PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Water Supply in regard to Fire Following Earthquake

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ABSTRACT

A major earthquake in Los Angeles, San Diego or the San Francisco Bay Area is expected to result in numerous fires. A survey of fire and water agencies (with responses from those serving about one third of urbanized California) found poor understanding of the post-earthquake fire issue, and poor communication between fire and water agencies on this issue. In order to mitigate this problem, it is recommended that meetings should be held within the California fire service and the California water distribution community, to highlight this problem and enlist both communities in an effort to develop state-wide requirements for post-earthquake firefighting water supply target goals, to be achieved by a given date. Possible ways of assuring satisfactory post-earthquake water supply may include development of a standardized California portable water supply system (PWSS) for use in major urban areas, consideration of a saltwater high pressure system for the Los Angeles Metropolitan Area (Los Angeles and Orange counties), to be used in conjunction with the PWSS, and development and deployment of neighborhood equipment container caches, for use by NERT, CERT and other volunteers, to enhance their currently very limited post-disaster firefighting capability.

EXECUTIVE SUMMARY

Fire following earthquake (FFE) is a significant problem in California. Historically, every significant earthquake in California has resulted in multiple simultaneous fires that have strained, and at least in 1906 overwhelmed, the fire service. In both the 1971 San Fernando and the 1994 Northridge earthquake, there were over 100 ignitions. Other disasters clearly demonstrate that massive fires are a problem in California under even non-earthquake ignitions, when only one or a few ignitions are involved – the numerous wildland urban interface fires that occur in California almost every year are only the most telling example of this – another example is the 1988 First Interstate Bank Fire, which totally destroyed 4 floors of the state's tallest building (at that time) and severely damaged the rest of the building through water and smoke damage. The 2008 ShakeOut and associated Golden Guardian Exercise examined potential fires assuming a Mw 7.8 southern San Andreas event affecting Southern California on a morning in mid-November, with breezy, low humidity conditions. The analysis found approximately 1,600 ignitions occur, with the central Los Angeles basin experiencing hundreds of large fires. The final loss was estimated to be hundreds to perhaps a thousand lives, and approximately 200 million sq. ft. of residential and commercial building floor area, worth perhaps as much as one hundred billion dollars, and virtually all insured.

Regarding insurance, the industry has played a key role in U.S. fire protection for over 100 years, and continues to do so today. This is due in part to the enormous exposure of the industry - about 9.5 million residential and 1 million commercial property insurance policies were in force in California in 2009, with a total value of $ 4.7 trillion, almost all of it exposed to fire following earthquake. The insurance industry through its periodic review of fire departments and their water supplies seeks to assure that fire departments remain well trained and equipped, and adequately supplied with water, for normal firefighting conditions. However, guidance provided by the insurance industry for adequacy of public water supplies does not mention or consider earthquake. This study examines a more densely built-up neighborhood in San Francisco, where it is shown that the water required for post-earthquake conflagration is far in excess of that required by current insurance standards. Further background and detail on this aspect is provided in Appendix C.

While the fire service in California since 1906 has professionalized and advanced technologically to the point of being perhaps the best in the world, it has not been tested by a major earthquake since 1906. Water systems in California have failed in virtually all urban earthquakes in California – as a result, water departments have engaged in major reviews of their system's seismic vulnerability, and spent hundreds of millions of dollars seismically upgrading their systems. Exemplary programs include LADWP and MWD in Southern California, and EMBUD and San Francisco's Hetch Hetchy system in Northern California, to name a few of the larger programs.

Nevertheless, the Achilles Heel of these systems, and the entire fire following earthquake problem, remains the distribution system – despite massive seismic retrofit programs, it has not been possible to replace all of the distribution systems, and it is quite possible that numerous distribution breaks will occur in the high intensity areas of a major earthquake, which are also the areas most likely to have fires. Distribution breaks will not cause system-wide loss of water, but will cause loss of water in the neighborhood of the fire – for the firefighter, effectively the same thing. Knowing this, fire departments have identified and developed plans to access alternative water sources – in most cities for example, these include swimming pools, tanks, creeks, ponds and storm water drains. San Francisco, due to its experience in 1906, has gone far beyond this, to develop and maintain the high pressure seawater-supplied Auxiliary Water Supply System (AWSS) and 172 cisterns (underground water tanks spread throughout the city). In fact, San Francisco in June 2010 approved $104.2 million to enhance this system as part of a $412.3 million bond, which also included a new police/fire headquarters and rehabilitation of existing fire stations. However, most other cities, particularly Los Angeles, San Jose and San Diego, lack such systems and, quite worryingly, the capacity of their water supplies (normal, and alternative) have been little examined vis-à-vis the demands that multiple simultaneous post-earthquake fires will place on those supplies.

To further examine this issue, a survey of fire and water agencies was conducted. Responses were received from agencies representing about one third of urban California. The survey responses are detailed in the report – key findings included:

- Most larger urban fire and water agencies could be better informed regarding the specifics of their earthquake risk

- Earthquake is recognized as a key issue by fire and water agencies, although many water agencies see provision of potable water as a higher priority in some cases than firefighting.
- Water agency system vulnerabilities are not well understood by fire agencies, although water and fire agencies both generally believe most municipal water supply systems are unreliable in a major earthquake.
- Some fire agencies have vigorously addressed this issue, developing innovative high pressure and/or portable water supply systems. Many have not.
- Some water agencies have alternatives given loss of normal water supply, but many are not well enough equipped to actually move water a significant distance.
- Fire and water agency liaison is not very good, and is often somewhat indirect solely through larger enterprise-wide coordination meetings. Emergency firefighting water supply is not a focus.

In summary, this report finds that the risk of post-earthquake conflagration in urban California is very significant, and that the crucial need for post-earthquake firefighting water supply is falling through a gap. Reasons why this is happening are briefly explained, but the key issue is how to correct the situation. To do so, the following general recommendations are provided:

1. Highlight the problem to the California Fire Service, for example by a meeting of the Metro Fire Chiefs, perhaps in conjunction with the Seismic Safety Commission and CalEMA.
2. Enlist the Water Community via a joint meeting of key senior fire chiefs and water department managers, perhaps held under the auspices of the Seismic Safety Commission and CalEMA.
3. Develop state-wide requirements for development of post-earthquake firefighting water target goals, and that water and fire agencies should develop and submit plans for measures intended to achieve these goals by a given date.

Additionally, three specific measures are suggested for further study:

- Development of a standardized California portable water supply system (PWSS) that would be deployed in major urban areas. This PWSS system would suffice for the San Francisco Bay Area.
- Development of a saltwater high pressure system for the Los Angeles Metropolitan Area (Los Angeles and Orange counties), to be used in conjunction with the PWSS. The LAM area saltwater system is quite feasible, if existing larger storm drain channels can be used for pipeline rights-of-way.
- Development and deployment of neighborhood equipment container caches, for use by NERT, CERT and other volunteers, to enhance their currently very limited post-disaster firefighting capability.

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1 Introduction

1.1 PURPOSE OF THIS REPORT

The purpose of the paper is to qualitatively review the current status of emergency water supply in California vis-à-vis fire following earthquake, and provide a series of recommendations for improvements if/where needed. While some recommendations will be possible given information in hand, recommendations for some other potential improvements (while probably needed) won't be possible to make given current information, so that a final recommendation will be an outline of necessary research.

The focus of the paper will be on fire following earthquake in urban areas (including the special problem of tall buildings). Low density communities and non-earthquake fires (e.g., the urban wildland interface fire problem) will not be treated except insofar as relevant to the fire following earthquake problem.

The audience for this report is primarily the fire and water agencies that serve urban California. In various places, such agencies may be referred to as "water departments" but this should be understood to also include water districts and investor-owned water companies. Similarly, while the term "fire departments" is often used, it should be understood to refer to all relevant firefighting entities, including city fire departments, fire protection districts, regional and state agencies, and private and corporate fire protection.

1.2 BACKGROUND OF EARTHQUAKES AND FIRE FOLLOWING EARTHQUAKES

Earthquakes cause damage by a variety of damaging agents, including fault rupture, shaking, liquefaction, landslides, fires, release of hazardous materials, tsunami, etc. Shaking is present in all earthquakes, by definition, and is the predominant agent of damage in most earthquakes. Occasionally, however, building density and flammability, meteorological conditions and other factors can combine to create a situation in which fire following earthquake, or post-earthquake conflagration, is the predominant agent of damage. Large fires following an earthquake in an urban region are relatively rare phenomena, but have occasionally been of catastrophic proportions. Most disastrous earthquakes in fact cause relatively few fires – recent major disasters such as the 2004 Indian Ocean earthquake and tsunami (250,000 killed), 2005 Pakistan (80,000+ killed), 2008 Wenchuan (80,000 killed) and 2010 Haiti (200,000+ presumed killed) have been accompanied by few if any major fires.

However, in particular regions, earthquakes tend to cause many fires, some of which can be disastrous. In both Japan and the United States, fire has been the single most destructive seismic agent of damage in the twentieth century. The fires following the San Francisco 1906 and Tokyo 1923 earthquakes rank as the two largest peacetime urban fires in man's history, and were both terribly destructive. The 2011 Easter Japan earthquake and tsunami caused over 300 fires, several of which grew to conflagration proportions. While not widely perceived today by the public or even many professionals in the earthquake or fire service fields, fire following earthquake is recognized by professionals specializing in this field as continuing to pose a very substantial threat in both countries.

Although fire following the 1906 earthquake was the overwhelming cause of the damage San Francisco and Santa Rosa, and has continued as a significant cause of damage since, it has received relatively little attention in the US. Why fire following earthquake has received little attention is due to several factors:

a) Earthquakes historically have been the professional concern of seismologists and structural engineers, who as a class of professionals are largely uninformed of fire,

b) Fire protection engineers and fire service personnel have similarly ignored earthquakes, seeing their goal as the mitigation of chronic fire losses by code implementation and other techniques, rather than as earthquake response,

c) Major conflagrations were a common occurrence in the US prior to WW2, so that the 1906 experience was seen as more of a conflagration than an earthquake phenomenon.

d) The subsequent decline in US urban conflagrations, due to improved fire and building codes, and to improved fire service response due primarily to better communications, training and equipment, has only increased this sense of "it can't happen here".

e) Lastly, not all, and particularly most smaller, earthquakes cause few significant fires.

This last point has been crucial to contributing to the lack of attention to post- earthquake fire:

a) The lack of a major urban US earthquake since 1906. It is little appreciated that it takes a great earthquake, striking a large urban region, to create the conditions of dozens or hundreds of ignitions that overwhelm the fire service and result in a conflagration. San Francisco 1906 and Tokyo 1923 fulfilled this condition. Earthquakes since 1906 (1933 Long Beach, 1964 Alaska, 1971 San Fernando, 1987 Whittier in the United States, 1989 Loma Prieta and 1994 Northridge in the US, and in Japan the 1968 Tokachi-oki, 1978 Miyagiken-oki, 1984 Nihonkai-chubu, 1995 Kobe, 2004 Nihonkai Chuetsu and 2011 Eastern Japan events) have generally not fulfilled these two conditions – a great earthquake in a large urban region. Note however, that there were many ignitions in 1971, 1989, 1994 and 1995, and that there were conflagrations of many acres in Kobe in 1995, and several hundred ignitions in the 2011 Tohoku earthquake.

b) The general lack of awareness of the existence of an analytical framework within which to model the many factors involved in post-earthquake fire, and to quantify these factors and the outcome: many small fires, or conflagration?

That large fires following earthquakes remain a problem is demonstrated by ignitions following the 1994 Northridge, 1995 Kobe and 2011 Eastern Japan earthquakes, as well as several recent large non-earthquake conflagrations, including the 1991 East Bay Hills and 1993 Southern California wild fires. While long a concern to fire departments and the insurance industry, consideration of the problem has been subject to debate regarding the likelihood and severity of post-earthquake fires in any future events.

Until recently, perhaps the only group at all concerned with post-earthquake fire has been the insurance industry, who due to 1906 is quite aware of the potential for catastrophic loss due to this phenomenon. (Steinbrugge, 1982) presents probably the best summary of knowledge deriving from this field. (Scawthorn et al., 1981) developed a probabilistic post-earthquake fire ignition and spreading model, which has subsequently been applied at two levels:

1. *Jurdisdictional*: a detailed modeling, with ignitions, fire loading, engine location and other parameters modeled gridwise at about the 10 hectare level of resolution, Due to the sizable data collection and computational effort involved, this model has only been applied to one US jurisdiction, the City of San Francisco (Scawthorn, 1986) and

2. *Regional:* a coarser model based on approximations derived from the Jurisdictional model. Applied to the San Francisco and Los Angeles and other regions (Scawthorn, 1987, Scawthorn, 1992, Scawthorn, 2001) this model permitted for the first time quantified estimates of the aggregate losses due to fire following earthquake. This work has largely served the needs of the insurance industry.

The fact that fire following earthquake has been little researched or considered in North America is particularly surprising when one realizes that the conflagration in San Francisco after the 1906 earthquake was the single largest urban fire in history to that date. It remains today the single largest earthquake loss in U.S. history, in terms of life and economic loss. The loss over three days of more than 28,000 buildings within an area of 12 km^2 was staggering: $250 million in 1906 dollars, and over 3,000 killed[1]. That fire has since only been exceeded in a peacetime urban fire by the conflagration following the 1923 Tokyo earthquake, in which over 140,000 people were killed and 575,000 buildings destroyed (77% of the buildings destroyed were by fire) (Usami, 1981).

Fires following large earthquakes are a potentially serious problem, due to the multiple simultaneous ignitions which fire departments are called to respond to while, at the same time, their response is impeded due to impaired communications, water supply and transportation.

[1] Exact number of fatalities is unknown – until the 1980's, it was believed approximately 700 had been killed. Research by Gladys Hansen, San Francisco Librarian, indicated that far more people killed had not been accounted for. In painstaking research over many years, she slowly gathered evidence from letters of the time, gathered from all over the world, of many more deaths. Of particular interest was the fact that many minority fatalities, especially in San Francisco's large Chinatown, were known in 1906, but not included in the official count. Her work is on-going as of this writing, and the count is still increasing. See Hansen and Condon, 1989.

Additionally, fire departments are called to respond to other emergencies caused by the earthquake, such as structural collapses, hazardous materials releases, and emergency medical aid.

1.3 OUTLINE OF THE REPORT

The next section of this report reviews selected historic fires following earthquake, and several recent studies. Relevant building code and legislative requirements, and insurance aspects, are also briefly discussed. Section 3 then presents the results of a survey of urban California fire and water agencies, and reviews exemplary measures undertaken by a few fire departments. Section 4 then summarizes our findings and presents recommendations for mitigation of the fire following earthquake / water supply problem. References, a glossary and other materials conclude the report.

2 Fire Following Earthquakes

This section briefly reviews selected large earthquakes and the fires they caused, provides a summary overview of modeling of fire following earthquake, discusses the importance of water in regard to fire following earthquake, and concludes with a discussion of the insurance aspects of fire following earthquake.

2.1 FIRES FOLLOWING SELECTED EARTHQUAKES

Table 1 lists all US events with post-earthquake ignitions. This section briefly summarizes selected US and foreign earthquakes – since many aspects of these events are well-known, only summary information is provided with emphasis on the fires and water supply, with more detailed information on each event is provided in cited references and (TCLEE, 2005).

2.1.1 The 1906 San Francisco, California, Earthquake and Fires

The Mw 7.8 earthquake occurred at 5:12am on 18 April 1906 and was the most devastating earthquake in US history. While the region of destructive shaking extended over a distance of 600 kilometers, the vast majority of the damage in the entire earthquake, and especially in San Francisco, was due to fire. Of the approximately 28,000 buildings lost in the event, 80% were attributed to fire. (Scawthorn and O'Rourke, 1989) compiled data on the 52 known ignitions in the City of San Francisco, which are shown in Figure 1.

The San Francisco Fire Department in 1905 protected approximately 400,000 persons occupying an urbanized area of approximately 21 square miles (about half of today's city), and consisted of a total of 585 full paid fire force deployed in 57 companies. The department was however totally overwhelmed - the NBFU Conflagration Report (Reed, 1906) concluded

> *'the lack of regular means of communication and the absence of water in the burning district made anything like systematic action impossible: but it is quite likely that during the early hours of the fire the result would not have been otherwise, even had not of these abnormal conditions existed'* [sic].

That is, the NBFU concluded that even under normal conditions the multiple simultaneous fires would have probably overwhelmed a much larger department, such as New York's, which had three times the apparatus (NBFU, 1905).

Several factors contributed to the initial ignitions rapidly growing out of control. While the weather was relatively hot and dry, undoubtedly the primary factor leading to the conflagration was the failure of the water system (Scawthorn and O'Rourke, 1989). In summary, in 1906 water to San Francisco was supplied from two series of reservoirs to a second series of smaller terminal reservoirs within the city limits, and then distributed by means of trunk and distribution pipelines.

Figure 2 is a map of the 1904 water supply within the San Francisco City limits. There were nine reservoirs and storage tanks, for a total capacity of 354 million liters. Approximately 92% of this total, or 325 million liters, were contained in the Lake Honda, College Hill, and University Mound Reservoirs. These reservoirs and the pipelines linking them with various parts of the city were the backbone of fire protection. All trunk lines, 400 mm or larger in diameter, are plotted in Figure 2. Trunk lines are shown connected to the Lake Honda, College Hill, University Mound, Francisco Street, and Clay Street Reservoirs; all other reservoirs were connected to piping 300 mm or less in diameter. Superimposed on the figure are the zones of lateral spreading caused by soil liquefaction, as delineated by (Youd and Hoose, 1978). It can be seen that multiple ruptures of the pipeline trunk systems from the College Hill and University Mound Reservoirs occurred in the zones of large ground deformation, thereby cutting off supply of over 56% of the total stored water to the Mission and downtown districts of San Francisco. Two pipelines, 400 and 500 mm in diameter, were broken by liquefaction induced lateral spreading and settlement across Valencia Street north of the College Hill Reservoir. These broken pipes emptied the reservoir of 53 million liters, thereby depriving fire fighters of water for the burning Mission District of San Francisco.

Reservoirs were within the zone of most intense fire, and therefore capable of providing water directly to fight the blaze. The combined capacity of these reservoirs was only 21 million liters, or 6% of the system capacity. The usefulness of such limited supply was further diminished by breaks in service connections, caused by widespread subsidence, burning and collapsing buildings. Schussler identifies service line breaks as a major source of lost pressure and water. There were roughly 23,200 breaks in service lines, between 15 and 100 mm in diameter. Fallen rubble and collapsed structures often prevented firemen from closing valves on distribution mains to diminish water and pressure losses in areas of broken mains and services. The Lake Honda Reservoir was able to provide a continuous supply of water to the western portion of the city. The fire eventually was stopped along a line roughly parallel to Van Ness Avenue, where water still was available from the Lake Honda Reservoir. Moreover, the southern and southeastern extent of the fire is bounded by areas south and southeast of the trunk system ruptures. It is likely that these unburnt areas had water from the University Mound Reservoir.

Key lessons to be drawn from this event are:

- The numerous ignitions approximately equal in number to the number of fire companies, which would have been extremely challenging under any circumstances.
- The availability of water in reservoirs, but numerous water main breaks due to large permanent ground deformations resulting in loss of water supply in the NE quadrant of the city, corresponding to the final burnt area;
- The better ground and availability of water supply in the SE and western parts of the city, where fires were halted; and
- The contributing factor of thousands of service line connection breaks, a factor largely overlooked but which may have further 'bled' the system.

Recognition of the critical damage to the water system lead to the construction of San Francisco's Auxiliary Water Supply System (AWSS), which is described later in this report

2.1.2 The 1989 Loma Prieta, California, Earthquake and Fires

The M_w 7.1 earthquake occurred on October 17, 1989 at 5:04pm local time with epicenter located about 30 km south of San Jose and 100 km south of San Francisco. Major damage included the collapse of the elevated Cypress Street section of Interstate 880 in Oakland, the collapse of a section of the San Francisco-Oakland Bay Bridge, multiple building collapses in San Francisco's Marina district, and the collapse of several structures in Santa Cruz and other areas in the epicentral region. Damage and business interruption losses were estimated as high as $6 billion. Human losses were 62 people dead, 3,700 people reported injured, and over 12,000 displaced. At least 18,000 homes were damaged, 960 were destroyed and over 2,500 other buildings were damaged and 145 destroyed. There were 916 documented water system pipe breaks in the event, Figure 3 (TCLEE, 2005).

The earthquake resulted in only moderate shaking for most of San Francisco, typically of MMI VI, although shaking was perhaps as much as MMI VIII in the Marina district, Figure 4. Twenty-six fires occurred in San Francisco as a result of the earthquake, 11 on the 17th. One of these fires occurred in the Marina District, and threatened to become a major conflagration. At the same time in the Marina, 69 breaks in the domestic water supply and more than 50 service connections to water mains quickly dissipated all domestic water supply in the 40 blocks of the district. The AWSS main serving the Marina district remained intact. However, as a result of the shaking in locations other than the Marina, the AWSS sustained significant damage and major leakage from these breaks completely drained the Lower Zone of the AWSS in approximately 15 minutes so that first arriving engines at the Marina fire found no water when they connected to AWSS hydrants, Figure 6.

Firefighting efforts were thus severely hampered due to lack of MWSS and AWSS service to hydrants, due to the severe liquefaction and resulting pipe breakage in the Marina and elsewhere. Firefighters were forced to resort to drafting from nearby lagoons which however was inadequate, and the fire continued to grow. Because the fire was located only two blocks from the Bay, the fireboat *Phoenix* was called for, arriving at about 6:30 P.M. At approximately the same time, PWSS hose tenders arrived at the scene and were able to connect to the *Phoenix*, laying approximately 6,000 ft. of 5-in. hose. The *Phoenix* pumped 6000 gpm at 180 psi for over 18 hours (i.e., a total of 6.5 million gallons, equivalent to ten Olympic size swimming pools). Fire spread was stopped at about 7:45 P.M. by master streams from the monitors on the hose tenders, as well as ladder pipes and hand lines.

The 1989 Loma Prieta earthquake provided a number of valuable observations and lessons, including:

- Although a relatively modest event, almost 1,000 pipe breaks were sustained throughout the region.
- The Marina fire was potentially very severe - it was a very large fire in a dense neighborhood of wood frame construction - an unusually calm wind was a very fortuitous circumstance

- The fire was within 500 ft. of San Francisco Bay and the Pacific Ocean - the largest body of water on earth. However, this inexhaustible supply of water was inaccessible (could not be drafted from by arriving fire engines).

- The MWSS system had over 400 million gallons of storage within San Francisco, but the numerous breaks in the Marina prevented adequate pressure or volume at Marina hydrants - elsewhere in the City, MWSS performance was generally satisfactory.

- The AWSS is designed for earthquake ground motions, and did not sustain damage in the Marina despite widespread liquefaction - nevertheless, it lost pressure in the Lower Zone due to breaks several miles away.

- Deployment of San Francisco's PWSS in conjunction with the fireboat Phoenix provided the only adequate source of firefighting water, which was the only way the Marina fire was extinguished. That is, the "backup to the backup" – the PWSS backing up the AWSS which backs up the MWSS – provided firefighting water for extinguishment at the Marina fire. The PWSS' flexibility and portability proved adequate to the task.

2.1.3 The 1994 Northridge, California, Earthquake and Fires

The Northridge earthquake was the most significant earthquake to occur within a US city in more than 20 years. The 4:31 AM January 17, 1994 Mw 6.7 earthquake was centered under the Northridge section of the San Fernando Valley area of the Los Angeles region and resulted in Modified Mercalli Intensity (MMI) shaking intensities greater than MMI VIII over approximately 700 square miles of the northern Los Angeles area. The population most heavily affected was in the San Fernando Valley, which is primarily protected by the Los Angeles City Fire Department.

Table 2 lists fire departments significantly affected by the earthquake, and their summary statistics – see (Scawthorn et al., 1997) for additional detail. Approximately 110 fires were reported as earthquake-related on January 17, as shown in Table 3 and Figure 7. The time line in Figure 8 shows all calls for assistance with fires on the day of the earthquake. Structure fires predominate (86%) the earthquake-related fires.

The Northridge earthquake effected the water supply for portions of the San Fernando Valley – for the LA Dept. of Water and Power system alone (consisting of, for diameters to and including 24 inch, 7,848 km of cast iron pipe; 433 km of ductile iron pipe; and 961 km of asbestos cement pipe) a total of 1,405 pipe repairs were reported, including 673 repairs for cast iron pipe; 24 repairs for ductile iron pipe; 26 repairs for asbestos cement pipe, and 216 repairs for steel pipe. The damage to the system resulted in dropping the water pressure to zero in some areas. On January 22nd, five days after the earthquake, between 40,000 and 60,000 customers were still without public water service, and another 40,000 were experiencing intermittent service.

Scawthorn et al (1997) have documented a number of specific fires and fire department operations, as well as all ignitions, in this event. One significant fire occurred on North Balboa Blvd. in the Granada Hills area of the San Fernando Valley, a residential area with one- and two-story wood-frame single-family dwellings, many with swimming pools. The fire was due to a broken 20-inch gas main under Balboa Boulevard which was ignited by electric arcing in a truck ignition system, creating a fireball and igniting two dwellings on the east side of Balboa and three on the west side, Figure 10. Radiant heat from the gas fire was a major factor in the spread of fire. Wind was 15 to 20 mph from the northeast. Ignition occurred about 20 minutes after the earthquake struck. A total of five homes were destroyed, with minor damage to four others. The same ground displacements that had broken the gas main had also broken water mains, so that arriving firefighters found dry hydrants, but located swimming pools and used them as water sources. A group of local citizen volunteers formed a "bucket brigade" using a swimming pool for a water source. Engine companies pumped water between 1 1/2 and 2 hours during the firefighting operation. It took about 2 hours for the natural gas leak fire to be reduced in size such that it presented a minimal threat from radiated heat. Water usage for selected fires in this event is shown in Table 4.

The 1994 Northridge earthquake provided a number of valuable observations and lessons, including:

- Over 1,000 water main breaks, and over 100 fires, occurred in this event.
- Permanent ground displacements broke gas mains, igniting fires, and also broke water mains at the same location, rendering surrounding fire hydrants inoperative.

- Backyard swimming pools were used as water supply sources, providing approximately 70 minutes of water flow.

- The 1994 Northridge earthquake occurred on a winter morning at almost the same location as the 1971 San Fernando earthquake. Both events had about 110 fires.

2.1.4 The 1995 Hanshin (Kobe), Japan Earthquake and Fires

The 5:46 AM January 17, 1995 Mw 6.9 (JMA M7.2) Hanshin (official name: Hyogo-ken Nambu) earthquake was centered under the northern tip of Awaji island near Kobe, in the Kansai region of Japan. The event resulted in Modified Mercalli Intensity (MMI) shaking intensities greater than MMI VIII did over approximately 400 square km of the Kobe-Ashiya-Nishinomiya area. Population of the affected area (MMI VIII or greater) is approximately 2 million.

The Kobe Fire Department (KFD) is a modern, well-trained fire response agency, organized into Prevention, Suppression, and General Affairs sections, and a Fire Academy. The city is served by 1,298 uniformed personnel. Equipment includes two helicopters, two fireboats, and 196 vehicles.

Approximately 100 fires broke out within minutes, primarily in densely built-up, low-rise areas of the central city, which comprise mixed residential-commercial occupancies, predominantly of wood construction, see Figure 11. Within 1 to 2 hours, several large conflagrations had developed. There were a total of 108 fires reported in Kobe on January 17, with fire response hampered by extreme traffic congestion, and collapsed houses, buildings, and rubble in the streets. Because of the numerous collapses, many areas were inaccessible to vehicles, and conflagrations developed in several areas, Figure 12.

Firewater in the area is primarily from the city water system, served by gravity from 30 reservoirs. Of these, 22 have dual tanks, with one tank having a seismic shutoff valve so that, in the event of an earthquake, one tank’s contents is conserved for fire fighting. In this event, all 22 valves functioned properly, conserving 30,000 cubic meters of water, which, however, could not be delivered because of approximately 2,000 breaks in the underground piping. The city has provided underground storage of water for disaster fire fighting in 968 cisterns, generally of 40 cubic meter capacity, sufficient for about a 10-minute supply of a pumper. All engines carry hard suction, so that additional water can be drafted from Osaka Bay or the several streams running through Kobe.

Water for fire-fighting purposes was available for 2 to 3 hours, including the use of underground cisterns. Subsequently, water was available only from tanker trucks. KFD attempted to supply water with a fireboat and relay system, but this was unsuccessful due to the relatively small hose used by KFD. The author overflew the area at about 5:00 p.m. on January 17 and was able to observe all of the larger fires (about eight in all) from an altitude of less than 300 meters. No fire streams were observed, and all fires were burning freely—several with flames 6 meters or more in height. No fire apparatus were observed in the vicinity of the large fires, although fire apparatus could be seen at other locations (their activities were unclear from the air). Some residents formed bucket brigades (with sewer water) to try to control the flames. Selected aspects of the 1994 Northridge and 1995 Hanshin earthquakes are compared in Table 5. The 1995 Kobe earthquake provided a number of valuable observations and lessons, including:

- A large number of ignitions were strongly correlated with damage to the water distribution system.
- Water was locally available (Osaka Bay, streams within the town, hillside water tanks) but could not be effectively conveyed to the fire ground.
- Water cisterns were widely available and were used, but were too small to be effective.
- The Northridge and Kobe events are more similar, in terms of ignition rates, water system damage and fire service resources, than they are dissimilar.

2.1.5 The 2011 Eastern Japan Earthquake and Fire

The 2011 Eastern Japan Mw 9.0 earthquake occurred offshore eastern Japan on 11 March 2011 at 2:46pm, and was accompanied by a major tsunami that in fact caused much more damage than the shaking. The earthquake is the largest magnitude event in Japan's entire history, and resulted in approximately 26,000 killed and missing, massive damage along hundreds of kilometers of coastline, and catastrophic damage to several nuclear power stations.

The earthquake also resulted in approximately 345 fires, Figure 13, which is perhaps more than is documented in all previous events combined. The fires were about 50% within the tsunami affected area, and 50% outside this area. In the Tokyo area, there were substantially more fires in less strongly shaken areas than in more strongly shaken areas, Figure 14, which is clearly due to the combination of shaking and building density, Figure 15 and Figure 16.

There were a substantial number of oil refineries in the affected area, two of which had major fires. Figure 17 shows the Cosmo oil refinery on Tokyo Bay in Chiba, where a gas sphere ignited due to shaking and burned for several days. Figure 19 shows the Japan Oil refinery in Sendai, which was inundated by the tsunami and also burned for several days.

Aside from these two, there were hundreds of other fires - Figure 20 shows one of a number of conflagrations that occurred in tsunami affected areas, due to ruptured fuel tanks releasing flammable liquids on the surface of the water, which are then easily ignited. Figure 21 and Figure 22 show a large foodstuffs warehouse in the Port of Sendai, where process-related open flames probably ignited ruptured edible oil tank contents.

Fire departments in almost all these cases were unable to respond to the fires, due primarily to being simply overwhelmed, Figure 23. However, review of post-event damage records shows that most domestic water supply lines were damaged in the affected area, so that water supplies would have been inadequate if fire suppression would have been attempted.

The 2011 Eastern Japan earthquake provided a number of valuable observations and lessons, including:

- Literally hundreds of ignitions occurred in this event, demonstrating the issue of multiple simultaneous ignitions remains with us today.
- Extensive damage to water supply lines, removing normal firefighting water supply
- Major fires at large industrial complexes, even at a distance from the event.

2.1.6 Summary of Lessons from Historical Events

The accumulation of experience based on observations of the above events, and others which space does not permit discussing here, leads to the conclusion that the potential exists for large conflagrations following a major earthquake in an urban area, particularly in a region with a large wood building stock. Under adverse meteorological and other conditions, these conflagrations may burn for several days. Water supply was extensively compromised in virtually all these events, but with each situation being unique:

- 1906 San Francisco saw the wholesale loss of water supply, and the largest peacetime urban fire in history to that date (only exceeded since by the 1923 Tokyo earthquake and fire)

- In context, 1989 San Francisco was a quite minor earthquake, but water supply was again lost at the site of the largest fire, and only the 'backup to the backup' saved the day. San Francisco is unique in this regard, in having multiply layered firefighting water supplies.

- In context, 1994 Northridge was also a relatively minor earthquake on the edge of a large urban region with perhaps the largest and best coordinated fire service in the world. In this instance, despite over 100 ignitions, firefighters improvised to find water for fighting relatively modest fires.

- 1995 Kobe was a major earthquake in the heart of a large urban area – virtually all normal water supply was lost and the more than 100 fires quickly grew out of control. Kobe had a large number of cisterns, but of relatively small size (10 minute supply) which were inadequate to the task, as were attempts to draft water from Osaka Bay.

- The 2011 Eastern Japan earthquake was one of the world's largest, but occurred offshore a relatively sparsely populated part of Japan – if there had been no tsunami, the event would have been relatively inconsequential. Nevertheless, several major industrial fires, and over 300 other fires, occurred, which generally could not be combated due to the general overwhelming of the fire service as well as loss of water supply. Over 30 fires occurred in Tokyo, distant from the event, which were quickly dealt with by the Tokyo Fire Department (the world's largest).

The essential lesson for California that can be drawn is that extensive well-drilled mutual aid systems are required, in order to mobilize large resources in response, but the deployment of these resources will be hampered by transportation difficulties and, perhaps most tellingly, failure of firefighting water supplies. Improvements in planning and infrastructure are absolutely essential to forestall this potential.

2.2 MODELING OF FIRE FOLLOWING EARTHQUAKE

The first step towards solving any problem is analyzing the problem and quantifying its effects. A full probabilistic methodology for analysis of fire following earthquake was developed in the late 1970s (Scawthorn et al., 1981) and has been applied to major cities in western North America (Scawthorn and Khater, 1992). A recent (TCLEE, 2005) details the current state of the art in modeling fire following earthquake, so that only a brief review is presented here. In summary, the steps in the process are shown in Figure 25:

- *Occurrence of the earthquake* –causing damage to buildings and contents, even if the damage is as simple as knockings things (such as candles or lamps) over.

- *Ignition* – whether a structure has been damaged or not, ignitions will occur due to earthquakes. The sources of ignitions are numerous, ranging from overturned heat sources, to abraded and shorted electrical wiring, to spilled chemicals having exothermic reactions, to friction of things rubbing together.

- *Discovery* – at some point, the fire resulting from the ignition will be discovered, if it has not self-extinguished (this aspect is discussed further, below). In the confusion following an earthquake, the discovery may take longer than it might otherwise.

- *Report* – if it is not possible for the person or persons discovering the fire the immediately extinguish it, fire department response will be required. For the fire department to respond, a Report to the fire department has to be made. Communications system dysfunction and saturation will delay many reports.

- *Response* – the fire department then has to respond, but are impeded by non-fire damage emergencies they may have to respond to (e.g., building collapse) as well as transportation disruptions.

- *Suppression* – the fire department then has to suppress the fire. If the fire department is successful, they move on to the next incident. If the fire department is not successful, they continue to attempt to control the fire, but it spreads, and becomes a conflagration. Success or failure hinges on numerous factors including water supply functionality, building construction and density, wind and humidity conditions, etc. If unable to contain the fire, the process ends when the fuel is exhausted or when the fire comes to a firebreak.

This process is also shown in the Fire Department Operations Time Line, Figure 26. Time is of the essence for the fire following earthquake problem. In this figure, the horizontal axis is Time, beginning at the time of the earthquake, while the vertical axis presents a series of horizontal bars of varying width. Each of these bars depicts the development of one fire; from ignition through growth or increasing size (size is indicated by the width or number of bars). Fire engines are shown responding to growing fires, spending some time there, and then proceeding to the next fire. Eventually, many of the engines converge on a fire that has grown very large (due to engines being at other fires), and the crux of the matter is whether enough engines arrive in time to contain the fire, or not. Two aspects of this process warrant emphasis:

Fire Growth and Spread

It is not generally appreciated how quickly structural fires grow and spread. An extreme example of fire spread is the 1991 East Bay Hills fire, where over 3,000 buildings were destroyed within the space of a few hours (Routley, n.d.,). Under normal conditions, the time to full fire involvement of a room ("compartment" in fire service terminology) varies greatly and most directly with the amount of heat input – overheated wiring or a smoldering cigarette on a mattress may take hours to finally burst into open flame – but once such a flame is combined with normal fuels (furniture, newspapers, carpeting…), the time to "flashover" and a roaring fire can be as short as a minute or two, and very often is less than ten minutes. The spread from room to room in a typical home is very quick, so that an entire house can be in flames within only a few minutes. Under normal California urban building densities, neighboring structures ("exposures") will be ignited within only a couple of minutes, and the process repeats itself.

Fire Response and Suppression

Under normal conditions, urban fire department response to a structural fire is usually a minimum of two fire engines and one ladder truck (additional apparatus responds in high value or extra hazard areas). These normal responses will not be possible following a large earthquake, since fires may outnumber fire engines. Based on review of actual operations following earthquakes, and discussions with senior fire department officials, it is likely that following an earthquake, initially only one engine will respond to reported fires, to suppress the fire and/or size-up the situation.

With regard to water required for suppression, fire flow under normal conditions can be computed on the basis of 4 gallons per minute (gpm) for each 100 cubic feet (cf) of occupancy directly involved in the fire or immediately exposed (Kimball, 1966), so that one engine can typically attack about 3,000 to 4,000 square feet of floor area if the monitor can be efficiently used, or half of this (i.e., one house) if additional personnel are not available. If minimal tactics are employed (i.e., no interior attack, perimeter protection only), which is likely following an earthquake, then the capacity of one engine can be considered to be increased (e.g., up to three or four hundred linear feet of perimeter).

Therefore, it can be seen that fire engines have to learn of the fire, and respond, quickly, in order that they are able to stay ahead of the fire, especially given possibly limited water supply.

A question arises whether fire department resources will initially be totally and primarily devoted to fire suppression, since it should be recognized that other demands (search and rescue, hazardous material response, emergency medical treatment) will also be placed on these resources? This question has been reviewed with senior officials of several fire departments, and their opinion is that some fire department resources will have to be diverted from firefighting to these other services. However, experience has shown that serious fires typically receive first priority, for the following reasons:

a) fire service training and tradition,

b) fires are dynamic while building collapses are relatively static-that is, a fire situation will worsen if neglected, while the building collapse and rescue situation can often wait several hours (indeed often must await the arrival of heavy equipment),

c) Ability of other services (police and others) to assist in building collapses, emergency medical treatment and hazardous materials management (via isolation and evacuation), while only the fire service is equipped to handle serious fires.

In addition to each jurisdiction's fire suppression resources (i.e., the department's first line and reserve engines, other equipment and personnel), auto and mutual aid need to be considered. These resources of course arrive somewhat later, from more distant locations.

2.3 RECENT ESTIMATES OF FIRE FOLLOWING EARTHQUAKE LOSSES

The above process has been widely adopted over the last several decades and is now the standard methodology employed by insurance companies as well as in HAZUS, the national loss estimation methodology and software developed by FEMA (DHS, 2003). Two recent applications of the methodology are of interest:

2.3.1 Southern California ShakeOut Exercise

> *In 2008, an earthquake-planning scenario document was released by the U.S. Geological Survey (USGS) and California Geological Survey that hypothesized the occurrence and effects of a Mw7.8 earthquake on the southern San Andreas Fault. It was created by more than 300 scientists and engineers…A custom HAZUS analysis and 18 special studies were performed to characterize the effects of the earthquake on the built environment. The scenario posited 1,800 deaths and 53,000 injuries requiring emergency room care. Approximately 1,600 fires are ignited, resulting in the destruction of 200 million square feet of the building stock, the equivalent of 133,000 single-family homes. Fire contributes $87 billion in property and business interruption loss, out of the total $191 billion in economic loss, with most of the rest coming from shake related building and content damage ($46 billion) and business interruption loss from water outages ($24 billion). Emergency response activities are depicted in detail, in an innovative grid showing activities versus time, a new format introduced in this study.*(Porter et al., 2011)

Analyses were performed for the ShakeOut Scenario, which are excerpted here:

> *The major water transmission lines within the city of Los Angeles are plotted in Figure 27. The FLAA, SLAA, and MWD's transmission of SWP water enter the city from the north at the Van Norman Complex and MWD supplies CRA water at Eagle Rock Reservoir. The LADWP distributes water to over 4 million people within the city of Los Angeles, covering a 1,204 km^2 area. This is accomplished using approximately 11,691 km of trunk and distribution pipelines ranging from 5 to 366 cm in diameter, 108 potable storage tanks and reservoirs having a total maximum capacity of 18.8 million m^3, 260 regulator stations, 80 pumping stations, three filtration plants, 25 chlorination stations, and over 712,000 service connections in 115 pressure zones. In addition, the LADWP maintains four raw water emergency storage reservoirs, having a maximum capacity of 30 million m^3, within the city.*
>
> *Table 6 summarizes the simulation results including nearly 2,700 pipeline repair locations, 150 on trunk lines. Figure 3 presents simulation results at 0 and 24 hours after the earthquake showing locations on the trunk line system where pipes are unpressurized and there is insufficient water flow to satisfy demand, prior to utilizing the raw water*

storage reservoirs. Results from GIRAFFE are presented in terms of system serviceability defined as the ratio of water flow after to water flow before the earthquake. System serviceability is approximately 76% immediately after the earthquake (at 0 hours) and drops to 34% after 24 hours. Severe deterioration in the ability to deliver water results over a 24-hour period due to damaged and leaking pipelines. A 34% system serviceability means that 66% of the normal water demand, throughout the entire system, is not met one day after the earthquake. Some areas within the system have higher or lower serviceability. The simulation results account for service line leakage and damage to interior piping of buildings, which draw more water from the system, but not for firefighting demand. Leaking pipelines draw down tanks and reservoirs causing some portions of the system to lose pressure, and in some areas all local sources of stored water. Following such a large event, approximately 24 hours is needed to mobilize the initial response to isolate and repair leaking pipelines. Thus, Figure 27(b) represents a likely flow state within one day following the earthquake, in the absence of fire demands. (Davis and O'Rourke, 2011)

Taking into account the loss of water, as well as shaking conditions, building density and other factors:

Employing population data for the region and intensity data from the scenario, the total number of fire <u>ignitions</u> likely to occur in the scenario was calculated to be approximately 1,600, as shown in Figure 28 and Table 7.

There are approximately 2,000 fire engines in the region, and many will be close by and able to rapidly respond to ignitions. The performance of lifelines, such as water supply, gas integrity, electric power, communications and transportation, is integral to the fire following earthquake process. Water pressure will drop in some portions of the more heavily shaken area due to pipe breaks and tank failures, despite widespread efforts over the last several decades to upgrade water supply systems in California. Fire departments in many areas will have to resort to alternative water supplies (creeks, ponds, swimming pools, etc). They will be handicapped in this since most engine companies today do not carry hard suction hose, although LAFD in the Northridge earthquake was able to make good use of swimming pools using 1.5" siphon ejectors. This initial lack of water supply will add to the number of large fires.

A particular concern is the large number of oil refineries, tank farms and related facilities in and around Long Beach. These facilities are responsible for half of California's gasoline, and one-third of the refined gasoline west of the Rockies. When strongly shaken, oil refineries and tank farms have typically had large fires which have burned for days. While the Long Beach area is shown to have lower intensity shaking, the long period effects at the site from the M7.8 scenario event has the potential to cause large sloshing in tanks, and fires. To put this in perspective, the 2003 Tokachi event caused one tank fire at a 140,000 bbl/day facility 230 km from the event epicenter, while the ShakeOut scenario is 80 km distant from 1.1 million bbl/day aggregate refining capacity.

Under the assumed scenario conditions, analysis shows that the approximately 1,200 large fires will result in an ultimate burnt area equivalent to approximately 200 million sq. ft. of residential and commercial building floor area, or 133,000 single family *dwellings (SFED[2]). To put this in perspective, Los Angeles county (particularly central Los Angeles) will sustain about 600 fires and a total burnt area of about 140 million sq ft. of building floor area. On average this is about 240,000 sq. ft. of building floor area burnt per fire, or about 2.5 city blocks per fire – that is, loss of entire city block, and loss of about three quarters of the blocks on either side (i.e., fire jumps one street each way, then burns out). Given the densities of wood buildings in Los Angeles as shown in* Figure 29*, this is not unreasonable. The ultimate burnt area of approximately 200 million sq. ft. of building floor area equates to approximately $40 billion of building value* [3]. (Scawthorn, 2011b).

2.3.2 San Francisco CAPSS Study

This report analyzed fire following earthquake for San Francisco as part of a larger project undertaken by the San Francisco Department of Building Inspection entitled *Community Action Plan for Seismic Safety* (CAPSS). A stochastic model for analyzing fire following earthquake for San Francisco was employed to assess fire following earthquake impacts due to four earthquake scenarios: magnitude 7.8, 7.2 and 6.5 events on the San Andreas fault near San Francisco, and a magnitude 6.9 event on the Hayward fault. These events cause high ground motions in San Francisco that result in ground failure in many parts of the City – ground motions are particularly high in the western part of San Francisco, which was not yet built up in 1906 and therefore is not protected by the special high pressure SFFD Auxiliary Water Supply System (AWSS). Depending on the specific earthquake scenario, these ground motions and ground failures are estimated to cause over 1,000 breaks in the potable water system, Figure 30, so that SFFD's AWSS and cisterns will be the only source of firefighting water in many parts of the City. The AWSS itself will sustain some damage, forcing SFFD to fall back to cisterns only in some places. At the same time, SFFD's 42 fire engines will almost certainly not be able to respond to all the post-earthquake fires, which are estimated to be about 100 on average (with a 10% chance of as many as 140) for the magnitude 7.8 San Andreas event. As a result, the methodology employed here estimates ignitions, building burnt areas and dollar losses for the

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[2] An average California single family dwelling is about 1,500 sq. ft. in floor area. This unit (1,500 sq. ft. floor area) is termed a Single Family Equivalent Dwelling (SFED) and is used to normalize and communicate overall building losses in a manner readily comprehensible to lay persons. A loss of 1.5 million sq. ft. of residential and commercial buildings for example is equivalent to 1,000 single family dwellings, or SFED. Most people can more readily comprehend the loss of 1,000 houses, than 1.5 million sq. ft. of floor area.

[3] Based on replacement cost of $200 per square foot – note this is a conservatively low estimate of replacement cost at current (2008) prices.

four scenario events. These results are presented in Table 8 as ranges within which losses will fall half (i.e., 50%) of the time (correspondingly, half the time the losses will be outside – that is, either more or less) than the indicated ranges: .

For example, for the Mw 7.8 event, essentially a repeat of the 1906 earthquake, losses will on average be about $7.6 billion, and half the time will be more than $4.1 billion and less than $10.3 billion, Figure 31 More detailed results are presented in the report, but the significance of these results is not in their precision, but rather in their overall magnitude. The model producing these results was validated by application to the 1989 Loma Prieta event, and examined for methodological and parametric sensitivity, with satisfactory results.

2.3.3 Discussion

The above two studies illustrate several key points:

- **Fires** - many hundreds of ignitions are expected in these scenarios (about 100 in the San Francisco CAPSS study, but when extrapolated to the entire San Francisco Bay Area, the Scenario events will cause several thousand ignitions – note that San Francisco represents only about 12% of the Bay Area's population).

- **Water** - the usual firefighting water supplies will almost certainly fail - about 1,000 pipeline breaks are estimated for the San Francisco study, while Davis and O'Rourke estimate almost 3,000 breaks for the ShakeOut Scenario (which is only for the portion of the Los Angeles basin served by LADWP).

- **Loss** - the estimated financial losses are very significant – about $40 billion of building value in the ShakeOut Scenario study, and $5~10 billion for the San Francisco study (depending on scenario) where, again, the San Francisco study only covered about 12% of the San Francisco Bay Area. (These are the only two such studies for urban areas in California, to the best of this author's knowledge. The wider San Francisco Bay Area and San Diego have not been similarly studied).

2.4 IMPORTANCE OF WATER IN FIRE FOLLOWING EARTHQUAKES

2.4.1 Experience

The importance of reliable water for fighting fires following earthquakes has long been recognized in California – indeed, one of the ironies of the 1906 San Francisco earthquake (other than that the city burned down despite being surrounded on three sides by the largest body of water on earth) was that in 1905 the fire department had proposed construction of a large ‘high pressure supply system.

Lessons sometimes have to be relearned however. As noted by Routley in the 1991 East Bay Hills fire:

> *Water supply was a major problem during most of the incident. Part of the problem related to the fact that many of the units that responded from distant areas were unable to hook up to Oakland hydrants. When California adopted a standard 2 l/2inch threaded connection for all hydrants, the cities of Oakland and San Francisco opted to maintain their 3-inch connections and to keep a supply of adapters on hand for mutual aid units. Fire departments in the area normally carry adapters on their apparatus, but the plan called for adapters to be obtained from the warehouse to meet incoming mutual aid strike teams at staging areas. Since this fire occurred on a Sunday, there was a delay in obtaining the adapters until off-duty personnel could open the warehouse and send them to the scene on supply trucks.*
>
> *Many of the incoming units were committed and discovered the adapter problem only when they needed water to supply hose lines or refill their tanks. This limited the ability of several units to work effectively until they could locate a unit with an adapter, or one of the supply trucks located them. Since some of these companies were in critical combat areas, it was difficult for the logistics system to find them and deliver the adapters.*
>
> *The water supply on the hills was known to be a problem from previous incidents and from risk analysis projects, including earthquake vulnerability studies. The water system on the hills was arranged as layered pressure zones, each supplied by a tank at a higher level. The storage tanks served areas where the difference in elevation would maintain static pressure in a desirable range at the delivery levels. The tanks were kept filled by a series of electrically powered pumps, which relayed the water from tank to tank, and the pumps were not provided with emergency generators. If a pump at a particular level failed, it isolated the tanks at higher levels from any capability for replenishment. The power began to fail early in the fire, as wooden poles burned, lines dropped, and transformers exploded. As pumps failed, the higher level tanks would begin to run out of water. When the high voltage lines shorted out, at 1315 hours, all of the power to the remaining pumps failed, and the whole system on the hills began to run dry.*
>
> *The demand on the system was also very high, as companies tried to establish large handlines and master streams to establish defensive lines. In addition, many of the homeowners were using their garden hoses to wet down their roofs and shrubbery to guard against flying brands and embers; some even left garden sprinklers running on*

their rooftops as they evacuated. As homes burned to the ground, their water connections were left spurting water into the rubble. All of these factors created an unprecedented demand on the system, quickly using all of the stored water. Companies on the hills reported hydrants going dry as early as Sunday noon, and the supply was not restored until that night, when portable generators were brought in to power some of the critical pumps. It does not appear that the water supply was a deciding factor in the outcome of the fire on the hills, since the crews were unable to make any progress against the flames before the hydrants went dry. The strength of the wind and the thermal forces made water almost totally ineffective to stop the downwind progress of the fire. The available water was useful in protecting certain positions, including some locations where firefighters took refuge, and in covering exposures on the flanks. In the Rockridge district there were also sections where the water supply was known from past experiences to be weak. Many of the mains in the area were old and inadequate, and at least 50 homes were burning by 1300 hours. San Francisco Strike Team One was assigned to this area and around 1420 hours the Strike Team Leader was able to call back to his department and have two of the city's large diameter hose tenders activated and dispatched to Oakland. The hose tenders were able to bring in large supply lines from streets on the edge of the district to supplement the supply.

One of the strong water supply areas was the private system installed at the Claremont Hotel. This system provided an adequate supply for the defensive streams that were established on the exposed side of the hotel. While these streams were maintained in a stand-by defensive posture, the crews were able to extend handlines up the hill to engage the fire on Alvarado Road and some of the smaller streets overlooking the hotel. This kept the fire from advancing further down the hill and causing a direct exposure to the hotel. (Routley, n.d.,)

2.4.2 Buildings Code Requirements for High-Rise Buildings

The importance of water supply for firefighting in high-rise buildings[4] has long been codified, due to the understanding that the normal water supply for automatic sprinklers from street mains may be lost in an earthquake. The 2006 International Building Code requires a secondary water supply for high-rise buildings, which typically equates to about a 15,000 gallon tank within the building:

> **903.3.5.2 Secondary water supply.** A secondary on-site water supply equal to the hydraulically calculated sprinkler demand, including the hose stream requirement, shall be provided for high-rise buildings in Seismic Design Category C, D, E or F as determined by this code. The secondary water supply shall have a duration of not less than 30 minutes as determined by the occupancy hazard classification in accordance withNFPA13. **Exception:** Existing buildings. (IBC, 2006)

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[4] Defined in the IBC as a building having an occupied floor more than 75 ft. above the lowest level of fire department vehicle access.

2.4.3 California Legislative Requirements

Article 9.5 of the California Emergency Services Act (CESA, 2009 as amended) requires:

> *§ 8607.2. Plans*
>
> *(a) All public water systems, as defined in subdivision (f) of Section 116275 of the Health and Safety Code, with 10,000 or more service connections shall review and revise their disaster preparedness plans in conjunction with related agencies, including, but not limited to, local fire departments and the office to ensure that the plans are sufficient to address possible disaster scenarios.* ***These plans should examine and review pumping station and distribution facility operations during an emergency, water pressure at both pumping stations and hydrants, and whether there is sufficient water reserve levels and alternative emergency power, including, but not limited to, on site backup generators and portable generators.***
>
> *(b) All public water systems, as defined in subdivision (f) of Section 116275 of the Health and Safety Code, with 10,000 or more service connections following a declared state of emergency shall furnish an assessment of their emergency response and recommendations to the Legislature within six months after each disaster, as well as implementing the recommendations in a timely manner.*
>
> *(c) By December 1, 1996, the Office of Emergency Services shall establish appropriate and insofar as practical, emergency response and recovery plans, including mutual aid plans, in coordination with public water systems, as defined in subdivision (f) of Section 116275 of the Health and Safety Code, with 10,000 or more service connections.* **[emphasis added]**

CESA 2009 clearly requires all larger public water systems to develop disaster preparedness plans in conjunction local fire departments…to assure ***sufficient water reserve levels and backup facilities.*** However, as we shall see in the next section, coordination between fire and water departments in many cases is less than satisfactory.

2.5 INSURANCE ASPECTS

2.5.1 Insurance Industry Exposure to Fire following Earthquakes

Property insurance contracts in the US typically exclude earthquake loss (i.e., earthquake may be covered under a separate rider or policy), but cover fire without exclusion if earthquake initiated. That is, earthquake shaking losses are only covered for the fraction of California property whose owners opt to do so, but fire following earthquake losses are covered for virtually all California property that has a fire policy (i.e., almost all).

In 2009 the specific amounts were that about 9.5 million residential and 1 million commercial property insurance policies were in force in California, with a total value of the property insured of $ 4.7 trillion ($2.5 trillion residential and $2.15 trillion commercial). The total insurance premium paid per year for these policies was about $10 billion. Of the total exposure, about 12% of residential policies (total value $ 416 billion) and about 9.7% of commercial policies (total value $141 billion) provided earthquake cover[5].

While the insurance industry has only about a 10% exposure to earthquake shaking losses, of total sums insured, its exposure to fire following earthquake losses is virtually 100% and, for any one event, in the many billions of dollars (as estimated and discussed above).

2.5.2 Insurance Industry Assessment of Public Water Supplies

The background for and current methods employed by the U.S. insurance industry to assess the adequacy of municipal water supplies for fire protection are reviewed in some detail in Appendix C of this report, and are summarized here. The review concludes that, while the industry has developed excellent tools for the development and management of economical fire protection and water systems under ordinary conditions, the **guidance provided by the insurance industry for adequacy of public water supplies does not mention or consider earthquake**. In no way considered are the earthquake associated numerous simultaneous ignitions that will each require fire department response, the overwhelming of fire alarm and telephone reporting, or damage to water mains and fire hydrants. Current standards employed by the insurance industry are predicated on timely arrival of firefighters at each fire, who will readily be able to access the needed fire flow. As has been observed in numerous earthquakes, some fires will not be responded to in a timely manner, and water will not be readily available. These two factors – delayed response and inadequate water supply – were long ago identified as key factors leading to urban conflagration.

In order to assess current insurance industry standards vis-à-vis water supply required following a major earthquake, a city block in a more built-up neighborhood of San Francisco, CA, Figure 53, is examined in Appendix C. Using the procedures referenced there, the Needed Fire Flow for a typical building in the subject city block is determined to be 2,500 gpm, which is

[5] California Department of Insurance, Summary of 2009 Residential & Commercial Market Totals, Earthquake Premium and Policy Count Data Call.

a reasonable estimate of the fire flow that would be required to contain and suppress a fire in one of these nearly 100 year old wood framed buildings, given timely fire engine response.

However, considering post-earthquake conditions, with a response delayed for an hour or so, it is quite likely given the type of construction in the subject neighborhood that much of one or more city blocks would be full involved in fire. In such a case, the only option for the fire department would be to try to prevent fire spreading beyond the block or two fully involved. The tactic to do this would be to deploy fire engine master streams in a ‘water curtain’, as shown in Figure 55. Calculations show that the total post-earthquake conflagration required fire flow would be in the range of 7,200 to 12,000 gpm – that is, **the post-earthquake conflagration required fire flow is far in excess of that required by current insurance standards.**

While the San Francisco example selected, of a densely built neighborhood of older wood frame buildings (often termed a ‘conflagration breeder’ in the fire service) is a pessimistic case, it clearly makes the point that large earthquakes will lead to large fires in large cities in California, which require much more water than required under non-earthquake conditions.

It is worth noting that the value of buildings and contents in the one city block examined in this exercise is on the order of $100 million, all of which is fully insured for fire, including fire following earthquake.

2.6 SUMMARY

The above discussion has highlighted the following points:

- California is highly seismic, and its earthquakes are always accompanied by numerous fires.
- While water system design and technical standards are much more advanced than in 1906, water distribution systems continue to have numerous breaks in large earthquakes.
- Building codes, building materials and internal fire protection systems are done much to eliminate the urban conflagration problem under normal circumstances. However, these rely on timely response by fire departments, which is unlikely following a major earthquake.

As a result, the fire following earthquake problem remains with us today. The size of the problem is difficult to accurately assess, but best estimates suggest a major earthquake in urban California will result in tens of billions of dollars in fire loss. In the next section we examine how well fire and water agencies in California are addressing this problem.

3 California's Urban Water Systems vis-à-vis Fire Following Earthquakes

3.1 INTRODUCTION

This section first reviews the current status of California's urban fire and water agencies vis-à-vis fire following earthquake. Our understanding of this status is based on a survey of several dozen fire and water agencies, as well as interviews with selected officials. We then review some special efforts being undertaken by selected agencies, to prepare for the special circumstances of fire following earthquake.

3.2 CURRENT STATUS OF CALIFORNIA'S URBAN FIRE AGENCIES EMERGENCY WATER SUPPLY AND FIRE FOLLOWING EARTHQUAKES

In order to understand the current status of urban fire and water agencies vis-à-vis fire following earthquake, a survey was conducted of several dozen fire and water agencies, as well as interviews with selected officials. The survey forms are presented in appendices, and responses are summarized here.

3.2.1 Survey of Fire Departments

3.2.2.1 Overview of the Survey

A survey form consisting of 27 questions was prepared and distributed electronically. The assistance of CalEMA was enlisted in eliciting responses, and a total of 26 responses representing 19 different larger urban California fire agencies was received. The 19 responding agencies protect over 10 million persons, or about 35% of California's urban population.

The questionnaire is presented in Appendix A, and consisted of five main sections:

1. Introduction – this section had no questions, but simply explained the purpose of the survey, that anonymity was assured, and that the survey would only take about ten minutes of the responder's time (responders were typically Chief officers).

2. Basic Information – identities were requested (these are confidential). In some cases, we followed up with telephone or in person interviews.
3. Fire following earthquake – this asked questions about the department's knowledge and preparedness, and responses are discussed in detail below.
4. Water Supply – similar to fire following earthquake section.
5. Conclusion – responders were given a chance to provide feedback.

The survey was intentionally limited so as to encourage responses – many more questions could have been asked (and in some cases were, during interviews).

3.2.1.2 Responses to Fire following Earthquake Section

The first question in this section was: **Does your department have a quantitative estimate of the number of damaged buildings, fire ignitions, damage to water supply and other impacts a major earthquake is likely to cause?**

Five of the 19 departments responded that they had such quantitative estimates. For these five, responses to the next question indicated that the basis for such estimates (i.e., the scenario event employed) appeared in general to be consistent with current knowledge of potential large earthquakes in California. However, most of the five departments appeared to not have had specialized studies for this purpose – rather, they had simply culled information from such sources as the Association of Bay Area Governments (ABAG) website, or from the ShakeOut Scenario project (discussed above). More specifically, their response as to the number of fire (for the five that responded) were:

Page 3, Q3. And, if so, about how many fires do you estimate will occur?	
1	19 to 26 fire ignitions
2	44
3	1,600 across L.A. County
4	More than 100 if a large enough scenario
5	1) 50 ignitions due to structure collapse, 2) 17 ignitions due to structure collapse
6	cannot find this number or estimates on ABAGs data/website
7	25 to 50

And, with regard to **sources of information**:

- Information is from a …in August 1994 …. The number of fire ignitions may be less than the 19 to 26 based on seismic retrofitting and building code improvements to structures. In addition the number of fires that can be suppressed quickly is greater due to increased fire protection systems, better trained and equipped population and improves to water supply for firefighting.

- I used the 2008 USGS and CGS Study on Fire Following Earthquake methodology…has 192,000 structures with approximately 420 million total square feet. All of ... falls into the MMVII-IX categories for the Hayward M6.9. Using MMVIII as the standard intensity, the ignition rate for fires needing fire dept response is 1 per every 10.5 per million sq feet. 420 million sq feet divided by 10.5 = a total of 44 potential ignitions requiring fire dept response. The relatively contiguous development in ... will allow for most of these to develop into "large" fires exceeding the ability of one engine company to contain. Many of these could be expected to grow into "conflagrations" consuming entire blocks. Depending on weather conditions, significant potential exists for "spotting" into areas of intact housing or the WUI.

- Per the Shakeout Scenario and Professor Skawthorne's [sic] reports.

- Most of our training scenarios revolves around a 7-8 on the Richter scale.

- We regularly experience shaking from the large number of faults, both within and outside City limits. The recent Calexico Earthquake on Easter Sunday produced large movements felt here in the City. Off shore faults as well as our own Rose Canyon faults are a major concern, and depending upon severity will cause failures in our water system that will deprive us of our supply quickly.

- Only train for protocols to follow and damage assessment. No specific zone or magnitude.

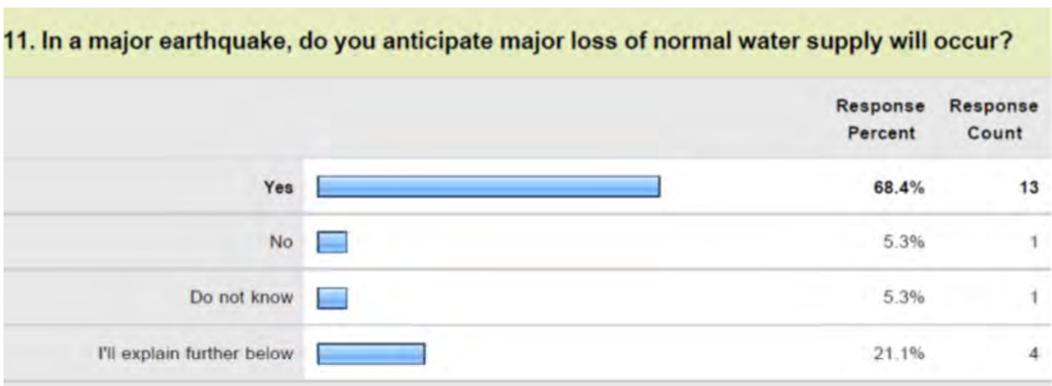
- Response in #3 was based on HAZUS Analysis from October 2009.

- Quantitative estimates are given on ABAGs website for damaged buildings, housing loss, damage to water supply. However, I am unable to find any quantitative information regarding fire ignitions. This would be very useful for planning models.

The key finding of this series of questions was that most large urban fire departments could be better informed as to the specifics of the earthquake risk they are tasked to respond to.

3.2.1.3 Responses to Water Supply Section

The next series of questions dealt with water supply following a major earthquake, with most departments simply anticipating loss of normal water supply:



Given loss of normal water supply, ***where would firefighters obtain water following an earthquake?*** Specific responses included:

- Under a major earthquake, the department believes there will be a loss of water pressure. If normal hydrants lack pressure, static sources (tanks, reservoirs and pools) will be used.

- Connection to adjacent water zones that have pressure. Use of Disaster/Emergency Water Delivery System.

- The city water grid is gravity fed with back-up diesel powered pumping to refill tanks in the upper elevations to maintain pressure and capacity. Additionally there are areas in the grid that can be cross connected to facilitate raising the pressure and volume. These areas can also be shut down to lessen the water loss due to water main damage. We have supplied each engine company earthquake supplies an emergency 200gpm portable pump as to utilize the many pools in the city as potential water sources.

- City has a combination water system, with a Gravity fed supply.
- From Swimming pools public and private, Fire Engine water tanks, pacific ocean, City above ground tanks.
- Will use a combination of water tenders and drafting from available water sources.
- The Department has a whole range of secondary sources of water, and they are included in earthquake plans and in fire station Emergency Information Files. Water tanks, draft from hydrants, dike and draft from ruptured water main runoff, dike and draft in flood channels, draft from lakes, reservoirs, aqueducts, streams, etc. Water-dropping helicopters into portable water tanks. Water-dropping helicopters and retardant-dropping fixed wing aircraft also.
- gravity feed from city tanks, suction from lakes, ponds, pools
- Water tenders, drafting static reservoirs, helicopter drops, large diameter piping.
- We will try to tap into alternate water supply with … University and use stored water from tanks in the hills. We have a portable tank, hard suction on every engine and several water tenders available in the city.
- Water Tenders, natural water sources
- We have water tenders, we will use the water already in our fire engines, and we have a cooperative agreement with the U.S. Navy to supply seawater from the bay through large manifolds at several locations for firefighting purposes. There are also several large cisterns that hold large amounts of water. If still accessible, they will also be used.
- Service interruptions may be limited to certain parts of our City. If interruptions occur, we have access to four Water Tenders (Tankers) in our City and can request additional Tenders via the Mutual Aid System and private contract. These will be

filled from water system sources that are not compromised. We have no Fire Department "drafting" capability to obtain water with the exception of that provided by our two medium lift fire-rescue helicopters. These are capable of quickly drafting 375 gallons from bodies of water (ocean, bay, rivers, lakes, swimming pools) and deliver directly on fires. We do have access to commercial tugboats that can pump into a manifold system purchased by the Port Authority to deliver large volumes of water from San Diego Bay.

- … has 2,285 miles of total water pipeline. Using the…scenario…could expect to see 627-1,045 water pipeline breaks. Drafting, emergency wells, tenders as sources.
- We have a 3000-gallon water tender and would shuttle water to the incident. Although this would be very limited and would not work for multi-fire scenario.
- Elevated stored water systems.

So, a number of departments have identified alternative sources of water. But, in regard to ***how they would move water from those alternative water sources to the fire scene***, the results are more mixed:

- Relay pumping is limited by quantity of large diameter hose (800 per Type I Engine).
- Current planning allows for moving of large volumes of water 6,000 to 12,000 gpm over distance of 2 to 3 miles. Max. distance of Ultra Hose 12" deployment 6 miles with flows less than 6,000 gpm. In addition Large Diameter Hose 5" is available for deployment for an additional 1.5 miles with flows less than 1,000 gpm. This deployment is in addition to hose carried on fire engines. Fire engines may be required to relay pump the 5" hose for max flow.
- In instances of needed relay pumping each engine company carries 1000 ft of 5 inch hose with a 4-way hydrant valve to assist in the relay operation. There is also an additional 2500 ft of 5 inch hose in supply in the department
- Unless catastrophic failure occurs to the pipe system, the gravity system, if all cisterns are operable, should leave a sufficient supply in the hydrant system to where relay pumping should not have to occur. If it does, each Eng. carries 1000 ft of 3'

hose that can be used for supply. We have 6 first line Engines with 4 in reserve to accommodate relay pumping. We also have a 2000-gallon water tender.

- Up to 2.0 miles. Our apparatus is well equipped to do so but will need various pumpers to do so. This use of multiple pumpers will reduce our ability to cover the City. Fires will have to be given priorities.
- Unknown how far we might have to relay water due to the large number of variables. Our Type 1 and 2 engines carry LDH (5") that would be used in a relay pumping evolution.
- Varies with part of the County. Up to several miles if needed.
- we are only prepared for shuttling water by fire apparatus
- Unknown, but we are relatively well equipped.
- We are not well equipped for relay operations.
- Potentially long distances.
- Unknown, but it could be extensive. Not only relaying, but the road condition will affect this capability. We would like to obtain more portable storage capacity and the ability to relay water further than our firefighting hose will allow, but finances prevent this initiative currently.
- Length of relays depends on the number of resources (pumpers, hose and personnel) available to support the operation. We are capable of relays of more than 1 mile.
- Up to three miles. We are marginally equipped, with some PWSS.
- Relay in … is designed for up to 3 miles with available 5 inch hose, portable hydrants and other appliances designed therefore.
- 5-10 miles, Only 2 tenders in City
- With our water tender.
- one mile.

- Not prepared sufficiently to cover the distance required. Lack of total hose, lack of water tender and lack of adequate pumpers.

Some of the responses reflect the reality that, even using Large Diameter Hose (LDH, typically 5 inch in diameter), water can't be pumped more than about a thousand feet (i.e., a few city blocks) without a 'relay' engine boosting pressure. Moving water a mile would tie up a significant number of fire engines – in many smaller cities, almost the entire department. A number of the responses appear to not have understood the limitations of the relay method.

To explore this issue further, the next question asked For your typical urban fire engine (pumper), what is the largest diameter hose, and how many lengths (or feet) of that hose, is normally carried?, with only a relatively few responses:

- 4" diameter hose at 800 feet.
- 4" hose....
- 800 ft 2.5 inch 400 ft. 1.5 inch.
- All 11 fire engines in the department (7 fist line, 4 reserve) carry 800 to 1000 ft. of 5" LDH and can pump 5" hose in relay.
- We carry 700 ft of 5 inch hose on all 9 Type I fire engines.

Furthermore, a small but crucial detail in accessing many alternative water supplies, is the use of "hard suction" hose, Figure 32 Hard suction hose is special metal reinforced hose that will not collapse when a fire engine attempts to draft water from a river or other source – without the reinforcement, ordinary fire house simply collapses due to the greater atmospheric pressure outside the hose. The need for hard suction hose is basic and universally understood among firefighters, and several decades ago all fire engines, even in the heart of cities, routinely carried two ten foot lengths of hard suction. However, in recent years and for a variety of reasons, many fire departments have chosen to no longer carry hard suction hoses on the engine – in fact, about two-thirds of departments surveyed:

15. Do you engines carry hard suction hose?

	Response Percent	Response Count
Yes	35.7%	5
No	64.3%	9

In many cases, the rationale is that it is stored in the fire station, and can be quickly loaded onto engines when needed (overlooking the fact that, in non-earthquake situations, this is difficult to foresee):

16. If above answer was "No", is hard suction 'ready to go' in the stations?

	Response Percent	Response Count
Yes	55.6%	5
No	44.4%	4

Additional detail was provided:

- 10 feet hard hose.
- Not all pumpers carry hard suction.
- One hard suction for the whole Department, stored at one of our five fire stations for annual pump testing.
- One of our Engines has hard suction and the other engine's hard suction is available in the station.
- Only at the headquarters station.
- Should water supply be required from an open water source the use of the submersible pumps is preferred over the restrictions presented by drafting.
- We carry 3 inch hard suction on all engines.

- We have it in some stations, but we want to reacquire this capability and spread it throughout our area of responsibility.

Interviews with Chiefs indicated that even the above was an optimistic picture – for example, one major urban department admitted they no longer had any hard suction in the department!

Most departments in fact have little practice in moving water even relatively short distances, and are not well-equipped to do so.

18. When was the last time your department practiced relaying water more than one mile?

	Response Percent	Response Count
Within last 6 months	0.0%	0
Within last year	25.0%	5
Within last five years	0.0%	0
Do not know	**75.0%**	**15**

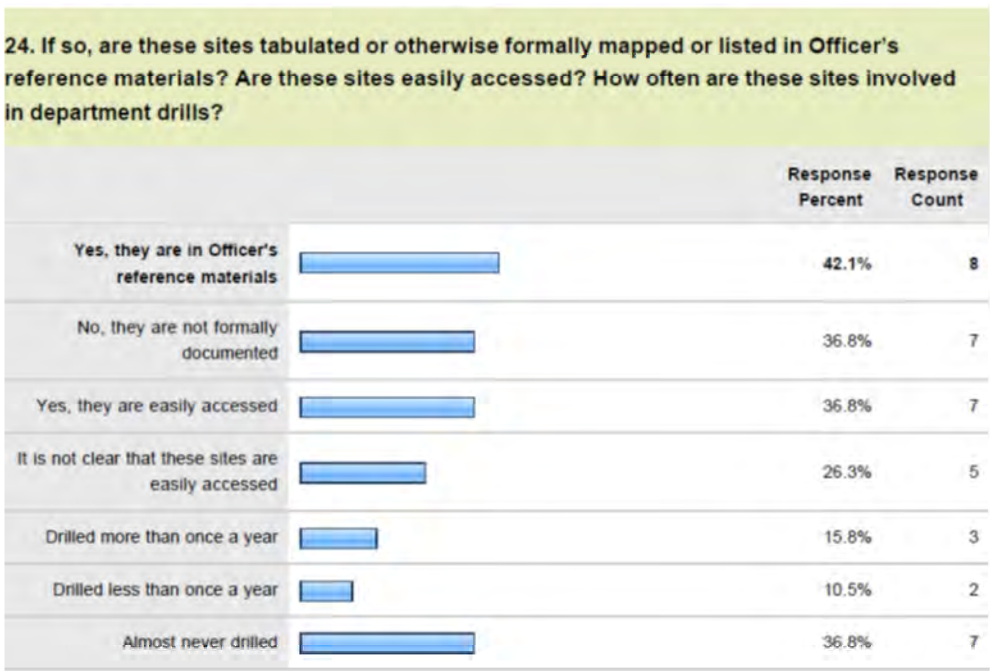
19. What special equipment does your department have for pumping or relaying water some distance?

	Response Percent	Response Count
Section pipe (stored or emergency access, such as to quick connect irrigation pipe)	5.0%	1
Large Diameter Hose, in significant quantities beyond that carried on pumpers	**45.0%**	**9**
Large or special pumps	10.0%	2
Special pump stations and high pressure system	10.0%	2
Fire boat	25.0%	5
Other (explain further below)	25.0%	5
None	40.0%	8

Clearly, not much attention is being paid to this issue – in response to the question ***Does your department have an officer specifically identified as responsible for Water Supply?*** Only one department responded "Yes".

Regarding ***Does your department have regular disaster planning meetings with the Water Department?*** 40% responded "Yes", but 'regular' was defined as once a year (or less) – only three departments had more than one meeting a year.

Regarding identification of where the water is to come from (i.e., ***specific locations of alternative water sources***) almost all departments responded that they had done this, but



24. If so, are these sites tabulated or otherwise formally mapped or listed in Officer's reference materials? Are these sites easily accessed? How often are these sites involved in department drills?

	Response Percent	Response Count
Yes, they are in Officer's reference materials	42.1%	8
No, they are not formally documented	36.8%	7
Yes, they are easily accessed	36.8%	7
It is not clear that these sites are easily accessed	26.3%	5
Drilled more than once a year	15.8%	3
Drilled less than once a year	10.5%	2
Almost never drilled	36.8%	7

about 50% indicated they were well identified, but in some cases not easily accessed, and in most cases rarely drilled. Specific elaboration on responses included:

- We have canals, creeks, reservoirs and the […large body of water] located throughout our fire district. They are marked on our response maps. There are also swimming pools that could be utilized as a water resource, but there identification and availability would be determined on a case by case basis.

- 3,000 gallon portable water tank. Water sources are listed on GIS maps accessed by Mobile Data Computers on all apparatus and in map books.

- A complete Emergency water supply system has been developed in…this began following the major disaster in 1906 with upgrades to present time. A complete Portable Water System has been developed since 1983, it has been deployed and was successful in the 1989 quake and fire in…plus in many other major emergencies since that time. It has not been completely deployed as yet in…due to budget restrictions, but the equipment is on hand and only needs to be assembled and completely equipped. A program to do so has been developed by the current Deputy Chief of Support Services.
- A set of water supply points has been developed and are being tested for actual use once that is completed a water source list will be developed. Because of the specialized water supply system currently available in the Fire Dept. a transition is in progress to expand the normal duties of a water supply officer. Currently a retired/part time member of the department fulfills the role with assistance from the Fire Prevention Division and Operations Chief for normal water supply issues.
- GIS mapping includes alternative water sources.
- Local sites first (swimming pools, settling ponds); emergency well sites known by water district.
- Many of these sites are on private property, and property owners, unless in an actual disaster, do not allow the practice. The water is too expensive to practice with.
- Pools throughout the city; gravity fed tanks on the hillside.
- Some extra large diameter hose.
- We have reached agreements with homeowners in the community to use water from there swimming pools during an emergency. Markings on the curb in front of the home indicate this has been approved for use.

The key finding of this series of questions were:

- Liaison with water departments is in general very infrequent.
- The normal water supplies are regarded by fire departments as seismically unreliable.

- Chief officers have considered this, and identified alternative water sources, but
  - These sources are often not particularly well documented, nor kept up to date nor regularly drilled
  - The very difficult task of moving water from these sources to the fire scene is in many cases not well thought out, not adequately equipped and not regularly drilled

3.2.1.4 Concluding Responses

The survey concluded with two questions, the first of which was: **How important is the fire following earthquake issue for your jurisdiction? What key things should your department be doing to improve its ability to respond?** The following responses were received:

- Significant issue - developing water shuttle resource plan and increasing the number of water tenders.
- Very important. The department currently has the local/normal fire events covered and has available a water system to assist with a disaster and large emergency level event. There is need to fill into the middle for other size events including wildland fire type events. Currently work is progress to improve firefighting and water supply issues. Flooding fighting is also a capability that has improved with new water system.
- It is a primary concern for triaging dispatch protocol within the EOC and a decision factor as to which and how many resources will be assigned to any specific incident.
- A priority with the City Manager and the Department. Increase Public education and preparedness at the home and businesses throughout the city. Plan for mass shelter (in progress).
- It is every important to plan for firefighting operations following an earthquake. We should be identifying potential water sources for use when water mains are not usable after an earthquake. We also need to preplan and provide relay pumping training and drills.

- It's an important issue, but not as high a priority as incidents involving life-safety intervention (e.g., rescues, emergency medical treatment of the seriously injured). Some key things we can do to improve our ability to respond are:
    - Clearly identify/define alternative water supply opportunities (access, limitations on use, etc.).
    - Identify availability of portable large-volume water supply systems in our operational area and/or Bay Area region (both public and private entities).
    - Identify those transportation routes that are likely to be restricted and/or inaccessible due to bridge/overpass collapse, general structural failure, or through use as a major evacuation route.
    - Perform multi-company drills involving drafting and relay-pumping operations.
- Huge, a top priority. Revision of the Dept. Earthquake Plan is occurring; updating fire station Emergency Info Files, adopting recommendations from the Multi-Agency Earthquake Task Force that Fire Chief…established.
- The community is filled with older homes and commercial structures. With the very limited resources available to the fire department things will be very difficult.
- Earthquake preparedness is an important issue, but the attention paid to it could be improved. Our resources for moving water from a distance are extremely limited.
- It is very important and we need to address relay pumping and identifying a Water Supply Officer.
- … risk is minimal, we anticipate being a resource for others during this type of emergency.
- It is important, but rescue and recovery, as well as provision of emergency medical services take priority.
- Fire is one of the major hazards anticipated following an earthquake. Efforts should be made to obtain additional mobile water sources and drafting capability, but are hampered by fiscal challenges. Drilling on longer relay operations should be

conducted more frequently, but are resource intensive and difficult to perform without impacting emergency response coverage.

- This issue is of great importance. We are strengthen our…adding cisterns, acquiring a third fireboat, attempting to construct a reinforced concrete pier for mooring and maintenance of the three fireboats, and have proposed funding for a six-fold increase in our […special water system], with additional training for select members of the NERT program to be able to assist uniformed members with the rapid deployment of this system. We have proposed the conversion of an existing, but obsolete, water department pump station at Lake…into an…pump station, which, with a short extension of…main, would allow the 2.5 billion gallons of water in the lake to be added to the system. We have a commitment from the Water Department to link a domestic water reservoir, which is near the principal… Reservoir and at slightly higher elevation and contains approximately 14 million gallons, into…Reservoir, which immediately will more than double the available water supply to the ….

- Could be more devastating than the shaking - up to 2% loss of built environment per Scawthorn study. Budget pressures have drawn down the line force and the potential off-duty staff that could respond. Attention to building code and permits will help minimize some ignition sources.

- The earthquake issue is very important in our city; we have an active fault that runs through our community. We need to identify our emergency water supply.

- No emphasis has been put on this issue. Greatest good would be to have available mobile water tenders to shuttle water.

Finally, we asked: **Have we overlooked key issues? Was this survey about on target, or are we off target? How can it be improved?** We received the following responses:

- There are some questions that could be worded differently. For example: Does your department have regular disaster planning meetings with the Water Department? We have a monthly emergency managers meeting for Alameda County, the water district is a member of the association, but we do not use this meeting for planning but for networking and sharing ideas.

- Firefighting vs. drinking water - The water district may look to preserve drinking water over providing firefighting water during a disaster EQ type event. Water quality vs. fire flow requirements that may reduce water available for firefighting. A question to ask an urban fire department. What is your 2nd and 3rd option for fighting a working structure assuming water is your 1st option? It does matter what you add to water or how you spray it you still need water to fight urban type fires.

- I believe preparedness at the home level should be a priority. Trained and equipped citizens can make our job in the event of disaster or conflagration much easier.

- Not that I can think of. This survey did question the preparedness of our Department's ability to obtain alternate water sources after a major earthquake AND deliver that water for use as a firefighting tool.

- I think the key issues were addressed in the survey questions.

- Excellent work, let's keep going....

- The issues are relevant. Perhaps questions concerning planning efforts with agencies other than water dept. are useful. County EMA is usually one of the key agencies.

- The survey is on target. I think you could ask about Auto Aid/Mutual aid agreements and collaboration with Public/Private organizations.

- We are obviously not truly prepared, but competing priorities and funding will drive this issue.

- On target and addressing vulnerability in response capability.

- The size of the fire protection agencies needs to be addressed, this includes, the number of fire stations, number of pumpers, amount of personnel available on daily shift per company. Fire following earthquake, pumpers are the only units that are vital, the ability to pump water at pressure is vital to control fires. Also vital is, do pumpers in each fire department carry hard suction? Please note: Not all fire pumpers in California carry hard suction; those that do not are not capable of using static water supplies that require ability to draft from suction. Also, do fire departments conduct regular suction or drafting drills? This is vital to retain operational capability to draft when needed. Survey: The California Seismic Commission should conduct a survey of all Fire Departments within the State of California to determine which departments require their pumpers to carry hard suction hose and how often do drafting drills be conducted. Why have them conduct this survey? It would be more specific and symbolic as to the vital need to have all fire pumpers equipped with hard suction for emergency service. When an earthquake occurs, it is too late to go to a central location to locate suction hose, (if it indeed exists at all), and the need is immediate when pumpers are dispatched for mutual aid or service within their own communities. Any Fire Department not having hard suction on their pumpers would be hard pressed to explain this deficiency following a conflagration where static water supplies are available but they could not utilize them due to lack of basic equipment.

- The real key to determining need for fire suppression is the quantification of threat. I conducted a gross calculation using the approach developed by one researcher. There may be better methods that could help quantify number of ignitions and number of fires needing fire dept. response - that would help to give everyone (internal and external) an idea of how large a threat this is. Also, given the EMS and USAR missions of most departments, fire suppression may lag as firefighters commit to these incidents while fires a relatively small.
- Our city is 17 square miles; no one could afford adequate hose storage to relay pump water. A shuttle system from one source to multiple locations would be most cost effective means of covering a big problem (lots of leaks) in a big area.

The key findings of this series of questions were

- Earthquake is seen as a very important issue for their communities, and various departments are pursuing a variety of efforts, aimed mostly at improving water supply capability. However, these efforts are piecemeal, not coordinated and often are ‘reinventing the wheel.’
- In addition to firefighting water supply, a number of officers also consider post-earthquake potable water supply to be a concern.

3.2.1.5 Key Findings from the Fire Department Survey

The key finding of the survey was that larger urban California fire departments:

- See earthquake as a very important issue for their communities.
- Could be better informed as to the specifics of the earthquake risk they are tasked to respond to.
- Have infrequent if any communication with their water departments.
- Consider their normal water supplies as seismically unreliable.
- Given this unreliability, are pursuing a variety of efforts, aimed mostly at improving water supply capability. However, these efforts are piecemeal, not coordinated and often are ‘reinventing the wheel’.
- Have identified alternative water sources, but
  - These sources are often not particularly well documented, nor kept up to date nor regularly drilled.
  - The very difficult task of moving water from these sources to the fire scene is in many cases not well thought out, not adequately equipped and not regularly drilled.
- In addition to firefighting water supply, a number of officers also consider post-earthquake potable water supply to be a concern.

3.2.2 Survey of Water Departments

3.2.2.1 Overview of the Survey

Similar to the fire department survey, larger urban water departments in California were surveyed on the issues of fire following earthquake, from the perspective of water supply reliability. The form consisting of 34 questions was prepared and distributed electronically. A total of 18 responses representing 18 larger urban California water departments was received. The 19 responding departments protect over 9.94 million persons, or about 32% of California’s urban population.

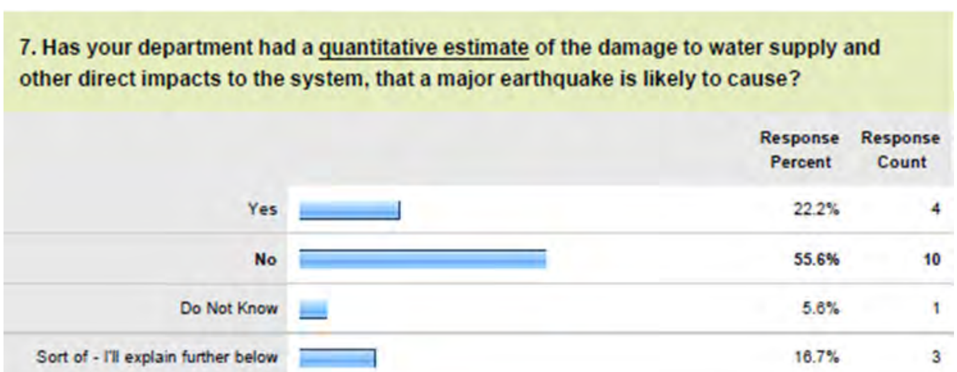
The questionnaire is presented in Appendix B, and consisted of four substantive sections:

1. Introduction – this section had no questions, but simply explained the purpose of the survey, that anonymity was assured, and that the survey would only take about ten minutes of the responder's time.
2. Basic Information – identities were requested (these are confidential). In some cases, we followed up with telephone or in person interviews.
3. Seismic Analysis and Upgrades – this asked questions regarding if the water department had done any analyses to identify seismic vulnerabilities, and/or in what ways seismic upgrades or retrofitting had been performed.
4. Earthquake Impacts – what estimates were of the likely impacts an earthquake would have on the current system.
5. Water-Fire Agency Interaction – similar to questions for the fire departments, 'are you talking'?
6. Conclusion – responders were given a chance to provide feedback.

The survey was intentionally limited so as to encourage responses – many more questions could have been asked (and in some cases were, during interviews).

3.2.2.2 Responses to Seismic Analysis Section

The first question in this section was: **Has your department had a quantitative estimate of the damage to water supply and other direct impacts to the system, that a major earthquake is likely to cause?** This had a mixed response:


7. Has your department had a quantitative estimate of the damage to water supply and other direct impacts to the system, that a major earthquake is likely to cause?

	Response Percent	Response Count
Yes	22.2%	4
No	55.6%	10
Do Not Know	5.6%	1
Sort of - I'll explain further below	16.7%	3

In effect, 22% could provide a definite Yes to this question. Six (33%) of respondents also indicated that the analysis had been performed within the last ten years. The scenarios employed were consistent with current knowledge of California's seismicity. The analyses that had been performed had been relatively comprehensive:

10. What portions of the system or facilities were analyzed?

	Response Percent	Response Count
Headquarters and/or offices, warehouses and other buildings?	66.7%	4
Major Transmission Lines?	**100.0%**	**6**
Terminal Reservoirs and/or Major Tanks?	83.3%	5
Water Treatment Plant(s)?	66.7%	4
Pump Stations?	**100.0%**	**6**
Local pressure or distribution reservoirs or tanks?	83.3%	5
Distribution System piping?	**100.0%**	**6**
	answered question	**6**
	skipped question	**12**

In only a few cases had the results been shared with the fire department:

11. Were the results of the seismic analysis shared with the Fire Department and/or other emergency responders?

	Response Percent	Response Count
Yes	**50.0%**	**3**
No	16.7%	1
Do not know	16.7%	1
I'll explain below	16.7%	1

For the few water departments that had done studies, specific responses included:

- At various times we have done seismic studies of our various reservoirs and other structures as well as major transmission and distribution lines especially all those crossing the Hayward Fault.
- City distributes 11.2 MGD through 206 mile pipeline network. Seven pressure zones maintained by 5 pump stations and PRVs. Design seismic event is magnitude 6.7 earthquake on Hayward fault (runs north-south through the city), with likelihood of 11.3% occurrence by 2032. Analysis showed expected 75 to 150 pipe breaks from

design event. Strategy is to reinforce a 15.6 mile "backbone" transmission lines at 2006 cost of $17.2 million. Additional actions are to tie down hillside tanks, acquire flex-hose for by-passes, and stockpiling repair materials.

- Some information on the ShakeOut scenario was shared with the FD, but not in great detail. System analyses using…in collaboration with…University. Component analyses analyzed over past 40 years using different methods.

- The District's source water is on the opposite side of San Andreas Fault vault from our customers. Furthermore, about a mile and quarter of the three mile transmission main feeding the District is located directly above the San Andreas Fault. The vulnerability of other piping, water tanks, pump stations and offices have all been studied individually as funding became available. The findings were discussed with the Fire District, but their focus is entirely firefighting which would use available water within a few hours. Our concern lies with being able to serve drinking water during after the major earthquake when it has taken as long as two weeks for aid to arrive in an area similar to ….

It is interesting to note the last response – that "their focus is entirely firefighting which would use available water within a few hours".

Encouragingly, almost all departments had had seismic upgrades or retrofits:

13. Has your system (or portions of it) had seismic upgrades or retrofits?

	Response Percent	Response Count
Yes	83.3%	15
No	5.6%	1
Do Not Know	0.0%	0
Kind of - I'll explain below	11.1%	2
answered question		18
skipped question		0

And the focus had been on key elements such as reservoirs and transmission lines, with less emphasis on distribution piping:

14. If so, what portions of the system or facilities were seismically upgraded?	Response Percent	Response Count
Headquarters and/or offices, warehouses and other buildings?	17.6%	3
Major Transmission Lines?	29.4%	5
Terminal Reservoirs and/or Major Tanks?	**76.5%**	**13**
Water Treatment Plant(s)?	29.4%	5
Pump Stations?	64.7%	11
Local pressure or distribution reservoirs or tanks?	58.8%	10
Distribution System piping?	35.3%	6

In regard to ***what drove the seismic programs***, 70+% responded that concern about loss of firefighting water was part of their motivation. Yet, this concern was quite vague, since only a few departments indicated they'd involved the fire department in their decision-making, or had quantified their concern in any manner.

16. If the above answer was Yes, then:	Response Percent	Response Count
Was a specific analysis done of fires following earthquake, to inform how and what to upgrade?	23.1%	3
Was the fire department involved or consulted?	23.1%	3
Not Applicable - the answer was No (FFE was not considered)	**61.5%**	**8**

About 60% of the seismic upgrades are still underway. Funding and measures included:

- Budget of $3.36 M to bolt tanks to foundation, install flex connections and provide structural reinforcement. We have 20 steel tanks which got upgrades as needed.
- The upgrades to our reservoirs have been going on for some time and we just completed doing one last month. One reservoir was recently doubled in size and of course we used the most recent seismic design for the replacement. We also added a second major transmission line to feed between the two zones which are crossed by the fault. We have also purchased special portable piping on a trailer that can be used to span the fault between fire hydrants. We have installed sudden lost valves on most of our reservoirs and presently have a contract completing that project. Being on the Hayward Fault we have spent quite a bit improving the seismic reliability of our system. The cost of our seismic upgrades has been around $30 million and of course we also are part of the SFPUC Hetch Hetchy system so through our rates we are paying more than 10% of that multi-billion improvement program.
- $1.5 million.
- $7 million.
- About $10 million.
- Overall cost for seismic specific upgrade projects was $5.5M. Other seismic upgrades were part of other projects to rehab and upgrade overall facility. Cost of seismic component unknown. Seismic specific upgrade projects included retrofitting major transmission lines crossing fault or liquefaction zones with seismic valves and/or bypass manifolds. Seismic upgrades to other projects included constructing/retrofitting building to current design codes.
- Approx. $300,000.
- Would have to pull that information from our Engineering Department.
- There were no significant considerations in the seismic upgrading for FFE, but there was to a limited extent. Many 100's of millions [of dollars] since the 1971 earthquake (in today's value).

- We replaced 2 of 14 water tanks for about $6M for 6 MG. A 3rd tank, damaged during the Loma Prieta Earthquake is under construction. Staff considered fire needs and maximized tank sizes to the extent possible. Staff has started to construct jumpers in the area above the San Andreas Fault. No work has been done yet to retrofit offices or pump stations.

- We retrofitted existing facilities such as restraining piping and equipment, provided freeboard for water tanks to accommodate sloshing waves, and added flexible coupling to existing piping. As facilities are rehabilitated, the components are brought to current seismic code requirements.

- 4.6 Billion WSIP included redundancy and continuity of operation as well as seismic.

- $1,000,000+. Seismic devices are included in all District design standards.

The key finding of this series of questions were:

- Most larger urban water departments could be better informed as to the specifics of the earthquake risk they are exposed to (i.e., two thirds had had no analysis in the last ten years).

- Even where water departments have knowledge of the vulnerabilities of their systems, this is not often (only 22%) communicated to fire departments.

- Many water departments are currently addressing their seismic vulnerabilities with significant engineering programs.

Overall, provision of firefighting water does not appear to be a significant criterion for water departments.

3.2.2.3 Responses to Earthquake Impacts Section

The first question in this section indicated strong agreement between fire and water departments – both expect major loss of water supply in a major earthquake, with the water department informing the fire department of the details of this about half the time.

19. In a major earthquake, do you anticipate major loss of normal water supply will occur, in a significant portion of your service area? This might include loss of distribution piping pressure in one or more neighborhoods, even if transmission integrity is preserved.

	Response Percent	Response Count
Yes	66.7%	12
No	11.1%	2
Do not know	16.7%	3
I'll explain further below	5.6%	1

20. If the answer is Yes, has the Fire Department been informed of where and how water supply may be lost?

	Response Percent	Response Count
Yes	46.7%	7
No	33.3%	5
Do Not Know	6.7%	1
Sort of - I'll explain below	13.3%	2

However, information communicated to the fire departments appear limited – for example, information on when water would be restored is sparse, but available in some cases:

21. If the answer was Yes, do you have estimates of when water supply for firefighting would be available or restored?

	Response Percent	Response Count
Yes	14.3%	2
No	42.9%	6
Do Not Know	7.1%	1
Sort of - I'll explain below	35.7%	5

22. If so, what is the estimate of approximately when water supply for firefighting would be restored?

	Response Percent	Response Count
less than an hour	11.1%	1
less than 6 hours	11.1%	1
less than 12 hours	22.2%	2
less than 24 hours	22.2%	2
more than 24 hours	**33.3%**	**3**

Encouragingly, some water departments have alternatives given loss of normal water supply:

23. If normal hydrants lack pressure, do you have any specific alternatives for furnishing water for firefighting?

	Response Percent	Response Count
Yes	**38.9%**	**7**
No	33.3%	6
Do Not Know	11.1%	2
Sort of - I'll explain further below	16.7%	3

Examples of such alternatives included:

- The hydrant locations near storage reservoirs have been supplied to the Fire Department.
- A lot depends on whether the major Hetch Hetchy system survives. If so then we think we can address any of the breaks in transmission lines crossing the fault with our emergency piping and our sudden loss valves. We also have emergency wells that can provide about half our normal needs and of course in an emergency non-essential use would be curtailed to provide water for fires. We also have interties with…and… although they may also have damage. We also have a major intertie through…that interconnects…and…to move 30MGD if one or the other had water to spare..
- Alternative emergency water connections with the cities of…and Compton as well as with the…Water District.

- City has two emergency wells and untreated water reservoirs that Fire can draw from. DPW Director and Fire Chief are working out how Fire can transport this water if firefighting area is far from storage area. This is a difficult problem without simple resolution because the City does not have large tankers.
- Existing City standby water wells and reservoirs.
- Water buffalos, Non-potable water connections.
- 1. use of swimming pools; 2. use of open reservoirs with helicopters; 3. hydrant to hydrant emergency pumping (to lift water from lower to higher pressure zones).
- Interties with other systems could be activated. Storage exists in part of the system. Emergency wells are planned.
- The severity of the quake, and consequently the damage to District piping and facilities, will dictate the response period. A restoration plan would include repairing the main pump station, transmission main and piping serving the City's two emergency shelters.
- Portable booster pumps.
- Open Reservoirs, Backup Booster Stations, Emergency interties.

Regarding: **How well and in what manner is your agency equipped to relay water, if the water system in the vicinity of a fire lacks pressure**?

- Limited amount of hoses.
- Staff can run jumpers to high pressure hydrants.
- See above. Also the city has purchased 7260 ft of 6" flexible hose that is stored on a trailer to be rapidly available to connect between fire hydrants located on either side of the Hayward fault in an emergency.
- Not prepared at all for this alternative.
- Not well.

- 1. Emergency response protocol is in place 2. Water system tied into SCADA system at key facilities for pressure and flow monitoring.
- Public Utilities is somewhat prepared to install 2" highline to relay water, however capacity and pressures would be significantly compromised under fire flow conditions.
- Multiple interconnections to wheel water.
- That would depend on the extent of the damage to the system and our Groundwater Treatment Plant.
- We are not aware of any details to relay water that have been worked out in advance. However, we have a highly redundant system where we commonly switch valves to flow water in a manner not normally used in order to relay water to critical areas.
- We have limited capacity.
- While the District has improved its connections to other agencies, we expect that our neighbor's piping that feeds those connections would be damaged by a large earthquake. The District owns and uses a potable flexible hose trailer and a truck mounted hose holder for deployment when emergency above ground piping is necessary. Currently, the flexible piping is limited to about 2,600’ of 4” and 6” diameter piping. Larger sizes and significantly more pipe would be needed to be adequately considered prepared.
- Tender trucks and mobile booster pumps will be utilized.
- … has the potential to supplement areas without domestic supply.
- Each pressure zone has backup systems, booster pumps, generators and more than one storage reservoir.

This in many cases sounds good, but may be unduly optimistic, especially when it appears that only a fraction (~1/3) are reasonably equipped to actually move water.

Examples of the specific equipment include:

- We have some engine driven pumps for domestic supply but they would not provide fire flows in excess of 300-400 gpm.
- Hose stored in warehouse.

26. When was the last time your department practiced relaying water more than one mile?

	Response Percent	Response Count
Within last 6 months	12.5%	2
Within last year	12.5%	2
Within last five years	0.0%	0
Do not know	**75.0%**	**12**

27. What special equipment does your department have for pumping or relaying water some distance?

	Response Percent	Response Count
Section pipe (stored or emergency access, such as to quick connect irrigation pipe)	31.3%	5
Large Diameter Hose (please enter diameter and total length your agency has, in space in next question)	31.3%	5
Large or special pumps	**43.8%**	**7**
Special pump stations and high pressure system	31.3%	5
Other (explain further below)	12.5%	2
None	25.0%	4

- In a major earthquake, the supply of water to the City from the SFPUC Hetch Hetchy system might be impacted, at least for a few days. There might be local damage sustained by the local storage and distribution system. Depending on severity of the earthquake, the estimate of when firefighting water impact can range up to a few days of below normal flow and pressure in some parts of the city. As noted also elsewhere, Hayward has a very robust, reliable and redundant emergency supply plan, including emergency wells and regional and local interties with neighboring agencies. Emergency water can be supplied as soon as any local distribution system damage has been isolated.

- The Fire Department had been involved with the results of the study from 2001. Due to staff attrition and changes, it is uncertain how much they know regarding the loss of water supply. Our goal is to restore limited fire protection to within 24 hours. Limited fire protection is considered that 75% of the area served will be within 2,000 feet of a serviceable hydrant with a minimum of 1,000 gpm at 20 psi residual pressure. In coordination with the fire department, emergency flows could be established to a location within 2-8 hours. Normal fire service would be expected to be restored within 30 days.

- 6" and 4" hoses, multiple portable trailer mounted pumps. Cooperation with FD on use of pumper trucks if needed for hydrant to hydrant pumping. The Fire Department has some limited information on potential loss of water from experience and the ShakeOut Scenario, but there have not been any significant sit-down meetings to discuss this topic.

- The District owns and uses a potable flexible hose trailer and a truck mounted hose holder for deployment when emergency above ground piping is necessary. Currently, the flexible piping is limited to about 2,600 ft. of 4” and 6” diameter piping. Larger sizes and significantly more pipe would be needed to be adequately considered prepared.

- 1200 feet of 2 inch fire hose; 400 feet of 4 inch fire hose.

The key finding of this series of questions were:

- Both water and fire departments expect major loss of water supply in a major earthquake, with the water department informing the fire department of the details of this about half the time.

- Information on when water would be restored is sparse.

- Some water departments have alternatives given loss of normal water supply, but only a fraction (~1/3) are reasonably equipped to actually move water.

3.2.2.4 Water-Fire Agency Interaction

The next series of questions had to do with water-fire agency liaison, with about half the water departments indicating they had an appointed person for liaising with the fire department, with regular meetings as shown below:

29. Does your department have a person specifically identified as responsible for Emergency Water Supply and/or liaising with the fire department?

	Response Percent	Response Count
Yes	47.1%	8
No	29.4%	5
Kind of - I'll explain further below	23.5%	4

31. If so, how often are these meetings?

	Response Percent	Response Count
Monthly	7.7%	1
Quarterly	30.8%	4
More than once a year	15.4%	2
Annually	15.4%	2
Every few years	30.8%	4

If quarterly (seasonal) would be an appropriate schedule (and, if there's not much to discuss, it can be a brief meeting), about 60% of such liaisons may be at a less than satisfactory frequency. Specific responses elaborating on the above question appears to reinforce this:

- The city has an Emergency Operations Center (EOC) and conducts drills quarterly. The Fire Department is in charge of disaster preparedness training.

- Being a city, our fire department is an integral part of our city planning and operations. They are well aware of our capabilities although no one can be exactly aware of what will occur in a major earthquake on the Hayward fault. We have not had the resources to do full scale planning exercises but they are working on one soon and we previously did a drill on a major earthquake on the Hayward Fault. We do use the Incident Management structure and although Fire is responsible for the overall plan, Public Works and specifically Utilities is an integral part of the planning.

- DPW Director and Fire Chief have discussed this problem, but do not meet on a regular basis and do not have resolution.
- The Public Utilities Department has a specific person responsible for emergency management and response. This person works with various local, state and federal agencies in association with all types of emergencies.
- There are some general emergency management meetings that the…and the FD attend together, but it is unclear to us how much they discuss FFE.
- For the most part, emergency planning/implementation is poor between our District and the Fire District. We typically find out from the City's Police Department (a different agency) when there is a disaster practice. It was the Police Department, on our behalf, that forced a disaster practice to include damaged water facilities and limited water availability.

The key findings of this series of questions were that fire and water department liaison are not very good, and are often somewhat indirect, through larger enterprise-wide coordination meetings. Emergency water supply is not a focus.

3.2.2.5 Concluding Responses

The survey concluded with two questions, the first of which was: **How important is the fire following earthquake issue for your jurisdiction? What key things should your department be doing to improve its ability to respond?** The following responses were received:

- It is important enough that we are working on our storage to withstand a seismic event ($3.36 M). Although all of our storage facilities have been through several events, the retrofit work seemed prudent. Our storage is elevated on a hill side so that if the tanks survive, there is a good chance we will have water. We also have a valve program so that isolating a main break will likely occur without discovering inoperable valves.

- Ensuring that we can provide water for firefighting needs is at the heart of our emergency preparedness efforts. Our fire department knows we have an excellent system, but again we have not exercised as much as we should and because of our excellent system. I believe Fire may not be able to deal with a situation where water is limited.

- Very important, as well as supplying water to the community. The key things include storing spare pipe and other appurtenances for emergency repairs and we are retrofitting our water system with emergency generators. We are also doing a preliminary survey of sites for a new above ground reservoir that we would be more seismically prepared.

- Develop water relaying schemes. Determine portions of the distribution system most likely to fail after an earthquake. We are currently upgrading our reservoirs to handle a seismic event. We are also improving our well system in the event that our supplier is unable to deliver after a seismic event. Our current plan class for the ability to supply normal loads for an 8 hour period. With our currently approved capital projects we will be able to achieve this goal. Coupled with water restrictions our plan is to be able to operate the water distribution system indefinitely during a curtailment of our traditional supply. We also have interconnects with surrounding agencies to deliver or receive water during an emergency and we are currently expanding the number of interconnects. We are also budgeting to have emergency power available at our pump stations on a fulltime basis.

- Annual scenario play quarterly discussions quarterly issue of updates to Utility Emergency Response Manuals.

- The issue is important to our agency. Our agencies need to refresh/revisit the results of the study and ensure both Public Utilities and Fire Department staff understands potential scenarios and are prepared to efficiently and effectively respond.

- It is a very important issue. We should have detailed meetings on some kind of periodic basis to review scenarios and how to work together in an emergency.

- Firefighting is very important to our jurisdiction, but drinking water is essential to life.
- More table top exercises. Improve mutual aide. Federal/State must make more grants available for emergency equipment.
- Very important, as the 1906 quake proved. The City is currently undertaking an AWSS upgrade that will evaluate system condition and recommend long range upgrades. Infrastructure related to the piping distribution system will undergo R&R in first phase.
- Water for firefighting is in the top 5 categories.

Finally, we asked: **Have we overlooked key issues? Was this survey about on target, or are we off target? How can it be improved?** The following responses were received:

- It seems this survey was more keyed to when the fire service is not part of the same city structure or when the water service is not part of a city such as a separate district. Either way there will be more potential for lack of information sharing.
- Portable water chlorination systems and water supply to emergency hospitals.
- Your survey recognizes that water is a critical resource after a major seismic event. It is important that you understand that firefighting water is a subset of the municipal potable drinking water supply. A major earthquake would likely knock out our wholesale suppliers which means the City could be without treated potable water supply for a week to a month. Fire cannot drain all of the City's limited water storage and leave the public without drinking water for this period. You need to consider alternate means of firefighting that do not rely on high-pressure water (emphasis added).
- There should be an industry standard methodology to conduct analysis of a water system based on likely seismic events. This analysis would include the determination of critical facilities, focus on distribution materials most likely to fail and give the operator a sense of which portions of the system should be isolated immediately after an earthquake. …recently adopted high density polyethylene for our primary water main and service material. This material HDPE has proven to provide superior

performance during seismic events. Our current replacement plan of 3 miles per year (200 mile system) focuses on cast iron which in my opinion is most likely to fail during an earthquake. It will take several years at this rate to replace our system.

- Questions could be asked regarding asset management and levels of service (LOS) to be achieved during an emergency.
- The survey seems to be on target. An improvement may be to have both fire and water personnel responding together so that it generates a fuller/more accurate reflection in the responses.
- The survey seems to generally be on target.
- Over the years I have worked for many agencies where folks recognize that there will be limited water available during emergencies, but then make decisions about firefighting that assumes limitless water. Each agency or region needs to answer the following questions:
  - How will a community's drinking water [needs] be met after a major earthquake? Should we set aside water in each tank/reservoir and thus limit the water available to fight fires?
  - How long before outside relief can be provided to each and every person impacted by the major earthquake; three days, two weeks (as in the case of Katrina)?
  - How much water can be used to fight fires with water before some other method is needed. Based on what was learned during the 1906 San Francisco earthquake is a community ready to employ this "other" methods and have fire fighters studied those possibilities to minimize losses to critical facilities?
- Explain why the emphasis was on FIRE and not loss of water service

The key finding of this series of questions were:

- Responding water department personnel concur that fire following earthquake is a key problem for their communities.

- However, they see provision of firefighting water as only one of their responsibilities, with provision of potable water following a disaster as at least as important.

- Given the multiple goals of a water department, many of the responders suggest more use be made of non-potable water sources and/or alternative firefighting methods.

- Lastly, one responder asks for an industry standard methodology to conduct analysis of a water system based on likely seismic events. He might have gone farther, and suggested a standard methodology that analyses water systems in an integrated manner, considering fire following earthquake as well as potable and other needs.

The key finding of this series of questions was that earthquake is seen as a key issue by most water departments, but that provision of potable water has a higher priority in some cases than firefighting.

3.2.2.6 Key Findings from the Water Department Survey

The key findings of the survey were that:

- Most larger urban water departments are not aware of the specifics of the earthquake risk they are exposed to (i.e., two thirds had had no analysis in the last ten years).

- Earthquake is seen as a key issue by most water departments, but that provision of potable water has a higher priority in some cases than firefighting.

- Even where water departments have knowledge of the vulnerabilities of their systems, this is not often (only 22%) communicated to fire departments.

- Both water and fire departments expect major loss of water supply in a major earthquake, with the water department informing the fire department of the details of this about half the time.

- Many water departments are currently addressing their seismic vulnerabilities with significant engineering programs.

- Information on when water would be restored is sparse.

- Some water departments have alternatives given loss of normal water supply, but only a fraction (~1/3) are reasonably equipped to actually move water.

- Fire and water department liaison is not very good, and are often somewhat indirect, through larger enterprise-wide coordination meetings. Emergency water supply is not a focus.

3.3 ALTERNATIVE WATER SUPPLY SYSTEMS

This section reviews efforts selected fire departments have undertaken, in order to assure adequate water supply following a major earthquake. In essence, these efforts may be categorized as

a) Building a dedicated firefighting fixed in-ground water distribution system, separate from and redundant to the normal dual purpose municipal water supply system. Such systems are often termed 'high-pressure' systems.

b) Similarly, developing a system that has many attributes of the high-pressure system, but is portable and avoids the high capital cost of the high-pressure system. Such systems are often termed 'portable water supply systems.'

3.3.1 High Pressure Systems

3.3.1.1 San Francisco AWSS

High pressure systems were a development of later nineteenth century America, a by-product of whose rapid urban growth were urban conflagrations, due to highly flammable wooden construction, an outrun and inadequate water supply, and inadequate fire protection. The solution were high pressure systems in a number of American cities, the history of which has been reviewed elsewhere (Scawthorn et al., 2006). The largest of these systems was built in San Francisco following the 1906 earthquake and fire, and has since been extended and enhanced. This section briefly describes that system.

San Francisco possesses two water supply systems: (a) the Municipal Water Supply System (MWSS), owned and operated by the San Francisco Water Department (SFWD) and serving both fire fighting and municipal (potable water) uses; and (b) the Auxiliary Water Supply System (AWSS), first developed following the 1906 earthquake and fire and extended periodically thereafter. The AWSS consists of several major components:

- Static Supplies: The main source of water under ordinary conditions is a 10 million gallon reservoir centrally located on Twin Peaks, the highest point within San Francisco (approximately 750 ft. elevation), see Figure 33.

- Pump Stations: Because the Twin peaks supply may not be adequate under emergency conditions, two pump stations exist to supply water from San Francisco Bay - each has 10,000 gpm at 300 psi capacity. Both pumps were originally steam powered but were converted to diesel power in the 1970s.

- Pipe Network: The AWSS supplies water to dedicated street hydrants by a special pipe network with a total length of approximately 120 miles. The pipe is bell and spigot, originally extra heavy cast iron (e.g., 1" wall thickness for 12" diameter), and extensions arc now Schedule 56 ductile iron (e.g., .625" wall thickness for 12" diameter). Restraining rods connect pipe lengths across joints at all turns, tee joints, hills and other points of likely stress, see Figure 34.

- Cisterns: Lastly, in addition to the above components, San Francisco has 172 underground cisterns, again largely in the northeast quadrant of the City. These cisterns arc typically of concrete, 75,000 gallons capacity (about one hours supply for a typical fire department pumper), see Figure 35, Figure 36, and Figure 37.

- Fireboat Phoenix[6]: The pipe network has manifold connections located at several points along the City's waterfront in order to permit the City fireboat Phoenix to act as an additional "pump station", drafting from San Francisco Bay and supplying the AWSS. The Phoenix's pump capacity is 9,600 gpm at 150 psi, about the same as Pump Station No. 2, see Figure 38 (PS 2 can pump to a higher pressure however).

The AWSS is a system remarkably well designed to furnish large amounts of water for firefighting purposes under normal conditions and contains many special features to increase reliability in the event of an earthquake. It is highly redundant, with a 10 million gallon reservoir

[6] Within days following the 1989 Loma Prieta earthquake, San Francisco Fire Department purchased a fireboat which Vancouver, B.C. had just discarded. Renamed the *Guardian*, the fireboat is arguably the largest in North America, with 20,000 Igpm pumping capacity. The *Phoenix* and the *Guardian* are both active as of this writing, with each alternately in service for one to several months, and the other in reserve. Both are stationed near the foot of Folsom St., close to the San Francisco-Oakland Bay Bridge.

at the highest point in the City feeding a highly gridded and valved extensive pipe network specially reinforced for earthquake, two pump stations to inject seawater into the pipe network if needed, numerous fireboat manifolds for allowing fireboats to add their pump capacity to the fixed pump stations, and the entire system backed up by 172 cisterns. The AWSS is routinely used for greater alarm fires in San Francisco, meaning that it is regularly 'drilled' and many firefighters are accustomed to using it. See (Scawthorn et al., 2006) for more detail on San Francisco's AWSS.

3.3.1.2 Vancouver, B.C. DPFS

Most US high pressure system construction halted with WW1, and US cities gradually reduced their conflagration problem through investment in better building codes, more reliable water systems and a more professionalized fire service. Nevertheless, rapid urban growth could still create a fire load that outstripped the municipal water supply system. The City of Vancouver, B.C. found itself in this position in the 1990s – it had experienced a large amount of high-rise construction in its central business district, and found the existing municipal system was not able to provide the fire flows demanded by the building density (and the insurance industry). As a result, Vancouver undertook the construction of a Dedicated Fire Protection System (DFPS), closely modeled after San Francisco's AWSS. Construction of the system was begun in the early 1990s, with the first pump station going online in 1995. Figure 39 and Figure 40 show the two pump stations, as well as a plan of the system.

3.3.2 Portable Water Supply Systems

While high pressure systems are highly reliable, they are also capital intensive – expensive to build and requiring regular maintenance. Furthermore, they require extensions to keep up with urban growth. Recognition that a better alternative might exist led San Francisco Fire Department Asst. Chief Frank Blackburn in the 1980s to develop the concept of a Portable Water Supply System (PWSS). As Blackburn has observed, the idea of the PWSS was not new – hose wagons had been used by fire departments for a hundred years. But, by combining the elements of hose tenders, the newly available Large Diameter Hose, portable hydrants, pressure reducing valves, gated wyes and hose ramps, he was able to develop a PWSS – a system that enabled an 'above ground water main system' to be quickly put into place. The PWSS was originally conceived as an extension of San Francisco's AWSS – that is, it would extend the "reach" of the AWSS to the newer outer neighborhoods of San Francisco, where the AWSS did not extend.

The PWSS is far more than the sum of its parts – it has been used in a number of fires, including at the 1991 East Bay Hills fire (see above), as well as in providing potable water distribution in a number of instances.

The PWSS have now been adopted by several departments in the San Francisco Bay Area, as shown in Figure 41. In that figure, the yellow Vallejo FD PWSS hose tender is seen with a Hydro-sub, a portable pump equivalent to a fire engine in capacity. Figure 42 and Figure 43 show some of the elements of the PWSS.

Most recently, the Berkeley Fire Department under the leadership of Asst. Chief Dave Orth has extended the PWSS using 12 inch Ultra LDH, in a system termed the Berkeley Aboveground Water Supply System (BAWSS), as shown Figure 43 and Figure 44. The BAWSS system is necessitated by the need to provide large fire flows from the Berkeley bay shore inland about two miles to higher elevations along Shattuck Ave and further east. Relaying using LDH would have required all and more fire engines than BFD has.

3.4 SUMMARY

This section surveyed and interviewed selected urban fire and water departments to determine the current status of their preparedness for fire following earthquake. Results of the survey were followed by a review of selected efforts being undertaken by fire departments, to prepare for the special circumstances of fire following earthquake. The following observations may be made:

- Most larger urban fire and water departments could be better informed as to the specifics of their earthquake risk.
- Earthquake is recognized as a key issue by fire and water departments, although many water departments see provision of potable water has a higher priority in some cases than firefighting.
- Water department system vulnerabilities is not well understood by fire departments, although water and fire departments both generally believe most municipal water supply systems are unreliable in a major earthquake.
- Many water departments are currently addressing their seismic vulnerabilities with significant engineering programs. Not discussed above are major seismic

improvement programs completed or underway by water utilities such as Contra Costa Water District, Los Angeles Department of Water and Power, East Bay Municipal Utilities District, San Francisco Public Utilities Commission, Metropolitan Water District, Santa Clara Valley Water District, to name only a few of the larger efforts.

- Some fire departments have vigorously addressed this issue, developing innovative high pressure and/or portable water supply systems. Many have not.
- Some water departments have alternatives given loss of normal water supply, but only not many are reasonably equipped to actually move water a significant distance.
- Fire and water department liaison is not very good, and is often somewhat indirect, through larger enterprise-wide coordination meetings. Emergency firefighting water supply is not a focus.

4 SUMMARY AND RECOMMENDATIONS

This section first summarizes the current situation with regard to water supply for firefighting following earthquakes. Recommendations are then offered for improving the current situation.

4.1 CURRENT SITUATION

4.1.1 Risk

The risk is very significant. Based on the review of historic earthquakes and associated fires, it should be clear to anyone that the urban areas of California in high seismicity areas – that is, the San Francisco Bay Area (population 7.5 million), the Greater Los Angeles area (population ~ 20 million), and the San Diego metropolitan area (population 3 million) – under adverse meteorological conditions could have very significant losses due to fire following earthquake. This can be clearly seen from:

Los Angeles Metropolitan Area

The approximately 17 million people living in the Los Angeles-Long Beach-Riverside region sit atop numerous active faults, as well as being subject to a large earthquake on the San Andreas Fault. A Mw 7.8 on this latter fault was the focus of the ShakeOut Scenario which was discussed above – estimates are 1,600 ignitions and 2,700 pipeline repair locations (for the LADWP system only – the entire number of breaks may in fact be several times this estimate), versus about 2,000 fire engines in the entire affected area. Taking these factors into account, estimates of losses are about $40 billion (structure only).

There will be about as many fires as fire engines, and much less water. Mutual aid will have to come from the Central Valley and Northern California, and will be delayed by disrupted transportation networks.

San Francisco Bay Area

- **Earthquake and Exposure**: The 7.5 million people of the Bay Area live mostly in a "U" bounded on the east by the East Bay (along which is the Hayward fault), on the west by the Peninsular (along which is the San Andreas fault) and on the south by the City of San Jose and other communities (which straddle the Hayward and San Andreas faults), see Figure 45.

- **Fires**: The entire Bay Area has not been modeled for fire following earthquake, but approximate rules of thumb indicate that for a major earthquake on either the Hayward or San Andreas event, that as many as five hundred ignitions would occur.

- **Firefighting Resources**: in the same area, there are approximately 280 fire stations.

- **Water Supply Disruption**: As has happened in all major earthquakes, when one of the above faults ruptures, water distribution lines throughout the strongly shaken area will rupture, especially in the softer soils along the Bay margins. The hundreds to thousands of pipe breaks will quickly drain the distribution network, and also perhaps many hillside tanks, leaving hydrants dry.

There will be more fires than fire engines, and much less water, despite the Bay being quite close. Mutual aid will have to come from the Central Valley and Southern California, and will be delayed by disrupted transportation networks. The net result of all these factors remains to be modeled, with the exception of the City of San Francisco.

The situation in San Diego has not been examined, but undoubtedly has many parallels.

Lastly, in all these locations there are many high-rise buildings. The challenge these pose under normal circumstances can be seen from the 1988 First Interstate Bank Building fire, Figure 46, the tallest high-rise building in California at the time. Five floors were burned out, with the remainder of the building heavily damaged by smoke and water. The fire required one-third of the entire Los Angeles City Fire Department to combat. Discussions with senior fire officers in Northern and Southern California indicate their anticipated response in an earthquake to high-rise fires will be attempt to assure safe evacuation, but not to commit to firefighting, given the other demands on their resources.

4.1.2 Readiness

Excepting a few special measures undertaken by a few fire departments discussed above, earthquake readiness in most urban California fire and water departments is much less than it could be. This is not to say nothing is being done. Most major water utilities in California have completed or are in the midst of significant seismic improvement programs (cited above, section 0) intended to assure reliable potable water following an earthquake (and some initial limited disruption). However, in most cases water utility seismic improvement programs focus on reservoirs, transmission lines, pump stations – that is, facilities other than the distribution network[7]. Distribution networks, which serve the hydrants firefighters rely on for water, are not typically addressed due to the immensity of the challenge (hundreds to thousands of miles of buried pipe) and the strategy of not trying to prevent any breaks but rather to quickly repair them. While this is justified from some perspectives, this means that immediately following the earthquake, breaks will result in many hydrants (especially in the more heavily damaged areas) being dry. That is, the agreement of most fire and water departments that they will lose firefighting water supply from the normal distribution system is justified. In effect, **post-earthquake firefighting water supply is falling through a gap.**

This is confirmed by the surveys of fire and water departments:

- Some water departments have alternatives given loss of normal water supply, but only a fraction (~1/3) are reasonably equipped to actually move water.
- For most fire departments, the very difficult task of moving water from the alternative water sources to the fire scene is in many cases not well thought out, not adequately equipped and not regularly drilled
- Fire and water department liaison is not very good, and are often somewhat indirect, through larger enterprise-wide coordination meetings. Emergency firefighting water supply is not a focus.

Why is this?. Water departments strive to provide, but are not required to guarantee, firefighting water. In general, fire and water departments follow guidelines such as those of the

[7] See http://ebmud.com/sites/default/files/pdfs/sip_annual_2005.pdf for a good description of an excellent seismic improvement program that however does not mention the distribution network.

American Water Works Association (AWWA), the National Fire Protection Association (NFPA) and the Insurance Services Office (ISO) that prescribe goals for fire flows, hydrant spacing, distribution pipeline design and fire department organization and equipment. When these guidelines are followed, communities receive favorable fire insurance rates. If prevailing standards have been employed and firefighting water fails, fire and water departments will typically have no liability for fire losses under the doctrine of "fire suppression immunity". A clear example of this was the 1991 East Bay Hills fire (discussed above) in which water supplies failed early and often – the local water utility was sued, but paid no claims[8].

Fire departments on the other hand are responsible for putting out the fires, and understand that good practice requires they identify alternative water sources. More or less, they have done this. But, most have not thought out, adequately equipped or regularly drilled for the very difficult task of moving water from the alternative water sources to the fire scene. Why not? It appears to be a combination of reduced budgets, ongoing attrition of firefighters (engine staffing has gone from 6 firefighters per engine, to 4 or even 3 over the last 40 years), shifting focus of fire departments from firefighting to emergency medical services, and more pressing problems than a very rare earthquake, which may 'never' happen.

4.2 RECOMMENDATIONS ACTIONS AND MEASURES

The previous section has shown that urban California has a very significant risk due to fire following earthquake, and that provision of post-earthquake firefighting water supply is falling through a gap. This section provides recommendations for actions to address this problem, and suggests a possible program for the San Francisco and Los Angeles regions.

4.2.1 Recommendation Actions

A fundamental part of the fire following earthquake/ water supply problem is that fire and water department liaison is not very good, and emergency firefighting water supply is not a focus. The following actions are recommended:

1. **Highlight the problem to the California Fire Service:** The first step towards remedying this problem is probably to discuss it within the broader California fire

[8] Personal communication, East Bay Municipal Utilities District legal counsel

service, particularly urban fire departments. An excellent venue for this discussion would be a meeting of the Metro Chiefs (a subsection of the International Association of Fire Chiefs), perhaps in conjunction with the Seismic Safety Commission and CalEMA. The meeting would serve to provide further detail on this topic, and build development of state-wide leadership on this issue.

2. **Enlist the Water Community:** The next step would be to bring the water community into the discussion, particularly the larger urban water distribution agencies. This could be accomplished via a joint meeting of key senior fire chiefs and water department managers, perhaps held under the auspices of the Seismic Safety Commission and CalEMA.
3. **Develop state-wide guidelines:** This action would be undertaken by a joint fire-water agency task force composed of key senior urban California fire chiefs and water department managers, perhaps working with the Seismic Safety Commission and CalEMA. Ideally, the task force would develop into a standing committee. The goal would be to develop legislation similar to Article 5.9 of the California Emergency Services Act (2009, discussed above), which currently only has two relevant requirements –fire hydrant standardization, and that water agency disaster planning be carried out in "conjunction with related agencies, including, but not limited to, local fire departments". **Basically, the legislation should be amended to require development of post-earthquake firefighting water target goals, and that water and fire agencies should develop and submit plans for measures intended to achieve these goals by a given date.**

4.2.2 Recommended Measures

This section suggests a possible program of measures for the San Francisco and Los Angeles regions.

San Francisco Bay Area

As discussed above, a few fire departments in the San Francisco Bay Area have undertaken measures to assure reliable post-earthquake firefighting water supply. These measures are the high pressure AWSS in San Francisco, and the various portable water supply systems developed by San Francisco Fire Department, Oakland FD, Vallejo FD and Berkeley

FD. Much of the population of the Bay Area is within about 3 miles of San Francisco Bay (excepting southern portions of San Jose), Figure 45. It is suggested that development of a regional PWSS system be explored, using standardized hose and equipment that would be adopted by most fire departments in the Bay Area. Design of the system might use 5 inch LDH, which is already in common use, and/or in selected cases might adopt an Ultra LDH approach similar to Berkeley's BAWSS. In any event, while specifics would have to be regionally determined, the concept is that perhaps 100 or more PWSS units (hose tenders and appropriate portable pumps) be developed and acquired by the various fire departments in the Bay Area. Following a large earthquake, these units working together would allow movement of firefighting water in sufficient quantities for anticipated fires.

Los Angeles Region

In contrast to the San Francisco Bay Area, much of the population in Los Angeles and Orange counties lives relatively far from the ocean. In certain neighborhoods, swimming pools serve as 'cisterns' but other neighborhoods, such as central Los Angeles, don't have many swimming pools, see Figure 29. It is suggested that development of a regional high pressure / PWSS system be explored, as shown in Figure 47 to Figure 50. The first figure shows the large number of ignitions, overlaid on fire stations. Clearly a lot of water is going to be needed, quickly. The next figure shows a typical larger Los Angeles storm drain channel, while Figure 49 shows the dense network of storm drain channels, and also ground elevations – it can be seen that most of the high density / high ignition areas are less than 165 feet (50m) above sea level. Preliminary engineering calculation show that a 3 ft. diameter steel pipe, easily accommodated in the storm drain channel cross-section, can deliver 18,000 gpm 20 miles inland for use by fire engines. Pumping capacity required would be about 2,300 hp, which is a medium-sized industrial diesel engine. If a few pump stations are built along the coast, in the vicinity of Santa Monica, Redondo Beach, Long Beach, Seal Beach and Newport Beach, with 3 ft. diameter pipes going up the larger storm drain channels, and interconnected so as to be a gridded network, much of the high ignition / high risk area can be furnished with a redundant unlimited alternative firefighting water supply. If this network is coupled with a PWSS as described above, most of the high risk regions can be covered. This is shown in Figure 50, which shows selected existing larger Los Angeles and Orange county storm drain channels (blue lines) with connectors to be built (black lines) overlaid on ShakeOut scenario ignitions. Blue buffer zones around lines would be areas reachable by a PWSS. The cost of such a network would be in the many tens of millions of dollars, perhaps equivalent to several dozen houses. How many houses might it save from fire following earthquake?

State-wide Urban Equipment Caches

Los Angeles has trained thousands of its citizens in earthquake preparedness under its CERT program (Community Emergency Response Team, http://www.cert-la.com/index.shtml). San Francisco has similarly done so under its NERT program (Neighborhood Emergency Response Team, http://www.sf-fire.org/index.aspx?page=859), and many other fire departments have similar programs. However, these volunteers are currently only trained and equipped for light search and rescue and minimal fire extinguishment. San Francisco is now examining the concept of more extensive training of NERT volunteers for firefighting, and has designed a program to place container caches in each of its fire battalion districts, each container holding firefighting equipment including a portable pump and hose, see Figure 51. A similar program is underway in Istanbul, Turkey, see Figure 52. It is suggested that a standardized equipment container cache be developed for California, that would equip trained neighborhood volunteers to assist firefighters in fighting conflagrations.

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GLOSSARY

ASCE	American Society of Civil Engineers
AWSS	Auxiliary Water Supply System (San Francisco)
AWWA	American Water Works Association
BAWSS	Berkeley Aboveground Water Supply System
BFF	Basic Fire Flow (ISO methodology)
CalEMA	California Emergency Management Agency (formerly Governor's Office of Emergency Services)
Cal Fire	California Department of Forestry and Fire Protection
CDOI	California Department of Insurance
CSS	Credit for Water Supply System (ISO methodology)
DFPS	Dedicated Fire Protection System (Vancouver, B.C.)
FEMA	[United States] Federal Emergency Management Agency
FFE	Fire following earthquake
FSRS	Fire Suppression Rating Schedule (ISO methodology)
HAZUS	A multihazard loss-estimation methodology and software package developed by FEMA
ISO	Insurance Services Office
LDH	Large Diameter Hose
M_w	moment magnitude scale for earthquakes
NBFU	National Board of Fire Underwriters
NFF	Needed Fire Flow (ISO methodology)
NFPA	National Association for Fire Protection
NSHMP	National Seismic Hazard Mapping Project
OES	see CalEMA
PEER	Pacific Earthquake Engineer Research Center (see http://peer.berkeley.edu)
PFRB	Pacific Fire Rating Bureau (now defunct)
PGA	Peak ground acceleration, a measure of shaking intensity in an earthquake
PGV	Peak ground velocity, a measure of shaking intensity in an earthquake
PWSS	Portable Water Supply System (ISO methodology)
TLC	Capability of Water System at Test Location
USGS	United States Geological Survey
Vs30	the average shear wave velocity of the top 30 m of the soil column.

Table 1 **U.S. post-earthquake Ignitions (TCLEE, 2005) based on various sources compiled by author ("a" indicates fire caused by aftershock)**

Year	M	City or Area Affected	Ignitions
1906	8.3	Berkeley	1
1906	8.3	Oakland	2
1906	8.3	San Francisco	52
1906	8.3	San Jose	1
1906	8.3	Santa Clara	1
1906	8.3	San Mateo Co.	1
1906	8.3	Santa Rosa	1
1933	6.3	Los Angeles	3
1933	6.3	Long Beach	19
1933	6.3	Norwalk	1
1952	7.7	Bakersfield	1
1957	5.3	San Francisco	1
1964	8.3	Anchorage	7
1969	5.7	Santa Rosa	2
1971	6.7	Burbank	7
1971	6.7	Glendale	9
1971	6.7	Los Angeles	128
1971	6.7	Pasadena	2
1971	6.7	San Fernando	3
1979	6.4	El Centro	1
1983	6.5	Coalinga	4
1984	6.2	Morgan Hill	4
1984	6.2	San Jose	5
1986	5.9	N. Palm Springs	2
1987	6	Whittier	38
1989	7.1	Daly City	3
1989	7.1	Berkeley	1
1989	7.1	Marin Co.	2
1989	7.1	Mountain View	1
1989	7.1	San Francisco	26
1989	7.1	Santa Cruz	1
1989	7.1	Santa Cruz Co.	24
1994	6.8	Los Angeles	77
1994	6.8	Santa Monica	15
2000	5.2	Napa	1
2001	6.8	Seattle, WA	1
2002	7.8	Tok, Alaska	1a
2003	6.5	Cambrian	1

Table 2 **Fire departments affected by the January 17, 1994, Northridge earthquake (source: Scawthorn et al., 1997).**

Fire Department	Estimated Population (thousands)	Area (Sq Miles)	Number of Stations	Fire Fighting Personnel	Number of Engines
Los Angeles City	3,400	469	104	2,865	104
Los Angeles County	2,896	2,234	127	1,842	144
Ventura County	700	126	30	327	40 +/-
Santa Monica	97	8	4	100	5
Burbank	94	17	6	120	6
Pasadena	132	23	8	150	8
Glendale	166	30	9	167	9
South Pasadena	25	3	1	27	2
Beverly Hills	34	6	3	81	7
Culver City	41	5	3	66	5
Fillmore	12	2	1	9	1

Table 3 **Fire Following the January 17, 1994, Northridge earthquake (source: Scawthorn et al., 1997),**

Community	Number of Earthquake-Related Fires
Los Angeles City	77
Los Angeles County	~15
Ventura County	~10
Santa Monica	4
Burbank	0
Pasadena	1
Glendale	0
South Pasadena	0
Beverly Hills	1
Culver City	0
Fillmore	2
TOTAL	~110

Table 4 Water Usage, Balboa Blvd. fire (source: Scawthorn et al., 1997).

Engine 8	■ One 1 1/2-inch siphon ejector in pool supplying approx. 100 gpm
	■ One 1 1/2-inch supply line laid to Engine 18 for their water source
	■ One 1 1/2-inch tip line with spray tip - 125 gpm ■ TOTAL: 8,750 gallons
Engine 18	■ One 1 1/2-inch supply line in to fill tank
	■ One 1-inch line with spray tip - 25 gpm ■ TOTAL; 1,750 gallons
Engine 74	■ One 1 1/2-inch siphon ejector in pool supplying approx. 100 gpm ■ Two 1-inch lines/spray tips 50 gpm ■ TOTAL: 3,500 gallons
TOTAL ESTIMATED WATER EMPLOYED TO CONTROL/EXTINGUISH FIRES: 14,000 GALLONS	

Table 5 Comparative analysis of the Hanshin and Northridge earthquakes.

Aspect	Factor	Northridge	Hanshin
Event	Magnitude (M_W)	6.7	6.9
	Date (winter)	Jan 17	Jan 17
	Time	0431	0546
Region	Population (MMI 8)	1~1.5 million	2 million
	Density (pop/sq km)	1,000~1,500	4,000
Ignitions	Number (total)	110	108
	Structural Fires	86%	97%
	Rate (MMI 7) Ign/pop:	14,719	13,676
Response	FD Communications	manual dispatch	
	Resources (ff/popul):	1,338	1,138
	Stations	104	26 (Kobe)
	Traffic Congestion	Minor	Major
	Mutual Aid	Available - not needed	after 10 hrs
Water	Water System Damage	Some	Total?
	Cisterns	Swimming Pools	946, mostly 40 tons (10 mins)
Wind		Calm	Minor
Gas	Automatic Shut-offs	? few %	70% - ineffective due to structl collapse
Spread		Minor	Major: 5,000 bldgs

Table 6 ShakeOut Scenario effects on LADWP water system.

Maximum PGA	0.3g
Maximum PGV	200 cm/s
Shaking duration	55 seconds
MMI	IV to X
Total pipe repairs	2,700
Trunk Line repairs	150
Serviceability	76% at 0 hours
	34% at 24 hours
	100% at 15 months

Table 7 Estimated ignitions, large fires and final burnt SFED M7.8 ShakeOut scenario (12 noon 13 Nov 2008 10 mph wind low humidity).

	Est No. Ignitions	**Est. No. Large Fires**	**Est. Burnt SFED (thous)**	**Est. Burnt Bldg. Floor Area (thous. Sq. ft.)**
Imperial	131	45	negligible	negligible
Kern	167	82	negligible	negligible
Los Angeles	612	583	94	140
Orange	206	165	37	56
Riverside	239	157	1	2
San Bernardino	234	151	1	2
Ventura	18	0	negligible	negligible
Total	**1,606**	**1,182**	**133**	**200**

Table 8 Bounds for losses to buildings due to fire following earthquake, for the four CAPSS scenarios.

	25% ~ 75% Confidence Range		
	Ignitions	**Loss** $ billions	**Total Burnt Building Floor Area** mill. sq. ft.
San Andreas Mw 7.8	68 ~ 120	$ 4.1 ~ $ 10.3	11.2 ~ 28.2
San Andreas Mw 7.2	52 ~ 89	$ 2.8 ~ $ 6.8	7.7 ~ 18.6
San Andreas Mw 6.5	48 ~ 70	$ 1.7 ~ $ 5.1	4.7 ~ 14.0
Hayward Mw 6.9	27 ~ 46	$ 1.3 ~ $ 4.0	3.6 ~ 11.0

Table 9 Key factors employed in ISO FSRS.

Receiving and handling of fire alarms	
Receipt of fire alarms by commercial telephone — ISO compares the number of telephone lines provided with the number of telephone lines needed for emergency and business calls. The number of needed lines depends on the population served by the communication center. ISO also evaluates telephone directory listings.	**2%**
Operators — ISO compares the number of fire alarm operators provided with the number of operators needed. The number of needed operators depends on whether the community is meeting its performance standards with existing operators for receiving and dispatching alarms. Alternatively, if performance data is unavailable, the number of needed operators is based upon the number of alarms received.	**3%**
Alarm dispatch circuits — All fire departments (except for single-station departments with full-time personnel receiving alarms directly at the station) need adequate means of notifying personnel of fire locations. ISO evaluates the type and arrangement of those facilities.	**5%**
	Receiving and handling of fire alarms total: 10%
Fire department	
Pumpers — ISO compares the number of in-service pumpers and the equipment carried with the number of needed pumpers and the equipment identified in the FSRS (or equivalency list). The number of needed pumpers depends on the Basic Fire Flow, the size of the area served, and the method of operation.	**10%**
Reserve pumpers — ISO evaluates the adequacy of the pumpers and their components with one (or more in larger communities) pumper out of service.	**1%**
Pump capacity — ISO compares the pump capacity of the in-service and reserve pumpers (and pumps on other apparatus) with the Basic Fire Flow. ISO considers a maximum Basic Fire Flow of 3,500 gpm.	**5%**
Ladder/service — Communities use ladders, tools, and equipment normally carried on ladder trucks for ladder operations, as well as for forcible entry, utility shut-off, ventilation, salvage, overhaul, and lighting. The number and type of apparatus depend on the height of the buildings, needed fire flow, and the size of the area served.	**5%**
Reserve ladder and/or service — ISO compares the adequacy of ladder and service apparatus when one (or more in larger communities) apparatus is out of service.	**1%**
Distribution of companies — ISO credits the percentage of the community within specified response distances of pumpers (1-1/2 miles) and ladder/service apparatus (2-1/2 miles).	**4%**
Company personnel — ISO credits the personnel available for first alarms of fire. For personnel not normally in the fire station (for example, volunteers), ISO reduces the value of the responding members to reflect the delay due to decision, communication, or assembly. ISO then applies an upper limit for the credit for manning, as it is impractical for a very large number of personnel to operate a piece of apparatus.	**15%**
Training — Trained personnel are vital to a competent fire-suppression force. ISO evaluates training facilities and their productivity; training at fire stations; training of fire officers, drivers, and recruits; and building familiarization and prefire planning inspections.	**9%**
	Fire department total: 50%
Water supply	
Adequacy of water supply — ISO compares the available water supply at representative community locations with the needed fire flows for those locations. The supply works, the water main capacity, or fire hydrant distribution may limit the available supply.	**35%**
Hydrants: size, type, and installation — ISO evaluates the design capacity of fire hydrants.	**2%**
Hydrants: inspection and condition — ISO evaluates the frequency of fire hydrant inspection, the completeness of the inspections, and the condition of the hydrants.	**3%**
	Water supply total: 40%
Divergence	
Divergence — An inadequate water supply may limit the ability of even the best fire department to suppress fires. Similarly, an inadequate fire department may not be able to make effective use of an abundant water supply. So, if the quality of the fire department and the water supply are different, ISO adjusts the total score downward to reflect the limiting effect of the less adequate item on the better one.	

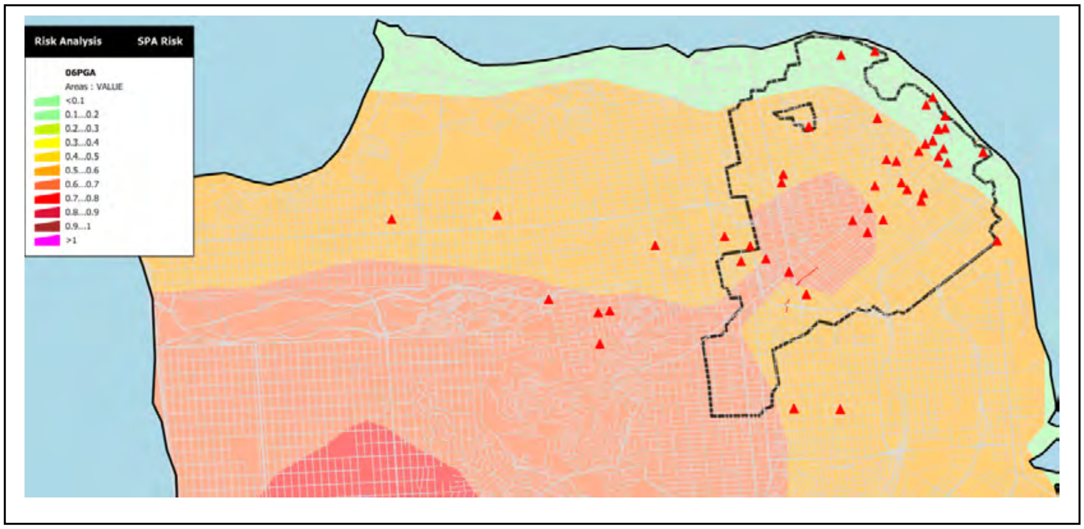

Figure 1 **San Francisco 1906 fire: ignitions overlaid on peak ground acceleration and final burnt area (black outline).**

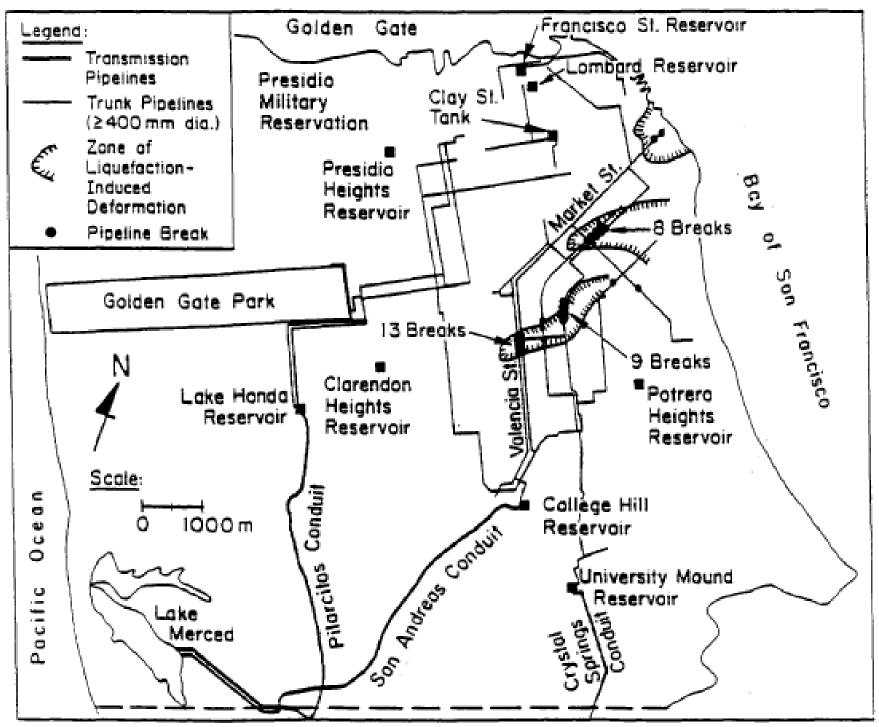

Figure 2 **Map of the 1904 San Francisco water system, with ground failures superimposed (source: Scawthorn and O'Rourke, 1989).**

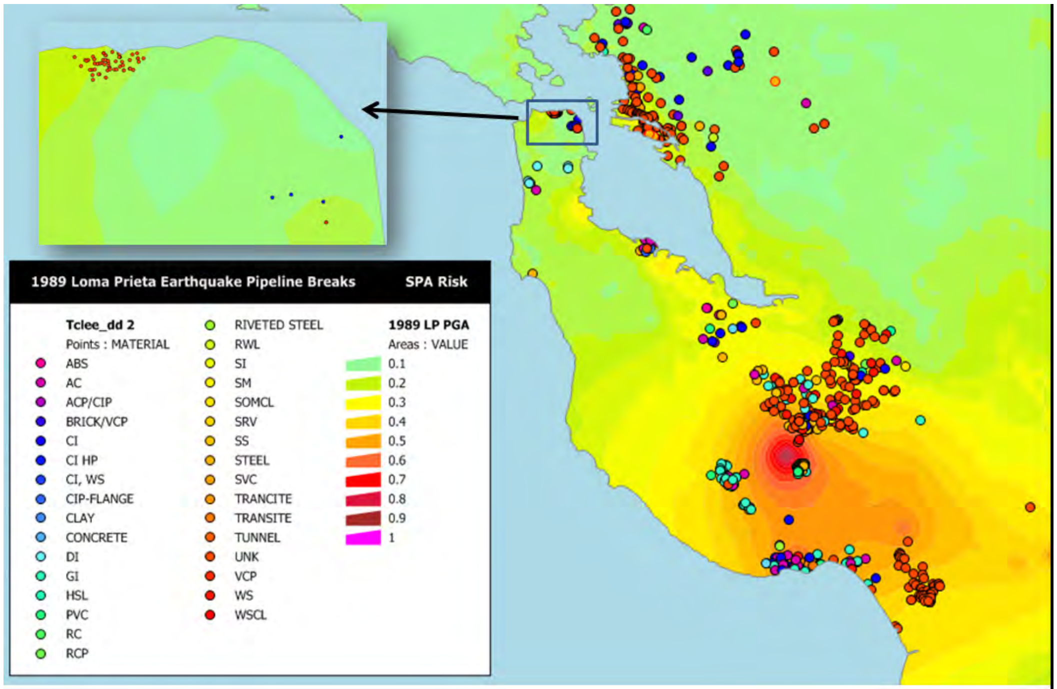

Figure 3 **1989 Loma Prieta earthquake water system pipe breaks overlaid on peak ground accelerations.**

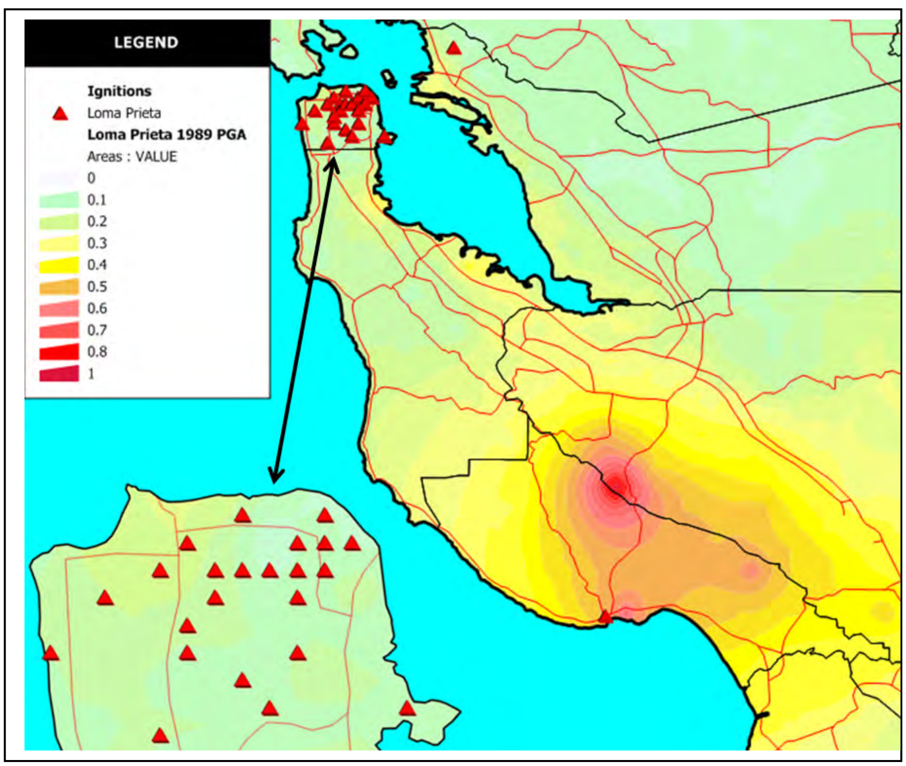

Figure 4 **1989 Loma Prieta earthquake ignitions overlaid on peak ground accelerations, with detail for San Francisco.**

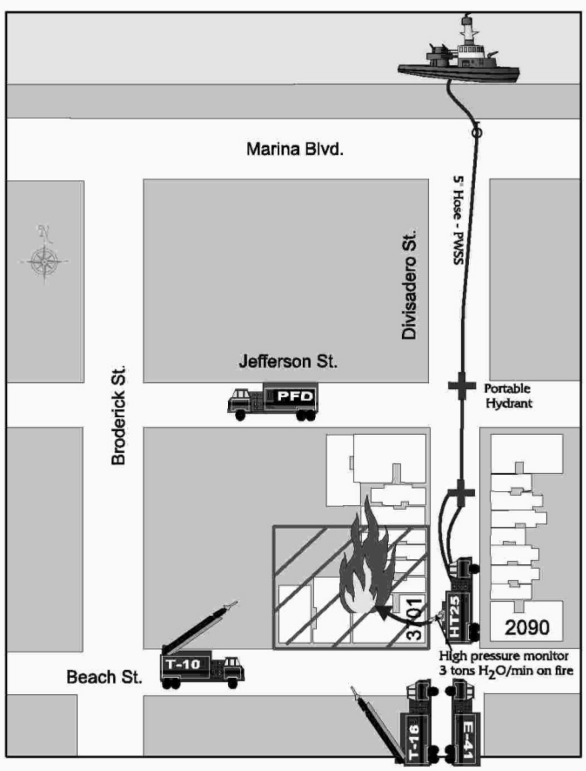

Figure 5 Detail of the Marina fire, San Francisco, 1989 Loma Prieta earthquake, showing proximity of fire to Bay to North.

Figure 6 Marina fire, 1989 Loma Prieta earthquake (source: www.sfmuseum.org).

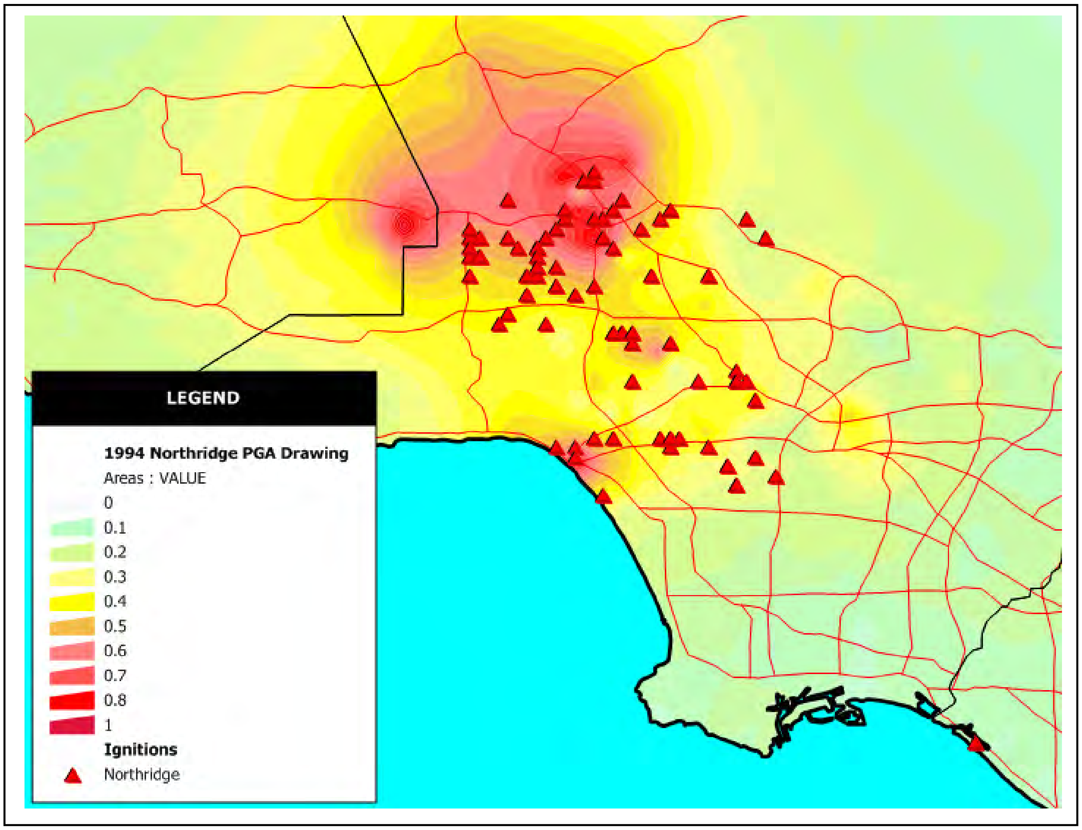

Figure 7 1994 Northridge earthquake ignitions overlaid on peak ground accelerations.

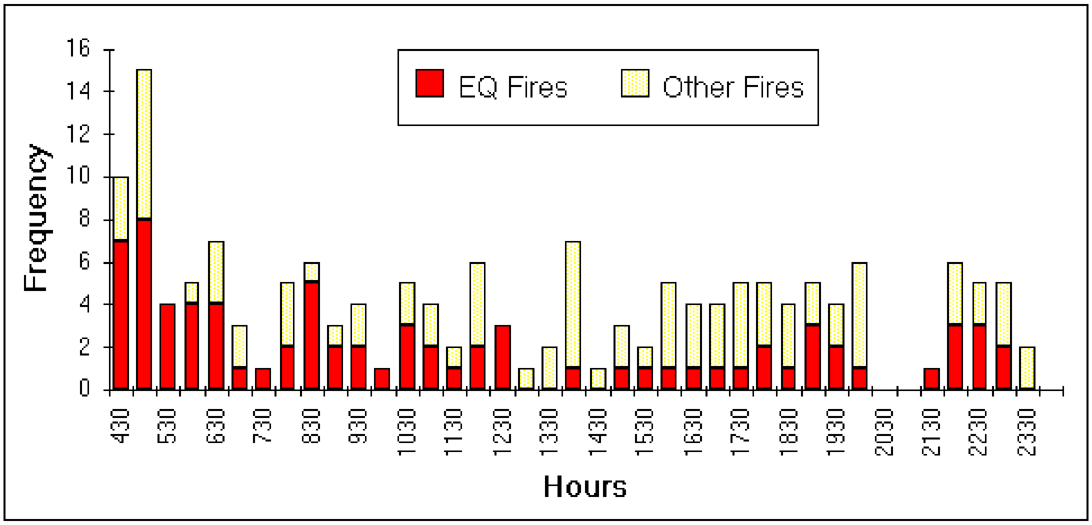

Figure 8 LAFD Fires, 4:31 to 24:00 hrs, January 17, 1994 (source: Scawthorn et al., 1997).

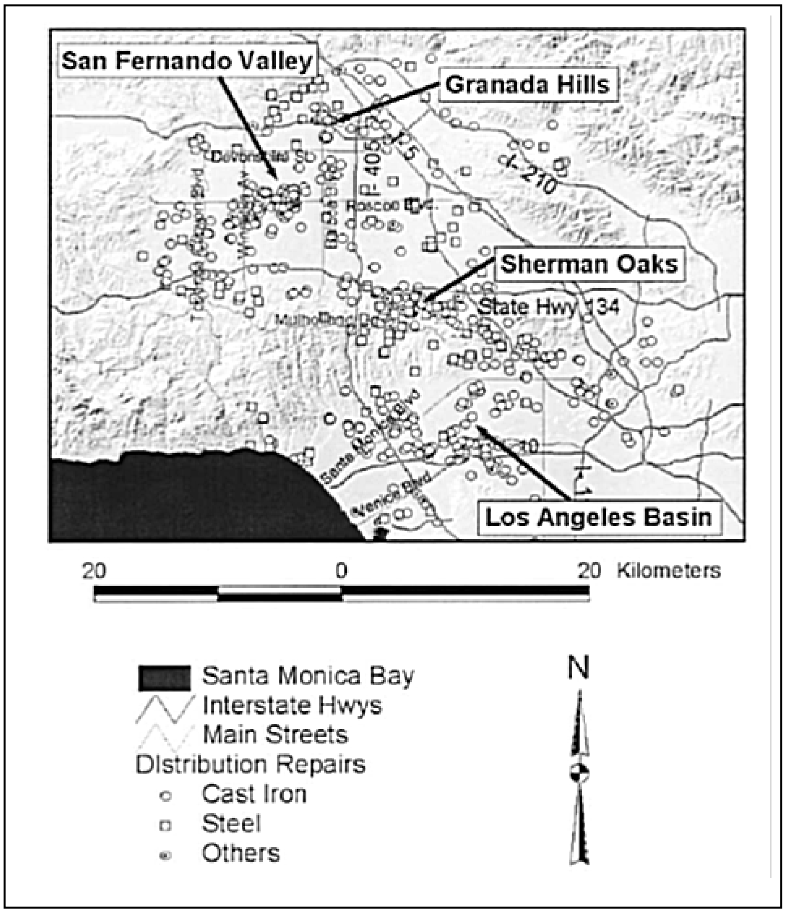

Figure 9 **LADWP pipeline breaks, 1994 Northridge earthquake (source: Jeon and O'Rourke, 2005).**

Figure 10 **North Balboa Boulevard fire, 1994 Northridge earthquake (source: www.americanprogress.org)(Jeon and O'Rourke, 2005).**

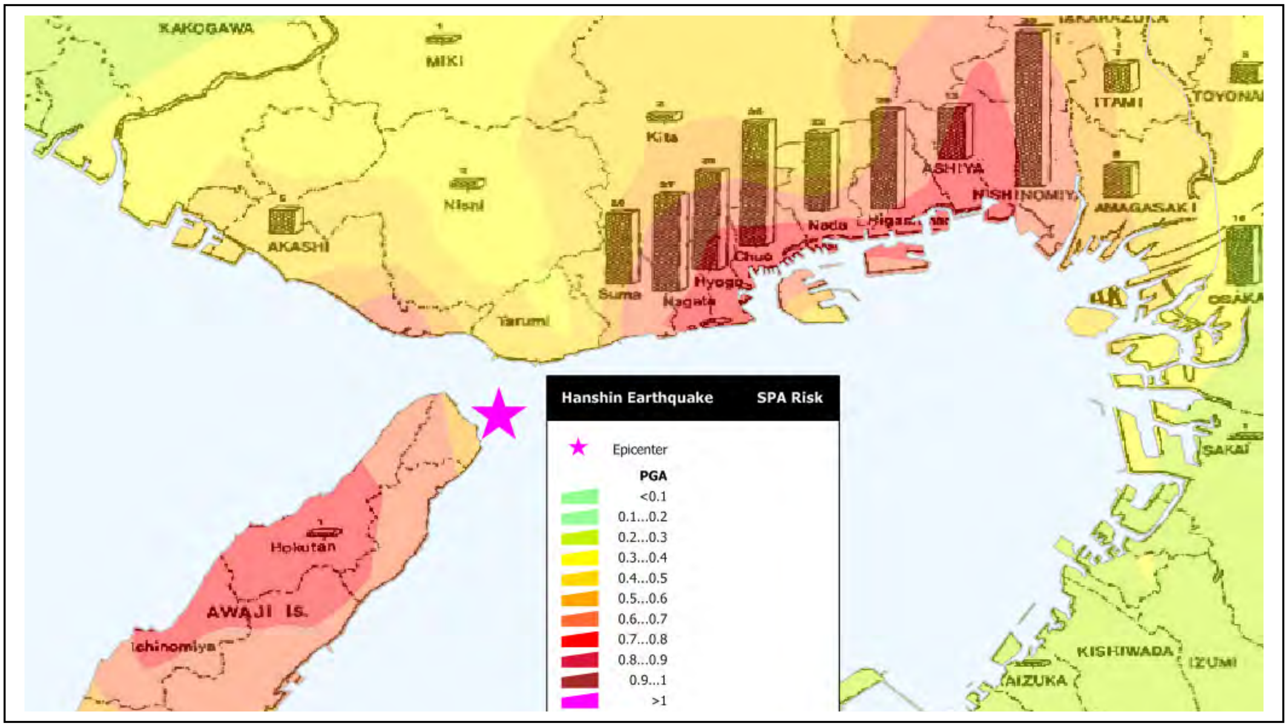

Figure 11 1995 Kobe earthquake fire occurrences overlaid on peak ground accelerations.

Figure 12 Aerial view, burnt area, 1995 Kobe earthquake.

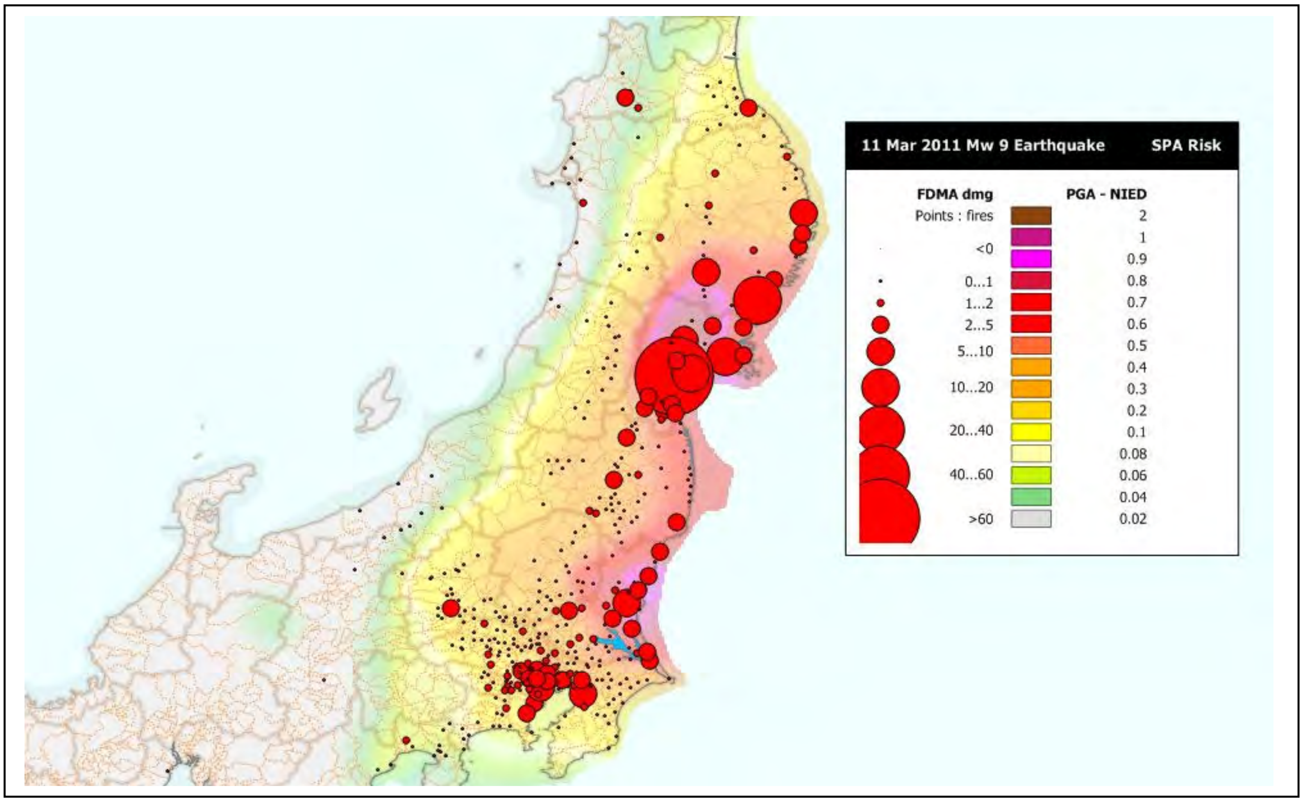

Figure 13 2011 Eastern Japan earthquake; ignitions overlaid on peak ground accelerations.

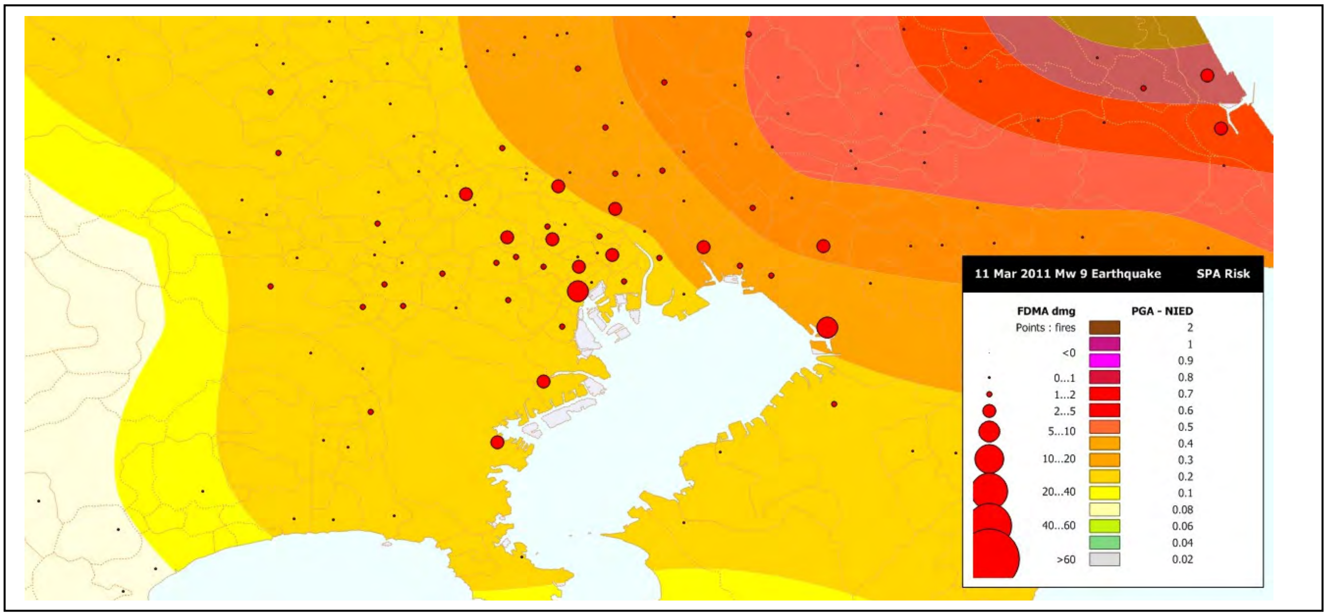

Figure 14 Detail of Tokyo area in 2011 Eastern Japan earthquake; ignitions overlaid on peak ground accelerations.

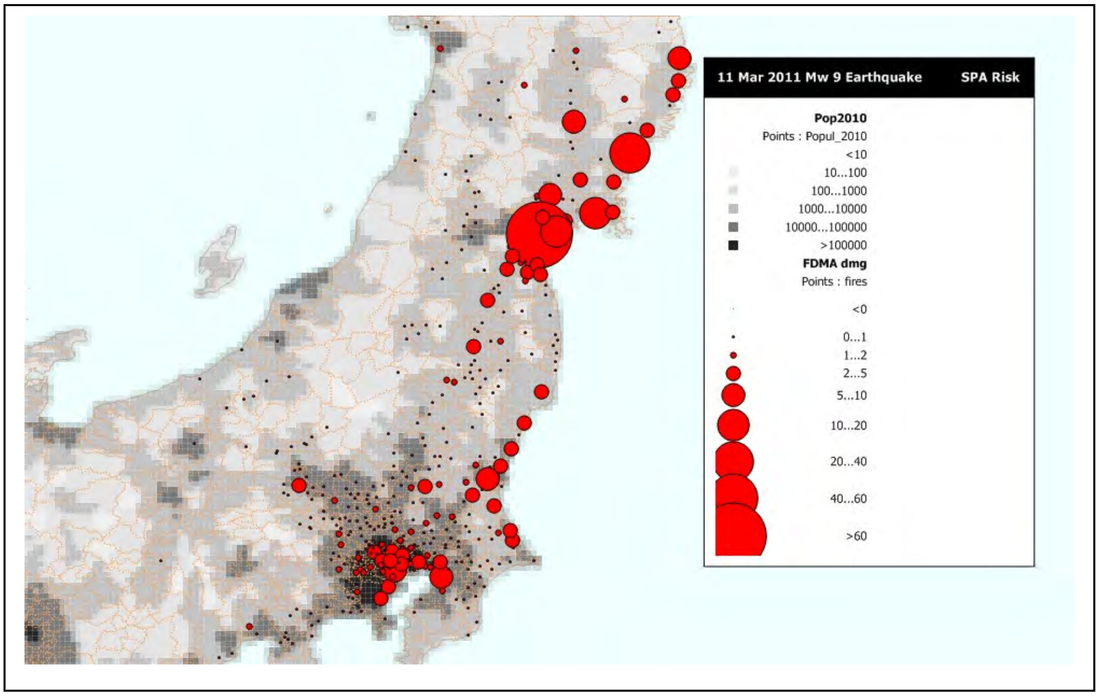

Figure 15 2011 Eastern Japan earthquake; ignitions overlaid on population density.

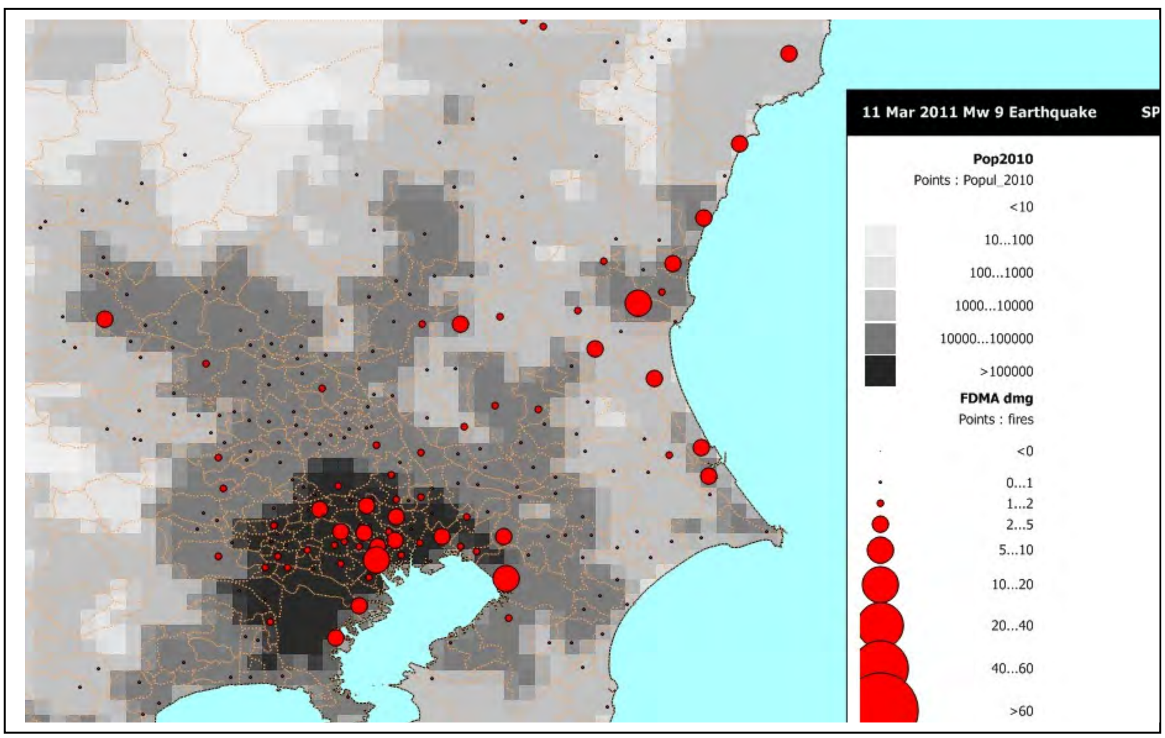

Figure 16 Detail of Tokyo in 2011 Eastern Japan earthquake; ignitions overlaid on population density.

Figure 17 Gas sphere ignition at Cosmo Refinery, Chiba, 2011 Eastern Japan earthquake (Source: www.planetsave.com).

Figure 18 View of fire, central Tokyo, 2011 Eastern Japan earthquake.

Figure 19 Japan oil refinery fire, Sendai, 2011 Eastern Japan earthquake.

Figure 20 Kessenuma conflagration, 2011 Eastern Japan earthquake.

Figure 21 **Foodstuffs warehouse fire, Port of Sendai, 2011 Eastern Japan earthquake (Source: C. Scawthorn).**

Figure 22 **Interior of warehouse above, 2011 Eastern Japan earthquake (source: C. Scawthorn).**

Figure 23 Damage to fire engine, Onagawa, 2011 Eastern Japan earthquake (source: C. Scawthorn).

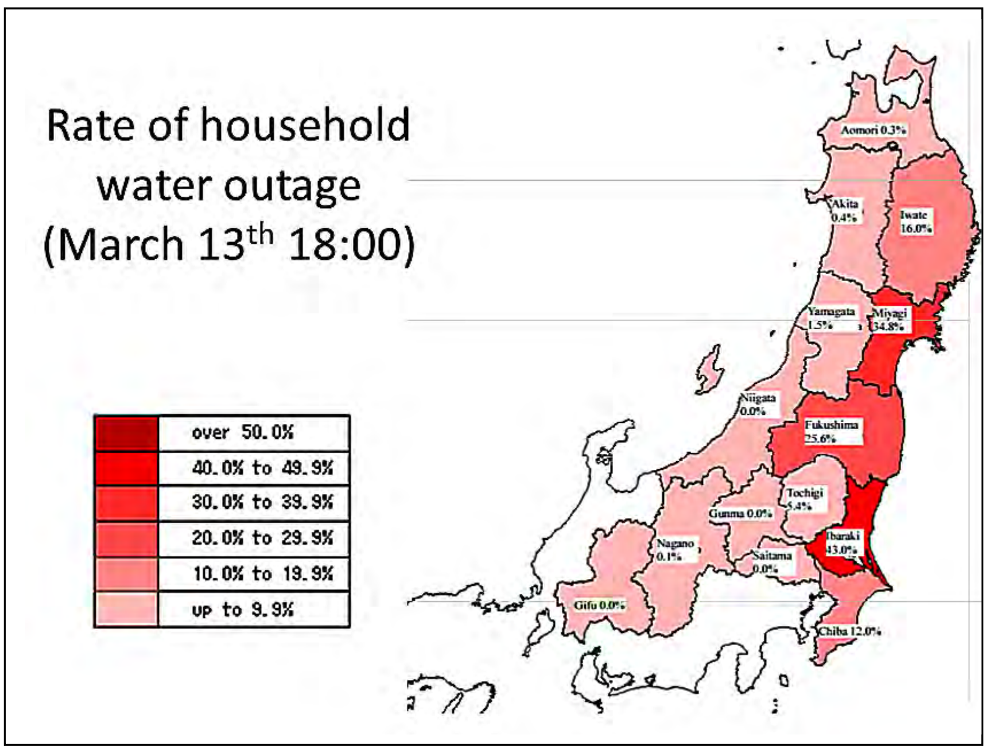

Figure 24 Rate of household water outage, 13 March 2011, Eastern Japan earthquake (source: S. Takada and M. Javanbarg).

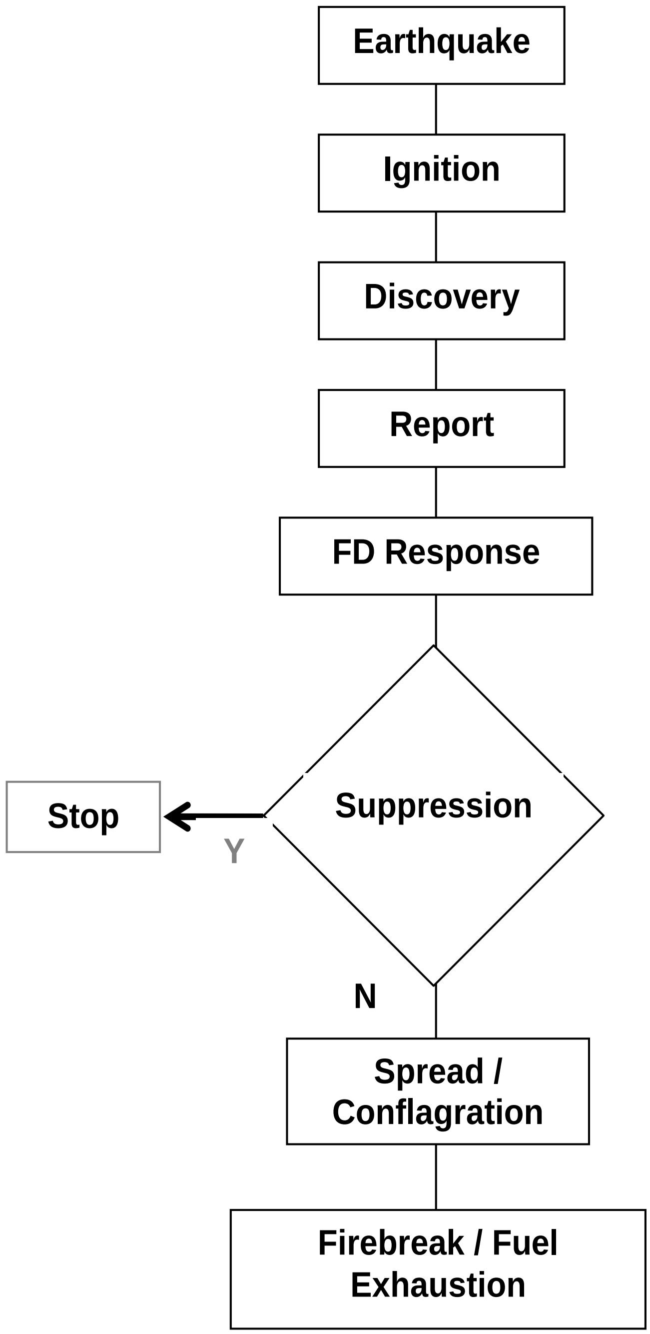

Figure 25 Fire following earthquake process.

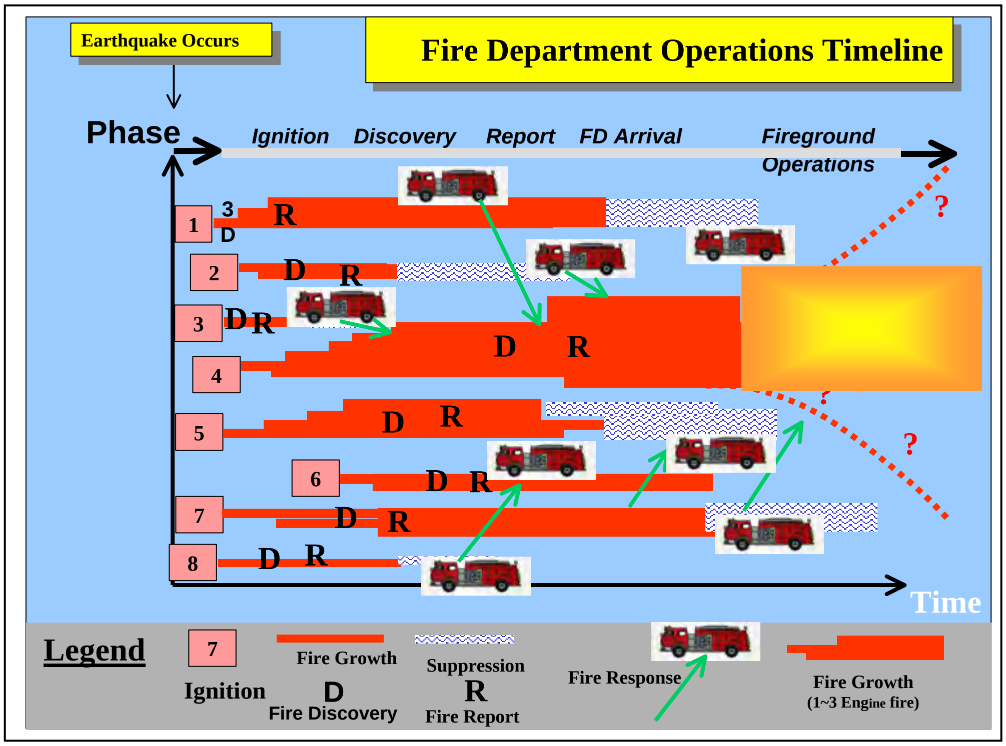

Figure 26 Fire department Operations Time Line.

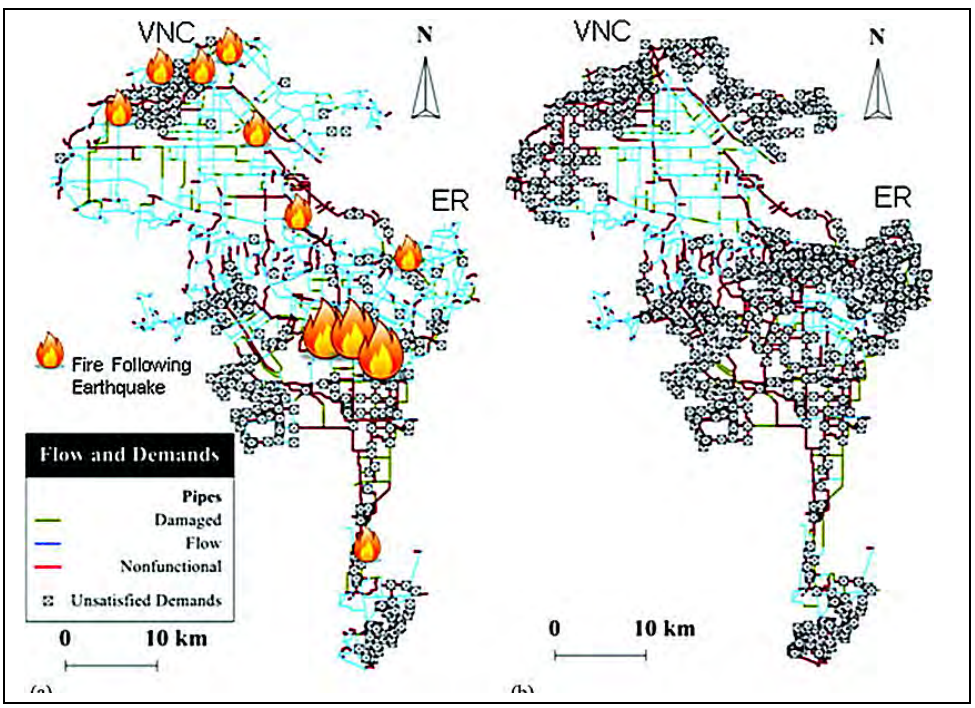

Figure 27 Plot of the major transmission pipelines in Los Angeles indicating system flow state and unsatisfied demands for: (a) 0 and (b) 24 hours after the earthquake. Predicted fire following earthquake locations, large fires and super conflagrations, are identified based on (Scawthorn, 2011b) VNC and ER are the Van Norman Complex and Eagle Rock Reservoir, respectively (source Davis and O'Rourke, 2011).

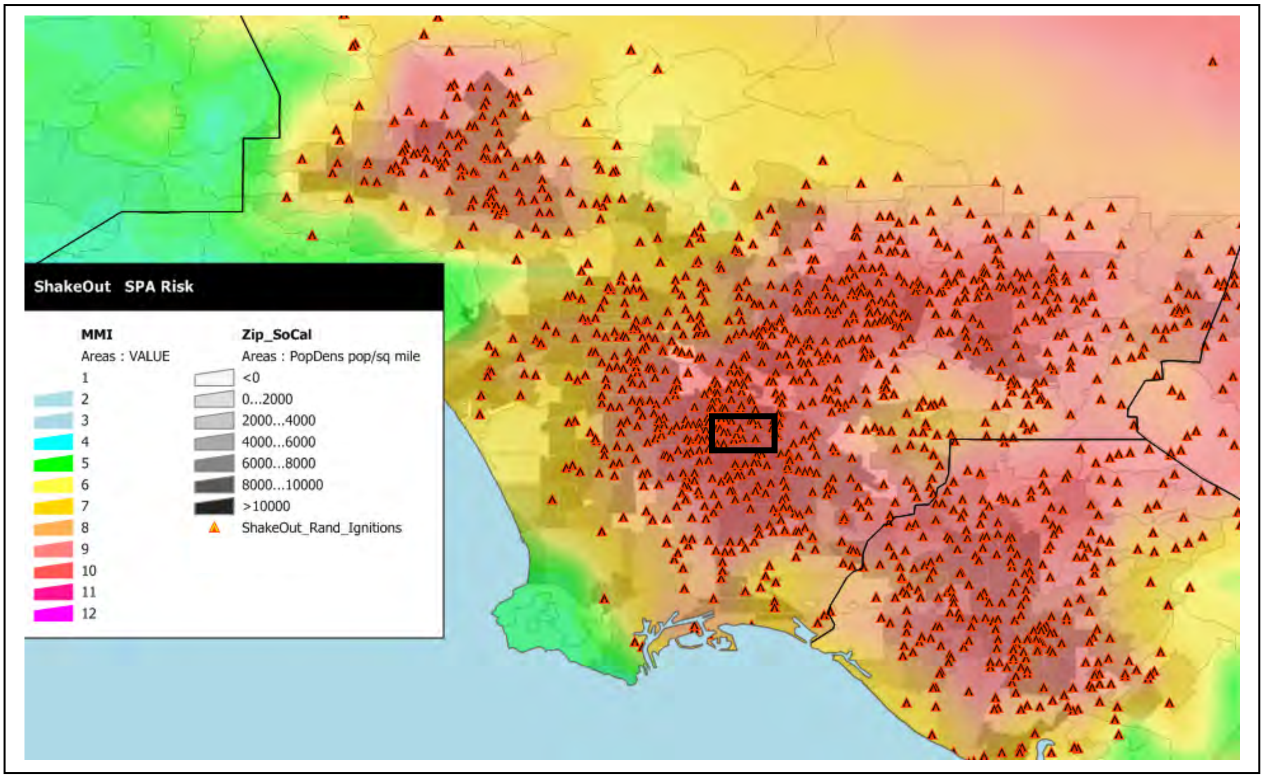

Figure 28 Ignitions (one trial) overlaid on MMI for M7.8 SOSAFE Scenario and Population Density by zip code, Central LA Basin (black rectangle corresponds to zip 90002) (source Scawthorn, 2011b).

Figure 29 A typical Los Angeles area, just north east of the 110-105 Freeway intersection, showing high density of wood buildings, typical of much of LA basin.

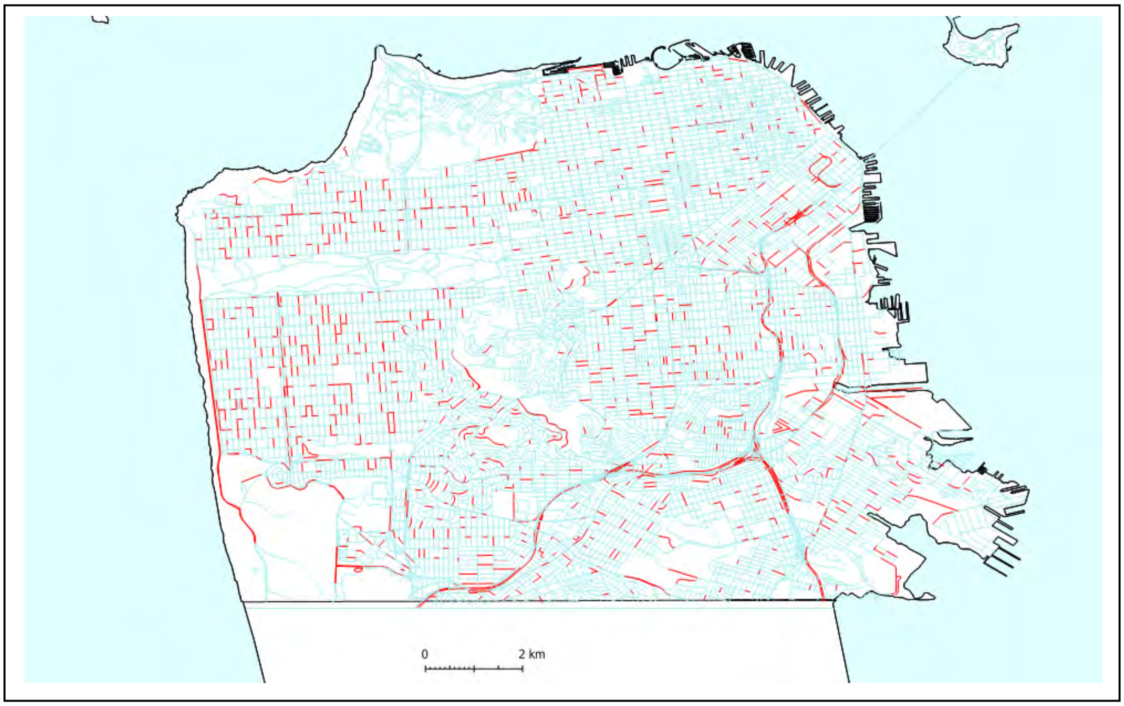

Figure 30 San Francisco proxy Municipal Water Supply System (i.e., potable water system) with estimated pipe sections with breaks shown in red, for San Andreas Mw 7.8 scenario. Note that the estimation of the pipe breaks is a random process, so that only the general distribution, and not specific locations, of breaks are meaningful.

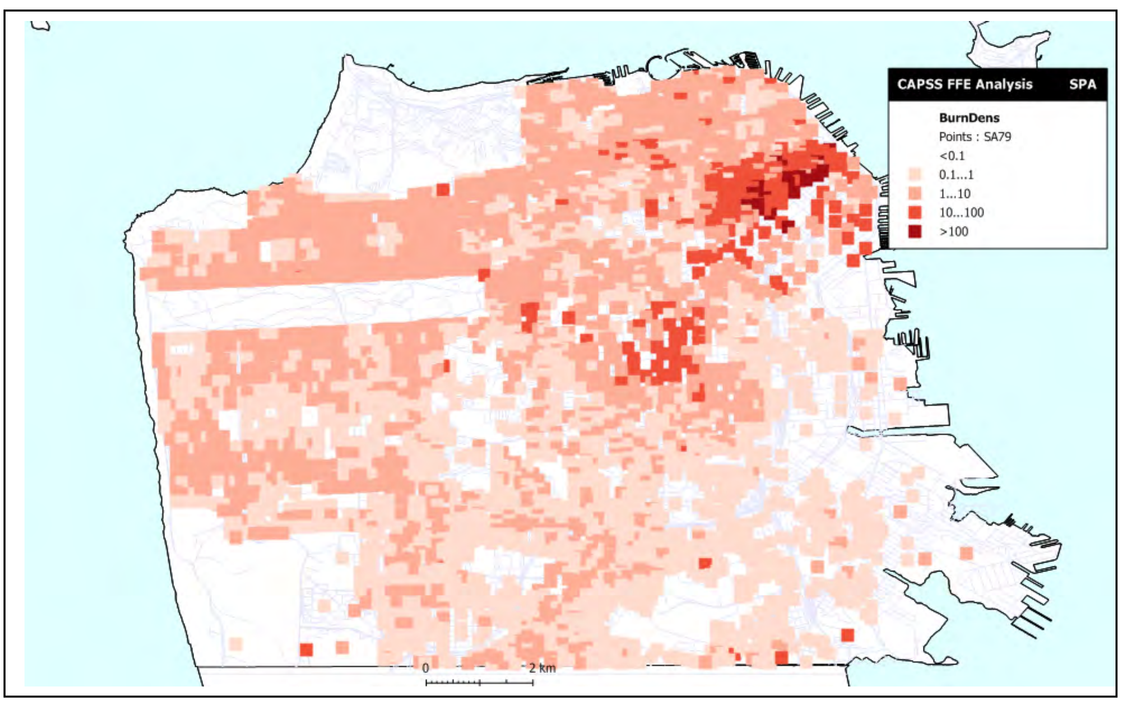

Figure 31 Distribution of Burn Density per block (millions $) for San Andreas Mw 7.8 Scenario.

Figure 32 Illustration of hard suction hose.

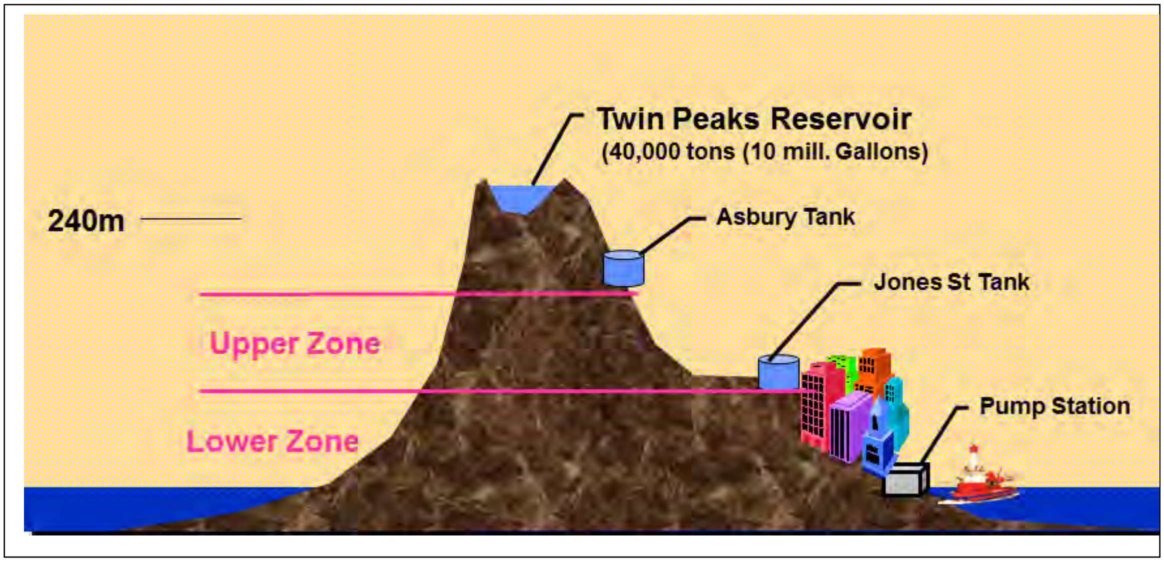

Figure 33 Schematic of San Francisco AWSS.

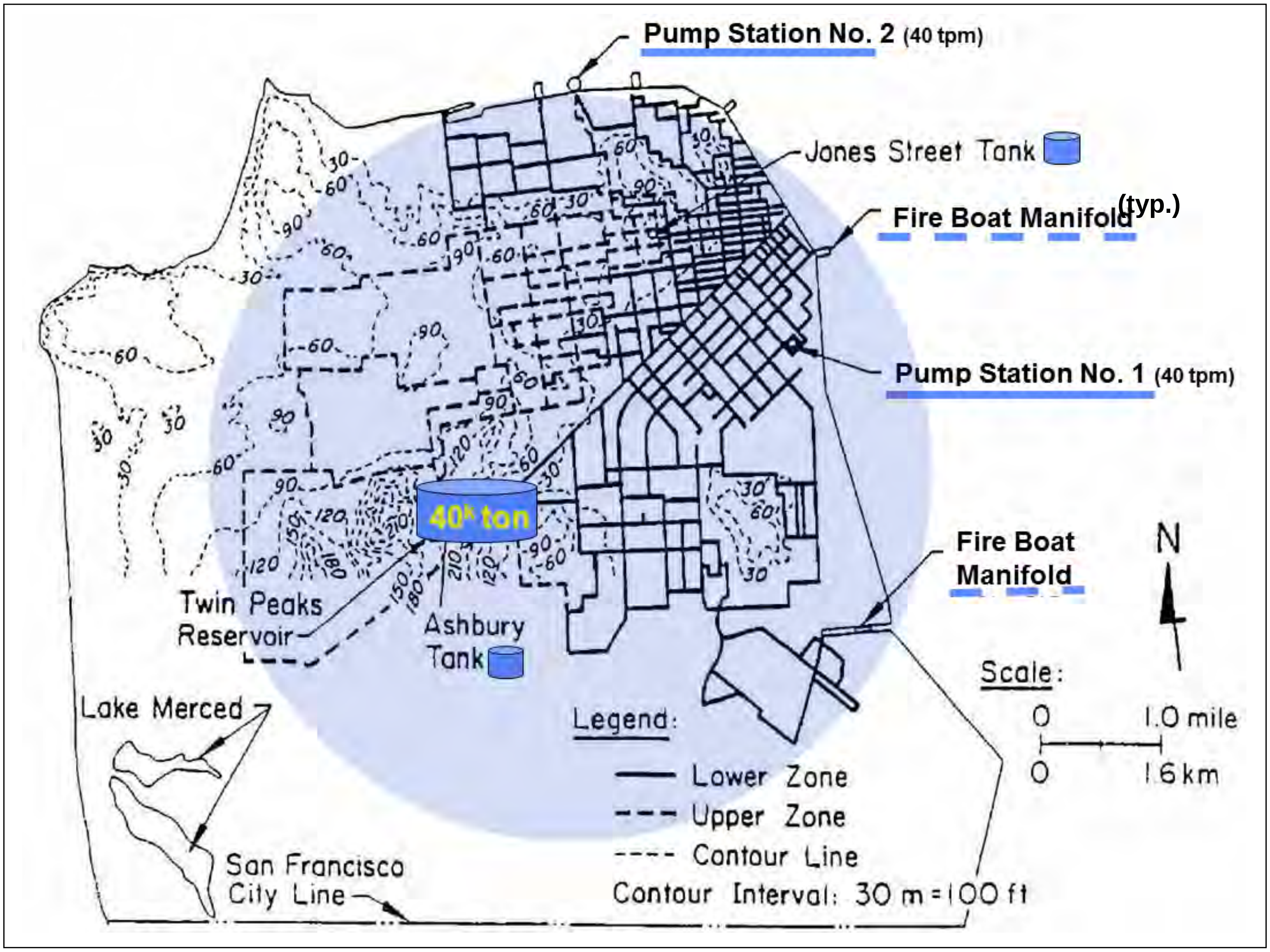

Figure 34 Plan View San Francisco AWSS.

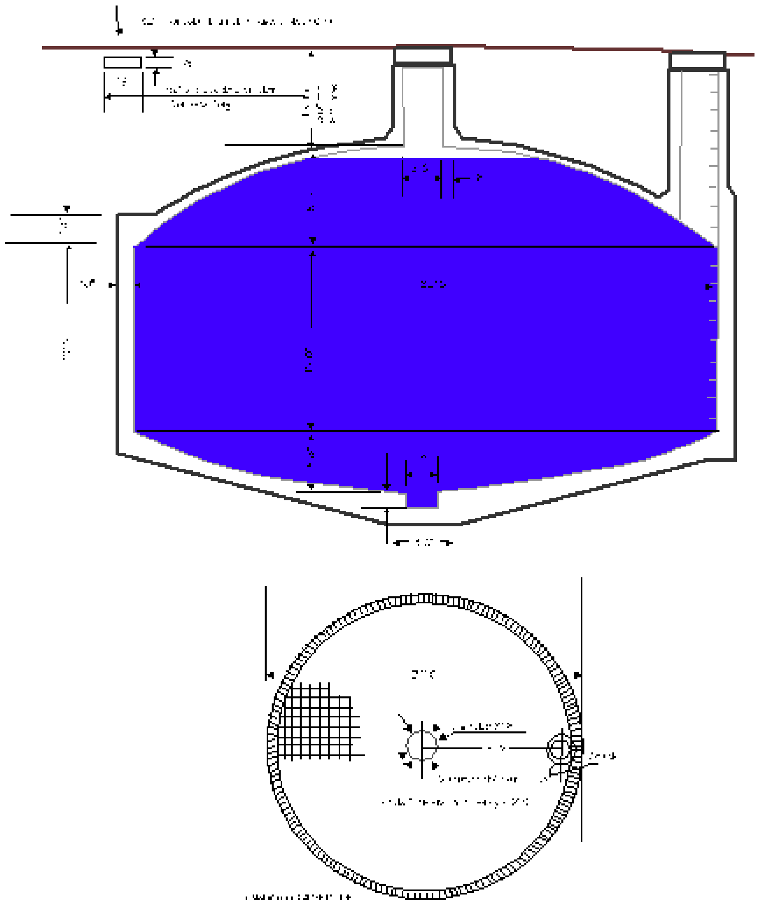

Figure 35 Typical San Francisco Fire Department cistern.

Figure 36 Typical San Francisco Fire Department cistern under construction.

Figure 37 San Francisco Fire Department drafting from cistern (using hard suction hose).

Figure 38 San Francisco Fireboats and fireboat manifold.

Figure 39 Plan of Vancouver, B.C. Dedicated Fire Protection System.

Figure 40 Vancouver, B.C. Dedicated Fire Protection System False Creek Pump Station (top) and Coal Harbor (bottom).

Figure 41 San Francisco, Oakland and Vallejo FD PWSS units.

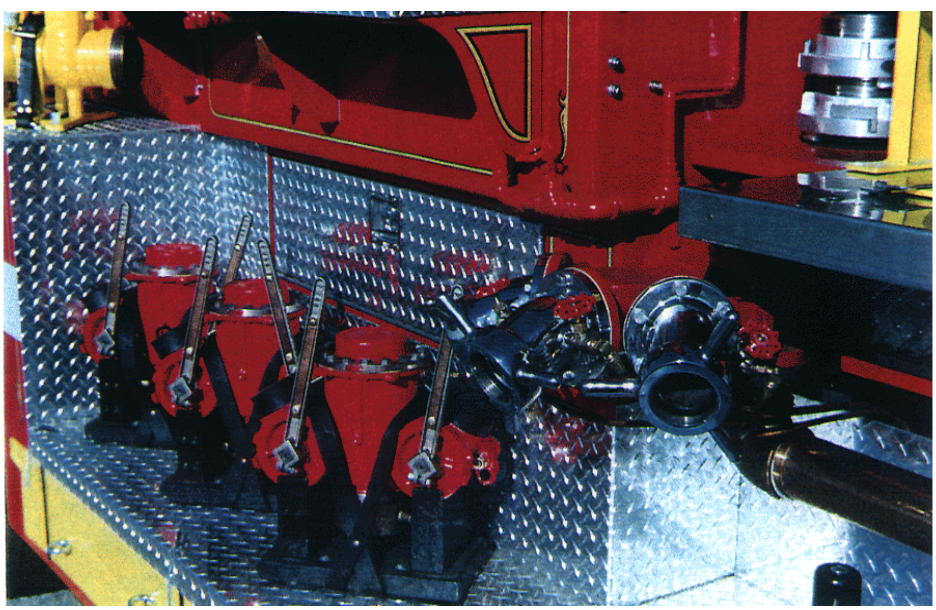

Figure 42 Detail of San Francisco Fire Department PSWW hose tender, showing Gleeson pressure reducing valves (red), portable hydrants (yellow, upper left and right), and hose ramps (yellow, lower left, slung under the rig).

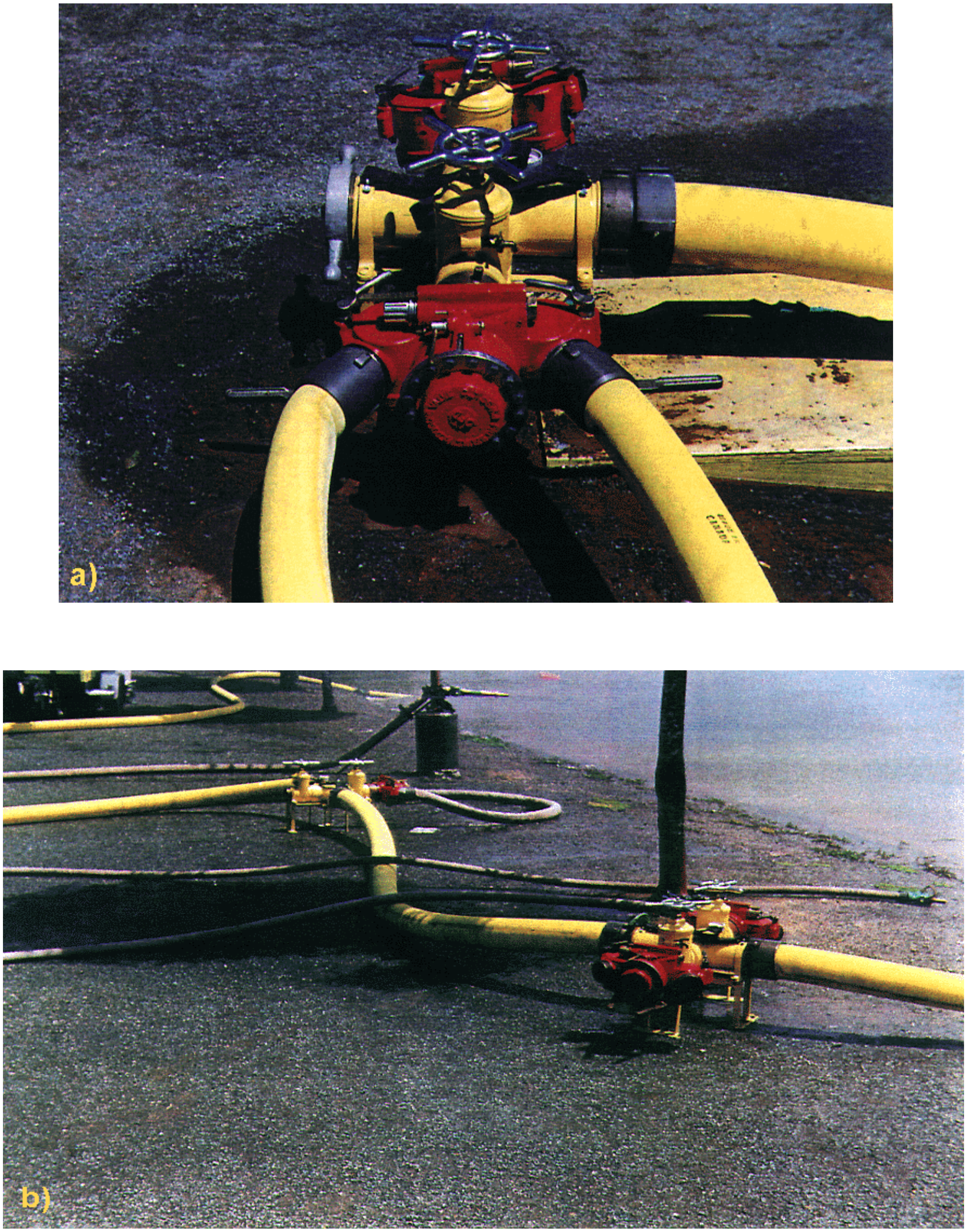

Figure 43 LDH, portable hydrants (yellow) and Gleeson pressure reducing valves (red). Note hose ramp in upper photo.

Figure 44 Berkeley FD BAWSS – (top) HydroSub unit, (mid) 12 inch Ultra LDH being flaked out from transporter-borne container, and (bottom) hose being reeled back into container.

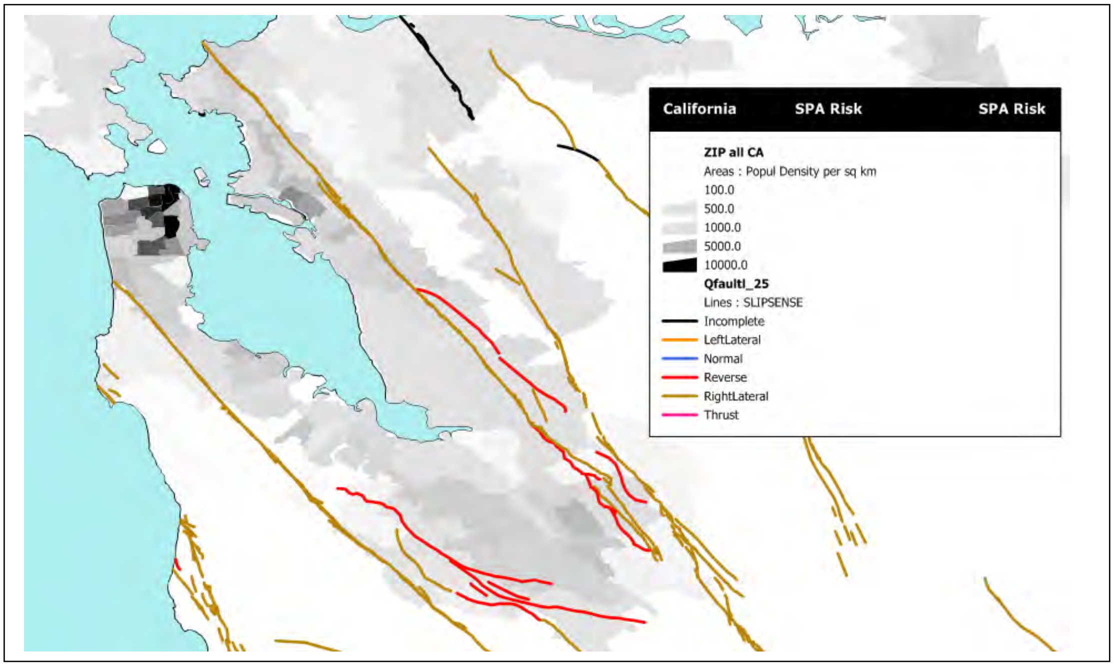

Figure 45 San Francisco Bay Area, population density and active faults.

Figure 46 First Interstate Bank Building fire, 1988.

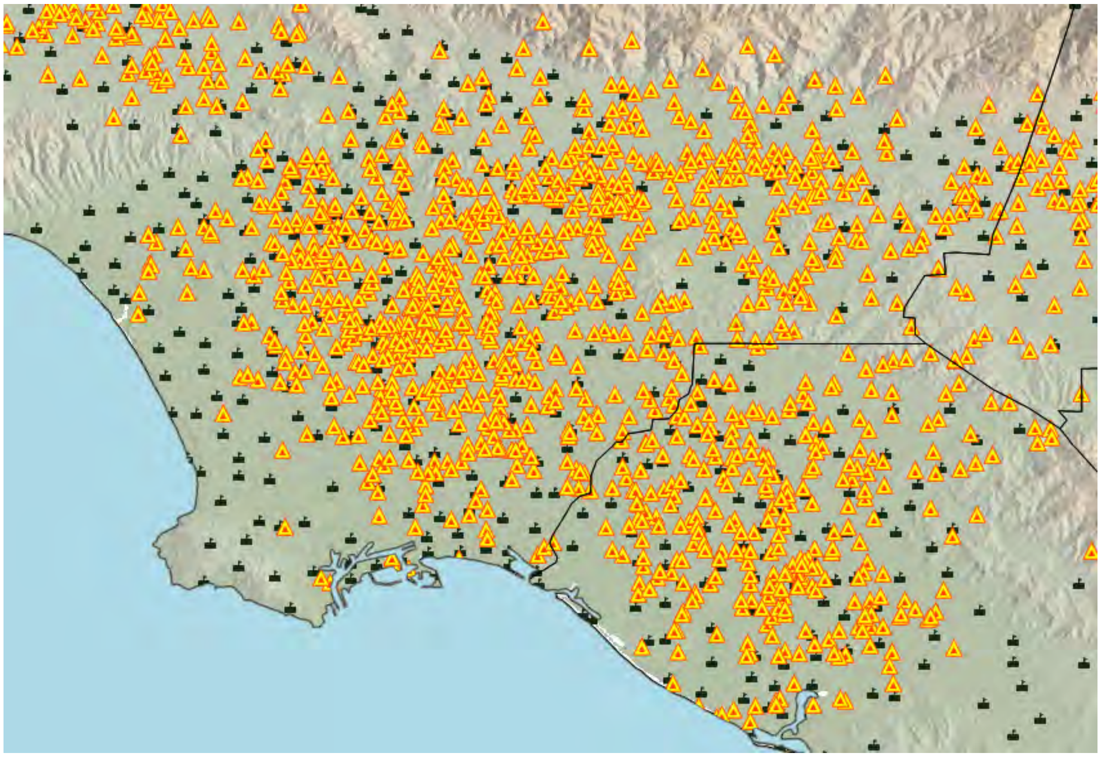

Figure 47 Los Angeles region; ignitions for ShakeOut Scenario (triangles) and fire stations.

Figure 48 Los Angeles: one of the larger storm drain channels.

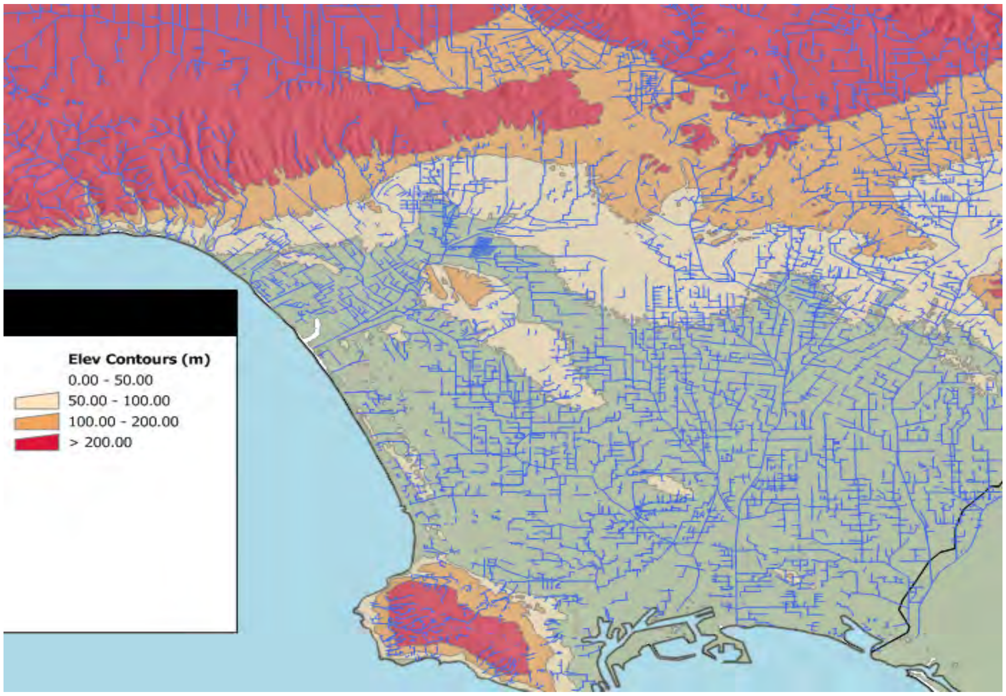

Figure 49 Los Angeles County storm drain channel network.

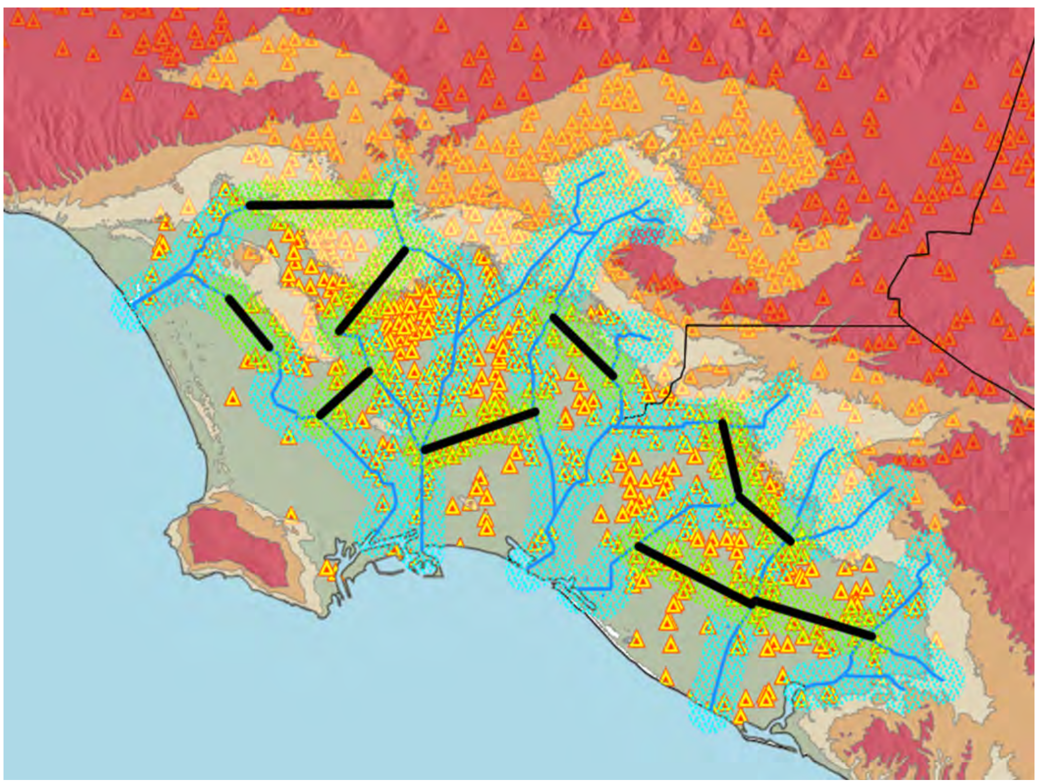

Figure 50 Selected existing larger Los Angeles and Orange County storm drain channels (blue lines) with connectors to be built (black lines) overlaid on ShakeOut scenario ignitions. Blue buffer zones around lines would be areas reachable by a PWSS.

Figure 51 San Francisco NERT equipment container cache.

Figure 52 Istanbul equipment container cache being placed in a neighborhood.

Figure 53 Typical San Francisco block in a more built-up portion of the city.

Figure 54 Aerial view of same block.

Figure 55 SFFD portable monitor deploying a water curtain (source: http://sfearthquakesafety.org/the-bond/firefighting-water-supply-system/).

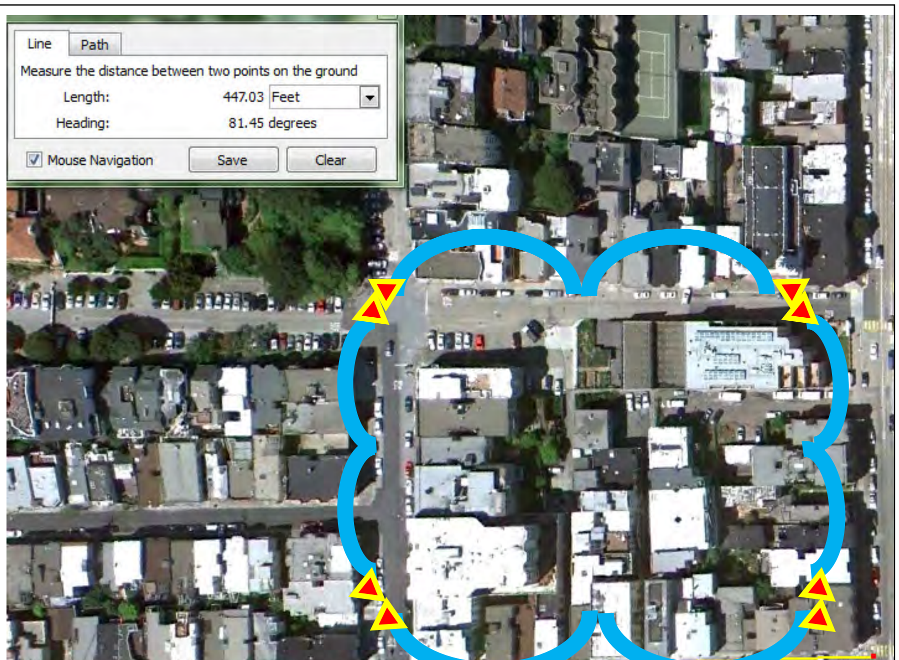

Figure 56 Water curtains deployed to contain a city block conflagration.

Appendix A – Fire Department Survey Form

Fire Dept Survey re Fire Following Earthquake

1. Introduction

This survey seeks to understand post-earthquake firefighting water supply reliability within California, and identify how it might be improved.

While California is *earthquake country*, major earthquakes don't happen every year but wildland fires do. However, when a major earthquake does occur in a large California city, it may be followed by multiple simultaneous ignitions that, combined with loss of water supply and communications and the other demands on the fire service such as search and rescue and EMS, may grow into one or more major urban conflagrations. While there are many critical aspects that contribute to the potential for urban conflagration, **loss of water supply is perhaps the most crucial issue.**

In order to address this issue, this survey is part of a project being conducted by the University of California's Pacific Earthquake Engineering Research Center (PEER) under the sponsorship of the **California Seismic Safety Commission** and the **California Emergency Management Agency**. The purpose of the survey is to understand emergency and alternative water supply preparedness within California, and identify how it might be improved. For further information on the overall project, go to Project Summary

This survey is brief – it shouldn't take you more than about 15 minutes to complete. Most of the questions are multiple-choice, but some provide opportunity for you to comment, as well as your being able to make a general comment at the end.

While we ask for your and your department's identity, the results of the survey will be collated such that **your individual specific responses will not be disclosed.** The survey results will be used to formulate a general understanding of how reliable California's firefighting water supplies are following a major earthquake – how much they can immediately be counted upon for fire suppression purposes – and what measures might be instituted to improve this post-earthquake reliability.

We thank you for your answers and participation in the survey, which we hope will contribute to improving California's earthquake preparedness.

Contact person for this survey is Charles Scawthorn

2. Basic Information

Please answer each of these questions (* indicates an answer required):

*** 1. What is the name of your fire department?**

2. What size population does your department protect?

*** 3. What is your name?**

*** 4. What is your rank?**

*** 5. What is your email?**

6. What is your telephone number?

3. Fire Following Earthquake

1. Does your department have a <u>quantitative estimate</u> of the number of damaged buildings, fire ignitions, damage to water supply and other impacts a major earthquake is likely to cause?

- ☐ Yes
- ☐ No
- ☐ Kind of - I'll explain further below

2. If so, what is a specific earthquake scenario you plan for? (please specify the earthquake fault or approximate zone, and magnitude).

3. And, if so, about how many fires do you estimate will occur?

4. Explain further or provide more detail if you wish

4. Water Supply

1. In a major earthquake, do you anticipate major loss of normal water supply will occur?

- ○ Yes
- ○ No
- ○ Do not know
- ○ I'll explain further below

2. If normal hydrants lack pressure, where and how will you obtain water for firefighting?

3. How far do you anticipate having to relay water, and how well equipped are you to do that?

4. For your typical urban fire engine (pumper), what is the largest diameter hose, and how many lengths (or feet) of that hose, is normally carried?

5. Do you engines carry hard suction hose?

- Yes
- No

6. If above answer was "No", is hard suction 'ready to go' in the stations?

- Yes
- No

7. If you wish to explain further regarding hard suction, please do so here:

8. When was the last time your department practiced relaying water more than one mile?

- ○ Within last 6 months
- ○ Within last year
- ○ Within last five years
- ○ Do not know

9. What special equipment does your department have for pumping or relaying water some distance?

- ☐ Section pipe (stored or emergency access, such as to quick connect irrigation pipe)
- ☐ Large Diameter Hose, in significant quantities beyond that carried on pumpers
- ☐ Large or special pumps
- ☐ Special pump stations and high pressure system
- ☐ Fire boat
- ☐ Other (explain further below)
- ☐ None

10. Does your department have an officer specifically identified as responsible for Water Supply?

- ○ Yes
- ○ No
- ○ Kind of - I'll explain further below

11. Does your department have regular disaster planning meetings with the Water Department?

- ○ Yes
- ○ No
- ○ Do not know

12. If so, how often are these meetings?

- Monthly
- Quarterly
- More than once a year
- Annually
- Every few years

13. Has your department identified Alternative Water Supplies for post-disaster firefighting (for example, swimming pools, reservoirs or tanks, creeks or bays)?

- Yes
- No
- Do not know
- Kind of - I'll explain further below

14. If so, are these sites tabulated or otherwise formally mapped or listed in Officer's reference materials? Are these sites easily accessed? How often are these sites involved in department drills?

- [ ] Yes, they are in Officer's reference materials
- [ ] No, they are not formally documented
- [ ] Yes, they are easily accessed
- [ ] It is not clear that these sites are easily accessed
- [ ] Drilled more than once a year
- [ ] Drilled less than once a year
- [ ] Almost never drilled

15. Please explain further or elaborate on any of the above questions:

5. Conclusion

Fire Dept Survey re Fire Following Earthquake

Thank you very much for participating in this survey. These final set of questions allow you to identify issues we've overlooked, and give us feedback.

1. How important is the fire following earthquake issue for your jurisdiction? What key things should your department be doing to improve its ability to respond?

2. Have we overlooked key issues? Was this survey about on target, or are we off target? How can it be improved?

Appendix B – Water Department Survey Form

Water Dept/Agency Survey re Fire Following Earthquake

1. Introduction

This survey is part of a project that seeks to understand water supply reliability within California, especially in regard to post-earthquake firefighting, and identify how it might be made more reliable.

While California is *earthquake country*, major earthquakes don't happen every year. However, when a major earthquake does occur in a large California city, it may be followed by multiple simultaneous ignitions that, combined with loss of water supply and communications and the other demands on the fire service such as search and rescue and EMS, may grow into one or more major urban conflagrations. While there are many critical aspects that contribute to the potential for urban conflagration, **loss of water supply is perhaps the most crucial issue.**

In order to address this issue, this survey is part of a project being conducted by the University of California's Pacific Earthquake Engineering Research Center (PEER) under the sponsorship of the **California Seismic Safety Commission** and the **California Emergency Management Agency**. The purpose of the survey is to understand emergency and alternative water supply preparedness within California, and identify how it might be improved. For further information on the overall project, go to Project Summary

This survey is brief – it shouldn't take you more than about 15 minutes to complete. Most of the questions are multiple-choice, but some provide opportunity for you to comment, as well as your being able to make a general comment at the end.

While we ask for your and your agency's identity, the results of the survey will be collated such that **your individual specific responses will not be disclosed.** The survey results will be used to formulate a general understanding of how reliable California's firefighting water supplies are following a major earthquake – how much they can immediately be counted upon for fire suppression purposes – and what measures might be instituted to improve this post-earthquake reliability.

We thank you for your answers and participation in the survey, which we hope will contribute to improving California's earthquake preparedness.

Contact person for this survey is Charles Scawthorn

2. Basic Information

Please answer each of these questions (* indicates an answer required):

*** 1. What is the name of your water department or agency?**

2. Approximately, what size population does your department or agency serve?

*** 3. What is your name?**

*** 4. What is your position?**

*** 5. What is your email address?**

6. What is your telephone number?

[ ]

3. Seismic Analysis

1. Has your department had a quantitative estimate of the damage to water supply and other direct impacts to the system, that a major earthquake is likely to cause?

- ○ Yes
- ○ No
- ○ Do Not Know
- ○ Sort of - I'll explain further below

4. Seismic Analysis (cont.)

1. If so, when was the analysis done?

- ○ in the last 10 years (i.e., post-2000)?
- ○ in the 90s?
- ○ in the 80s?
- ○ earlier

2. If so, what earthquake scenarios were analyzed? (please specify the earthquake faults or approximate zones, and magnitudes).

[ ]

3. What portions of the system or facilities were analyzed?

- ☐ Headquarters and/or offices, warehouses and other buildings?
- ☐ Major Transmission Lines?
- ☐ Terminal Reservoirs and/or Major Tanks?
- ☐ Water Treatment Plant(s)?
- ☐ Pump Stations?
- ☐ Local pressure or distribution reservoirs or tanks?
- ☐ Distribution System piping?

4. Were the results of the seismic analysis shared with the Fire Department and/or other emergency responders?

- ○ Yes
- ○ No
- ○ Do not know
- ○ I'll explain below

5. Please explain here any details of the seismic analysis you wish to share.

5. Seismic Upgrade

1. Has your system (or portions of it) had seismic upgrades or retrofits?

- ○ Yes
- ○ No
- ○ Do Not Know
- ○ Kind of - I'll explain below

6. Seismic Upgrade (cont.)

1. If so, what portions of the system or facilities were seismically upgraded?

- ☐ Headquarters and/or offices, warehouses and other buildings?
- ☐ Major Transmission Lines?
- ☐ Terminal Reservoirs and/or Major Tanks?
- ☐ Water Treatment Plant(s)?
- ☐ Pump Stations?
- ☐ Local pressure or distribution reservoirs or tanks?
- ☐ Distribution System piping?

2. Was concern about loss of water for post-earthquake firefighting one of the concerns that drove the seismic upgrading?

- ○ Yes
- ○ No - fire following earthquake was not explicitly considered
- ○ Sort of - I'll explain below

3. If the above answer was Yes, then:

- ☐ Was a specific analysis done of fires following earthquake, to inform how and what to upgrade?
- ☐ Was the fire department involved or consulted?
- ☐ Not Applicable - the answer was No (FFE was not considered)

4. Are the seismic upgrades substantially completed?

- ○ Yes
- ○ No - still on-going

5. What was the overall cost or budget for the seismic upgrading? Also, please explain any details about the seismic upgrading that you wish to share (or input a website, or email us attachments separately - our email is cscawthorn@berkeley.edu).

7. Earthquake Impacts

1. In a major earthquake, do you anticipate major loss of normal water supply will occur, in a significant portion of your service area? This might include loss of distribution piping pressure in one or more neighborhoods, even if transmission integrity is preserved.

- ○ Yes
- ○ No
- ○ Do not know
- ○ I'll explain further below

2. If the answer is Yes, has the Fire Department been informed of where and how water supply may be lost?

- Yes
- No
- Do Not Know
- Sort of - I'll explain below

3. If the answer was Yes, do you have estimates of when water supply for firefighting would be available or restored?

- Yes
- No
- Do Not Know
- Sort of - I'll explain below

4. If so, what is the estimate of approximately when water supply for firefighting would be restored?

- less than an hour
- less than 6 hours
- less than 12 hours
- less than 24 hours
- more than 24 hours

5. If normal hydrants lack pressure, do you have any specific alternatives for furnishing water for firefighting?

- Yes
- No
- Do Not Know
- Sort of - I'll explain further below

6. If so, what are the alternatives?

7. How well and in what manner is your agency equipped to relay water, if the water system in the vicinity of a fire lacks pressure?

8. When was the last time your department practiced relaying water more than one mile?

- ○ Within last 6 months
- ○ Within last year
- ○ Within last five years
- ○ Do not know

9. What special equipment does your department have for pumping or relaying water some distance?

- ☐ Section pipe (stored or emergency access, such as to quick connect irrigation pipe)
- ☐ Large Diameter Hose (please enter diameter and total length your agency has, in space in next question)
- ☐ Large or special pumps
- ☐ Special pump stations and high pressure system
- ☐ Other (explain further below)
- ☐ None

10. Please explain here any details you wish to share with us:

8. Water - Fire Agency Interaction

1. Does your department have a person specifically identified as responsible for Emergency Water Supply and/or liaising with the fire department?

- Yes
- No
- Kind of - I'll explain further below

2. Does your department have regular disaster planning meetings with the Fire Department?

- Yes
- No
- Do not know

3. If so, how often are these meetings?

- Monthly
- Quarterly
- More than once a year
- Annually
- Every few years

4. Please explain further or elaborate on any of the above questions:

9. Conclusion

Water Dept/Agency Survey re Fire Following Earthquake

Thank you very much for participating in this survey. These final set of questions allow you to identify issues we've overlooked, and give us feedback.

1. How important is the fire following earthquake issue for your jurisdiction? What key things should your department be doing to improve its ability to respond?

2. Have we overlooked key issues? Was this survey about on target, or are we off target? How can it be improved?

Appendix C – Insurance Industry Assessment of Water Supply for Fire Suppression

This Appendix provides background on the role of, and the methods employed by, the insurance industry in assessing municipal water supply for fire protection.

Background

The relationship between fire protection and insurance begin with the London Great Fire of 1666, prior to which London had no organized fire protection system. Subsequently, insurance companies formed private fire brigades to protect their clients' property, which were identified with fire insurance marks. In 1667, the City Council established the first fire insurance company , "The Fire Office". In the 18th and early 19th century, America followed suit, with Ben Franklin, George Washington and others serving as volunteer firefighters. However, it was not until 1853 that the first full-time paid professional fire department was established in the United States, in Cincinnati, OH[9].

In 1886 the state of New York created the Standard Form Fire Policy (also known as the "165 lines"), which became the basis for virtually all fire insurance policies in the U.S. The significance of the Standard Fire Policy is that it followed British insurance practice which, since the Great Fire of 1666, had provided cover for fire due to all causes except those specifically excluded. Since earthquakes were almost non-existent in Britain, they were not specifically excluded in British policies, and this practice extended to all English-speaking countries, including the U.S. As a consequence, while the peril of earthquake has to be specifically included as a rider to the building's insurance policy, in the U.S. fire following earthquake is covered under the normal fire policy.

As fire insurance companies grew, they were in need of more and more data to inform their risk decision-making. This thirst for data led to the development of insurance mapmaking companies[10], and the growth in the U.S. of numerous fire rating bureau, such as the Pacific Fire Rating Bureau (PFRB) headquartered in San Francisco, and the National Board of Fire Underwriters (NBFU, founded in 1866). Following a spate of conflagrations including the great

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[9] http://www.cincinnati-oh.gov/cityfire/pages/-6664-/

[10] http://www.lib.umd.edu/NTL/Sanbornhistory.html

Baltimore fire of 1904, the NBFU expanded its scope and developed the Municipal Inspection and Grading System. Under that program, engineers evaluated the fire potential of many cities. In response, those cities improved their public fire-protection services. By mid 20th century this development of and compliance with good municipal fire service practice had caused the great urban conflagrations of the 19th and 20th centuries, such as 1871 Chicago, 1904 Baltimore and 1905 San Francisco, to become a thing of the past.

In 1971 a number of underwriting service organizations, including PFRB and NBFU were merged into the Insurance Services Office (ISO). As ISO notes:

> *Since 1909, the Municipal Inspection and Grading System and its successors have been an important part of the underwriting and rating process for insurers writing personal and commercial fire policies. ISO's Public Protection Classification (PPC™) Service is a direct descendent of the earlier grading systems. The PPC program gives insurers credible data to help them develop premiums that fairly reflect the risk of loss in a particular location…*
>
> *ISO collects information on municipal fire-protection efforts in communities throughout the United States. In each of those communities, ISO analyzes the relevant data using our Fire Suppression Rating Schedule (FSRS). We then assign a Public Protection Classification from 1 to 10. Class 1 generally represents superior property fire protection, and Class 10 indicates that the area's fire-suppression program doesn't meet ISO's minimum criteria.*
>
> *By classifying communities' ability to suppress fires, ISO helps the communities evaluate their public fire-protection services. The program provides an objective, countrywide standard that helps fire departments in planning and budgeting for facilities, equipment, and training. And by securing lower fire insurance premiums for communities with better public protection, the PPC program provides incentives and rewards for communities that choose to improve their firefighting services. ISO has extensive information on more than 47,000 fire-response jurisdictions.*

With regard to water supply, ISO's main activity is its review of available public fire suppression facilities via its *Fire Suppression Rating Schedule* (FSRS), in order to develop a Public Protection Classification for fire insurance rating purposes. The FSRS measures the major elements of a city's fire suppression system. These measurements are then developed into a Public Protection Classification number on a relative scale from 1 to 10, with 10 representing less than the minimum recognized protection. The Schedule is a fire insurance rating tool, and is not intended to analyze all aspects of a comprehensive public fire protection program, nor for purposes other than insurance rating.

We next briefly discuss the FSRS.

Fire Suppression Rating Schedule (FSRS)[11]

[11] excerpted from http://www.isomitigation.com

The Fire Suppression Rating Schedule (FSRS) is a manual containing the criteria ISO uses to calculate a total score on a scale of 0 to 100, based on three main areas of a community's fire-protection program:

Fire alarms

Ten percent of a community's overall score is based on how well the fire department receives and dispatches fire alarms. Our field representatives evaluate:

- the communications center, including the number of operators at the center
- the telephone service, including the number of telephone lines coming into the center
- the listing of emergency numbers in the telephone book
- the dispatch circuits and how the center notifies firefighters about the location of the emergency

Fire department

Fifty percent of the overall score is based on the fire department. ISO reviews the distribution of fire companies throughout the area and checks that the fire department tests its pumps regularly and inventories each engine company's nozzles, hoses, breathing apparatus, and other equipment. ISO also reviews the fire-company records to determine things such as:

- type and extent of training provided to fire company personnel
- number of people who participate in training
- firefighter response to emergencies
- maintenance and testing of the fire department's equipment

Water supply

Forty percent of the overall score is based on the community's water supply. This part of the survey focuses on whether the community has sufficient water supply for fire suppression beyond daily maximum consumption. ISO surveys all components of the water-supply system, including pumps, storage, and filtration. We observe fire-flow tests at representative locations in the community to determine the rate of flow the water mains provide. We also review the condition and maintenance of fire hydrants. Last, we count the distribution of fire hydrants no more than 1,000 feet from the representative locations.

These three aspects are summarized in Table 9, where it can be seen that 35% of the overall schedule is weighted towards adequacy of water supply.

Adequacy of Water Supply and Needed Fire Flow

In the FSRS, the adequacy of water supply is scored as ratio of the sum of the furnished water supply from hydrants or cisterns at various locations, termed Capability of Water System at Test Location at location “i” (ΣTLCi) to the sum of Needed Fire Flows (ΣNFFi). That is,

$$CSS = \frac{TLC}{NFF} \times 35$$

$$TLC = \sum_{i=1}^{n} TLC_i \text{, where n = number of test locations.}$$

$$NFF = \sum_{i=1}^{n} NFF_i \text{, where n = number of test locations.}$$

and the factor of “35” in the first equation reflects the 35% weight assigned to the Credit for Supply System (CSS). In this, TLC is the minimum of NFF, or the Supply Works Capacity (i.e., the capacity of water sources), or the Mains Capacity (i.e., the capacity deliverable by the water main system) or the Hydrant Distribution (i.e., the capacity deliverable by hydrants within 1,000 ft. of the location).

- The primary guide for determination of the water supply needed for public fire protection – that is, the NFF – is the ISO *Guide for Determination of Needed Fire Flow* (“Guide”) which can be obtained online at http://www.isomitigation.com/downloads/ppc3001.pdf .

The Guide is 34 pages in length, and only key points are excerpted and summarized here. As the Guide’s Foreword notes:

> *ISO has prepared this guide as an aid in estimating the amount of water that should be available for municipal fire protection. ISO calls this the needed fire flow. This publication is only a guide and requires knowledge and experience in fire protection engineering for its effective application.*

and its Preface states:

> *ISO is the premier source of information, products, and services related to property and liability risk. For a broad spectrum of types of insurance, ISO provides statistical, actuarial, underwriting, and claims information and analyses; consulting and technical services; policy language; information about specific locations; fraud-identification tools; and data processing. In the United States and around the world, ISO serves insurers, reinsurers, agents, brokers, self-insured, risk managers, insurance regulators, fire departments, and other governmental agencies.*
>
> *One of ISO's important services is to evaluate the fire suppression delivery systems of jurisdictions around the country. The result of those reviews is a classification number that ISO distributes to insurers. Insurance companies use the Public Protection Classification (PPC™) information to help establish fair premiums for fire insurance – generally offering lower premiums in communities with better fire protection.*
>
> *ISO uses the Fire Suppression Rating Schedule (FSRS) to define the criteria used in the evaluation of a community's fire defenses. Within the FSRS, a section titled "Needed Fire Flow" outlines the methodology for determining the amount of water necessary for*

providing fire protection at selected locations throughout the community. ISO uses the needed fire flows to:

*1. Determine the community's "**basic fire flow." The basic fire flow is the fifth highest needed fire flow in the community. ISO uses the basic fire flow to determine the number of apparatus, the size of apparatus fire pumps, and special fire-fighting equipment needed in the community.*** [emphasis added]

2. Determine the adequacy of the water supply and delivery system. ISO calculates the needed fire flow for selected properties and then determines the water flow capabilities at these sites. ISO then calculates a ratio considering the need (needed fire flow) and the availability (water flow capability). ISO uses that ratio in calculating the credit points identified in the FSRS.

ISO developed the needed fire flow through a review of actual large-loss fires. ISO recorded the average fire flow and other important factors, including construction type, occupancy type, area of the building, and exposures. Those factors are the foundation of the needed fire flow formula.

The following pages include a number of excerpts from another ISO document, the Specific Commercial Property Evaluation Schedule (SCOPES). ISO uses the SCOPES manual to weigh features of individual properties for the purpose of defining the building's vulnerability to fire loss. Insurers also use this information in their underwriting and ratemaking decisions.

To estimate the amount of water needed to fight a fire in an individual, nonsprinklered building, ISO uses the basic formula:

$$NFF = (Ci)(Oi)[(1.0+(X+P)i]$$

where

NFFi = the needed fire flow in gallons per minute (gpm)

Ci = a factor related to the type of construction = 18F $(Ai)^{0.5}$, where Ai is the effective area of the subject building (sq. ft.) and F is a coefficient related to the class of construction

Oi = a factor related to the type of occupancy

X = a factor related to the exposure buildings

P = a factor related to the communication between buildings

That is, the NFF is essentially a function of the size of the building (Ai), its material of construction (F), its occupancy (Oi), neighboring or ‘exposure’ buildings (X) and potential for pathways for fire between buildings (communication, P).

The NFF as calculated using this equation is constrained, as follows:

- The value of Ci shall not exceed
  - 8,000 gpm for Construction Class 1 and 2
  - 6,000 gpm for Construction Class 3, 4, 5, and 6

    - 6,000 gpm for a 1-story building of any class of construction

- The value of Ci shall not be less than 500 gpm.

- ISO rounds the calculated value of Ci to the nearest 250 gpm.

where Class 1 is wood frame construction, Class 6 is fire-resistive construction), and increasing class generally corresponds to lower combustibility.

- The maximum needed fire flow is 12,000 gpm. The minimum is 500 gpm.

- ISO rounds the final calculation of needed fire flow to the nearest 250 gpm if less than 2,500 gpm and to the nearest 500 gpm if greater than 2,500 gpm.

- For 1- and 2-family dwellings not exceeding 2 stories in height, ISO uses the following needed fire flows:

DISTANCE BETWEEN BUILDINGS NEEDED FIRE FLOW

More than 100'	500 gpm
31-100'	750 gpm
11-30'	1,000 gpm
10' or less	1,500 gpm

- For other types of habitational buildings, the maximum needed fire flow is 3,500 gpm.

Substantial data and expertise is involved in properly determining the values of these factors, and the reader is referred to the Guide for more detail.

While essentially empirical, the basic NFF calculation captures relevant factors in a rational approach, and has proven reasonably accurate and conservative in practice.

The NFF is a subsidiary calculation that feeds into ISO's *Fire Suppression Rating Schedule* (*http://www.isogov.com/services/infrastructure/docs/FSRSWaterSupplySection.pdf*), which The FSRS has three main parts — Fire Alarm and Communications (10%), the Fire Department (50%), and Water Supply (40%) — which reference nationally, recognized standards developed by the National Fire Protection Association and the American Water Works Association. Of particular relevance here is section 604 of the Water Supply portion of the FSRS, which states:

> ***604. FIRE FLOW AND DURATION:*** *The fire flow duration should be 2 hours for Needed Fire Flows (NFF_i) up to 2,500 gpm, and 3 hours for Needed Fire Flows of 3,000 and 3,500 gpm.*

Therefore, if the NFF is determined to be 2,500 gpm, two hours duration corresponds to 300,000 gallons, while 3 hours duration at 3,500 gpm corresponds to 630,000 gallons. For fire flows in excess of 3,500 gpm, the specified durations is four hours so that, for example, if the NFF is the maximum of 12,000 gpm and it is required for example for 4 hours, the total required amount of water would be 2.88 million gallons.

Note that most urban fire engines today typically have a maximum pumping capacity of 1,200 to 1,500 gpm, so that a fire flow duration corresponding to a NFF of 2,500 gpm corresponds to two engines pumping at capacity for two hours, three engines for three hours for fire flow duration corresponding to a NFF of 3,500 gpm, and 12,000 gpm would correspond to about ten fire engines pumping at capacity for four hours.

NFF and Earthquake

All of the above has been by way of background, to illustrate how fire departments and insurers approach the issue of water supply for 'normal' situations – that is, a fire in a building when fire engines can arrive in a timely manner.

However, review of the ISO methodology indicates that **the FSRS and the Guide do not mention or consider earthquake** and the associated numerous simultaneous ignitions that will each require fire department response. Overwhelming of fire alarm and telephone reporting is not considered. Damage to water mains and fire hydrants is not considered. The FSRS is predicated on timely arrival of firefighters at each fire, who will readily be able to access the needed fire flow. As has been observed in numerous earthquakes[12], some fires will not be responded to in a timely manner, and water will not be readily available. These two factors – delayed response and inadequate water supply – were long ago identified by the National Association for Fire Protection (NFPA) as two key factors leading to urban conflagration[13].

As an example, examine a block in a more built-up neighborhood of San Francisco, CA, Figure 53. Using the procedures outlined in the ISO Guide, the NFF for a typical building on this street is determined to be 2,500 gpm, which is a reasonable estimate of the fire flow that would be required to contain and suppress a fire in one of these nearly 100 year old wood framed buildings, given timely fire engine response.

On the other hand, if a response is delayed for an hour or so, it is quite likely given the type of construction in this neighborhood that much of one or more city blocks would be full involved in fire. In such a case, the only option for the fire department would be to try to prevent fire spreading beyond the block or two fully involved. The tactic to do this would be to deploy fire engine master streams in a 'water curtain', Figure 55. The maximum distance a fire engine or portable monitor can deploy a water curtain is approximately 200 ft.[14]. Given that the block is about 450 ft. long by about 285 ft. wide, the block's perimeter is therefore about 1,470 ft., so that between six and eight fire engines would be required to entirely surround one block with a water curtain. With each fire engine pumping 1,200 to 1,500 gpm, the total post-earthquake conflagration required fire flow would be in the range of 7,200 to 12,000 gpm, as shown in Figure 56.

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[12] TCLEE (2005) Fire Following Earthquake. Scawthorn, C., J. M. Eidinger, A.J. Schiff (Editors), Technical Council on Lifeline Earthquake Engineering Monograph No. 26, pp. 345pp. American Society of Civil Engineers, Reston.

[13] NFPA (1951) Conflagrations in America since 1900: a record of the principal conflagrations in the United States and Canada during the first half of the twentieth century. National Fire Protection Association, Quincy, MA.

[14] Freeman, J. R. (1889) Experiments relating to hydraulics of fire streams. Trans. American Society of Civil Engineers,, XX!, pp. 303-451 and Discussion pp. 452-482,.

Admittedly, the San Francisco example selected, a densely built neighborhood of older wood frame buildings (often termed a 'conflagration breeder' in the fire service) is somewhat extreme, but it makes the point that large earthquakes will lead to large fires in large cities in California, which require much more water than required under non-earthquake conditions.

Conclusion

ISO's FSRS and *Guide for Determination of Needed Fire Flow*, while excellent tools for economical fire and water systems under ordinary conditions, are shown by this example to significantly underestimate the required fire flow for the conflagration situations that may exist following a major earthquake.

It is of value to note that the value of buildings and contents in the one city block shown in Figure 56 is on the order of $100 million, all of which is fully insured for fire, including fire following earthquake.

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities, several consulting companies, and researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering.

These research programs aim to identify and reduce the risks from major earthquakes to life safety and to the economy by including research in a wide variety of disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, architecture, economics, risk management, and public policy.

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