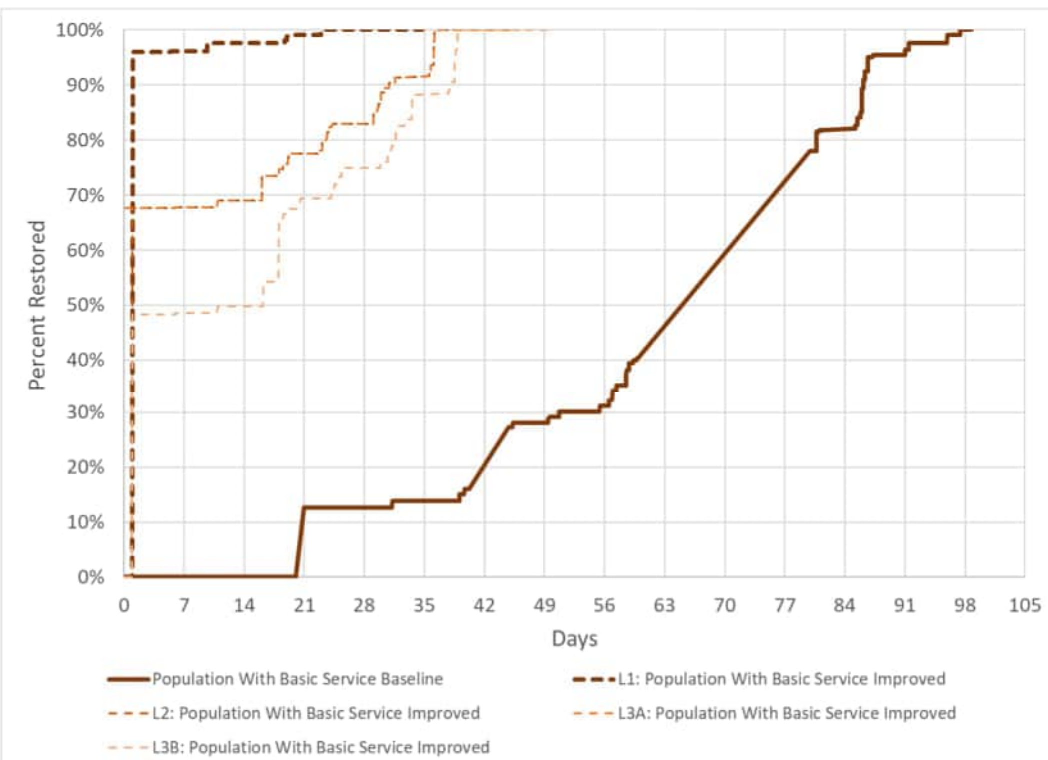


Figure 6: Long-Term CSZ Economic Impact Improvement

Note: L3A and L2 have the same restoration curve

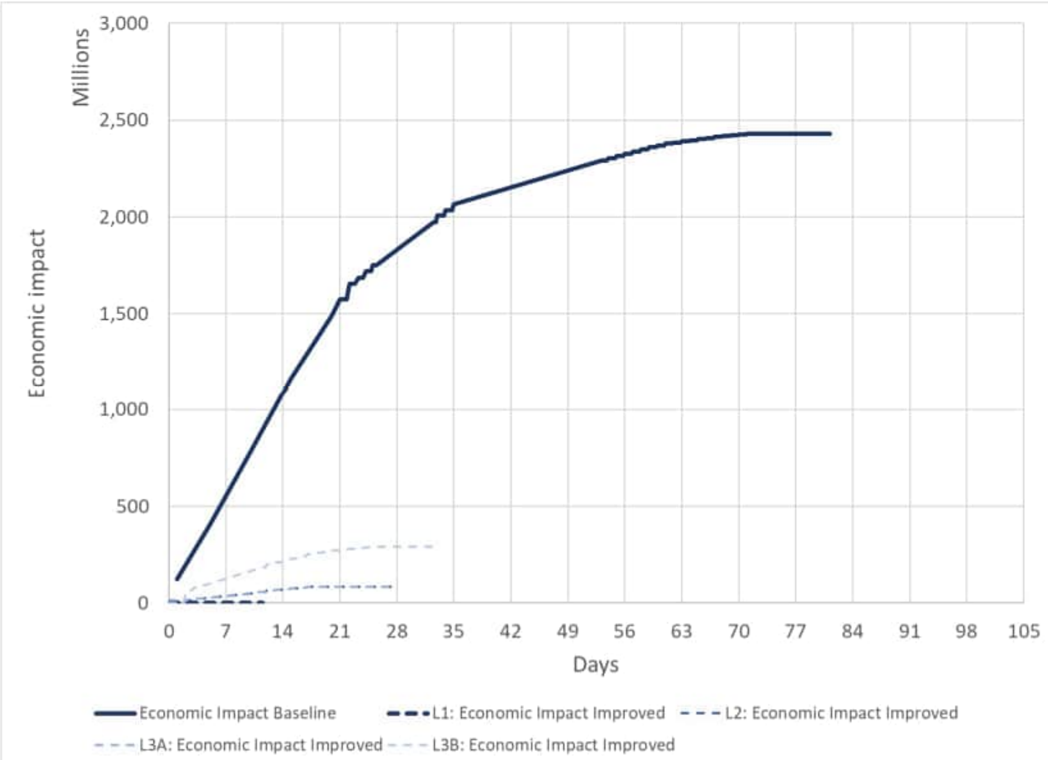
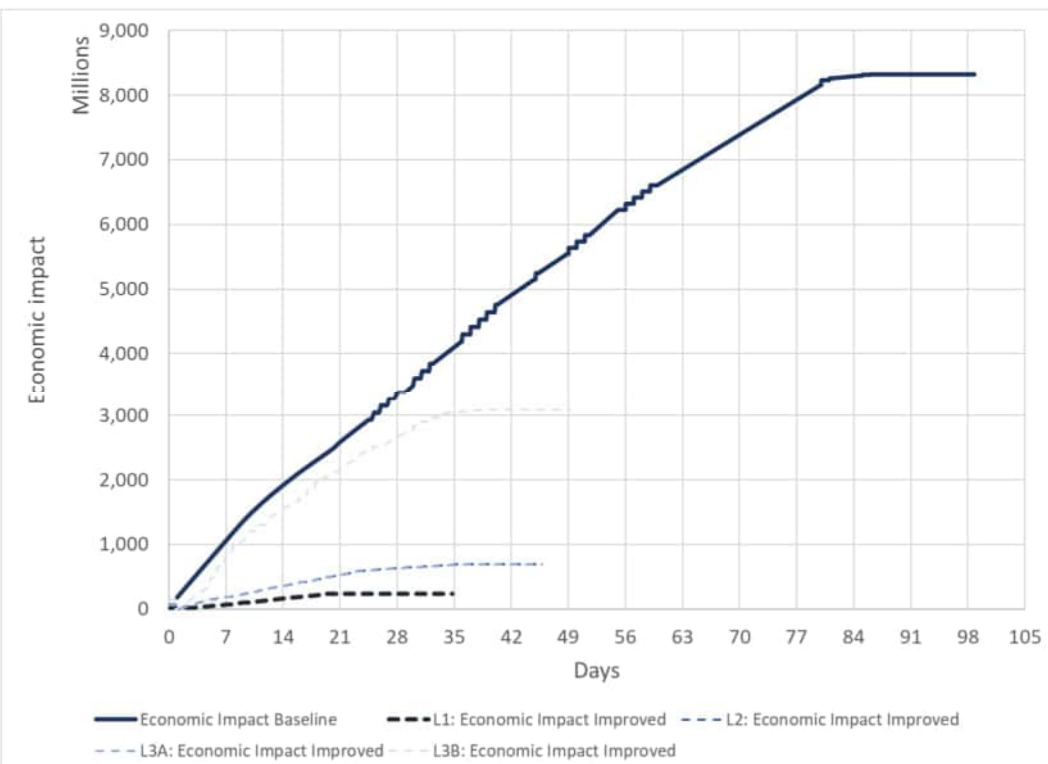


Figure 7: Long-Term SFZE Economic Impact Improvement

Note:L3A and L2 have the same restoration curve



For the Long-Term improvement combinations, the capability to have the SPU Supply returned quickly and incorporate significant system strengthening as included in L1 provided the most benefit in terms of restoration times. Both L1 and L2 returned service to critical customers quickly, and L1 returned service more quickly to the entire system as observed with the return of service to more customers across the system as compared to the other Long-Term combinations. Having the emergency well supply available immediately in combinations L3A and L3B and then the SPU supply in 7 days plus the selective strengthening of key pressure zones and incorporation of backbone improvements to move water throughout the system returned service slightly slower than L1 and L2 but also met the PE-LOS goals at a lower cost than L1 and L2. When comparing L3A and L3B, the benefit to strengthening the BV 400 zone vs a full backbone shows that strengthening BV 400 provides more benefit for the rest of the water system due the large area that BV 400 covers. Given that the performance of the SPU supply system is out of the City of Bellevue's control, L1 and L2 were not considered to be viable options.

5.2 Mid-Term Improvement Combinations

Table 2 shows the improvement combinations for the Mid-Term PE-LOS goals, and Figure 8 and Figure 9 show the restoration curves for the CSZ earthquake while Figure 10 and Figure 11 show the restoration curves for the SFZE earthquake. The reduction in the economic impact with the Mid-Term improvements incorporated for the CSZ earthquake is shown in Figure 12 and in Figure 13 for the SFZE earthquake.

Table 2: Mid-Term Improvement Combinations

Combination	Supply	Facility Improvements		Pipe Improvements	Backbone System	Cost (2021 $)
M1	SPU Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3	Forest Hills Newport Parksite 670	Strengthening key zones (BV0400, FA0293, LH0520)	No backbone	$416M
M2	SPU Supply + Well Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3	Forest Hills Newport Parksite 670	Strengthening key zones (FA0293, LH0520)	Expanded Partial backbone[1]	$313M
M3	SPU Supply + Well Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3	Forest Hills Newport Parksite 670	Strengthening key zones (BV0400, FA0293, LH0520)	Expanded Partial backbone[1]	$416M

[1]Segments included in M2 and M3 Expanded Partial Backbone: A, B, G, L, M

Figure 8: CSZ Mid-Term Critical Customer Restoration Curve

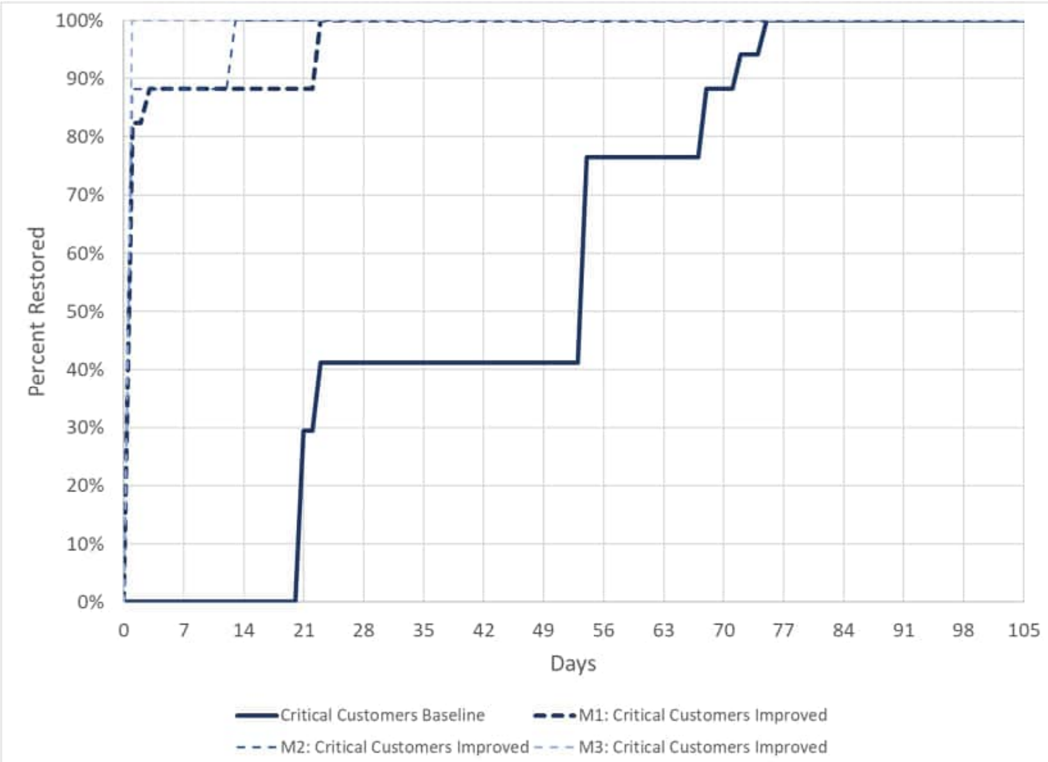


Figure 9: CSZ Mid-Term System-Wide Restoration Curve
Note: M2 and M3 follow the same curve

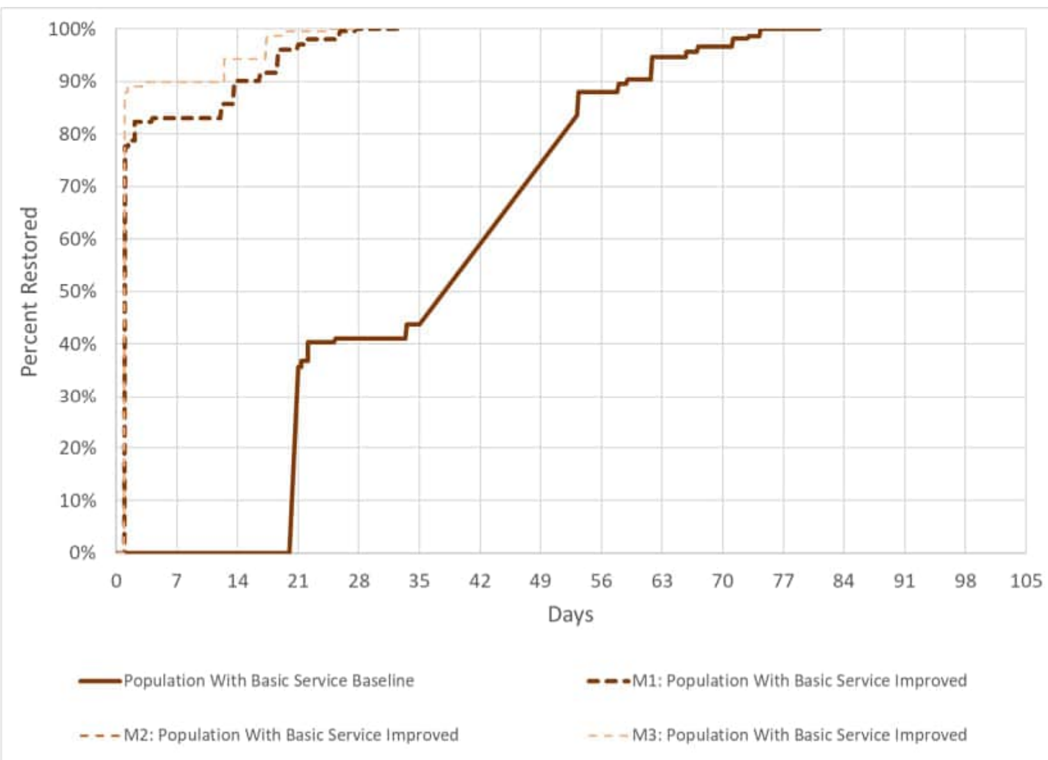


Figure 10: SFZE Mid-Term Critical Customer Restoration Curve

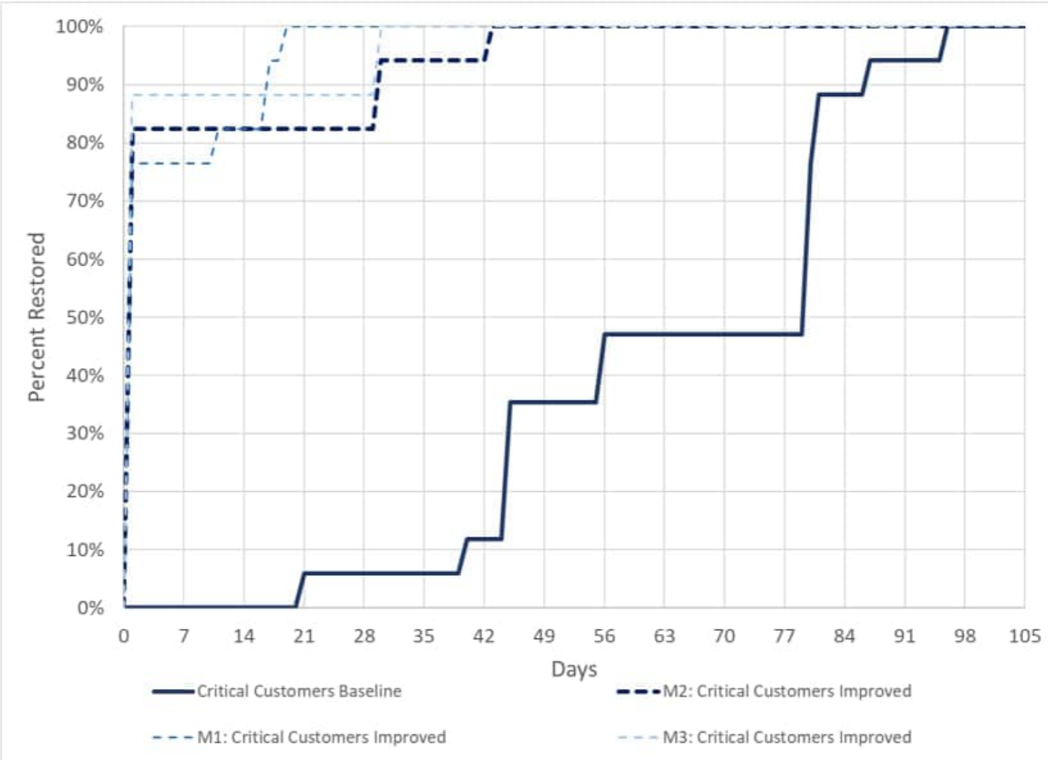


Figure 11: SFZE Mid-Term System-Wide Restoration Curve

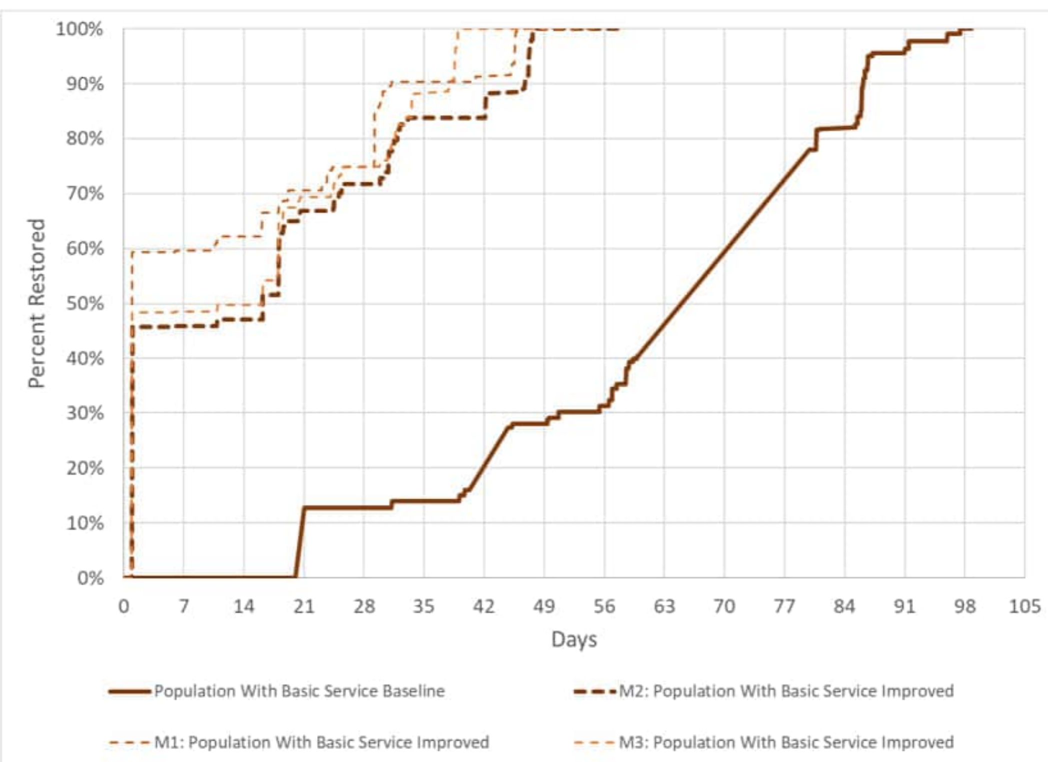


Figure 12: Mid-Term CSZ Economic Impact Improvement
Note: M2 and M3 follow the same curve

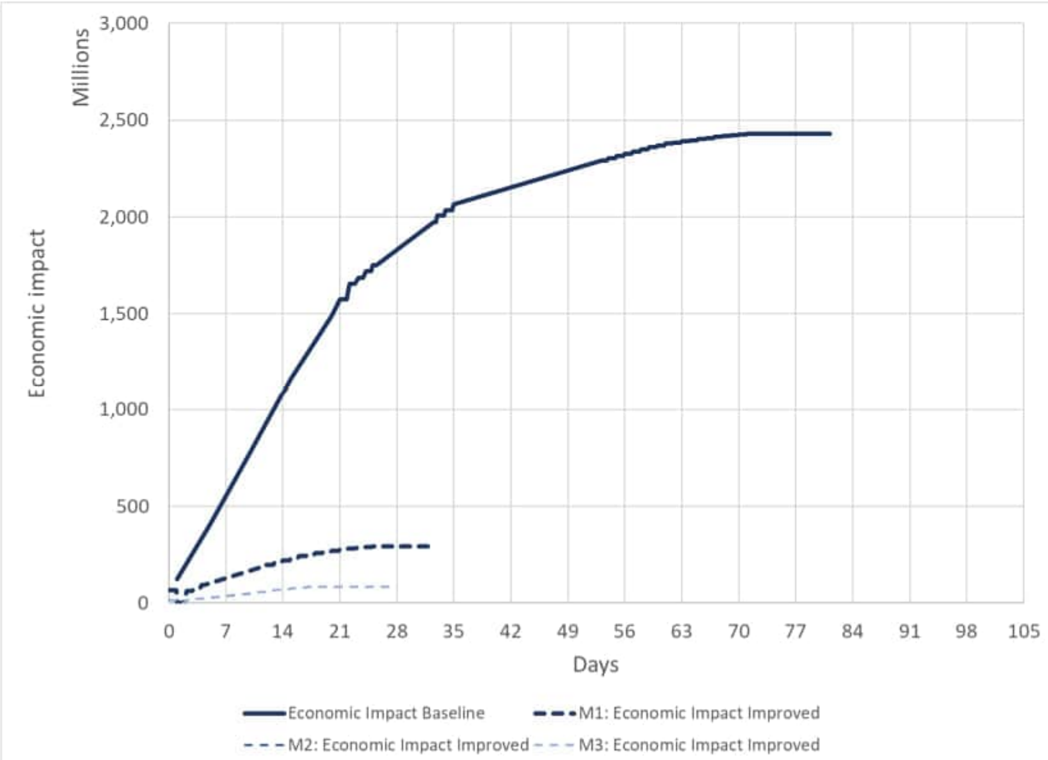
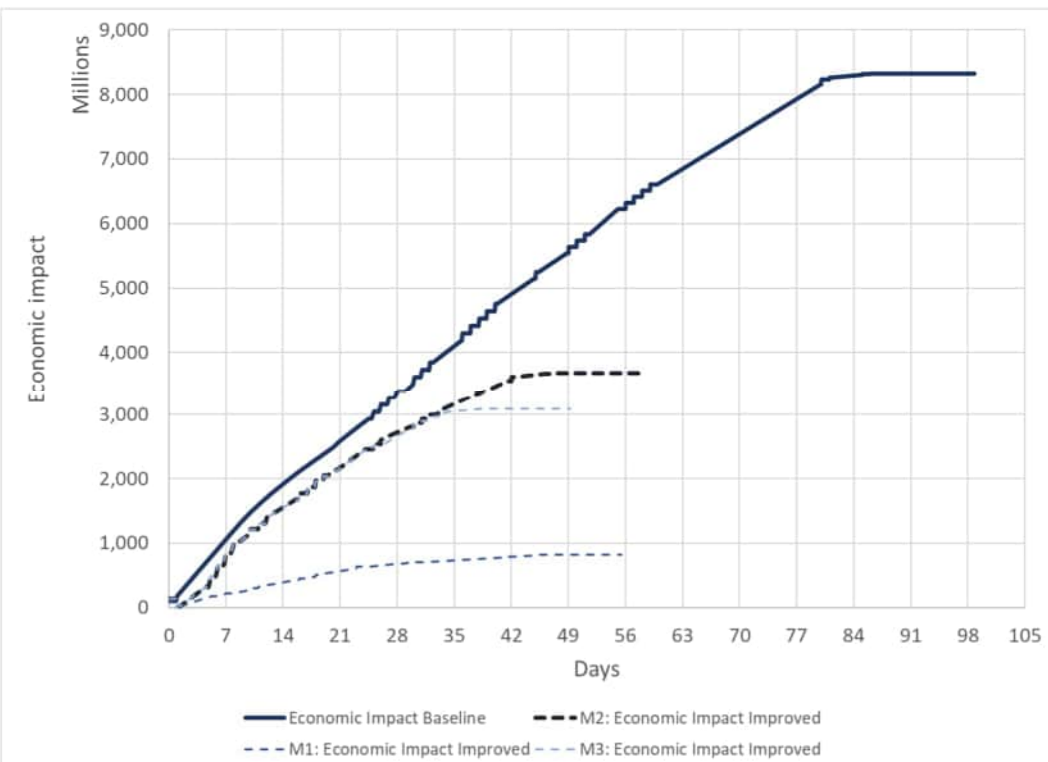


Figure 13: Mid-Term SFZE Economic Impact Improvement



5.3 Short-Term Improvement Combinations

A summary of the Short-Term improvement combinations is presented in Table 3, and the critical customers and system-wide restoration curves for the CSZ earthquake are shown below in Figure 14 and Figure 15 and in Figure 16 and Figure 17 for the SFZE earthquake. Figure 18 and Figure 19 show the reduction in the economic impact with the Short-Term improvements incorporated for the CSZ earthquake and the SFZE earthquake.

Table 3: Short-Term Improvement Combinations

Combination	Supply	Facility Improvements		Pipe Improvements	Backbone System	Cost (2021 $)
S1	Well Supply	Clyde Hill Cougar Mountain 1 Cougar Mountain 2	Cougar Mountain 3 Parksite	No Zone Strengthening	Partial backbone	$55M
S2	Well Supply	Cougar Mountain 1 Cougar Mountain 2	Cougar Mountain 3 Parksite	Strengthening BV400	No backbone	$147M
S3-CSZ	Well Supply	Cougar Mountain 1 Cougar Mountain 2	Cougar Mountain 3 Parksite	Strengthening LH520	No backbone	$231M
S3A-CSZ	Well Supply	Cougar Mountain 1 Cougar Mountain 2	Cougar Mountain 3 Parksite	Strengthening LH520 and BV400	No backbone	$338M

[1]Segments included in S1 Partial Backbone: A, B, L

The improvement combinations shown in Table 3 were developed to compare the relative benefit that strengthening of select zones versus a partial backbone system. Water supply and facility improvements were the same for each combination, and the variation was the zone strengthening and use of a partial backbone system. The S3 and S3A combinations were also focused on assessing the benefit of additional zone strengthening for the CSZ earthquake.

Figure 14: CSZ Short-Term Critical Customer Restoration Curve

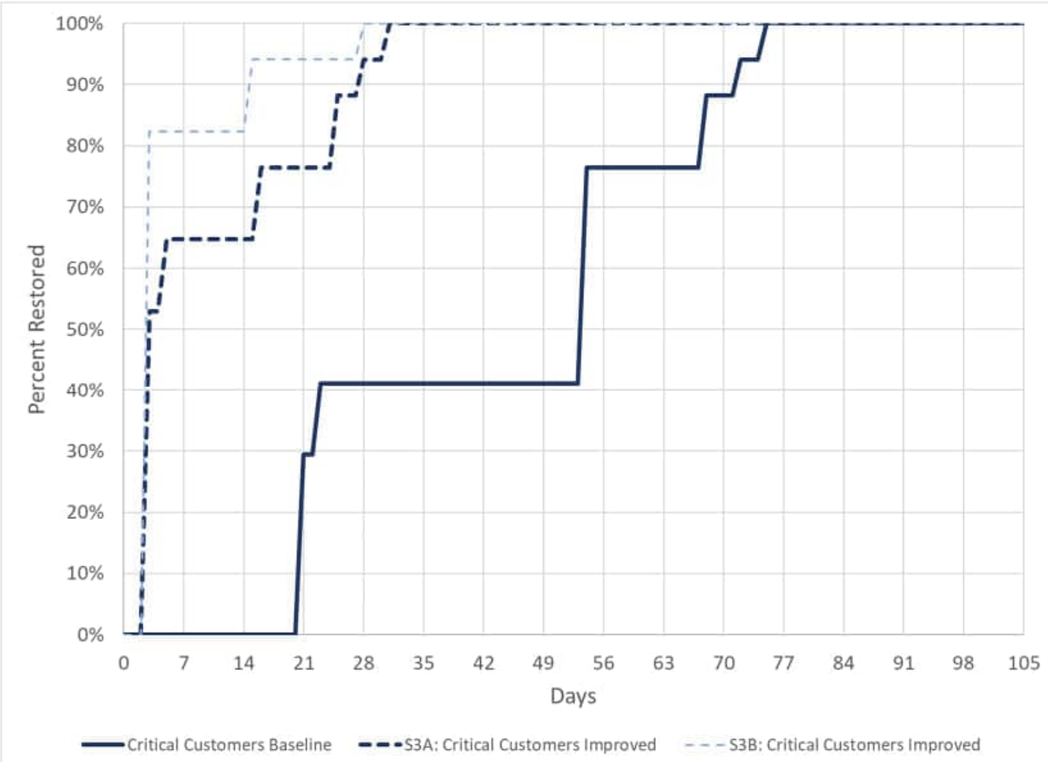


Figure 15: CSZ Short-Term System-Wide Restoration Curve

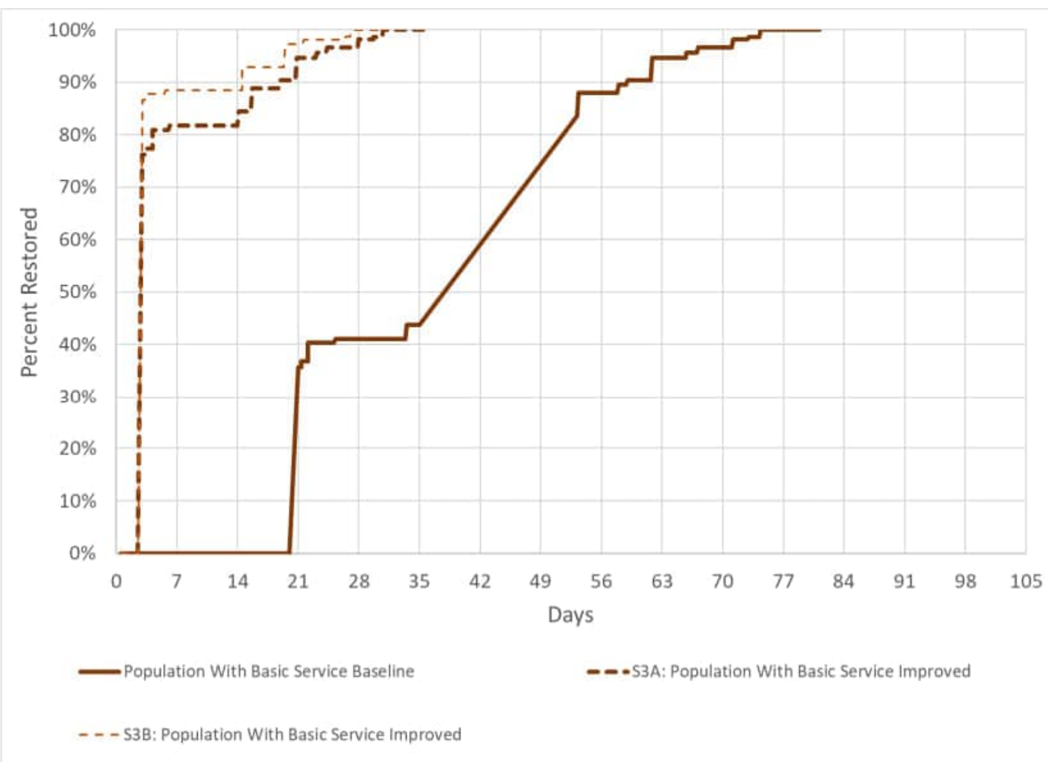


Figure 16: SFZE Short-Term Critical Customer Restoration Curve

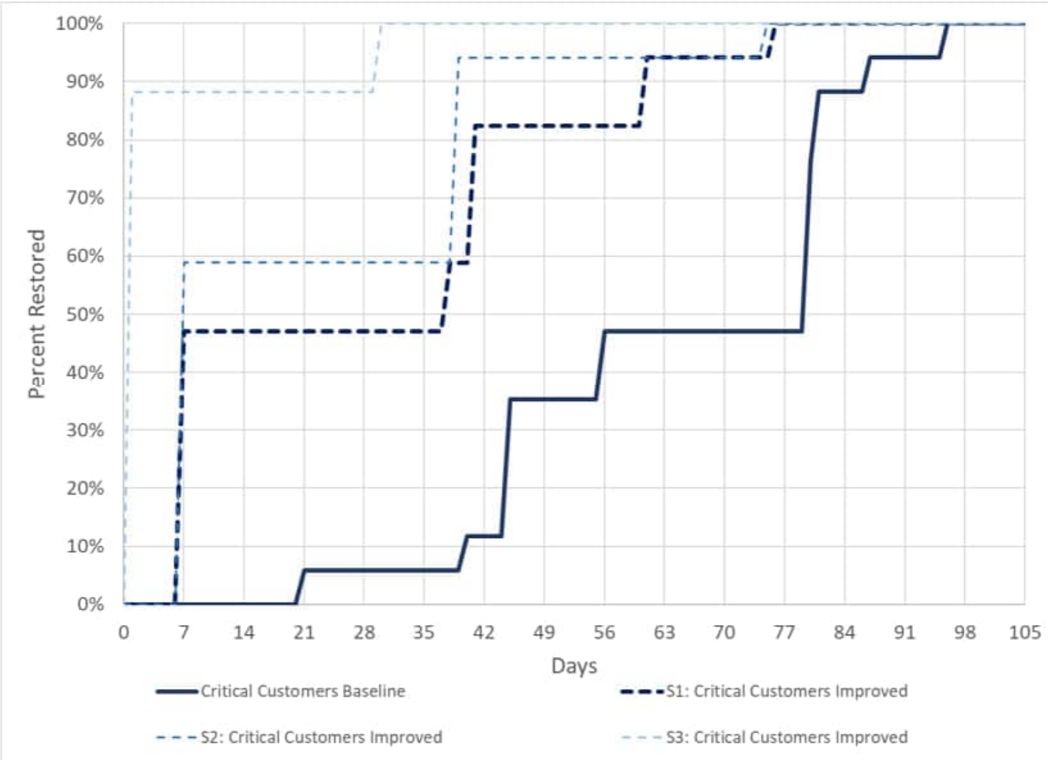


Figure 17: SFZE Short-Term System-Wide Restoration Curve

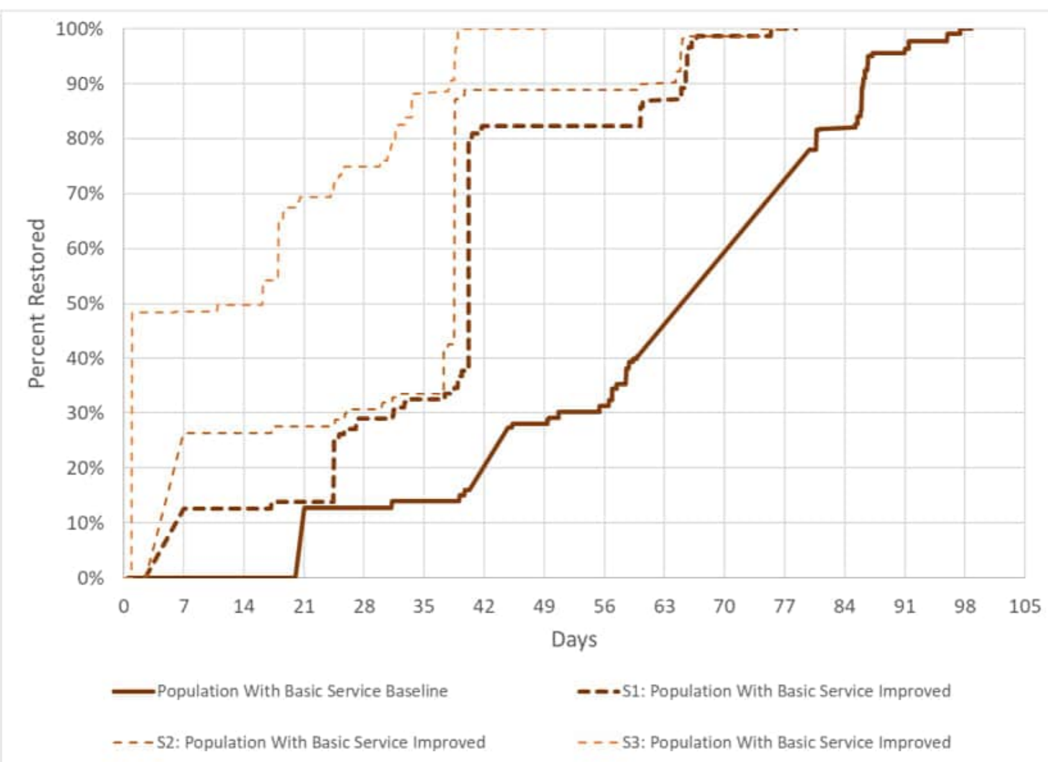


Figure 18: Short-Term CSZ Economic Impact Improvement

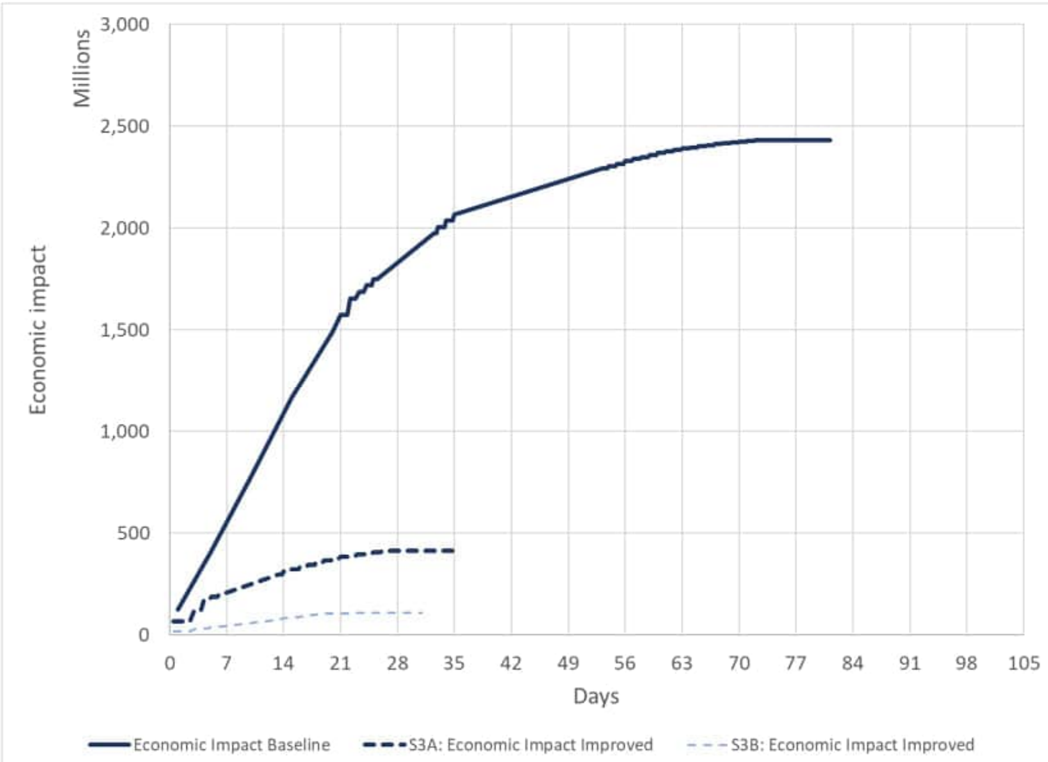
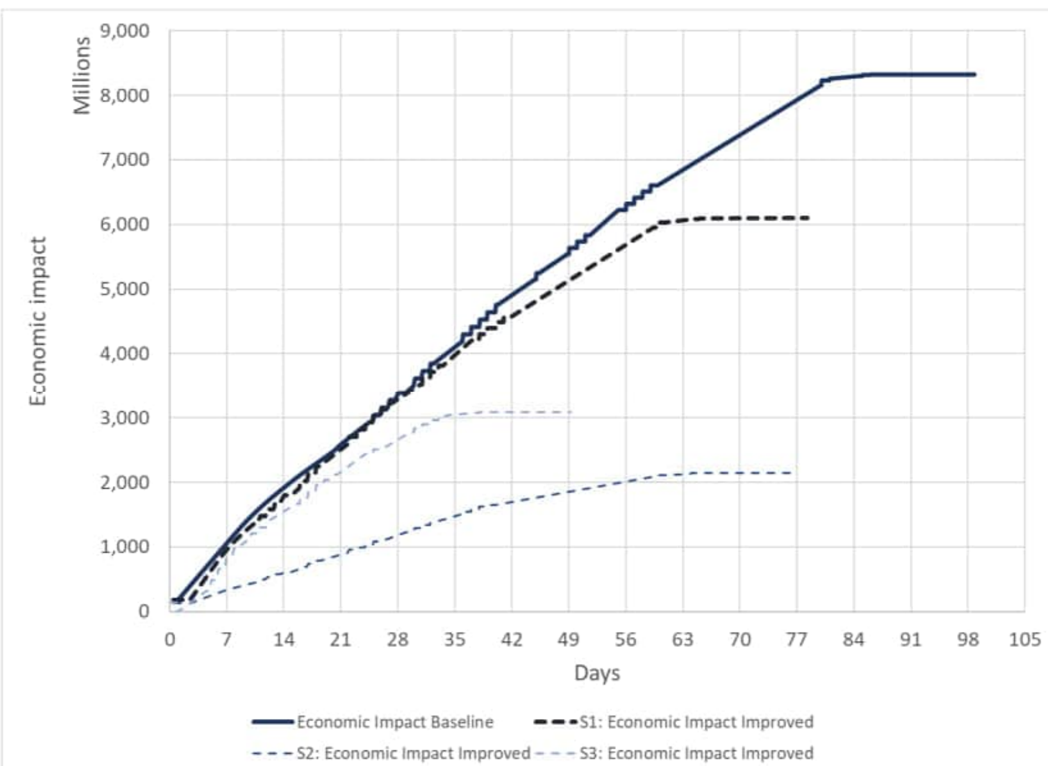


Figure 19: Short-Term SFZE Economic Impact Improvement



Comparing the Short-Term improvement combinations, S3 returned a greater percentage of service to critical customers and the overall water system more quickly but at a higher cost. At 42 days after the earthquake event, all combinations had returned over 80% of the service and by 75 days, all combinations had similar performance of returning service to customers.

6. Improvement Prioritization

To select and prioritize the improvements for the City, the Benefit/Cost ratio was calculated for each combination of improvements for the Long-Term, Mid-Term, and Short-Term horizons. An assessment of the common features of improvement combinations and the phasing potential was also reviewed to support the prioritization.

6.1 Benefit Cost Evaluation

Each of the combinations of improvements was evaluated on a Benefit/Cost Ratio perspective. The Benefit is calculated as the 100-year net present value (NPV) of the reduction in economic risk, and the Cost is the capital cost of the improvements.

To generate the Benefit portion of the Benefit/Cost ratio, the economic risk is calculated by taking the economic impact to the regional economy generated from the economic impact parameters developed as described in TM5: Economic Impact Parameters and multiplying it by the annual likelihood of occurrence of the seismic event (1/500 for CSZ and 1/800*0.5 for SFZE) to get the economic risk for each seismic event in $/year as shown in Equation 1.

Equation 1: Annual Risk Calculation

$$Annual\ Risk\ \left(\frac{\$}{year}\right) = Economic\ Impact\ from\ Seismic\ Event\ (\$) * \frac{1}{Earthquake\ Return\ Period\ (Years)}$$

Where:

Economic Impact from Seismic Event is calculated by the model using economic impact parameters defined in TM5.

Earthquake Return Period = 500 years for CSZ and 800/0.5 for SFZE-

The economic risk reduction associated with a specific improvement combination is calculated by taking the annual economic risk for both earthquake scenarios in the as-is state, and subtracting the annual economic risk for both earthquake scenarios after mitigation from implementing improvements as shown in Equation 2.

Equation 2: Risk Reduction Calculation

$$Risk\ Reduction\ \left(\frac{\$}{year}\right) = \ Annual\ Risk\ pre\ mitigation\ \left(\frac{\$}{year}\right) - Annual\ Risk\ post\ mitigation\ \left(\frac{\$}{year}\right)$$

The NPV of the risk reduction benefit is then calculated using the following NPV input parameters:

- Discount Rate = 5.0%
- Inflation Rate = 2.0%
- Project Lifecycle = 100 years

Use of the above NPV parameters results in a factor of 32.1 that is multiplied by the annual economic risk (cost) to obtain the 100-year NPV.

Using the calculation of the economic risk reduction for both the CSZ and the SFZE earthquake events, the Benefit/Cost ratio is calculated by dividing the 100-year NPV of the combined economic risk reduction (benefits) generated by implementing the identified improvements by the capital cost of the improvements. Benefit/Cost ratios that are greater than 1 are considered improvements that will pay for themselves from a risk perspective, ratios less than one would require additional justification outside of just risk mitigation. For the seismic improvements described in Section 5, all were developed with a focus on achieving the target PE-LOS goals. When evaluating these improvements against each other, the Benefit/Cost Ratio can be used to determine which of the improvements developed to meet the PE-LOS goals provides the most benefit for the money spent.

A summary of the Seismic Benefit/Cost calculations for each of the assessed improvement combinations is presented in Table 4. The Short-Term combinations all showed Seismic Benefit/Cost ratios greater than 1, and the Long-Term and Mid-Term Seismic Benefit/Cost ratios were slightly lower and less than 1. Note that, Seismic Benefit/Cost Ratio accounts only for benefit from seismic risk reduction. Other benefits such as system capacity and renewed asset life are not accounted for in this benefit/cost ratio.

The City's existing renewal and replacement program will eventually replace all of the asbestos cement and cast iron pipe in use in the distribution system, so pipe replacement that is targeted at those pipes is not necessarily additive to the current projected spending that is incorporated into water rates. Table 5 shows a comparison of the total cost for each improvement combination and the cost for the improvement combination if replacement of AC and CI pipe is excluded.

Table 4: Improvement Combination Benefit/Cost Summary

Improvement Combination	Total Cost to Achieve	Bellevue Supply Improvements	Bellevue Share of SPU Transmission Improvements	Bellevue Facilities	Bellevue Distribution System	Total Length of Pipe Replacement, ft	Seismic Risk Reduction (Cumulative), $/yr	Seismic Benefit /Cost Ratio
S1	$55 M	$20 M	$0	$19 M	$16 M	32,732	$4.4 M	2.6
S2	$147 M	$20 M	$0	$17 M	$110 M	244,403	$7.7 M	1.7
S3	$231 M	$20 M	$0	$19 M	$192 M	452,598	$7.3 M	1.0
S3A	$338 M	$20 M	$0	$17 M	$302 M	697,001	$4.6 M	0.4
M1	$416 M	$0	$45 M	$39 M	$332 M	754,085	$9.4 M	0.7
M2	$313 M	$20 M	$15 M	$39 M	$239 M	540,967	$ 7.2 M	0.7
M3	$416 M	$20 M	$15 M	$39 M	$342 M	771,950	$ 8.0 M	0.6
L1	$847 M	$0	$45 M	$65 M	$737 M	1,695,475	$ 9.9 M	0.4
L2	$457 M	$0	$45 M	$48 M	$365 M	825,021	$ 9.5 M	0.7
L3A	$447 M	$20 M	$15 M	$48 M	$365 M	825,021	$ 9.5 M	0.7
L3B	$379 M	$20 M	$15 M	$48 M	$297 M	663,650	$ 7.5 M	0.6

Notes:

- Each Improvement combination is the total cost to achieve that goal, as if no prior improvements had been completed. This means that the costs to achieve a specified long-term goal are all inclusive, and any previous improvements that are part of that improvement can be removed in order to get the incremental cost of the improvement combination.
- Seismic Benefit/Cost Ratio accounts only for benefit from seismic risk reduction. Other benefits such as system capacity and renewed asset life are not accounted for in this benefit/cost ratio.
- Improvement costs shown are in early 2021 $ and do not reflect extreme inflation that occurred in 2021 and beyond.

Table 5: Comparison of cost to replace all pipe vs. only pipe other than AC and CI

Improvement Combination	Including Cost for All Pipe to be Replaced		Excluding Cost to Replace AC and CI Pipe	
	Total Improvement Combination Cost	Bellevue Distribution System	Total Improvement Combination Cost	Bellevue Distribution System
S1	$55 M	$16 M	$27 M	$1 M
S2	$147 M	$110 M	$40 M	$14 M
S3	$231 M	$192 M	$50 M	$24 M
S3A	$338 M	$302 M	$64 M	$38 M
M1	$416 M	$332 M	$121 M	$50 M
M2	$313 M	$239 M	$98 M	$38 M
M3	$416 M	$342 M	$111 M	$50 M
L1	$847 M	$737 M	$198 M	$101 M
L2	$457 M	$365 M	$132 M	$53 M
L3A	$447 M	$365 M	$122 M	$53 M
L3B	$379 M	$297 M	$113 M	$43 M

Notes:
- Each Improvement combination is the total cost to achieve that goal, as if no prior improvements had been completed. This means that the costs to achieve a specified long-term goal are all inclusive, and any previous improvements that are part of that improvement can be removed in order to get the incremental cost of the improvement combination.
- Improvement costs shown are in early 2021 $ and do not reflect extreme inflation that occurred in 2021 and beyond.

6.2 Recommended Improvements

Based upon a review of Benefit/Cost ratio information shown in Table 4, improvements that provided the most benefit were identified, and an implementation strategy from Short-Term to Mid-Term to Long-Term was developed to achieve the most benefit at the least cost, while achieving the target PE-LOS goals. The selected combinations included S1 for Short-Term, M2 for Mid-Term, and L3A for Long-Term. Figure 20 shows the implementation strategy by timeframe, demonstrating how to achieve the long-term goals identified in combination L3A. The improvements are shown with an incremental approach in Figure 20 to highlight the additive nature of the improvements to achieve the improvements selected for the Long-Term L3A combination and how the PE-LOS goals are met for each horizon. By implementing the improvements through the approach outlined in Figure 20, the City will reduce economic risk by executing selected improvements for supply resiliency as well as facility and piping improvements.

Figure 20: Improvement Implementation by Combination

Category	Short-Term (S1)	Mid-Term (M2)	Long-Term (L3A)
Supply Improvements	Emergency Wells	7-day SPU Supply	
Facility Improvements	Clyde Hill Cougar Mountain 1 Cougar Mountain 2 Cougar Mountain 3 Horizon View 2 Parksite	Forest Hills Newport 670	Woodridge
Distribution Strengthening		LH 520 FA 293	BV 400 SS 850 EG 330
Backbone System	Partial Backbone	Expanded Partial Backbone	

While only five backbones were identified as being required to achieve the target PE-LOS goals, there is still some value in implementing the other resilient pipe backbone routes evaluated. However, unless backbones are mostly isolated from the rest of the system, they do not provide value until all the connecting valves can be closed, which may be more time consuming than repairing pipe breaks and leaks within the connected piping and zones. As a result, the City could evaluate on a case-by-case basis the value if adding additional backbone routes other than the five identified, but the improvements shown in Figure 20 should be prioritized.

Figures 21 and 22 show the system-wide and critical service restoration curves for the as-is system and each of the three improvement combinations. Figure 23 shows the economic impact for the as-is system and each of the three improvement combinations.

Figure 21: System-Wide Service Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0 | Seattle Fault Zone East Mw 6.6

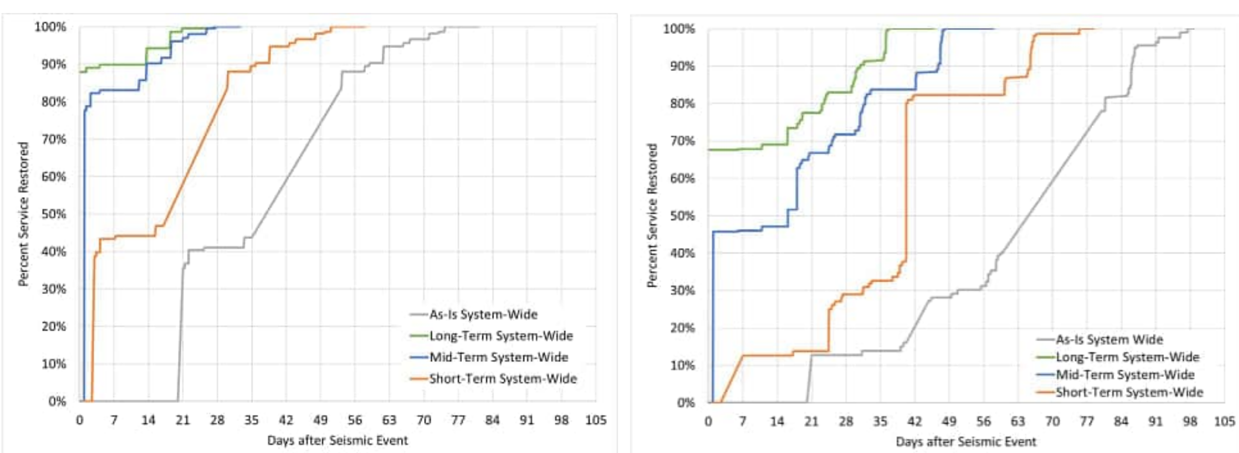


Figure 22: Critical Customer Service Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0 | Seattle Fault Zone East Mw 6.6

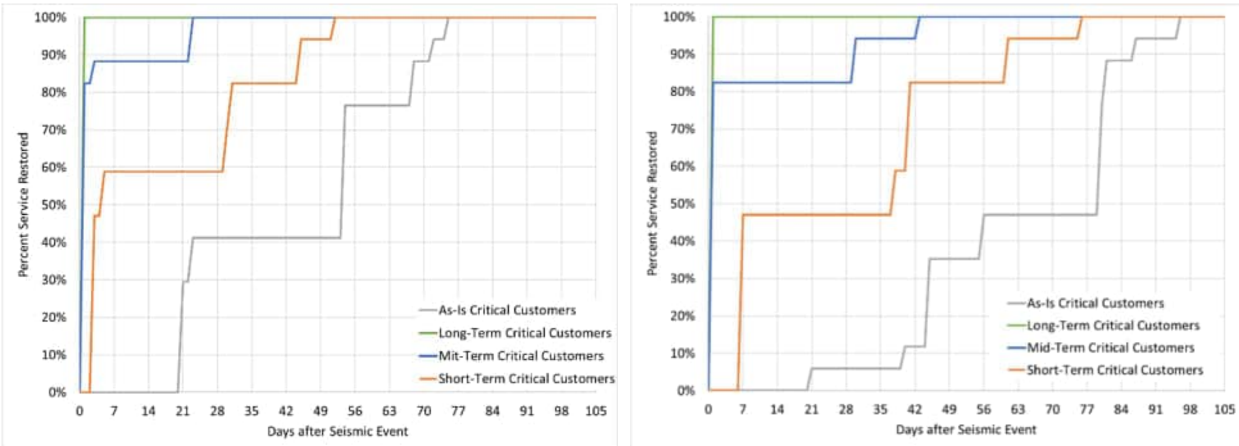
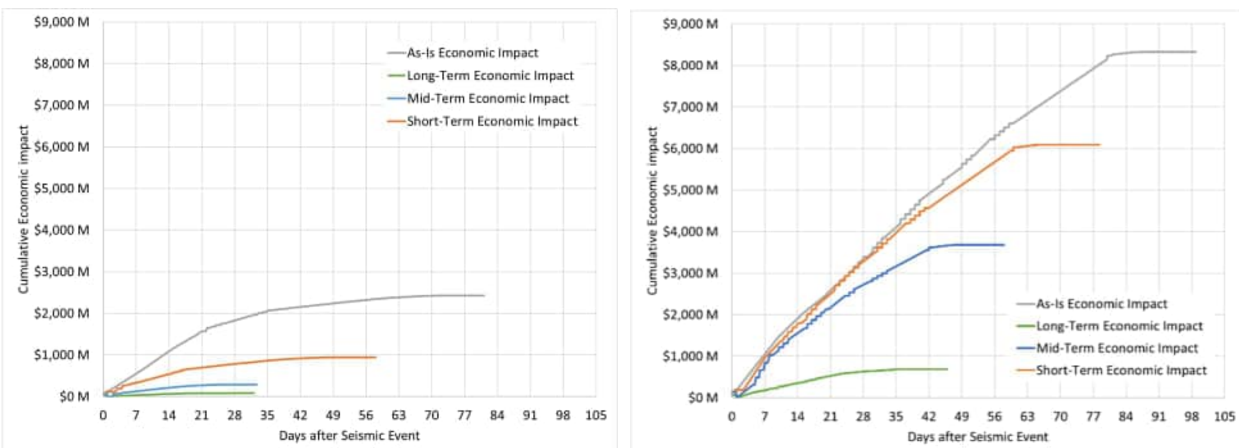


Figure 23: Economic Impact Improvement with Selected Combinations

Cascadia Subduction Zone Mw 9.0 | Seattle Fault Zone East Mw 6.6



6.3 Improvement Implementation Timeframe

The City will decide the implementation timeframe for the improvements to achieve the PE-LOS goals, once adopted. As a general guidance, it is assumed that most short-term improvements can be implemented in 10 years, with the exception of the emergency well improvements which are likely to take 15 years. Mid-term improvements can likely be accomplished in 25 to 30 years, primarily due to cost constraints. Long-term improvements are assumed to be achievable in 40 to 50 years.

Once the city has incorporated the proposed improvements into the water system rate model, a more definitive implementation timeframe can be developed to approximate the added cost above the existing renewal and replacement programs.

Attachment A: Improvement Combination Detail Matrix

Improvement Combination	L1	L2	L3A	L3B	M1	M2	M3	S1	S2	S3-CSZ	S3A-CSZ
SPU Supply (Restoration Time)	1 day	1 day	7 days	7 days	1 day	7 days	7 days	N	N	N	N
Emergency Wells at 9 MGD	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y
Pressure Zone											
BV0400	Y	Y	Y	N	Y	N	Y	N	Y	N	Y
EG0300	Y	Y	Y	Y	N	N	N	N	N	N	N
FA0293	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
LH0520	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y
SS0850	Y	Y	Y	Y	N	N	N	N	N	N	N
All other Zones	Y	N	N	N	N	N	N	N	N	N	N
Backbones											
A	N	Y	Y	Y	Y	Y	Y	Y	N	N	N
B	N	N	Y	Y	N	Y	Y	Y	N	N	N
G	N	Y	Y	Y	N	Y	Y	N	N	N	N
L	N	Y	Y	Y	N	Y	Y	Y	N	N	N
M	N	N	Y	Y	N	Y	Y	N	N	N	N
All other Backbones	N	N	N	Y	N	N	N	N	N	N	N
Pump Stations											
Clyde Hill	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N
Cougar Mountain 1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cougar Mountain 2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cougar Mountain 3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Forest Hills	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
Lake Hills (Crossroads)	Y	N	N	N	N	N	N	N	N	N	N
NE 40th Reservoir PS	Y	N	N	N	N	N	N	N	N	N	N
Newport	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
Parksite	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Woodridge	Y	Y	Y	Y	N	N	N	N	N	N	N
670	Y	Y	Y	Y	Y	Y	Y	N	N	N	N
Legend:	Purple = Selected Improvement Combination				Blue = Included Improvements				Gray = Not Included		