THE LIFELINES COUNCIL
The City and County of San Francisco

LIFELINES INTERDEPENDENCY STUDY I REPORT
APRIL 17, 2014

OFFICE OF THE
CITY ADMINISTRATOR

Edwin M. Lee, Mayor
Naomi M. Kelly, City Administrator

San Francisco Lifelines Council
Interdependency Study

On October 14, 2009 the City convened the first meeting of the Lifelines Council. This citywide post-disaster resilience and recovery initiative set out with the task of achieving the following goals:

1. Develop and improve collaboration in the City and across the region.
2. Understand inter-system dependencies to enhance planning, restoration and reconstruction.
3. Share information about recovery plans, projects and priorities.
4. Establish coordination processes for lifeline restoration and recovery following a major disaster event.

We understand how vital lifelines are to San Francisco's resilience and ability to respond and recovery from a major disaster which is why this dynamic group of private utility providers and City officials was established. Creating a Lifelines Council was also a recommendation of the SPUR (2009) Resilient City policy paper which was essential in laying out a conceptual roadmap for this work. We are extremely grateful to the more than 30 lifeline service providers who have committed considerable time and effort to this partnership with the City over the past 4 years to improve collaboration and coordination in disaster planning, restoration and recovery.

While each provider is working hard to improve the resilience of their own systems, we recognized early on that collectively we needed to better understand the degree to which each provider depended upon the post-disaster functionality of other lifeline systems to respond and restore their own services. This is why we launched the lifelines interdependency study in 2012 and over the past two years, members of the Lifelines Council have been engaged in a system-by-system analysis of their utility's performance, disruptions, interdependencies, and restoration processes following a major earthquake in order to better understand the major challenges that we would likely face in such an unfortunate situation. We choose a repeat of 1906 earthquake (a M7.8 earthquake on the San Andreas Fault system) as our scenario so that we could stress test each of provider's systems and organizational responses. We recognize that this is a 'worst case' scenario for San Francisco and thus the actual damage and challenges will be much less in almost any other disaster scenario including any smaller magnitude earthquake on the San Andreas Fault or other fault systems in the region. As the study shows, each of the operator's has been working hard over the past decades to retrofit and upgrade their system's to be more earthquake and disaster resilient.

We are extremely grateful to the eleven lifeline service providers, representing a dozen types of lifeline systems, who agreed to participate in this study. Not only were they willing to provide valuable staff time to this project, they each approached the study with a sincere openness and willingness to share insights about their system strengths and weaknesses as well as their likely restoration challenges and dependencies. Each recognized that it is only through this process of collective dialogue that we could begin to formulate an agenda of priority actions that was well-grounded in reality and mutual understanding of our collective needs.

The study identifies a series of actions for the Lifelines Council, the City and County of San Francisco, and lifeline service providers in San Francisco to pursue to improve lifeline system reliability and post-disaster function in the city after a major disaster. They are organized into three categories of focus:

1. Conduct more detailed studies of geographic "choke points' areas of the city where there are heavy concentrations of infrastructure in which system damages, disruptions, interdependencies, and restoration challenges may also be more concentrated.
2. Enhance coordination of disaster planning and preparedness efforts among lifeline system providers, the City and Council of San Francisco and other relevant entities.
3. Enhance coordination of mitigation efforts that could collectively improve lifeline system performance in the city after future disasters.

We are pleased to present this Interdependency Study but our work is far from finished. As a result of this two-year-long study, the Lifelines Council Co-chairs along with the City's Chief Resilience Officer are proposing a five-year implementation plan with the goal of reducing the potential impacts of a major disaster on our City's critical lifelines with the goal of making San Francisco safer and more resilient:

Current Work Underway	• Conducted an interdependency table top exercise planned by DEM and PG&E. • Develop priority route maps to assist in guiding post disaster planning efforts. Maps will be split to show the 0-24 hour, 24-72 hours and 72hour to 1 month time periods. • Examine existing cell site coverage and issues relating to post disaster coverage.
Year 1	• Work with utility providers to develop staging and equipment storage guidelines and strategies for lifeline system inspectors and repair personnel. • Initiate Financial District/Market Street corridor infrastructure damage and restoration study. • Support the Port of SF in assessing the Seawall by studying the impacts and colocation issues for utility providers. Develop a waterfront seawall multi-hazard risk assessment. • Look for ways to integrate regional initiatives with other cities to synchronize lifeline restoration priorities. • Plan post-disaster fuel supplies for lifeline operators.
Year 2	• Prioritize mitigation projects for the City and private utility providers. • Initiate Mission Creek/Southeastern City infrastructure damage and restoration study. • Plan for post disaster financing of lifeline system repair and restoration including training on federal assistance regulations. • Develop strategies and guidelines for utility service needs for temporary and interim housing needs. • Develop provisions of basic services, shelter and security for lifeline system

	inspectors and repair personnel.
Year 3	• Conduct a table top exercise addressing communication and coordination when there are significant disruptions of cellular phone and internet services to all lifeline operators. • Develop common resilience (level of service) and restoration standards for critical system components. • Conduct a table top exercise to assess mutual aid agreements among Lifeline operators including the Department of Building Inspection to refine post disaster inspection procedures for critical lifeline facilities.
Year 4	• Plan for public emergency drinking water and sanitation services. • Prioritize mitigation projects for private sector operators and advocate, as needed • Prioritize mitigation projects for CCSF capital planning and funding
Year 5	• Conduct additional lifeline interdependency studies assessing the risks of flooding, tsunamis and sea level rise. Develop common standards and a plan for addressing gaps in "smart" system monitoring and communications.

Sincerely,

Naomi Kelly

Naomi Kelly, Co-Chair
City Administrator
City and County of San Francisco

Chris Poland

Chris Poland, Co-Chair
NEHRP ACEHR
Senior Principal, Degenkolb Engineers

EXECUTIVE SUMMARY

The Lifelines Council of the City and County of San Francisco has completed a study of the interdependencies that different lifeline systems operating within the city limits have with each other both in normal functioning and would expect to have in restoring systems following a major magnitude 7.9 earthquake on the San Andreas Fault. Eleven lifeline operators managing 12 types of lifelines systems participated in a structured interview process that lifeline system impacts and consequences, response and restoration schemes, and dependencies upon other lifelines systems. The magnitude 7.9 San Andreas earthquake scenario used in the study was developed in 2006 by a team of earthquake loss estimation experts to develop a best estimate of the potential ground motions, building damage and losses, and consequences if the 1906 earthquake were to happen with 2006 exposures of people and buildings. The results of the interdependency study will provide a more complete picture of the potential lifeline system impacts and consequences to supplement the 2006 estimates of building damage.

The purpose of the study is to first build a workable understanding of lifelines system performance and system interdependencies in a major disaster in order to help expedite response and restoration planning among lifeline operators; and, secondly, to identify key assets and restoration schemes to prioritize post-disaster restoration and reconstruction activities for the city, and ultimately the region following a major disaster. Longer-term, the Lifelines Council aspires to develop a collective set of lifelines expectations under current system conditions that may evolve into a collective set of lifelines performance standards for the San Francisco Bay region.

The study found that the expected levels of system damage are not as severe as they might have been without the major retrofits and upgrades that have been made to many of the city's and region's lifeline systems over the past decades. Nonetheless, most lifeline systems are still vulnerable to moderate damage that could substantially affect system functioning and delay restoration. The study has also found that the restoration of some lifeline systems is closely coupled and interdependent with the performance and restoration of other lifelines systems. This coupling varies with time—in the first hours, days, weeks, and months—following a major disaster. And, thus, while some lifeline systems may only experience moderate damage, their restoration could be significantly delayed because of these interdependencies. The study also does not explicitly consider aftershocks, which could be substantial following an earthquake of such magnitude, which could cause additional damage to lifelines systems and also further delay restoration.

The most critical interdependency issues that could impact emergency response efforts and the safety of people and property following such a major earthquake are: 1) a significant level of damage, debris, and closures to San Francisco city streets that, in particular, would impact the ability of operators to manually manage valves for the auxiliary water supply system, water supply, and natural gas systems; 2) until system upgrades currently planned or underway are completed, any potential failures in the supply of water (regional potable or seawater) and full functioning of the auxiliary water supply system which could impair post-earthquake fire-fighting capabilities; 3) until system upgrades currently planned or underway are completed, an electric substation failure or other significant disruption of electric power within the city which could have direct impacts on telecommunications and, in some cases, the system controls of lifeline operators; 4) until system upgrades currently planned or underway are completed, a potentially catastrophic failure of a municipal or regional transit tunnel which could impact transit systems as well as overhead streets and any lifeline systems in the vicinity of the failure; and 5) a significant level of damage to the waterfront seawall which could impact all lifeline systems running along or crossing the waterfront seawall area.

In terms of system restoration, the most critical interdependency issues are: 1) sufficient clearance and repair of city streets to provide lifeline operator crews with timely access to re-fuel generators and inspect and repair key system components; 2) until system upgrades currently planned or underway are completed, power disruptions lasting more than 72 hours and particularly affecting those systems with a heavy power dependency and limited back-up power supplies, notably the wastewater, municipal transit and telecommunication systems; 3) until system upgrades currently planned or underway are completed, a failure in the regional water system could impact the ability resupply both the potable and auxiliary water systems in San Francisco (although the auxiliary water system can also use seawater to fight fires); 4) an extended interruption of fuel supplies in the region affecting the restoration efforts of all lifeline operators; and 5) areas of concentrated damage and infrastructure "hubs" with potentially significant ground failures, such as the Financial District and the southeastern reaches of the city around Mission and Islais Creeks, that could significant impede system restoration and recovery.

Lifeline issues that could significantly impact the recovery of neighborhoods and commerce in San Francisco are: 1) repairs to city streets; 2) a natural gas transmission line shutdown or damage that impacts the entire natural gas distribution system in San Francisco and takes many months to relight and restore households and businesses; 3) until system upgrades currently planned or underway are completed, significant damage to the potable water distribution system requiring major repairs; 4) a significant level of damage to the waterfront seawall, that underlies the Embarcadero roadway and promenade, requiring significant time and resources to repair and reconstruct effecting tourism and commerce; and 5) a major infrastructure reconstruction need that emerges as a result of damage sustained during the scenario earthquake; until system upgrades currently planned or underway are completed, this might include a portion of the regional highway or regional transit systems, and a major system facility, such as an airport control tower, wastewater treatment plant, an electric substation, or a major fuel pipeline.

The study also identified potential courses of action for the Lifelines Council, the City and County of San Francisco and the lifeline operators in San Francisco to pursue to improve lifeline system reliability and post-disaster functioning in the city after a major disaster. They are organized into three categories of focus:

1) Conduct more detailed studies of geographic "choke point" areas of the city where there are heavy concentrations of infrastructure and in which system damages, disruptions, interdependencies, and restoration challenges may also be more concentrated. Specifically, they are:
    - A multi-hazard risk assessment of the seawall vulnerabilities along San Francisco's waterfront due to liquefaction, sea level rise and flooding

- An infrastructure damage and restoration study in the Financial District and Market Street Corridor where major components of many lifeline systems are collocated and interdependent
- An infrastructure damage and restoration study in the southeastern reaches of the city near Mission and Islais Creeks where major components as well as operation yards of many lifelines systems are densely located.

2) Enhance coordination of disaster planning and preparedness efforts among lifeline system operators, the City and County of San Francisco, and other relevant entities. The Lifelines Council has already initiated work on three of the key recommended areas and these efforts should be continued and supported:
   - Design and conduct a tabletop exercise addressing lifeline system interdependencies.
   - Address issues with the installation of both permanent and temporary cellular sites in the city
   - Identify priority routes for lifeline operator access and staging areas following a major disaster

   Other recommended areas for enhanced coordination are:
   - Improved emergency communications and priority setting among lifeline operators and with the City's EOC
   - Planning for post-disaster fuel supplies for lifeline operators
   - Planning for public emergency drinking water and sanitation services until services are restored
   - Planning for the provision of basic services, shelter and security for lifeline system inspectors and repair personnel working in the city post-disaster
   - Developing mutual aid agreements among lifeline operators
   - Planning for post-disaster financing of lifeline system repairs and restoration and conducting training on federal assistance regulations
   - Conduct additional lifeline interdependency studies for other perils and situations.

3) Enhance coordination of mitigation efforts that could collectively improve lifeline system performance in the City after future disasters. They are:
   - Work to collectively prioritize mitigation projects for CCSF Capital Planning and funding
   - Develop common resilience (Level of Service) and restoration standards for critical components of all lifeline systems in the City
   - Collectively prioritize mitigation projects for private sector operators and advocate for their approval and funding, as needed
   - Develop common standards and a plan for addressing gaps among systems and operators in "smart" system monitoring and communications.

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1. INTRODUCTION

This document summarizes the lifelines interdependency study of the Lifelines Council of the City and County of San Francisco (CCSF) conducted from November 2011 through June 2013. Eleven lifeline operators managing 12 types of lifelines systems in the city participated in the study. They are:

- California Department of Transportation (Caltrans) District 4 – Regional roads
- Pacific Gas & Electric (PG&E) – Electric power and natural gas
- San Francisco Public Utilities Commission (SFPUC) – Potable water, auxiliary water (for fire-fighting), and wastewater
- San Francisco Department of Public Works (SFDPW)– City streets
- AT&T – Telecommunications
- Verizon Wireless – Telecommunications
- Comcast – Telecommunications
- San Francisco Municipal Transportation Agency (SFMTA) – Transit
- Port of San Francisco – Port
- San Francisco Airport (SFO) - Airport
- Kinder Morgan – Fuel

A complete list of study participants is available in Appendix A.

At its August 11, 2011 meeting, the Lifelines Council agreed on the purpose of the interdependency study as to first build a workable understanding of lifelines system performance and system interdependencies in a major disaster in order to help expedite response and restoration planning among lifeline operators; and, secondly, to identify key assets and restoration schemes to prioritize post-disaster restoration and reconstruction activities for the city, and ultimately the region following a major disaster. Longer-term, the Lifelines Council aspires to develop a collective set of lifelines expectations under current system conditions that may evolve into a collective set of lifelines performance standards for the San Francisco Bay region.

1.1 LIFELINES INTERDEPENDENCY STUDY APPROACH

The lifelines interdependency study used a magnitude (M)7.9 earthquake centered just off the coast of San Francisco as the scenario for the study. In a structured interview process, each lifeline operator used the scenario to address questions on lifeline system impacts and consequences, response and restoration schemes, and their dependencies upon other lifelines systems.

The M7.9 San Andreas earthquake scenario was developed in 2006 by a team of earthquake loss estimation experts, led by Charles Kircher and Associates.[1] The scenario study was

[1] Charles A. Kircher et al., 2006, "When the Big One Strikes Again – Estimated Losses Due to a Repeat of the 1906 San Francisco Earthquake," Earthquake Spectra, EERI: Oakland, CA.

commissioned by the Earthquake Engineering Research Institute (EERI), Seismological Society of America (SSA) and the California Office of Emergency Services (Cal OES) to develop a best estimate of the potential ground motions, building damage and losses, and consequences if the 1906 earthquake were to happen with 2006 exposures of people and buildings.

The 2006 scenario study relied primarily on the "Earthquake Model" of the Federal Emergency Management Agency's (FEMA) Hazus™ technology to estimate earthquake damage and loss across 19 counties in Northern California. Building inventory data was supplemented with expert engineering opinion as well as information from more detailed surveys, including the: assessor's and neighborhood building survey data from San Francisco's Community Action Plan for Seismic Safety (CAPSS) and unreinforced masonry data from the California Seismic Safety Commission. Updates to the Hazus™ methodology included: updates to building and contents replacement values and "time of day" populations to better reflect the region's 2006 conditions; development of new damage and loss functions for retrofitted buildings; and modification of economic loss functions to account for the post-disaster "surge" in repair and replacement costs as experienced in other recent disasters. Statistics on actual damage and loss caused by the 1989 Loma Prieta earthquake were used to validate the methodology.

The lifelines interdependency study questions were derived from approaches taken by other researchers and regions conducting lifelines interdependency studies.[2] They were also vetted with Lifelines Council members in a workshop held at its August 11, 2011 meeting. Lifeline operators were asked to assemble a panel that could speak to the physical design and seismic vulnerability of their system as well as those who are responsible the system and facilities operations and would be involved in response and restoration after a major disaster. Panelists were sent the interview guide ahead of time. The interviews started off with a brief presentation of the scenario earthquake followed by a discussion of the likely impacts on that particular operator's system and facilities. Next, discussion focused on the operator's immediate response and restoration priorities and activities, their dependencies on other lifeline systems in the response and restoration process, and the likely dependencies that other lifeline operators had on their lifeline system. After this, panelists were presented with the findings of prior operator interviews and their expected response and restoration timelines and discussion then focused on how this information impacted prior assumptions about response and restoration and lessons learned for mitigation and preparedness.

Each operator participating in the study has been asked to approve materials presented about their systems to other operators as well as the material contained in progress reports made regularly at the Lifelines Council meetings. Copies of the study progress presentations are available at: http://www.sfgsa.org/Lifelines Council.

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[2] Key study references: Stephanie Chang, Tim McDaniels, et al, 2008, Critical Infrastructure Interdependencies Study in Vancouver, British Columbia, presented at the 2008 National Earthquake Conference, Seattle, WA, April 22-26; and Keith Porter and Rachell Sherrill, 2011, "Utility Performance Panels in the ShakeOut Scenario (for Southern California)," Earthquake Spectra, 27-2: 443–458, EERI: Oakland, CA.

2. Scenario: Repeat of the 1906 San Francisco Earthquake

Shortly after 5 am on April 18, 1906, almost 300 miles of the San Andreas Fault ruptured and strong ground shaking lasted for well over a minute. Combined with the fires that ensued, more than 3,000 people were killed, over 28,000 buildings were destroyed, and 225,000 people were left homeless. The earthquake caused damage across a vast area, from Mendocino in the north to Sacramento in the east and Monterey in the south, but nowhere was the devastation more severe than San Francisco. In 1906, about 390,000 people lived in San Francisco and less than 1 million people lived in the 19-county region affected by the earthquake.

2.1 Impacts on People and Buildings (from Kircher et al., 2006)

If an earthquake similar in size and location to the 1906 earthquake were to happen today, it would directly affect over 10 million people and three million buildings within a 19-county region of Northern California. The highest levels of ground shaking and subsequent building and lifeline damage would occur in San Francisco, San Mateo, Alameda, Santa Clara, and Marin counties, where the majority of the region's property and population are located within 25 miles (40 km) of the San Andreas Fault.

The ground motions from a magnitude 7.9 earthquake on the San Andreas Fault are essentially the same as the minimum design loads prescribed by the latest seismic standards for building and other structures.[3] However, many of Northern California's buildings, especially in San Francisco, are much older and constructed to earlier and less resilient standards. Figure 1 is a map of the estimated peak ground accelerations from a magnitude 7.9 earthquake on the San Andreas Fault. In addition to strong shaking, areas of unconsolidated soils and artificial fills near the San Francisco Bay are likely to experience ground failure related damage due to liquefaction. Landslides could also be generated in hillside areas where soils are very susceptible to failure.

An estimated 90,000 to 130,000 buildings across Northern California would sustain extensive or complete structural damage in this magnitude 7.9 earthquake. Figure 2 shows the estimated building losses and building loss ratios from this earthquake. Between 80,000 and 120,000 residential buildings in the region would sustain major damage, displacing between 160,000 and 250,000 households or at least 400,000 people. In San Francisco, an estimated 15,000 to 24,000 single family dwellings would have extensive or complete damage (12% to 20% of 125,000 total) and 7,000 to 11,000 other types of residential buildings would have extensive or complete damage (19% to 30% of 37,000 total). This would initially displace an estimated 60,000 to 88,000 households (18% to 27% of the 330,000 households in the city). Furthermore, an estimated 7,000 to 10,000 commercial buildings would sustain major structural damage, including about 40% of all commercial buildings in San Francisco and San

[3] Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE), 2005, Minimum Design Loads for Buildings And Other Structures, ASCE/SEI 7-05 (accessed September 1, 2013, https://secure.asce.org/files/estore/896/40809_40809.pdf)

Mateo counties. For reference, more than 140,000 buildings were severely damaged or collapsed in the 1995 Kobe earthquake in Japan, and only about 15,000 buildings were severely damaged in the Northridge earthquake that struck Los Angeles in 1994. Building-related losses totaled about $80 billion in the 1995 Kobe, Japan earthquake, and only about $20 billion in the 1994 Northridge earthquake.

Depending upon whether the earthquake occurs during the day or night, building collapses would cause between 800 and 3,400 deaths. Building damage from a nighttime earthquake would cause 800 to 1,800 deaths. In a daytime earthquake, more significant human losses of between 1,600 and 3,400 deaths could be caused by severe damage to the many vulnerable classes of work-related structures. More than 50% of the estimated deaths are caused by the collapse of unreinforced masonry buildings, older reinforced concrete buildings, and other vulnerable structures that have not yet been strengthened; yet, these vulnerable structures represent less than 5% of all buildings in the study region. The most vulnerable building types are one- and two-story wood-frame structures with minimally reinforced first floors (i.e. soft-story buildings), unreinforced masonry, and older, non-ductile concrete structures.

It would cost more than $120 billion (2006 dollars) to repair or replace buildings and contents damaged by a repeat of the 1906 earthquake. Of this, San Francisco County would sustain as much as $34 billion in building-related losses, following by $28 billion in Santa Clara, $26 billion in San Mateo, and $15 billion in Alameda counties. The remaining $18 billion in building-related losses would be spread across the other 15 counties.

The 2006 study estimated that several hundred individual fire ignitions would cause an additional 5% to 15% in building damage as well as additional deaths. This is a region-wide estimate, and some counties, in particular San Francisco which has older buildings and a denser pattern of development, could suffer a greater percentage of fire-related losses. A conflagration similar in scale to the 1906 fire is not likely, but if it did happen it would cause an even greater loss. In 1906, the 3-day conflagration following the earthquake burned over 500 downtown blocks and was responsible for 80% to 90% of all losses in the city.

Considering all loss components, the total price tag for a repeat of the 1906 earthquake could reach $150 billion (2006 dollars). This includes both public and private buildings and contents damage, as well as infrastructure and business interruption losses. Damage to utilities and transportation systems were estimated to increase losses by an additional 5% to 15%.[4] It does not include the potentially significant and long-term losses that might be caused by widespread economic disruption, such as potential decreases in property values and property tax revenue, loss of tourism revenues, and other key income generators for the region. Prolonged utility and transportation outages would cause widespread disruption costing several times this amount. For comparison, this estimate is similar to the total losses from the 1995

[4] The 2006 study did not fully model and evaluate transportation and utility related losses and was based upon utility operator and expert estimations for all related losses in the region.

Kobe earthquake, roughly four times the total losses from the 1994 Northridge earthquake and about 10 times the total losses from the 1989 Loma Prieta earthquake (in 2006 dollars).

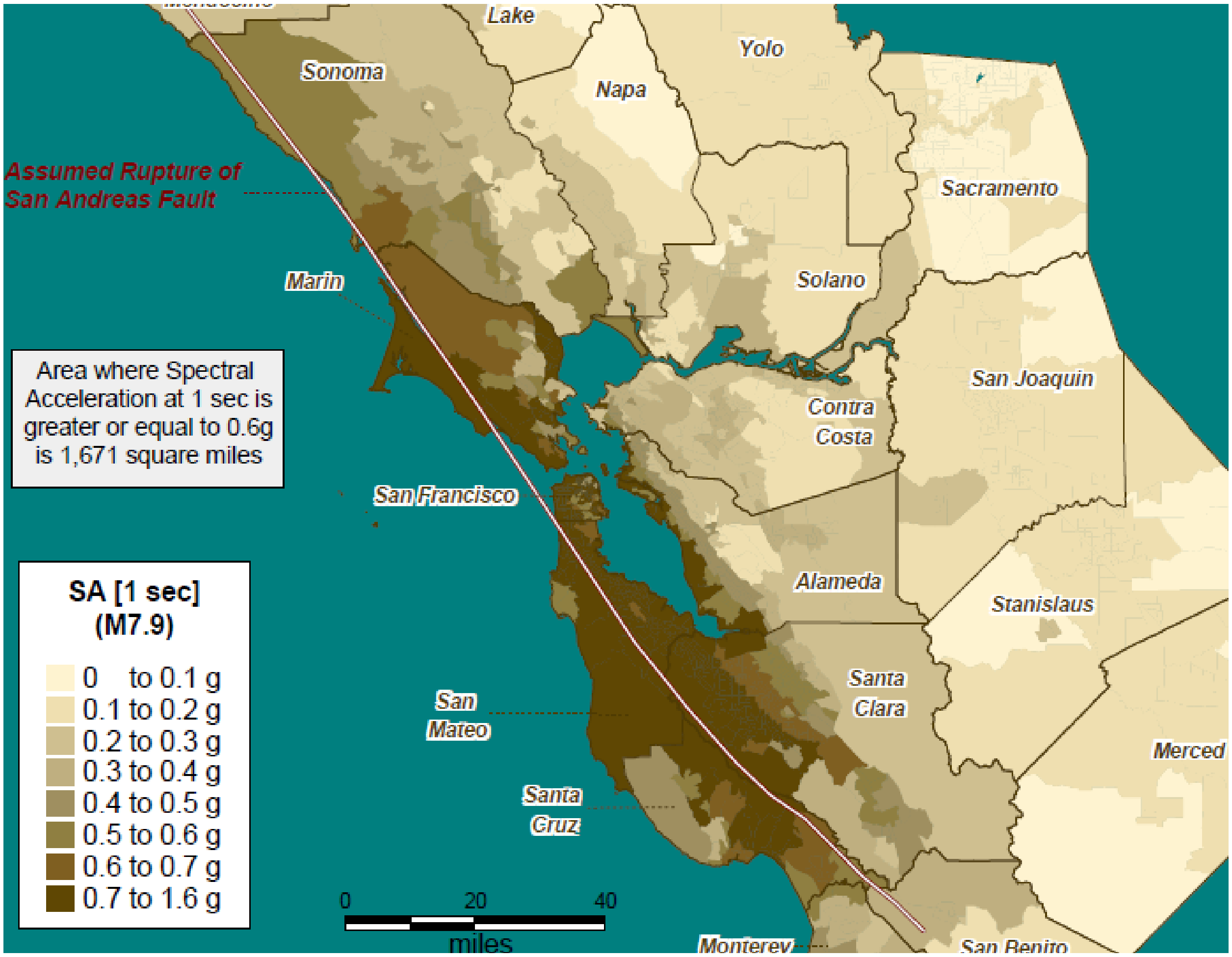


FIGURE 1. ESTIMATED GROUND MOTIONS FROM A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (SOURCE: C. KIRCHER, 2006)

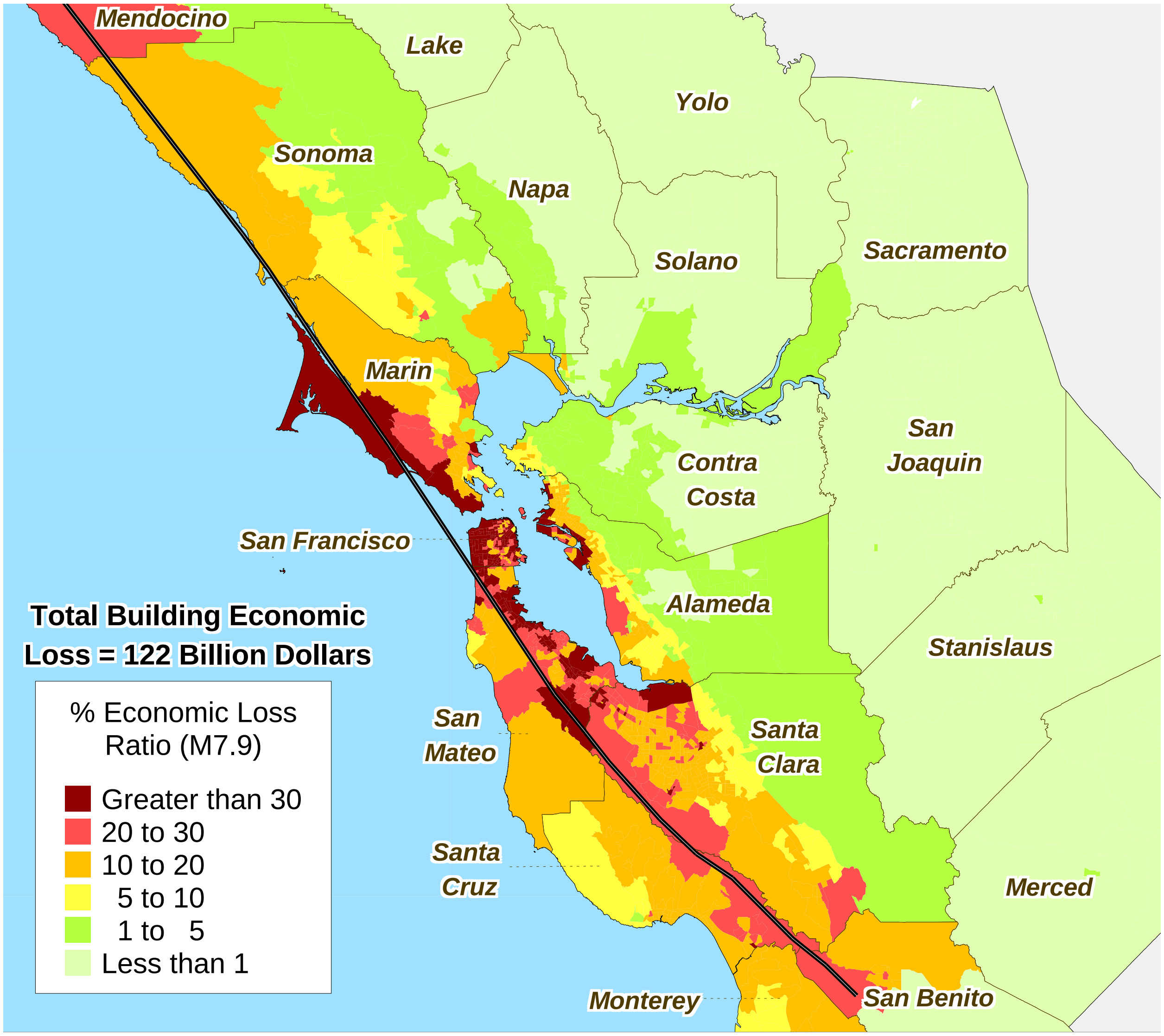


FIGURE 2. ESTIMATED BUILDING LOSSES FROM A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (SOURCE: C. KIRCHER, 2006)

2.2 Potential Lifeline System Impacts and Damage (from the Lifelines Interdependency Study)

As noted, the 2006 study did not fully model and evaluate transportation and utility related losses. One purpose of the CCSF lifelines interdependency study has been to augment the building related information developed in the 2006 study to obtain a comprehensive scenario of the likely impacts from a M7.9 earthquake on the San Andreas Fault, particularly in the City and County of San Francisco.

Lifelines systems across Northern California would be affected by the strong and protracted ground motions generated by a magnitude 7.9 earthquake on the San Andreas Fault. Thus, many of San Francisco's lifeline operators would likely experience system damage across a much wider geographic area that extends well beyond the city's limits. Within San Francisco, lifeline systems and facilities located in areas vulnerable to liquefaction and other ground failures are likely to sustain higher levels of damage. Figure 3 is a map of liquefaction and landslide susceptibility areas of San Francisco. Also, the study does not explicitly consider aftershocks, which could be substantial following an earthquake of such magnitude, which could cause additional damage to lifelines systems.

Table 1 summarizes the impacts that lifeline operators expect on their systems with an emphasis on the effects within the city limits of San Francisco for this particular scenario. Readers are cautioned that this is a descriptive summary of the potential damages provided by study participants and should not be used as a predictive model of performance in a future earthquake or other disaster. The following shading represents a qualitative interpretation of the overall level of damage that is likely to disrupt lifeline system functioning in San Francisco based upon the lifeline operator interviews:

Severe damage across major parts of the system or to critical facilities that would significantly affect system functioning
Moderate damage across portions of the system or critical facilities that would have some moderate effect on system functioning
Limited damage to the system or critical facilities that would have limited effect on system functioning

Based upon this analysis, it is important to note that the level of damage is not as severe as it would have been without the major retrofit and upgrade that have been made to many of the city's and region's systems over the past decades. Particularly since the 1989 Loma Prieta earthquake struck the Bay Area nearly 24 years ago, many of the region's lifelines operators have been performing extensive upgrades and retrofits of their systems and critical facilities. Table 2 summarizes some of the key upgrades. Also, many operators have been installing new systems and system upgrades as part of ongoing capital improvements and system expansions which also contribute to increased lifeline resiliency in San Francisco and the Bay region.

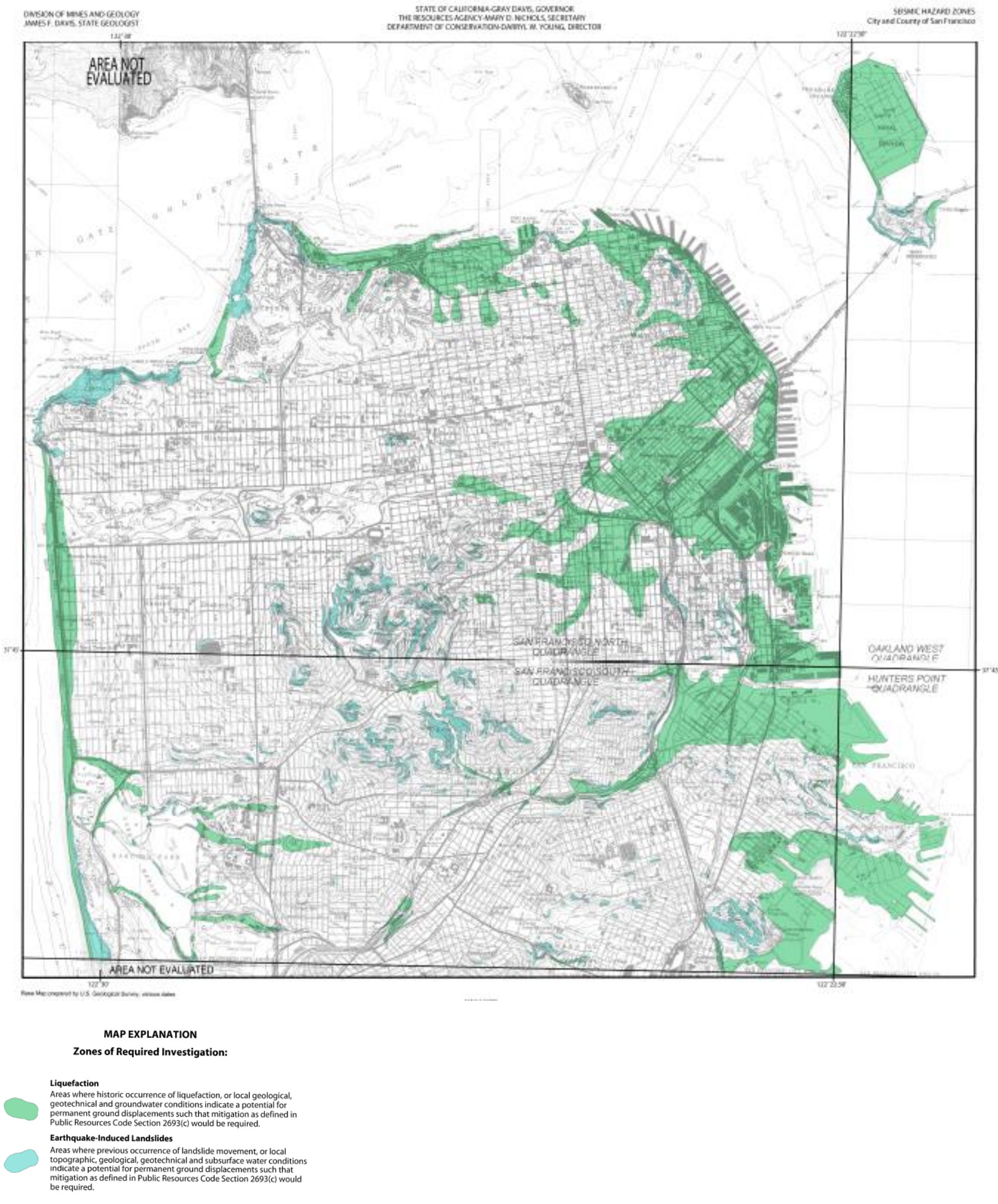


FIGURE 3. SEISMIC HAZARD ZONE MAP FOR SAN FRANCISCO SHOWING EARTHQUAKE-INDUCED LIQUEFACTION AND LANDSLIDE VULNERABLE AREAS OF THE CITY (SOURCE: CALIFORNIA GEOLOGICAL SURVEY, 2000)

Table 1. Potential Lifeline System Impacts and Damage from a Scenario M7.9 earthquake on the San Andreas Fault (as of November 2013)

Regional Roads	Key bridges and retrofit projects that are still under construction would likely suffer damage, notably the Doyle Drive approach to the Golden Gate Bridge (US-101) (scheduled for completion in late 2014). Also, while key components of region's highways have been strengthened to withstand shaking levels anticipated with the scenario earthquake, there would still likely be some ground failure-related damage at the approaches to the region's 7 major bridges, and along portions of US-101, I-80, I-880, the El Camino Real, and Highway 1. There may also be some structural damage at major freeway interchanges and the I-280 bridges near the San Andreas fault. Caltrans District 4 headquarters is unlikely to have structural damage but lifeline interruptions into the building and non-structural damage is possible.
City Streets	Strong ground shaking and ground failures (liquefaction, landsliding, and lateral spreading) could directly damage city streets and also damage buried infrastructure causing collateral damage to city streets. Areas of high ground failure susceptibility would likely have higher levels of damage. Fires and debris in the streets from damaged or collapsed buildings would also block some streets.
Electric Power	San Francisco is served by three transmission lines that enter from the peninsula, and a DC line that crosses under San Francisco Bay. If a critical substation in San Francisco is significantly damaged, electric transmission could be disrupted, severing power to the entire city. PG&E's Embarcadero-Potrero Transmission Project (to be completed by December 2015) would construct a new 3.5 mile long cable transmission line between the Embarcadero substation and the Potrero Switchyard, enhancing PG&E's ability to reroute power and decrease the system's vulnerability to a major power loss. Damage to the underground electric distribution system could also be significant. Other portions of PG&E's 5-year, $1.2 billion infrastructure improvement plan (announced in February 2013) will improve electric substations and the distribution system in the city. PG&E headquarters would suffer only minor damage, but lifeline interruptions and non-structural damage are possible.
Natural Gas	San Francisco receives natural gas from three gas transmission lines that enter from the peninsula and meet at a single point in San Francisco. Gas is then distributed throughout the city. Damage in two or three transmission lines could result in a pressure loss and gas service would be curtailed throughout the city. Flexible gas distribution lines installed throughout the city are not likely to have significant damage. Any gas leaks would be controlled through 2,200 manually operated valves located throughout the city.
Telecom	There would likely be modest levels of damage to more modern and upgraded telecommunications components and lines. Many key switching centers are expected to perform well given recent upgrades and back-up power supplies. Heavier damage may occur to equipment located in older buildings and to older equipment and lines. Buried system damage could also occur in areas susceptible to ground failure. Water or wastewater system failures could cause collateral damage. Broadcast transmission facilities at Sutro Tower were impacted during the 1989 earthquake and transmission could be impacted in this scenario. Cell sites reliant on back-up batteries and without backup generators would fail within the first day if power is lost, and remain inoperable until power is not restored. Cell tower antennas may require adjustments.
Water	The major water transmission pipelines, pump stations, and reservoirs of the seismically upgraded regional transmission system from the Hetch Hetchy reservoir to the San Francisco peninsula are all expected to perform well in a M7.9 earthquake on the San Andreas fault. Half of the water storage facilities in San Francisco have also been seismically upgraded; the last remaining upgrade, to Sutro reservoir, will soon be completed in 2014. The water distribution system in San Francisco is generally reliable but portions with older cast iron pipes would likely have more damage than areas with newer ductile iron pipes. In the 1989 Loma Prieta earthquake, there were no distribution pipeline breaks in ductile iron pipes but there were breaks in the cast iron pipes especially in liquefaction prone areas.

TABLE 1. POTENTIAL LIFELINE SYSTEM IMPACTS AND DAMAGE FROM A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (AS OF NOVEMBER 2013)(CONTINUED)

Auxiliary Water (for fire-fighting)	Major seismic improvements funded by the 2010 Earthquake Safety and Emergency Response (ESER) Bond are currently underway to improve the auxiliary water supply system's reservoir, water tanks and pump stations by 2016, and complete cistern and pipeline upgrades by 2018. With upgrades already made as of October 2013, the existing system is expected to remain functional in this scenario. Additional water sources for fire-fighting can be supplied via San Francisco Bay, though seismic improvements are needed at pumping station 1 tunnel. Some portions of the piping system could also have damage, particularly in liquefaction prone areas, and some city neighborhoods do not have auxiliary water pipeline or cistern coverage. The citywide system reliability to respond to a major fire following an earthquake will increase from near 50% to nearly 70% when the improvement program is completed in 2018. A planning study is nearing completion and will identify a seismic improvement program to increase overall citywide system reliability to greater than 90%; implementation will occur over the next 20+ years.
Wastewater	Until the SFPUC Sewer System Improvement Program (SSIP) is completed (in 2035), damage is likely at all three of the city's wastewater treatment plants. Damage to the collection and conveyance system is also more likely to occur in ground failure areas across the city. The system is largely controlled by gravity but a loss of water would likely impact system flow. Loss of power will impact pumping and treatment facilities which have very limited back-up power supplies.
Transit	There is a diverse fleet of diesel and hybrid buses, electric trolleys and street cars, cable cars, and light rail for municipal transit in San Francisco. Fleet operations are vulnerable to ground failures causing street, cable system, and rail line damage, debris and road closures, and electric power losses. System control and operations/maintenance facilities, fuel tanks, rail lines, and tunnels that have not been seismically retrofitted could also be vulnerable to structural damage and closure. Underground power supplies, overhead electric lines, and electric substations could also experience damage. Until seismic retrofits are completed, potentially catastrophic damage could occur in the subway portion of the municipal light rail system if there is a major failure and flooding of the regional Transbay tube/tunnel.
Port	Potential failure of the waterfront seawall, which runs approximately 4 miles from Fisherman's Wharf to Pier 54, could cause liquefaction, lateral spreading into the bay, and vertical subsidence. There was ground failure damage in and around the seawall in both the 1906 and 1989 earthquakes. Lifelines that run along the Embarcadero and through the seawall and out to the piers could be damaged. Access and entry to the piers and ferry terminals could also be impacted by a seawall (Embarcadero roadway and promenade) failure and other ground related damages. Piers and bulkheads along the waterfront that have not been seismically retrofitted, and all buildings and assets along them that are not seismically retrofitted to withstand ground motions associated with a M7.9 earthquake, could be damaged. The retrofitted Ferry Building, downtown Ferry terminal, Pier 9 (San Francisco Bar Pilots), and China Basin Ferry terminal are among the waterfront structures that could be damaged and not functional after a M7.9 earthquake.
Airport	Damage could occur to liquefaction-vulnerable runways and roadways and older buildings that are not yet retrofitted, including Boarding Area E (to be completed in January 2014), the control tower (new tower to be completed in late 2015); Terminal 1 (redevelopment starting in 2014 with estimated completion in 2019) and Terminal 3 (retrofit in the planning stages). There also could be damage to key lifelines located on liquefaction-prone soils in and around the airport, including highways, telecommunications, power, transit, and fuel pipelines.
Fuel	There are not any major refining or storage facilities within the CCSF boundaries. However, fuel is a critical lifeline supporting the functioning of other lifeline systems and thus included in the study. The region's fuel system is complex and includes port terminals, refineries, pipelines, storage tanks, and terminal/service centers. All are in varying states of seismic resilience and thus are likely to sustain varying levels of damage in a M7.9 earthquake. There are major fuel pipelines that pass through the county en route to SFO and nearby storage facilities in Brisbane.

TABLE 2. LIFELINE SYSTEM SEISMIC UPGRADE EFFORTS COMPLETED OR UNDERWAY (AS OF NOVEMBER 2013)

Regional Roads	Since the 1989 and 1994 earthquakes, Caltrans has been undertaking a multi-billion dollar, statewide program to inventory, prioritize, and seismically strengthen and retrofit state highway bridges. This includes major projects such as the retrofit of all the region's toll bridges, including the western span and replacement of the eastern span of the Bay Bridge; and replacement of Doyle Drive elevated highway that runs from the Golden Gate Bridge through the Presidio. The statewide program is now almost complete.
City Streets	Starting in 2006, the City has been making considerable investments in its streets, bridges, and tunnels. The city maintains a database of all city street segments and pavement conditions for each segment, and based on this assessments street segments are selected and prioritized for maintenance. The overall condition and quality of roadways has improved steadily and is expected to reach top quality within the next 10 years due in large part to the voter-approved $248 million 2011 Road Repaving and Street Safety bond.
Electric Power	Over the past decades, significant enhancements have been made to region's electric power generation, transmission, and distribution systems to improve overall reliability and seismic performance. Since San Francisco lacks a power generating source within the city limits, it is particularly vulnerable to regional transmission vulnerabilities. In February 2013, PG&E announced a 5-year, $1.2 billion infrastructure improvements plan for San Francisco. It includes: reconstruction of major electric substations, installation of a new electric transmission line, streetlight upgrades and replacements, and a series of upgrades to the electric system. In addition, the San Francisco Public Utility Commission is in the process of making significant improvements to its hydroelectric power plant at the Hetch Hetchy Reservoir in Yosemite National Park.
Natural Gas	Over the past decades, significant seismic enhancements have been made to region's natural gas transmission and distribution systems. PG&E's 5-year, $1.2 billion infrastructure improvement plan for San Francisco includes upgrade to both the natural gas transmission and distribution systems in the city. All remaining (23 miles) of seismically-vulnerable cast iron pipe will be replaced by the end of 2015.
Telecom	Telecommunication operators have made significant investments to expand and upgrade network equipment and lines. Since 1989, AT&T has seismically evaluated and retrofitted many of its central switching centers and other network assets. Verizon has invested $641 million to expand and upgrade its California network. Comcast has invested in seismically upgrading and securing all racks at its major facilities.
Water	In November 2002, San Francisco voters approved the use of a revenue bond funded by local and regional water rates to support the $4.6 billion Water System Improvement Program (WSIP) to repair, replace and seismically upgrade the regional and local water systems within San Francisco and all the way to the Hetch Hetchy Reservoir in Yosemite National Park. It is one of the largest water infrastructure programs in the nation and includes more than 80 projects to upgrade pipelines, tunnels, reservoirs, pump stations, storage tanks, and dams. The project will be completed in 2016 (with the exception of upgrades to Calaveras Dam, which generally safeguard against a Hayward fault earthquake) and includes projects to manage the safe crossing of three major seismically active fault systems: the Calaveras, Hayward, and San Andreas faults. The distribution system within San Francisco will also be seismically improved. These improvements will support fire suppression immediately following an earthquake and reduce neighborhood evacuations due to loss of potable water or water needed for sanitary operations. The SFPUC is presently working on performance criteria to support these 3 post-event functions.

TABLE 2. LIFELINE SYSTEM SEISMIC UPGRADE EFFORTS COMPLETED OR UNDERWAY (AS OF NOVEMBER 2013) (CONTINUED)

Auxiliary Water	In June 2010, San Francisco voters passed the Earthquake Safety and Emergency Response (ESER) Bond Program that includes $102.4 million for seismic upgrades to the Auxiliary Water Supply System (AWSS). Design and construction of the upgrades is happening in phases. The first phase of improvements has already begun and includes: upgrades to the reservoir, water tank and pump station facilities, cistern repairs and new installations, and pipeline upgrades. In addition, a major planning and hydrological study is nearing completion to scope the system reliability and future project and program alternatives.
Wastewater	In 2005, the SFPUC initiated a master planning effort to evaluate the condition and future needs of San Francisco's combined sewer and stormwater management system. The $7 billion Sewer System Improvement Program (SSIP) includes many seismic improvements, including structural upgrades to the city's two major treatment facilities to ensure that they are functional within 72 hours of a major earthquake.
Transit	Based upon a seismic evaluation in 2007, three SFMTA metro stations (Church, Castro, and West Portal) were designated for seismic upgrades. The Church Street station was retrofitted in 2008 as part of BART's earthquake safety program. In 2012, a more detailed seismic vulnerability study was completed for the Sunset Tunnel and Twin Peaks Tunnel and seismic strengthening work is scheduled to be completed over the next 3 years on isolated areas of vulnerability identified in the study.
Port	Seismic retrofit repairs and improvements have been made to Piers 1, 1 ½, 15, and 48; AT&T Ballpark; Ferry Building and its associated terminals; China Basin Ferry Terminal; and the Fire Boat station at Pier 22 ½.
Airport	San Francisco Airport's International Terminal and the recently retrofitted Terminal 2 are built to meet essential facility level seismic standards. Additional retrofits to parking structures, bridges, roadways, and utilities finished in the last two years and the $203 million six year Runway Safety Area project is well underway (to be completed in 2015). A new air traffic control tower (to be completed in late 2015), Terminal 1 (redevelopment starting in 2013), and Terminal 3 (retrofit in the planning stages) will also be constructed to high seismic standards.

2.3 POTENTIAL LIFELINE SYSTEM RESTORATION TIMEFRAMES (FROM THE LIFELINES INTERDEPENDENCY STUDY)

Table 3 summarizes the level of service disruption that lifeline operators expect on their systems in a M7.9 San Andreas Fault earthquake, with an emphasis on the effects within the city limits of San Francisco. Readers are cautioned that this is a descriptive summary of the best estimates of likely system performance timeframes provided by study participants and should not be used as a predictive model of performance in a future earthquake or other major disaster. The following shading represents the qualitative interpretation of the overall level of service disruption that is likely to affect system and service restoration to customers in San Francisco based upon the lifeline operator interviews:

Severe service disruption across major parts of the system or to critical facilities that significantly affect system functioning
Moderate service disruption across portions of the system or critical facilities that would have some effect on system functioning
Limited service disruption to the system or critical facilities that would have limited effect on system functioning

Figure 4 provides an integrated view of the lifeline restoration timelines that study participants estimated for their systems following a M7.9 San Andreas Fault earthquake. These too should not be viewed as a predictive model of performance in a future earthquake or other major disaster.

A great deal of system retrofit and upgrade work has already been completed or is underway in San Francisco, all of which will enhance lifeline system restoration following a major disaster. But, some systems are still vulnerable to significant damage that could substantially delay restoration. Also, as the study has revealed, the restoration of some lifeline systems are closely coupled and interdependent with the performance and restoration of other lifelines systems. While some lifeline systems may only experience moderate damage, their restoration could be significantly delayed because of these interdependencies. Also, the study does not explicitly consider aftershocks, which could be substantial following an earthquake of such magnitude, which could cause repeated delays in restoration efforts.

Many of the lifeline operators have experienced significant system disruptions and restoration efforts that have provided helpful insights for mitigation and preparedness efforts in anticipation of future disasters. Some of the accounts shared as part of the study interviews are provided in Table 4.

TABLE 3. POTENTIAL LIFELINE SYSTEM RESTORATION CONSIDERATIONS FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (AS OF NOVEMBER 2013)

Regional Roads	The region's redundant highway network helps ensure that some level of access is available to all parts of the region, including San Francisco, even with the expected damage levels. However, the level of service would be impacted and travel times may significantly increase until repairs are completed. Crews would start minor repairs immediately. A region-wide assessment of travel conditions would take about 12 to 18 hours to complete and prioritize where more intensive structural inspections would occur. For the first week, there might be limited access to major bridges and overpasses until they are inspected, and significant aftershocks could require additional rounds of inspections. System restoration timelines would vary on highways depending upon priorities, resources, and the actual repairs required. Travel patterns would likely change after a major disaster which would also affect priorities.
City Streets	Street clearance would initially focus on routes for emergency responders and other priority users. A rapid damage assessment could take 12 to 24 hours and then more detailed assessments could take weeks, especially to scope the repairs and determine costs. Debris clearance would take several months, by which time street reconstruction would also be underway. Ongoing building demolitions and repairs to buried infrastructure would create additional debris and impact streets for an extended period of time. It may take a year to complete all the street clearance and initial repairs. Major reconstruction projects would take longer.
Electric Power	Even if the transmission system is undamaged, the electric distribution system throughout San Francisco could be subject to rotating outages following a major earthquake. Much of San Francisco's electric distribution system is underground and challenging to repair. For a M7.9 San Andreas earthquake, PG&E estimates power restoration in San Francisco would be at 25% within 48 hours, 95% within one week, and 100% within one month following the earthquake. (Estimates depend on many variables outside PG&E's control. Service may be restored earlier or later, depending upon the state of the transmission system and availability of qualified personnel.)
Natural Gas	If gas transmission service is lost, restoration could not begin for 3 weeks (due to necessary integrity testing before re-pressurizing the lines). For a M7.9 San Andreas earthquake, PG&E estimates that it could take up to 6 months for full restoration in San Francisco. Compressed natural gas (CNG) fueling sources would also have limited capacity for the extent of the outage, and rationing restrictions would need to be applied. (Estimates depend on many variables outside PG&E's control. Service may be restored earlier or later, depending upon the state of the transmission system and availability of qualified personnel.)
Telecom	Telecom functionality is coupled with electric power service. Post-earthquake system functionality is expected to be high, such as 90%, where there is a strong supply of batteries, generators and network redundancy. But, many of San Francisco cell sites do not have back-up generators so cellular service would decline in the first 8 hours if power is not restored and batteries run out. Some telecom operators have disaster recovery "fleets" that can be deployed to provide a temporary system. However, overall system restoration is heavily linked to electric power restoration and access for crews to refuel generators or provide back-up power. Repairs may be delayed in areas of water and wastewater system damage. Damaged equipment located in damaged buildings may also be difficult to access and repair. Temporary cell towers and microwave systems would likely be needed.

TABLE 3. POTENTIAL LIFELINE SYSTEM RESTORATION CONSIDERATIONS FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (AS OF NOVEMBER 2013) (CONTINUED)

Water	The Water System Improvement Program (WSIP) and other seismic improvements will be completed by 2016 (with the exception of the Calaveras Dam improvements which will be completed in 2018). With about 75% of the program completed to date, the regional water transmission would likely achieve most of its post-seismic performance objectives within the first 24 hours if a M7.9 San Andreas earthquake occurred today. In San Francisco, there are about 3 to 4 days of potable water stored in reservoirs. Most reservoirs and any portions of the distribution system that withstood the earthquake would form the interim distribution system for the public, mass care facilities and fire-fighting. With some portions damaged, water distribution to all existing service connections in San Francisco (about 190,000) would not be likely. Water mains in streets would be isolated and repaired first (allowing hydrants to act as supply sources for neighborhoods) with service connections to individual properties repaired on a priority basis later. Standards for the fully upgraded regional water system are to resume 70% of transmission capacity to San Francisco within 24 hours, and reach full capacity within 30 days of a major earthquake. SFPUC is currently working to assess the condition of the city's water distribution system and prioritize pipeline upgrades to enhance citywide seismic performance. Major water distribution pipelines (24 to 48 inch diameter) would likely be online within 24 hours. Otherwise, distribution restoration priorities would need to be determined after a disaster, general repairing the largest pipelines first. The SFPUC is working on improving the seismic performance of large diameter distribution pipelines to support fire suppression, potable supply, and sanitary service. The objectives will be expressed as percentages of functionality over time (e.g. 75% of large diameter pipelines are pressurized within 2 hours following an earthquake).
Auxiliary Water (for fire-fighting)	Initial system functioning post-earthquake requires a water supply. There would be supply in the Twin Peaks reservoir when an earthquake occurs and the regional water transmission system is expected to be able to replenish the reservoir within 24 hours. The auxiliary water supply system can also pump in seawater from San Francisco Bay. The Fire Department also manages a portable water supply system that could be utilized in combination with potable water or seawater if necessary. Another challenge is that crews would need access to manually close and isolate leaks and keep the system pressurized. In 3 to 4 years, system upgrades will allow for more remote pressure management.
Wastewater	Regardless of damage, the wastewater treatment plants would shut down for inspection immediately following a major earthquake. A power loss would affect functioning of pumping stations along the major conveyance routes. Although treatment may stop and power may be lost, the vast majority of the collection system would keep functioning since it is largely gravity fed. Instead of being pumped to the treatment plants, however, it would collect in the larger pipes and major storage and conveyance structures that can hold over 200 million gallons of combined sewer and stormwater. The majority of the wastewater system is expected to back up and running in 72 hours after electric power is restored. The goal of sewage system upgrade plans is to have the primary treatment facilities on-line within 72 hours of a major earthquake.
Transit	A diverse fleet provides added redundancy. Municipal transit would initially shutdown rail and electric trolley bus services for safety inspections following a major earthquake. Even with a power loss, back-up power supplies can maintain subway lighting and ventilation and train control for several hours. Emergency generators can also be deployed. If power isn't restored within a few hours, then the municipal diesel bus fleet might become the primary form of transit until power is restored. Access to move around city streets and access to diesel fuel would be critical to diesel fleet functioning. Damage to a system control facility could affect fleet operations until controls can be re-established at an alternative location.

TABLE 3. POTENTIAL LIFELINE SYSTEM RESTORATION CONSIDERATIONS FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (AS OF NOVEMBER 2013) (CONTINUED)

Port	Initial inspections of critical and top priority facilities would likely be completed in 72 hours after the earthquake. Full inspection of all the piers has taken 30 to 40 days in the past. It would likely take a month to several months to relocate essential functions, stabilize any ground failure, building and pier damage areas and reopen key access points. Repairs to the seawall and reconstruction of damaged waterfront piers and buildings could take years to complete.
Airport	Life safety, facility assessments, runway repair, and business resumption would be the key response and restoration priorities. Runway repair is critical to both emergency use and restoration of commercial operations. SFO has significant power redundancy and emergency generator power capabilities, but if these back-up systems are not operational, a loss of power would impact telecommunications and flight operations. Potential loss of the control tower and fuel supply could significantly impair business resumption. However, there are on-hand fuel supplies and aircraft could "tanker" fuel to mitigate these potential impacts. The airport must ensure that security and runway safety are restored before it can reopen. Post-earthquake, commercial demand may change which could also affect business resumption.
Fuel	Regardless of damage, operators would shut down many critical system components for a minimum of 24-48 hours for inspection and restoration; detailed inspections and repairs would take longer. There may be enough supply in the system to cover a short-term shutdown but there could be a shortage of certain fuel products. Supplemental supplies could come from other undamaged facilities in the region if roads are passable. Commercial service stations would likely have disruptions. Minor repairs to critical fuel system components could take days to weeks, and major repairs could take months. Some refineries have limited storage capacities and a major customer outage could back-up the system and slow production and supply. If a major refinery was shut down, waterborne fuel cargo (produced elsewhere) could be brought into ports and fed into pipelines and other system distribution points.

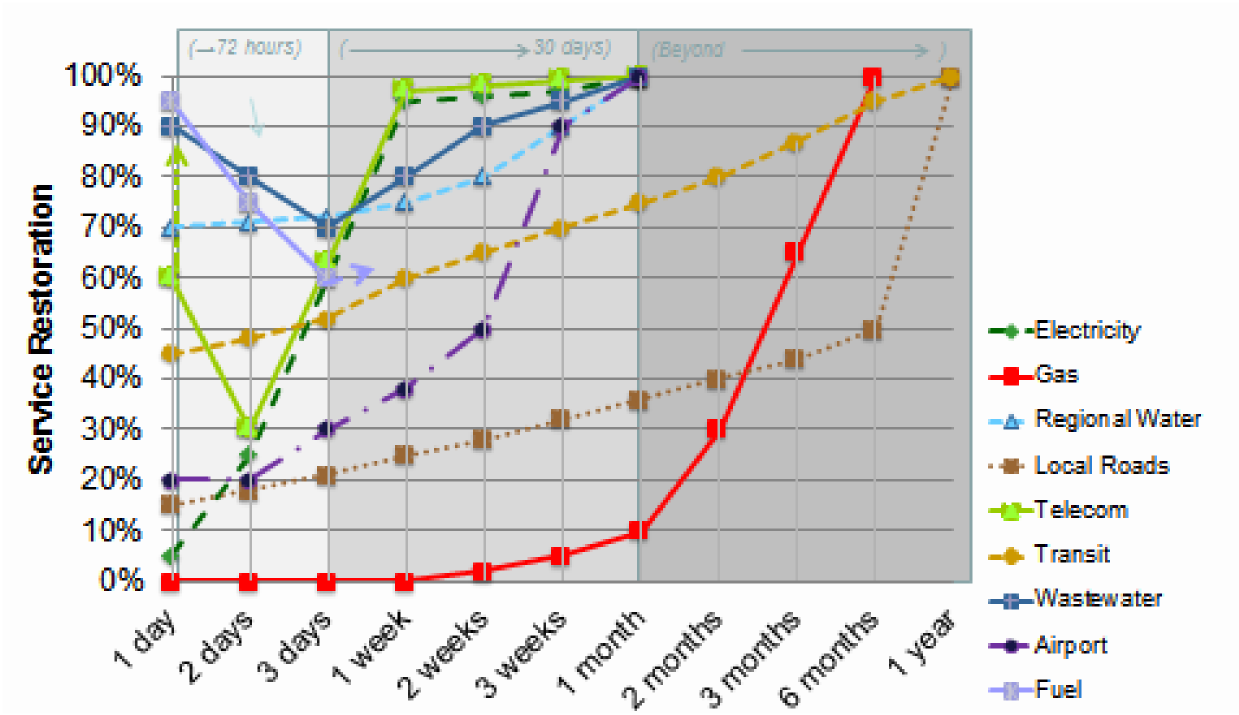


FIGURE 4. POTENTIAL LIFELINE SERVICE RESTORATION TIMEFRAMES FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (AS OF NOVEMBER 2013)*

*Restoration timeframes are not included for the regional roads water distribution system, auxiliary water supply system, and the port and seawall. Also, readers are cautioned that this is only a descriptive summary of the best estimates of likely system performance timeframes provided by study participants and should not be used as a predictive model of performance in a future earthquake.

Table 4. Lifeline Operators' Successful Experiences with System Restoration

1989 Loma Prieta Earthquake	Caltrans repaired and reopened the damaged Bay Bridge in 30 days.
2003 San Simeon Earthquake	Power was disrupted after the earthquake, but 70% of Verizon's cell sites had back-up generators and they also had back-up microwave support, so the system remained operational following the disaster.
2007 I-880/I-580 Accident	Caltrans, the Metropolitan Transportation Commission, and other private sector and government partners, reconstructed the I-880 and the I-580 approaches to the San Francisco- Oakland Bay Bridge in 26 days following a major accident that compromised the structure.
2012 Hurricane Sandy	Comcast had 6 fiber cuts in the impact area of Hurricane Sandy. They were able to restore service within hours of getting access to most areas.
2013 Asiana Airlines Crash	Asiana Flight 214 crashed on approach to SFO on July 6, 2013, and resulted in 3 fatalities and approximately 185 injuries. All San Francisco Airport runways were initially closed for a 4-hour period. Significant flight cancellations/delays resulted from the closure of runways, and irregular operations programs were implemented at major West Coast airports to accommodate diverted flights. All runways were restored to service in 5 days. The impacts described above were also mitigated by the relatively low number of fatalities and the location of the accident on the airfield.

3. Study Findings

3.1 Lifeline Interdependency Analysis

Lifeline systems depend upon each other to function. When disaster strikes, multiple systems are affected simultaneously and those dependencies and interactions are stressed. This analysis focuses on defining the critical "upstream" dependencies that each lifeline system has on other lifeline systems, as well as the "downstream" dependencies that a system's disruption can have on other systems. Both are critical to understanding and improving lifeline system resilience.

Table 5 summarizes the level of interaction and dependence that lifeline operators interviewed for this study expect to have on other lifeline systems to maintain and restore service after a M7.9 earthquake (the scenario). The dependency that a lifeline system has on other lifeline systems is shown horizontally (read across each row). The overall interaction and dependency on each particular lifeline system is shown vertically (read down each column). Shading represents the overall level of interaction and dependency that could affect system performance and service restoration, particularly in San Francisco:

Significant interaction and dependency on this lifeline system for service delivery and restoration efforts
Moderate interaction and dependency on this lifeline system for service delivery and restoration efforts
Limited interaction and dependency on this lifeline system for service delivery and restoration efforts

One word is used to identify some of the key interdependencies and these are further described in Table 6. They are:

- Functional disaster propagation and cascading interactions from one system to another due to interdependence
- Collocation interaction, physical disaster propagation among lifeline systems
- Restoration interaction, various hindrances in the restoration and recovery stages
- Substitute interaction, one system's disruption influences dependencies on alternative systems
- General interaction between components of the same system. (All systems would have general interaction issues but some are more crucial issues for the system's potential disruption and restoration.)

Finally, Figure 5 illustrates the combined effects of damage levels and service disruption that may cause potential delays in restoration for different lifeline systems and the level of interdependency between them. These tables and illustrations are followed by some discussion.

TABLE 5. LIFELINE SYSTEM INTERDEPENDENCIES FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT

The overall interaction and dependency on a particular system (read down each column)

Lifeline operators' dependency on other lifeline systems (read across each row)

	Regional Roads	City Streets	Electric Power	Natural Gas	Telecom	Water	Auxiliary Water	Waste-water	Transit	Port	Airport	Fuel
Regional Roads	General	Restoration Substitute	Restoration	Restoration	Restoration	Restoration		Restoration	Substitute		Restoration	Restoration
City Streets	Substitute, Restoration	General	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Substitute, Restoration	Collocation, Restoration		Restoration
Electric Power	Restoration	Collocation, Restoration	General		Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration		Collocation	Restoration	Restoration
Natural Gas	Restoration	Functional, Collocation, Restoration	Substitute	General	Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration		Collocation	Restoration	Restoration
Telecom	Restoration	Collocation, Restoration	Functional, Restoration	Restoration	General	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration			Restoration	Restoration
Water	Restoration	Restoration	Restoration		Restoration	General				Collocation		Restoration
Auxiliary Water	Restoration	Functional, Restoration	Restoration		Restoration	Functional, Restoration	General			Collocation, Restoration		Restoration
Waste-water	Restoration	Collocation, Restoration	Functional, Restoration		Restoration	Functional, Restoration		General		Collocation, Restoration		Restoration
Transit	Substitute, Restoration	Functional, Substitute, Collocation, Restoration	Functional, Restoration		Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, General	Collocation, Restoration		Functional, Restoration
Port	Restoration	Collocation, Restoration	Collocation, Restoration		Collocation, Restoration	Collocation, Restoration	Collocation	Collocation	Collocation	General		Restoration
Airport	Restoration		Restoration		Restoration	Restoration		Restoration	Collocation, Restoration		General	Functional, Restoration
Fuel	Restoration	Restoration	Functional, Restoration		Restoration	Restoration				Restoration	Restoration	General

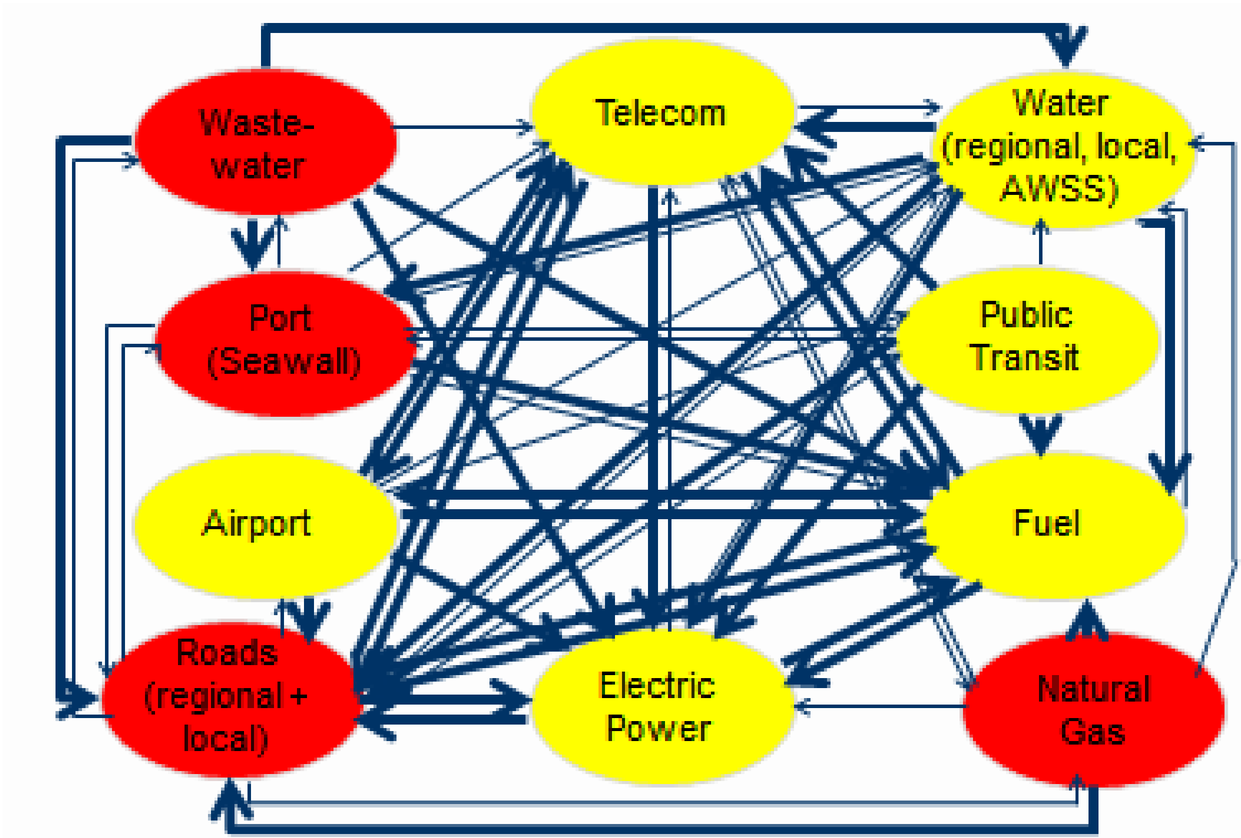
TABLE 6. DESCRIPTION OF KEY LIFELINES SYSTEM INTERDEPENDENCIES FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT

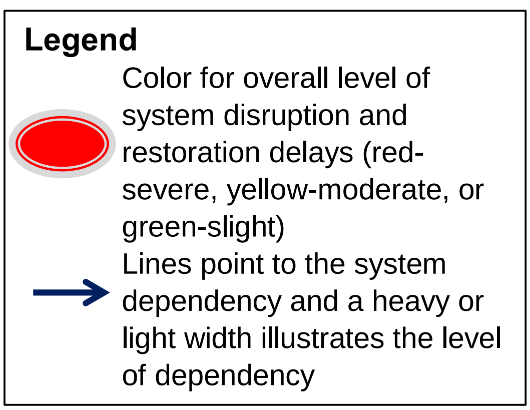
Functional disaster propagation and cascading interactions, from one system to another due to failure of interdependence	• Electrical system damage/shutdown could directly impact telecommunications (especially those with limited back-up power supplies), wastewater (pumping stations and treatment plants have limited back up power supplies), electric transit operations, and all other lifeline systems • Water supply damage/shutdowns could impact functioning of the wastewater system and the auxiliary water supply system (seawater is a back-up supply) • Roads (both regional and local) damage/closure could directly affect all lifeline operators, but is especially critical to fire-fighting, fuel distribution, and manual valve management of the auxiliary water and natural gas systems in the city. • Fuel and refinery damage/shutdowns could impact functioning of fuel-based public transit, San Francisco Airport and all lifeline operators
Collocation interaction, physical disaster propagation among lifeline systems	• Seawall damage caused by liquefaction along the San Francisco waterfront could cause a major failure of the Embarcadero roadway and promenade, and impact all lifelines running alongside and crossing the seawall with particular concern for regional and local light rail; auxiliary water system seawater pumping stations; wastewater outfall structures, pumping stations and the transport box running along the eastern waterfront; and power, sewage, and water services that cross the seawall and serve waterfront businesses. Functioning of the regional ferry system, barge transport and the harbor (bar) pilots which provide maritime services for all of San Francisco Bay could also be affected. • City streets, above ground transit, and all buried infrastructure have collocation dependency issues that will be especially vulnerable in heavy damage areas, such as liquefaction-prone areas. This includes the buried portions of water, auxiliary water and wastewater systems, undergrounded electric power and telecommunications, and natural gas. In some areas, it also may include underground components of the public transit system, including tunnels, power lines, and substations. • Damage and potential flooding in the Transbay transit tube/tunnel could impact the Market Street transit corridor and all utilities (buried or concentrated) within the lower Embarcadero and Market Street corridor. • In the infrastructure "hubs" of the densely-built Financial District (some areas of which could have ground failure issues) and the liquefaction vulnerable areas of the southeastern city (Mission and Islais Creek areas), lifelines could experience collocation interactions due to their close proximity

TABLE 6. DESCRIPTION OF KEY LIFELINES SYSTEM INTERDEPENDENCIES FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT (CONTINUED)

Restoration interaction, various hindrances in the restoration and recovery stages	• Delays in restoration of the electrical system could directly impact restoration of telecommunications and many other power needs of all operators • Delays in restoration of telecommunications could impact system monitoring and data communications, voice communications, and coordination efforts of all operators in conducting repair and restoration work • Delays in restoration of regional roads could impact transport of personnel, equipment, materials, and fuel into the city for lifeline operator's repair and restoration work • Delays in water supply restoration could impact restoration of wastewater, some telecommunications equipment cooling, refueling (if facilities lack water for fire suppression) and the provision of basic services for all lifeline operator personnel. • Delays in restoration of fuel, including compressed natural gas (CNG), could impact the repair and restoration work of all operators and the provision of back-up power supplies • Delays in restoration of the airport could impact transport of personnel, equipment, and materials to assist with lifeline operator's repair and restoration work. This was a more significant concern for nationwide telecommunications operators but could also be an issue for mutual aid to support local operators
Substitute interaction, influences on alternative systems	• Regional road, local roads, and transit damage/shutdown could place more travel demands on the other systems • Loss of natural gas supply could increase electric power usage and needs, especially in wintertime
General interaction, between components of the same system. (All systems would have general interaction issues but some are more crucial issues for the system's potential disruption and restoration.)	• Gas transmission line shutdown/damage could impact the entire distribution system in San Francisco • Electric substation failure could impact electric power reliability in San Francisco • Telecommunications operators depend in large part on the performance of transport facilities and other system equipment and facilities leased from other telecom operators • Regional "water" turnout failures could impact the ability to supply the city's water distribution system and auxiliary fire-fighting water system • Wastewater treatment plant and collection system damage could impact system functionality until any needed repairs are completed. There is no connection between the east and west portions of the system to provide some functional redundancy • Transit operation facility and major infrastructure (such as tunnel) damage could impact system functionality until alternatives are provided. There are also multi-modal dependencies of regional trains and light rail, regional ferries, and surrounding county transit operators with San Francisco systems and services. • Damage to the port seawall, Embarcadero roadway and promenade, a pier or bulkhead could impact other port facilities and functions • Damage to fuel pipelines and storage/terminal facilities could impact each other and regional fuel service delivery

FIGURE 5. COMBINED EFFECTS OF DAMAGE, SERVICE DISRUPTION THAT MAY CAUSE DELAYS IN INDIVIDUAL SYSTEM RESTORATION AS WELL AS THE INTERDEPENDENCIES AMONG LIFELINE SYSTEMS FOLLOWING A SCENARIO M7.9 EARTHQUAKE ON THE SAN ANDREAS FAULT





These tables and illustrations show that there are likely to be crucial interdependencies between different lifeline systems, and both their disruption and restoration, in San Francisco following a M7.9 earthquake. A M7.9 earthquake could pose some of the most severe ground shaking levels in San Francisco, and thus it would be reasonable to assume that these results are more akin to a "worst-case" analysis for lifeline system performance and interdependencies. In more moderate earthquakes, or other more isolated damage scenarios, such as a flood or tsunami disaster, then both the disruptions and restoration timeframes could be less.

For the M7.9 earthquake scenario, however, some of the most critical lifeline interdependency issues identified for the immediate post-earthquake period (0 – 8 hours) and which could affect emergency response and efforts to protect life and property in the city are:

- A significant level of damage, debris, and closures to San Francisco city streets that, in particular, would impact the ability of operators to manually manage valves for the auxiliary water supply system and natural gas systems.
- Until system upgrades currently planned or underway are completed, any potential failures in the supply of water (regional potable or seawater) and full functioning of the auxiliary water supply system which could impair post-earthquake fire-fighting capabilities.
- Until system upgrades currently planned or underway are completed, an electric substation failure or other significant disruption of electric power within the city which could have direct impacts on telecommunications (and in some cases, the system controls) of lifeline operators and also impact system functioning of those systems with a heavy power dependency and limited back-up power supplies, notably the wastewater, municipal transit and telecommunication systems.
- Until system upgrades currently planned or underway are completed, a potentially catastrophic failure of a municipal or regional transit tunnel which could impact transit systems as well as overhead streets and any lifeline systems in the vicinity of the failure.
- A significant level of damage to the waterfront seawall which could impact all lifeline systems running along or crossing the waterfront seawall area.

For the M7.9 earthquake scenario, some of the most critical lifeline interdependency issues identified for the early recovery period (8 - 72 hours) and which could affect short-term restoration efforts in the city are:

- A significant level of damage, debris, and closures to San Francisco city streets that impacts the abilities of operators to resupply back-up generators and conduct system initial inspections and repairs.
- Until system upgrades currently planned or underway are completed, a regional water system "turnout" failure could impact the ability resupply both the potable and auxiliary water systems.
- Until system upgrades currently planned or underway are completed, significant damage to the potable water distribution system could require emergency drinking water provisions to impacted neighborhoods, delay the restoration of some lifeline

operations, such as municipal transit and fuel, and also force the closure of impacted businesses.
- Until system upgrades currently planned or underway are completed, an electric power disruption would impact the restoration operations of all lifeline systems but especially those systems with a heavy power dependency and limited back-up power supplies, notably the wastewater, municipal transit and telecommunication systems which would deplete on-site battery supplies within as little as 8 hours.

For the M7.9 earthquake scenario, some of the most critical lifeline interdependency issues identified for the intermediate recovery period (72 hours – 1 week) and which could affect the restoration of neighborhood, business, and government functioning in the city are:

- A significant level of damage, debris, and closures to San Francisco city streets that impacts the abilities of operators to conduct system inspections and repairs, and also the ability of residents and businesses to stay and initiate recovery.
- Delays in the inspections, repairs and restoration of regional roads could impact the transport of personnel, equipment, materials and fuel into the city for lifeline operator repair and restoration work and also impact residential and business recovery.
- Until system upgrades currently planned or underway are completed, a prolonged electric power disruption would impact the restoration of all lifeline systems but, could have significant impacts on the ability of the wastewater system to restart treatment and pumping, the municipal transit system to restart electrified fleet operations, and the telecommunication operators to restore network services. Delays in the restoration of basic services such as water, wastewater, and public transit could impact the ability of residents and businesses to stay and initiate recovery.
- An initial interruption of fuel supplies in the region would likely be covered by the 1 to 3 day supplies already in storage. But shortages could emerge quickly for certain fuel products and for lifeline operators who rely on commercial service stations to refuel service fleets. There could also be significant impacts on major fuel users, such as the airports and transit systems.

For the M7.9 earthquake scenario, the most critical issues identified for the longer-term recovery period (beyond 1 week) and which could affect the restoration of neighborhood, business, and government functioning in the city are:

- A significant level of damage, debris, and closures to San Francisco city streets that impacts the abilities of operators to conduct systems repairs and restoration, and impacts the abilities of neighborhoods and commerce to restore and recover.
- A natural gas transmission line shutdown or damage that impacts the entire natural gas distribution system in San Francisco and takes many months to relight/restore households and businesses.
- A significant level of damage to the waterfront seawall that requires significant time and resources to repair and reconstruct and affects tourism and commerce.
- A major infrastructure reconstruction need that emerges as a result of damage sustained during the scenario earthquake. Until system upgrades currently planned or

underway are completed, this might include a portion of the regional highway or regional transit systems, and a major system facility, such as an airport control tower, wastewater treatment plant, an electric substation, or a major fuel pipeline.

- Areas of concentrated damage and infrastructure “hubs” in areas of potentially significant ground failure, such as liquefaction, landsliding, lateral spreading and vertical subsidence, which could have significant impacts on system restoration and recovery. Two areas of concern raised by the study are the Financial District and the southeastern reaches of the city around Mission and Islais Creeks.

In addition, the study also reviewed several other key issues and system dependencies that lifeline operators had beyond those considered in the study. They include:

- Debris management. Many operators identified the need for added debris management needs to recycle and dispose of the high volume of damaged system components that would be replaced.
- Rail transport. Some port operations depend upon rail transport connections. Also, rail transport could be an effective alternative to truck related movement of equipment for recovery, debris removal, and sewage-related solids.
- Water transport, which includes ferries, barges, and the harbor pilots. There may be increased needs for ferry and barge-related operations post-earthquake. It is also crucial to keep the harbor (bar) pilots in operation since they provide commercial maritime navigation services for all of San Francisco Bay.
- Regional transit. Concerns about system vulnerabilities and the need for regional multi-model transportation function were raised during the study.
- Hospitals and medical services. Many operators viewed hospitals and medical services as a critical lifeline system that needs to be assessed as part of the interdependency analysis. Operators also expressed concerns for needing access to hospitals and medical services for personnel and crews working in and around the city.
- Key commodities, equipment and materials (asphalt, gravel). Similar to fuel, several operators expressed concerns about needing special equipment and materials post-disaster to fulfill system repairs and restoration, and that there may be increased demand and competition for limited resources in a major disaster.
- Security. Many operators expressed concerns for needing to provide security to potentially damaged system sites, as well as repair personnel working in heavily damaged areas.
- Shelter and basic services for repair and restoration crews. Many operators also expressed concerns for having access to sufficient supplies of food and water, sanitation, and shelter for crews working in and around the city.

3.2 Setting Lifeline System Response and Restoration Priorities

All operators interviewed for the study have an internal organizational structure for managing system disruptions and emergency response. Table 7 shows the key linkage that operators have to government emergency management structures as well as secondary interactions and controls on priority setting for response and restoration activities. Most operator organizations use the Incident Command System (ICS)/Standardized Emergency Management Structure (SEMS), but some do not. Some system operators, particularly city streets and the publicly-owned municipal transit, water, wastewater systems, and airports have department operations centers (DOCs) that also are part of the Infrastructure Branch of the city's emergency operations center (EOC). A few operators, such as regional roads and some telecommunication operators, link directly with the state EOC. Other system operators, particularly the privately owned systems, have internal organizations that may or may not link into the city's EOC or state and national emergency management organizations. Operators with regional systems will also be considering restoration priorities at a regional level, which may conflict with city priorities. Some operators also have other restoration controls from other state and national regulatory bodies, such as the Federal Aviation Administration.

The degree to which these different organizational structures and emergency response linkages could affect lifeline system restoration communication and coordination efforts is a concern raised during operator interviews. Concerns center around two different time periods:

- The first would occur in the initial hours and days after a disaster when power and telecommunications linkages might be down or impaired, and the "fog of war" is known to impact information sharing, communication and coordination. Concerns raised include: how would operators get timely information on priority routes and access points for inspectors and repair crews? How would operators find out what the city's emergency response priorities are? How would operators communicate timely information on their system's conditions and restoration timeframes to help both the city's emergency response and other lifeline system operators to set priorities and develop their response and restoration plans? How would operators be allowed access to restore service and bring in back-up or temporary provisions?
- The second period would occur during the first weeks of a disaster when the repair and restoration crews of multiple lifeline system operators may need to coordinate and communicate and also want to understand the city's longer-term priorities for neighborhood and business restoration and recovery. During normal times, there are methods for coordinating repairs of collocated lifeline systems. San Francisco's Department of Public Works manages a Committee for Utility Liaison on Construction and Other Projects (CULCOP) that meets monthly to coordinate street excavation, utility work, paving and other construction projects in the public right of way. Concerns raised by operators included: Would existing coordination protocols be able to scale up to handle the volume of interactions and coordination activities that lifeline operators are likely to have? Are there opportunities for coordination that might be missed, increasing costs and time delays in both system restoration and the city's overall recovery efforts?

TABLE 7. KEY LINKAGES FOR GOVERNMENT EMERGENCY RESPONSE COMMUNICATION AND COORDINATION

	National	State/Region Level	County/City Level	Internal Organization
Regional Roads	❖	◆	❖	❖
City Streets			◆	❖
Electric Power		◆	❖	❖
Natural Gas		◆	❖	❖
Telecom	❖	❖/◆[5]		❖
Water		❖	◆	❖
Auxiliary Water			◆	❖
Wastewater			◆	❖
Transit			◆	❖
Port		❖	◆	❖
Airport	❖	❖	◆	❖
Fuel	❖	❖		◆

◆ – Key point of connection to government emergency management structures

❖ - Other interventions/directions that may affect priority setting

[5] Not all telecommunication operators have a formal link established with the state emergency management structures

3.3 LIFELINES SYSTEM PERFORMANCE AND RESILIENCE STANDARDS

A major goal of this interdependency study and the Lifelines Council has been to develop a collective set of lifelines performance expectations, both under current system conditions and as a future goal, for all lifeline system operators in the City and County of San Francisco and potentially across the entire Bay region.

The lifelines interdependency study has confirmed that there are a wide range of lifeline system conditions and expected performance standards, both in terms of the expected level of service disruption and the likely restoration timeframes. In parts of San Francisco, there are portions of some lifeline systems that are as old as the city itself, while other system components are quite modern and state-of-the-art. Most system operators are moving toward, or have already installed computer-based system monitoring and control systems, such as the SCADA (supervisory control and data acquisition) system, which has the ability to increase operators' knowledge and control of system performance post-disaster but, at the same time, increases their dependency on power and telecommunications systems.

Most operators that have instituted seismic upgrades have set recovery targets, or performance standards, for the systems as part of the planning and design for these programs. For example, the San Francisco Public Utilities Commission has set standards to ensure that critical dry-weather wastewater facilities (such as the southeastern and Oceanside treatment plants) will be on-line within 72 hours of a major earthquake and to restore 70% of the winter demand regional water transmission capacity to San Francisco within 24 hours after a major earthquake and a 100% within 30 days following a major earthquake. The SFPUC is also working on improving the seismic performance of large diameter distribution pipelines to support fire suppression, potable supply, and sanitary service. The objectives will be expressed as percentages of functionality over time (e.g. 75% of large diameter pipelines are pressurized within 2 hours following an earthquake).

Other operators have set performance standards for normal times which could positively affect overall system performance after a major disaster. For example, Comcast has a 4-hour restoration target for key commercial accounts. In addition, the California Public Utilities Commission (CPUC) and other regulatory bodies have set standards for the performance of different lifeline systems in both emergency and non-emergency conditions. For those operators affected by these standards, there could be some positive affect on overall system performance following a major, region-wide disaster, such as the scenario earthquake.

Establishing a collective set of performance standards for lifeline operators needs to consider the variations in system age, reliability, sensitivity, flexibility, complexity, and use of "smart" technology for monitoring and control. It also needs to consider the interactions among systems and the vulnerabilities that are introduced as a result of interdependencies. The lifelines interdependency study has shown that some systems will have a much stronger influence on the restoration timeframes for other lifeline systems post-disaster. Most notably, these include regional roads and city streets, electric power, telecommunications, and fuel. Most operators tried to factor these dependencies into the restoration estimates provided for the study’s scenario earthquake. However, aftershocks could also present additional restoration challenges and delays, and an unexpected or protracted delay in one system’s restoration is likely to have a significant “domino effect” on the restoration of other systems. Addressing the vulnerabilities of these highly interdependent systems could have a positive influence on the performance of many more lifeline systems in San Francisco.

4. POTENTIAL COURSES OF ACTION

There are three areas of potential follow-on activities resulting from the lifelines interdependency study:

- Conducting more detailed studies of geographic “choke point” areas of the city where there are heavy concentrations of infrastructure and in which lifelines system vulnerabilities, disruptions and interdependencies, and restoration challenges among operators may also be more concentrated.
- Areas for more coordinated disaster planning and preparedness efforts among lifeline system operators, the City and County of San Francisco, and other relevant entities.
- Areas for more coordinated mitigation efforts that could collectively improve lifeline system performance in the City and County of San Francisco after future disasters.

4.1 AREAS FOR MORE DETAILED AND COORDINATED STUDY

Conducting more detailed studies of geographic “choke point” areas of the city where there are heavy concentrations of infrastructure and in which vulnerabilities, system disruptions and interdependencies, and restoration challenges among operators may also be more concentrated. They are: the seawall along San Francisco’s waterfront, portions of the Financial District and the southeastern reaches of the city near Mission and Islais Creeks.

SAN FRANCISCO WATERFRONT SEAWALL MULTI-HAZARD RISK ASSESSMENT

San Francisco’s waterfront seawall defines much of the city’s shoreline along San Francisco Bay. As shown in Figure 6, the seawall roughly runs 4 miles from Hyde Street and Fisherman’s Wharf in the north to Pier 54 and Channel Street in the south; and it was constructed in 21 sections between 1878 and 1924, with a mix of design and construction methods. In many areas, the seawall was built by digging a 100-foot wide trench to depth of 25 feet, and filled in with rocks, sand, and clayey mud.[6] A considerable area of land along the waterfront was created by filling in behind the seawall. This land mass rests up against the seawall and mainly consists of sands, clays and occasional gravels.

Both the seawall and the land behind it are vulnerable to ground failure damage, including liquefaction, lateral spreading into the bay, and vertical subsidence, in a major earthquake. There was ground failure damage in and around the seawall both in 1906 and 1989. Following the 1989 Loma Prieta earthquake, San Francisco’s Department of Public Works commissioned a study of liquefaction risks for the Harding Lawson Associates North Beach, Embarcadero Waterfront, South Beach, and Upper Mission Creek areas of the city.[7] As shown in Figure 7, the study estimated that there could be 0.25 to 2 feet of vertical settlement and 0.25 to 1 foot of lateral spreading along the seawall from a M8 earthquake on the San Andreas Fault (comparable to the scenario earthquake used for the lifelines interdependency study).

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[6] Harding Lawson Associates et al., January 1992. Final Report, Liquefaction Study North Beach, Embarcadero Waterfront, South Beach, and Upper Mission Creek areas, San Francisco, CA.

[7] Ditto

All lifelines that run along the Embarcadero and run through the seawall and out to the piers could be damaged. This could include power, wastewater, and water services that cross the seawall and serve the waterfront businesses; the Transbay tube and transit tunnel and tracks; wastewater outfall structures all along the waterfront including the north shore sewer outfall; wastewater pumping stations along the waterfront; and possibly the auxiliary water intake valves and pumping stations. If any major portion of the seawall and piers collapsed, then there might also be significant damage to the Embarcadero roadway and other streets, as well as the wastewater transport box running along the eastern waterfront. If water supplies are cut then sprinkler functioning for fire suppression along the waterfront could also be impacted.

Access and entry to the piers and entry to the Ferry Building terminal also could be severed by a seawall failure and other ground related damages. This could impact ferry service and potential evacuation needs, as well as the functioning of the emergency water transport. Additionally, public and private assets along the waterfront are at risk of direct building damage or indirect losses due to potential ground failure and seawall damage, utility outages and prolonged closures.

Seawall conditions have degraded with time and are also now threatened by rising sea levels. The Port has applied for a Water Resources Development Act (WRDA) grant from the U.S. Army Corps of Engineers to provide seed money for a seawall vulnerability study, but it hasn't been awarded.

It is recommended that the Lifelines Council and the Port of San Francisco, working with a coalition of stakeholders, secure funding and undertake a more detailed, multi-hazard risk assessment of the seawall and adjacent land area along the waterfront to better understand the potential vulnerabilities, direct and indirect consequences of likely damage, and alternatives for upgrades. The seawall is not just an earthquake issue; it is also a flooding and sea level rise issue and any potential design for its repair should be done with all these issues in mind. Strengthening the seawall could be quite costly but the cost of post-disaster reconstruction and the potential economic consequences of a major waterfront closure could be far greater.

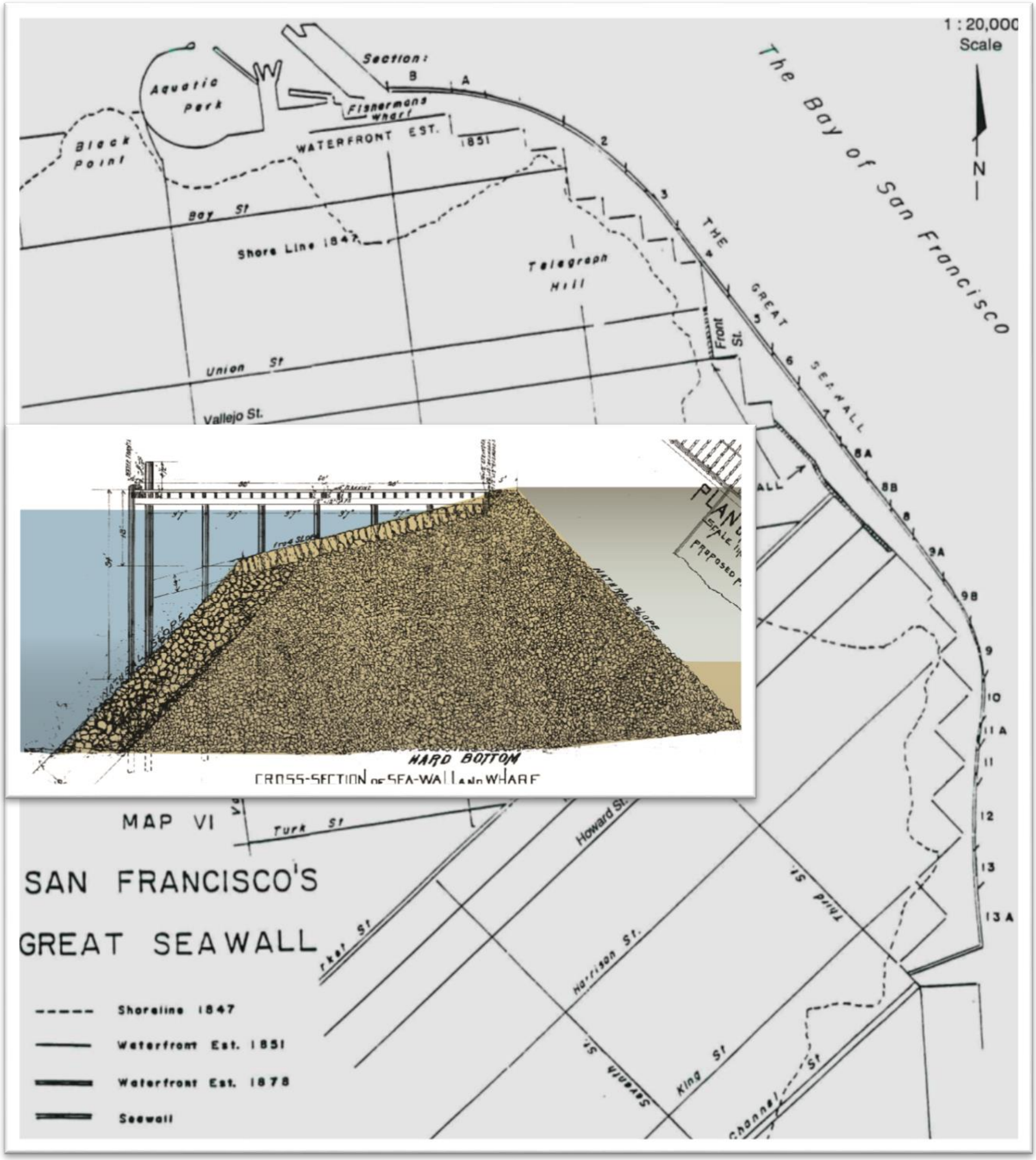

FIGURE 6. MAP OF THE SEAWALL SECTIONS ALONG SAN FRANCISCO'S EASTERN WATERFRONT AND A COLOR-ENHANCED CROSS-SECTION OF SECTION 12 OF THE SEAWALL CIRCA 1907

(Sources: Harding Lawson Associates et al. 1992 and Port of San Francisco)

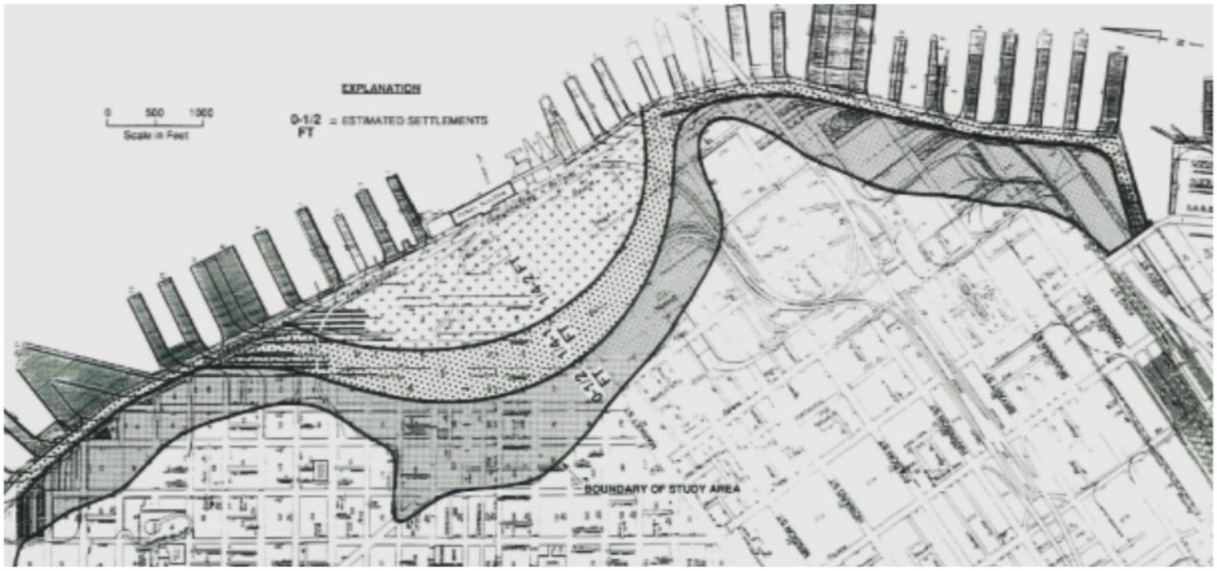

FIGURE 7. MAP OF POTENTIAL GROUND SETTLEMENT ALONG THE CENTRAL WATERFRONT FOLLOWING A POTENTIAL M8 EARTHQUAKE ON THE SAN ANDREAS FAULT

(Source: Harding Lawson Associates et al., 1992)

Financial District/Market Street Corridor Infrastructure Damage and Restoration Study

There is an infrastructure hub in the densely-built area of San Francisco's Financial District and, as shown in Figure 8, many portions of the Financial District along Market Street and to the south could have ground failure issues in a major earthquake. Areas around the Embarcadero and south of Mission Street experienced damage in both the 1906 and 1989 earthquakes. Modern construction of major buildings and lifelines components have likely improved the immediate ground conditions with the addition of pilings, deep mat foundations and other soil strengthening and compaction efforts. Nonetheless, serious ground failure damage and building damage could make access difficult for lifeline operators to repair and restore systems. Also, because of their close proximity, lifelines could experience collocation interactions with could amplify damage, disruption and restoration challenges. For example, a major water main failure could significant impact underground transit and buried infrastructure, especially telecommunications and electric power.

It is recommended that lifeline system operators with key infrastructure in the Financial District collaborate with the City of San Francisco's Department of Public Works and Department of Emergency Management to conduct a more detailed study of the potential damage, access, and restoration issues and identify potential mitigation opportunities. Mitigation might be achieved through construction and retrofit efforts, added system redundancy, and also the introduction of isolation points and work-arounds. It is further recommended that the study consider recent experiences in Christchurch, New Zealand, where a substantial part of the city's downtown business district was cordoned off for nearly two years due to extensive building and ground failure damage in the February 2011 earthquake. The Financial District is a major economic asset to the city and region and a prolonged closure could have significant indirect economic consequences.

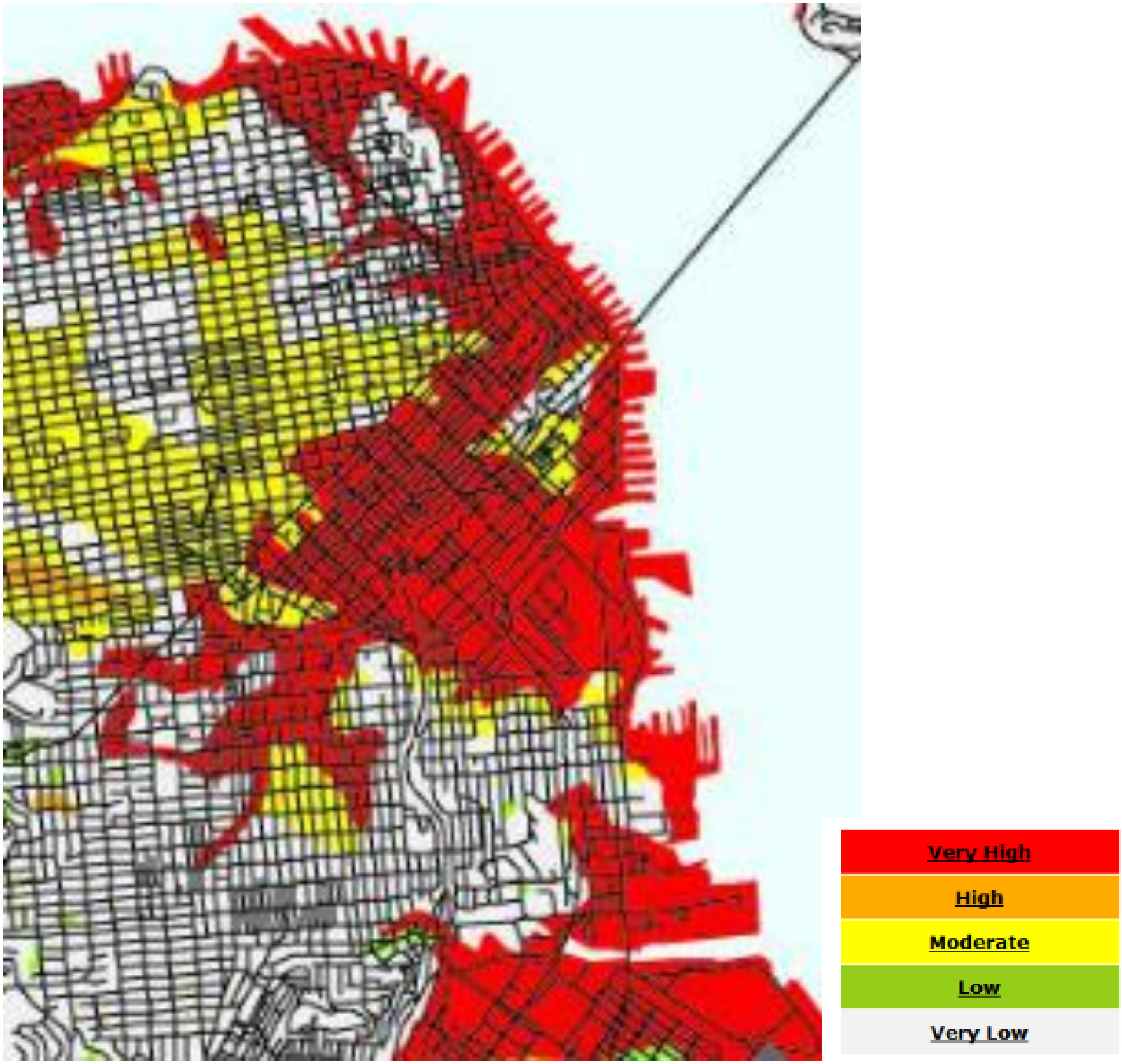

FIGURE 8. U.S. GEOLOGICAL SURVEY'S LIQUEFACTION SUSCEPTIBILITY MAP (ZOOMED IN ON SAN FRANCISCO'S FINANCIAL DISTRICT AND WATERFRONT AREA)

(Source: USGS, http://geomaps.wr.usgs.gov/sfgeo/liquefaction/susceptibility.html)

Mission Creek/Southeastern City Infrastructure Damage and Restoration Study

As shown in Figure 9, the southeastern reaches of the city, around Mission and Islais Creeks, is an infrastructure “hub”, where many of the city’s lifeline operators have operation yards, fuel storage areas, major pipelines and other critical system facilities and components. (Note: Only a small portion of operator assets is shown on the maps to illustrate the concentration of infrastructure in the area.) It is also an area of high ground failure potential in a major earthquake. The Mission Creek and Sullivan Marsh areas suffered ground failures and utility and building damage in both the 1906 and 1989 earthquakes. It is estimated, that there could be 0.5 to 2 feet (and up to 7 feet) of ground settlement, and 0.5 to 2 feet (and up to 7 feet) of lateral spreading in a magnitude 8 earthquake on the San Andreas Fault.[8]

It is recommended that lifeline system operators with critical infrastructure in the southeastern area of the city collaborate with the City of San Francisco’s Department of Public Works and Department of Emergency Management to conduct a more detailed study of the potential damage, access, and restoration issues in multiple hazard scenarios, as well as identify potential mitigation opportunities. Mitigation might be achieved through relocations, construction and retrofit efforts, added system redundancy, and the introduction of isolation points and work-arounds. Serious ground failure damage and building damage could make access difficult for lifeline operators to repair and restore critical system components. Also, because of their close proximity, lifelines could experience collocation interactions with could amplify damage, disruption and restoration challenges. The area is also vulnerable to flooding and sea level rise.

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[8] Harding Lawson Associates et al., January 1992. Final Report, Liquefaction Study North Beach, Embarcadero Waterfront, South Beach, and Upper Mission Creek areas, San Francisco, CA.

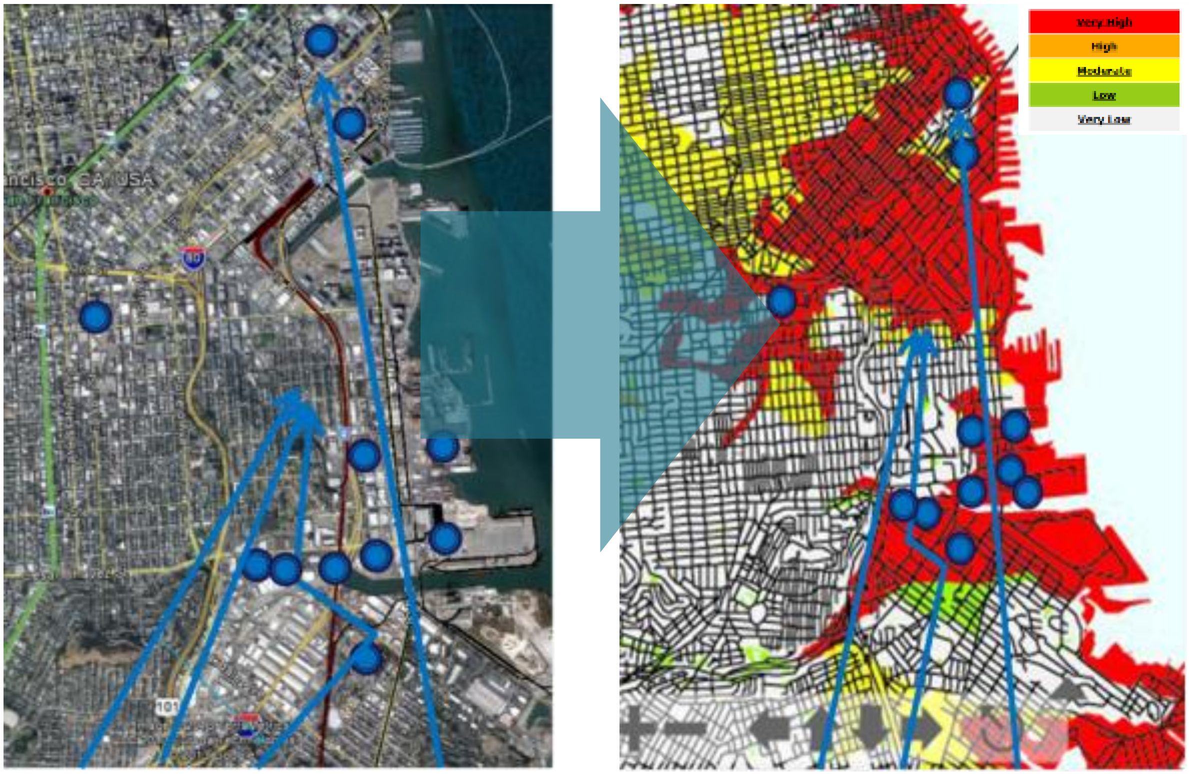

Figure 9. A Portion of Critical Lifeline System Components in the City's Southeastern Infrastructure "Hub" and Overlaid onto the U.S. Geological Survey's Liquefaction Susceptibility Map

(Sources: Lifeline operator interviews, Google Earth base map, USGS, http://geomaps.wr.usgs.gov/sfgeo/liquefaction/susceptibility.html)

4.2 Areas for Coordinated Planning and Preparedness

The lifeline interdependency study revealed a number of areas that could benefit from more coordinated disaster planning and preparedness efforts among lifeline system operators, the City and County of San Francisco, and other relevant entities. These two are listed in relative order of priority resulting from the interdependency study. The Lifelines Council has already initiated work on three key recommended areas: to design and conduct a tabletop exercise addressing lifeline system interdependencies; to address issues with the installation of both permanent and temporary cellular sites in the city; and to identify priority routes for lifeline operator access following a major disaster.

4.2.1 Near-term Recommendations for Coordinated Planning and Preparedness

Design and Conduct of a Lifeline Interdependency Exercise(s)

In early 2013, the Lifelines Council's lifeline operators and the city's Department of Emergency Management agreed to initiate work on the design and conduct of a tabletop exercise to better understand lifeline interdependency issues in a major disaster. At its December 4, 2013 meeting, Lifelines Council members participated in a tabletop exercise to consider the interdependency issues arising from a major power disruption in the city's Financial District. An after-action report will be available in 2014.

In the interdependency study interviews, lifeline operators identified high priority needs to exercise communications and decision making about priorities for response and restoration among lifeline operators and key decision makers, such as the City's emergency Policy Group which is led by the Mayor in emergency response and restoration. Other suggested topics for an exercise included: addressing communication and coordination when there are significant disruptions of cellular phone and internet services to all lifeline operators; coordinating access and movements along city streets of lifeline operators who may need to manually control valves (potable water, auxiliary water, and natural gas) quickly after a major disaster; coordinating the movement of major equipment along regional roads and city streets; and, addressing fuel sharing needs for lifeline system operators in the city. It is also recommended that exercises be designed to test regional plans for multi-agency coordination and lifeline system performance.

Improved Permanent and Temporary Cellular Communications

Regulations and permitting procedures within the City and County of San Francisco have limited the number of permanent cellular sites within the city, as well as the inclusion of back-up power supplies at these sites. Telecommunication operators report that existing City and County of San Francisco permitting procedures are quite labor and time-intensive, in some instances taking more than a year to complete. In early 2013, the Lifelines Council formed a work group comprised of telecommunication operators and relevant city agencies to study opportunities to improve permanent cell siting procedures and also plan for the post-disaster installation of temporary cellular systems. Based upon input from this study, it is recommended that there be additional planning for temporary telecommunications at post-disaster shelters, refuge areas, and interim housing sites. There is currently inadequate cellular coverage at many critical locations in the city, such as public parks, that may be important assets for post-disaster shelter and housing.

Access, Temporary Staging and Equipment Storage for Lifeline System Inspectors and Repair Personnel

In early 2013, the Lifelines Council formed a work group to examine current priority routes and plan for new ones to allow emergency responders, including lifeline system operators, access to critical facilities following a disaster. Members of the Police Department and California Highway Patrol should be included along with Lifelines Council members. In addition to pre-planning for lifeline restoration routes, lifeline operators also recommended that there be more advance planning for the temporary staging and equipment storage for lifeline system operators post-disaster, as well as the access procedures for private contractors, mutual aid providers, and other equipment and private service providers assisting in lifeline system inspections and restoration. Several operators also identified the need to improve their own planning and procedures for securing damaged property and equipment in the city after a major disaster.

4.2.2 Longer-term Recommendations for Coordinated Planning and Preparedness

Improved Emergency Communications and Priority Setting Among Lifeline Operators

As noted in Section 3.2, all operators interviewed for the study have an internal organizational structure for managing system disruptions and emergency response, but the key linkages that operators have to government emergency management structures vary. The degree to which the different organizational structures and emergency response linkages could affect lifeline system restoration communication and coordination efforts is a concern raised by the study. Many operators also have secondary interactions and regulatory controls that could also affect priority setting for response and restoration activities. It is recommended that the lifeline operators within the Lifelines Council work with the city's Department of Emergency Management to ensure that operators have appropriate staffing and communication plans in place to link with the city's EOC after a major disaster and to develop a framework for decision making and prioritization of actions. This planning effort might logically follow onto the interdependency exercise work currently underway with the Lifelines Council.

Fuel Supply Planning for Lifeline Operators

Fuel is a major dependency. Many operators have fuel supplies stored within the city limits, while others rely on outside storage facilities or the use of commercial fuel service stations that may not be operational or accessible after a major disaster. If regional fuel supplies are interrupted, then fueling needs will escalate after stored supplies are exhausted. It is recommended that the Lifelines Council form a working group comprised of fuel providers, lifeline system operations and purchasing personnel, and relevant city agencies to study post-disaster fueling needs for lifeline system operators after a range of plausible disaster scenarios, and consider improvements that could be made to fuel contract provisions and the potential development of centralized or redundant fuel distribution points for all lifelines system operators, as well as mitigation opportunities for enhancing the performance of fuel tanks and other storage facilities.

Planning for Public Emergency Drinking Water and Sanitation Services

It is recommended that water and wastewater system operators and the city's Fire Department and Department of Emergency Management work together to assess the potential emergency and interim drinking water and sanitary service needs following a range of plausible disaster scenarios, in order to understand the system vulnerabilities that currently exist and will remain when system upgrades (planned or underway) are completed. Consideration should be given to the development of a portable water supply system that could supply water for both fire-fighting and drinking water. While the Fire Department has used an above ground, flexible hose portable water supply system (PWSS) in more limited ways for fire-fighting, most famously in the Marina District after the 1989 earthquake, its viability as a citywide solution for fire-fighting or drinking water has not been fully assessed. Additional collaboration with state and national emergency management, non-governmental organizations such as the Red Cross, and private sector suppliers may be needed to address the anticipated needs.

Provision of Basic Services, Shelter and Security for Lifeline System Inspectors and Repair Personnel

It is recommended that the Lifelines Council form a work group comprised of lifeline system operators and relevant city agencies to assess post-disaster shelter, security, and basic service needs (including food, water, sanitation, and medical services) of the inspectors and repair personnel who would be working in the city in the initial response period following a major earthquake. There may be efficiencies in sharing in the planning for and provision of these services. More advance planning to anticipate and support the families of crew members may also be needed.

Mutual Aid Agreements Among Lifeline Operators

It is recommended that the Lifelines Council form a work group comprised of lifeline system operators and relevant city agencies to inventory existing logistics plans and mutual aid agreements that lifeline system operators already have in place, and develop model agreements and plans to address any gaps and help ensure that there are adequate personnel to support lifeline system inspections and repairs following a major disaster. San Francisco Airport suggested that the mutual aid agreement among airports, managed by the Western Airports Disaster Operations Group as a model meriting further study.

Planning for Post-disaster Financing of Lifeline System Repairs and Restoration and Training on Federal Assistance Regulations

It is recommended that the Lifelines Council form a working group of public and privately owned lifeline system operators, the City Controller's Office and other relevant city agencies, and Cal OES and FEMA representatives to study the post-disaster financing needs for lifeline system repairs and restoration in the city, and develop a framework for prioritizing repairs and adapting based on the financial realities following a major disaster. There are vulnerable lifeline system components that will be both costly and time-consuming to repair, and could have significant impacts on the city's overall recovery following a major disaster, most notably a major failure of the seawall, or significant damage to the water distribution or wastewater treatment systems. The adequacy of financial reserves and insurance coverages, as well as gaps, should also be assessed as part of the study. Some operators may have complex land and facility lease agreements that could complicate the insurance settlement process. Many operators also requested training on the rules and regulations of the federal Public Assistance program.

Conduct Additional Lifeline Interdependency Studies

It is recommended that the Lifelines Council conduct another interdependency study to assess the risks of flooding, tsunamis, and sea level rise to lifeline systems in the City and County of San Francisco. It is also recommended that a regional lifeline interdependency study be undertaken for the San Francisco Bay Area.

4.3 Areas for Coordinated Mitigation Efforts

The lifelines interdependency study also identified some areas for more coordinated mitigation efforts that could collectively improve lifeline system performance in the City and County of San Francisco after future disasters.

4.3.1 Near-Term Recommendations for Coordinated Mitigation

Prioritize Mitigation Projects for CCSF Capital Planning and Funding

The City and County of San Francisco, through its 10-Year Capital Plan, General Obligation and revenue bond programs, and other financing efforts, has committed billions of dollars to upgrade seismically vulnerable, city-owned lifeline system components and facilities. It is recommended that the city operators work with the Capital Planning Committee to support improvements that are underway or planned, identify and fund additional mitigation projects that address the vulnerabilities of city-owned systems and facilities raised in the study. These include but are not limited to the seawall, the lack of connectivity and redundancy between the city's two key wastewater treatment plants, roadway improvements along critical routes, vulnerable airport and public transit facilities and transit system components, radio and telecommunication improvements, and necessary upgrades beyond the current water, wastewater, and auxiliary water system upgrade programs.

Develop Common Resilience (Level of Service) and Restoration Standards for Critical System Components

As described in section 3.3, the lifelines interdependency study has confirmed that there are a wide range of lifeline system conditions and expected performance standards, both in terms of the expected level of service disruption and the likely restoration timeframes in San Francisco following a major disaster. It is a major goal of this study and the Lifelines Council to develop a collective set of lifelines performance expectations, both under current system conditions and as a future goal, for all lifeline system operators in the City and County of San Francisco and potentially across the entire Bay region.

It is recommended that the Lifelines Council establish a working group of members to develop a collective set of lifelines performance targets for the expected (M7.2) and larger M7.9 earthquakes on the San Andreas Fault. The results of this study can serve as points of reference to be reviewed and amended, as needed, by the work group. Establishing a collective set of performance standards for lifeline operators needs to consider the variations in system age, reliability, sensitivity, flexibility, complexity, and use of "smart" technology for monitoring and control. It also needs to consider the interactions among systems and the vulnerabilities that are introduced as a result of interdependencies. The lifelines interdependency study has shown that some systems will have a much stronger influence on the restoration timeframes for other lifeline systems post-disaster. Most notably, these include regional roads and city streets, electric power, telecommunications, and fuel. Most operators tried to factor these dependencies into the restoration estimates provided for the study's scenario earthquake. However, any unexpected or protracted delay in one system's restoration is likely to have a significant "domino effect" on the restoration of other systems. Addressing the vulnerabilities of these highly interdependent systems could have a positive influence on the performance of many more lifeline systems in San Francisco. The work group should also recommend a timeline for operators to achieve these resilience and restoration standards and recommend a work program for the Lifelines Council, the City and County of San Francisco, and lifeline system operators to pursue in adopting and implementing these standards.

In 2009, SPUR released a policy paper entitled "The Resilient City: Defining What San Francisco Needs from its Seismic Mitigation Policies" which made a series of specific recommendations as to what San Francisco has to do to improve the resilience of its buildings and lifelines to withstand a major earthquake.[9] SPUR defined the "expected earthquake" as a M7.2 earthquake on the Peninsula segment of the San Andreas Fault.[10] SPUR also proposed the following set of citywide recovery targets for lifeline systems[11]:

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[9] SPUR, 2009. http://www.spur.org/files/spur-reports/SPUR_Seismic_Mitigation_Policies.pdf

[10] This is the same earthquake source but a much smaller magnitude event than the scenario earthquake used for the lifelines interdependency study.

[11] For clarification, these are standards recommended by experts serving on the SPUR "Resilient City" committee and they have not been vetted or endorsed by the City and County of San Francisco Lifelines Council and member operators.

- First for critical response facilities, SPUR recommended that a 100% of lifeline service levels would be resumed within 4 hours.
- For lifeline systems serving housing and neighborhoods, standards of 90% service restoration with 72 hours, 95% within 30 days, and 100% within 4 months were proposed.
- And, for the balance of the city, it was assumed that lifeline systems would be restored as buildings were repaired and returned to operations and so standards of 90% service restoration with 72 hours, 95% within 30 days and 100% within 3 years (36 months) were proposed.

SPUR estimated the current levels of performance which, for most systems, were below the recommended performance standards, and it also recommended a 30-year timeline to achieve these proposed targeted states of recovery. The SPUR recommendations could serve as a starting point for the Lifelines Council to use in considering the potential development of common resilience and restoration standards for all lifeline system operators in the City and County of San Francisco and potentially across the entire Bay region.

4.3.2 Longer-Term Recommendations for Coordinated Mitigation

Prioritize Mitigation Projects for Private Sector Operators and Advocate, as needed

The operators or privately-owned lifeline systems have already committed considerable funding to upgrade seismically vulnerable system components and facilities, but there are additional vulnerabilities raised by this study. It is recommended that the Lifelines Council support private operators to identify additional mitigation projects and advocate, as needed, for their funding and approval.

Develop Common Standards and a Plan for Addressing Gaps in "Smart" System Monitoring and Communications

Most lifeline system operators are moving toward, or have already installed computer-based system monitoring and control systems, such as the SCADA (supervisory control and data acquisition) system, which have the ability to increase operators' knowledge and control of system performance post-disaster. It is recommended that the Lifelines Council establish a work group to inventory the use of monitoring and control systems, and recommend system standards and a plan for addressing gaps in the use of these monitoring systems, opportunities and needs for linking these systems with emergency operations centers and decision making, dependencies on power and telecommunications systems, and any other issues that may affect post-disaster system monitoring and control and ensuring reliable emergency communications and decision making.

Appendix A. Lifelines Interdependency Study Participants

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