SPA Risk

Analysis of Fire Following Earthquake Potential for San Francisco, California

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for the

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Abstract

San Francisco is at significant risk due to fire following earthquake. This report analyses 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). This specific report, on fire following earthquake, has been conducted with the support and assistance of the San Francisco Fire Department (SFFD).

A stochastic model for analyzing fire following earthquake for San Francisco has been developed, utilizing data received from CAPSS, SFFD and others, to assess fire following earthquake impacts due to four earthquake scenarios: magnitude 7.9, 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, 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 7.9 San Andreas event. As a result, the methodology employed here estimates ignitions, building burnt areas and dollar losses for the four scenario events. These results are presented in Table A-1 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: .

Table A-1
Bounds for Losses to Buildings due to Fire Following Earthquake

	25% ~ 75% Confidence Range		
	Ignitions	**Loss** $ billions	**Total Burnt Building Floor Area** mill. Sq. ft.
San Andreas Mw 7.9	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

For example, for the Mw 7.9 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. 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.

A number of opportunities exist for reducing the fire following earthquake in San Francisco, including further improvements in reliability of post-earthquake water supply, further support for NERT, and greater training for this problem for SFFD officers and firefighters.

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Revision Log

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1	22 October 2010	Revised minor editorial and graphics matters

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1 INTRODUCTION

San Francisco is at significant risk due to fire following earthquake.

Given the total destruction of much of the city in the 1906 earthquake and fire, this should be obvious. However, much has changed since 1906, and the degree to which the city is today at such risk is less clear. Today, San Francisco is the most densely-settled large city in the state of California and the second-most densely populated large city in the United States, and is the financial, cultural, and transportation center of the San Francisco Bay Area. This report analyzes the current situation in order to estimate today's risk.

We should begin by defining what we mean, and what our results will mean. *Fire following earthquake* refers to a series of events initiated by a large earthquake, each of which can have several possible outcomes. These events include whether or not a building or industrial facility is damaged by shaking, whether or not an ignition occurs in such a location, whether or not the ignition grows into a serious fire, whether or not (and at what time) such a fire is reported, whether or not the fire department responds, whether or not they have water in the hydrants…and so on. Such a chain of uncertain events is termed a *stochastic process*, the analysis of which involves many possible outcomes. The analysis presented here analyzes each link in the chain of events to determine how often the outcome is a few small fires, or a number of large fires, or one or more multi-block conflagrations. Due to the uncertainty involved in each step, the results of the analysis are necessarily probabilistic in nature – that is, we cannot say definitely this or that will happen, we can only say such and such will happen with this probability. The value of the analysis is not so much in the precision of the numbers, as in the degree to which it quantifies that it is likely that losses will be small, or catastrophic.

1.1 Purpose

This report is part of a larger project undertaken by the San Francisco Department of Building Inspection entitled Community Action Plan for Seismic Safety (CAPSS). The project began in 1999 and has been lead by the Applied Technology Council (ATC), with the involvement of a large number of professionals from the earthquake community, and significant input from the citizens, organizations and agencies of San Francisco. This specific report, on fire following earthquake, has been conducted with the support and assistance of the San Francisco Fire Department (SFFD).

The purpose of this report is to assess the potential losses in San Francisco due to fire following earthquake. "Earthquake" is characterized by four earthquake scenarios which have been employed throughout the CAPSS project, specifically a Mw 7.9, 7.2 and 6.5 occurring on a section of the San Andreas fault at its closest proximity to San Francisco, and a Mw 6.9 event on the Hayward fault at its closest proximity to San Francisco (Mw refers to moment magnitude, and as used in this report is synonymous with earthquake magnitude, and/or M).

The scope of work was defined by May 19, 2010 modification to an existing contract with ATC, and consisted of:

> *"Consultant will also update the fire loss estimates at a block level, based on recent changes within the San Francisco Fire Department that affect the city's fire fighting capability and a more rigorous analysis than was initially conducted. The updated losses and a written description of the analysis approach and the analysis results, which will be incorporated in the Task 2 Report on San Francisco's Earthquake Risk, are to be completed no later than July 30, 2010."* [the deadline was subsequently extended].

1.2 Fires and fire following earthquake

Fires occur following all earthquakes that significantly shake a human settlement, but are generally only a very significant problem in a large metropolitan area predominantly comprised of densely spaced buildings. In such circumstances, the multiple simultaneous ignitions can lead to catastrophic conflagrations that by far are the dominant agent of damage for that event. This of course occurred in San Francisco in 1906, when 80% of the damage was due to fire rather than shaking.

More recently, about 110 fires broke out after the 1994 Northridge earthquake in Los Angeles – however, this was a relatively modest earthquake (Mw 6.7) on the edge of a great metropolitan area, so that the fires were largely contained and major spread did not occur. About the same number of fires occurred the next year in the 1995 Kobe, Japan, Mw 6.8 earthquake. In that case, the fire department was greatly hampered by many broken water mains as well as transportation difficulties, and significant fire spread occurred, producing

> *"a total of 294 fires, resulting in the destruction of about 66 million m2 of residential and industrial land … 215 fires broke out on the day of the earthquake, fifty-one of which spread to an area more than 1,000 m2 and thirty-one fires spread to more than 3,000 m2…7,538 houses and buildings were destroyed by these fires… Kobe City Fire Department reported a total of 175 incidents of fire, 128 of which were reported through the "119" emergency telephone service while the rest were unreported" (Nagano, 1995)*

The method for determining fire following earthquake losses for this region in summary consists of collecting data on the building stock, ground conditions, water supply, fire service and related systems. This data was employed in an approach (Scawthorn et al., 1981, Scawthorn et al., 2005) which considers these factors in a stochastic framework that estimates ignitions caused by the earthquake, and tracks fire spread as a function of fuel (ie, the building stock and contents), wind, firefighting activities and other parameters

Although a combination of a professionalized fire service, improved water supply and better building practices has largely eliminated non-earthquake related large urban conflagrations in San Francisco, there is still a gap – an Achilles Heel – which is fire following earthquake. This is due to the correlated effects of a large earthquake, simultaneously causing numerous ignitions, degrading building fire resistive features, dropping pressure in water supply mains, saturating communications and transportation routes, and thus allowing some fires to quickly grow into conflagrations that outstrip local resources. It is not sufficiently appreciated that the key to modern fire protection is a well-drilled <u>rapid response</u> by professional firefighters in the early stages of structural fires, arriving in time to suppress the fires while that is still relatively feasible. A typical response goal for urban fire departments for example is <u>4 minutes</u> from time of report to arrival (SFFD averaged 4.92 minutes in 2008). If suppression is delayed, due either to delayed response, or lack of water, a single structural fire can quickly spread to neighboring buildings and grow to the point where an entire municipalities' fire resources are required, and perhaps even assistance from neighboring communities. This is for a <u>single</u> ignition. Simply put, most fire departments are not sized or equipped to cope with the fires following a major earthquake. A major earthquake and its associated fires is a low probability event which, however, may have very high consequences.

1.3 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 developed in the late 1970s (Scawthorn et al., 1981) and applied to major cities in western North America (Scawthorn, 1992), Japan and other regions was employed here for San Francisco. A monograph (Scawthorn et al., 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 1:

- *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 Figure 2 which is a Fire Department Operations Time Line. 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 following earthquake is a highly non-linear process, modeling of which does not have great precision and is such that in many cases the only clear result is differentiation between situations of a few small fires, versus major conflagration.

This process can be employed in several modes, two of which are:

- Scenario events, in which earthquake epicenter and magnitude, and as many other parameters as may be of interest, are precisely specified or 'determined'. Other parameters of interest might include rupture direction, time of day, season or wind speed. Other key parameters, such as ground motion and building damage, might also be precisely defined, or their inherent uncertainty might be recognized via a probabilistic distribution. Never minding that in this manner some parameters are 'deterministic' and others probabilistic, Scenario studies are usually termed 'deterministic'.
- Probabilistic analyses on the other hand typically try to recognize the inherent uncertainty in key parameters (event epicenter and magnitude, ground motion, wind speed…), and employ closed form and/or numerical methods to fully consider the range of variables. Never minding that in such studies many parameters are typically treated as deterministic, such studies are usually termed 'probabilistic', particularly when integration over the range of event location and magnitude is performed. Because probabilistic studies typically involve significant amounts of computation, specialized software has been developed.

This study is a Scenario study for four earthquake scenarios, which will be described more fully in the next section.

1.4 Previous Work

Explicit quantification of potential fire following earthquake losses for San Francisco was first performed in the mid 80s under National Science Foundation and insurance industry support (Scawthorn, 1987). That study examined the effects of a repeat of the 1906 earthquake (essentially the same as the SA7.9 scenario here), finding that in San Francisco on average 75 ignitions would occur and, for average wind conditions about 8.6% of the building value would be destroyed by fire following earthquake, equivalent in today's dollars to $21.5 billion. That study was updated in 1992 (Scawthorn, 1992), revising the losses for San Francisco downward to about a 4% mean loss (equivalent in today's dollars to $10 billion) considering variation on a number of factors, with however, losses being significantly higher under adverse meteorological conditions. More recently, (Grossi and Muir-Wood, 2006) have estimated that the fire following earthquake insured loss in San Francisco would be about $3 billion.

1.5 Outline of this Report

The remainder of this report follows the above succession of events. We begin by discussing relevant data collected, next algorithms employed to estimate the approximate number, distribution of ignitions, and their spread. We conclude with guidance on how to use the results, and some observations of mitigation the fire following earthquake problem in San Francisco.

Throughout the report, reference is made to San Francisco's experience in the 18 April 1906 Mw. 7.9 earthquake and subsequent fires, and the 17 October 1989 Mw 6.9 Loma Prieta earthquake and subsequent fires. These two events should be well-known to most readers and will not be elaborated here. Further information on these two events can be found from many sources, including specific discussion of relevance to the current topic (Scawthorn et al., 2006, Scawthorn, 1991).

2 Data Collection

2.1 Scenario Earthquakes

The four earthquake events for this study were specified by the CAPSS project, and are shown in Table 1 below:

Table 1 CAPSS Earthquake Scenarios

Event	Fault / segment	M_w	Max PGA
SA79	San Andreas	7.9	0.67g
SA72	San Andreas / Peninsular	7.2	0.61g
SA65	San Andreas / Peninsular	6.5	0.55g
H69	Hayward / North & South	6.9	0.36g

Ground motions, probability of liquefaction and other measures of hazards were furnished by the CAPSS project[1] for these events - for further details, the reader is referred to the CAPSS project documentation. Maps of peak ground acceleration (PGA) furnished by CAPSS are shown in Figure 3 for the four scenarios, and the maximum PGA for any one city block for each scenario are also shown in Table 1. Note that, while the SA79 is a much larger event overall than the SA65 event (total energy release is more than 100 times greater in the SA79 event), the PGA for the SA65 is still quite large (SA65 max PGA is 80% of SA79 max PGA).

Ground failure is a major effect of most earthquakes, and can take several forms, such as liquefaction, or landsliding. Failure of ground was widespread in 1906, occurred in the Marina in the 1989 Loma Prieta earthquake, and can be expected to occur in future San Francisco earthquakes. Assessing potential ground failure is important for analysis of fire following earthquake since ground failure is likely to cause high rates of underground pipe breakage, thus disrupting firefighting water supply and potentially damaging gas mains. San Francisco is recognized to have a significant potential for ground failure in some parts of the City, and this potential has been mapped by various agencies and experts. Figure 4 (top) shows a map of a liquefaction and ground failure dataset distributed by the City of San Francisco[2], with the bottom portion of the figure shows a mapping of liquefaction susceptibility provided by the CAPSS project. Also shown in the bottom figure, overlaid on the CAPSS project liquefaction susceptibility, are the SFFD Infirm Zones. These Zones were identified by the Fire Department following the 1906 earthquake, for special consideration in

[1] Here and elsewhere, data furnished by the CAPSS project are only presented and discussed in summary, and the reader is referred to the larger CAPSS project for further details.

[2] Available at http://gispubweb.sfgov.org . and described "The dataset represents the Liquefaction and Landslide Zones as determined by the California Dept. of Conservation Division of Mines and Geology. Liquefaction is the transformation of a confined layer of sandy or silty water-saturated material into a liquid -like state because of earthquake shaking. San Francisco Building Code Section1804.5 requires a geotechnical investigation in seismic hazard zones."

the design of the Department's Auxiliary Water Supply System (AWSS, discussed further below).

2.2 San Francisco Building Density and Construction

Two key parameters for estimation of fire following earthquake losses are building density and materials of construction. Detailed data at the city block level, for 5,323 blocks, was furnished by the CAPSS project, and included estimates of Total Floor Area (TFA) by 66 different building types, categorized by material of construction, height and applicable building code era. Figure 5 shows San Francisco's building inventory in terms of TFA per block for wood (shades of red), and fire resistive (shades of gray) buildings. The more 'red' an area, the higher the TFA of wood buildings. Most of the City, especially north and east of Golden Gate Park, is clearly dense wood construction, while downtown has little wood. The total TFA for all buildings in this database is approximately 510 million sq. ft.3, with a total replacement value of about $205 billion[4], Figure 6 (note that recent major development in Mission Bay area are not included).

The average building TFA per block in San Francisco is 95,000 sq. ft., while the maximum is 4.3 million sq. ft. Block sizes vary significantly in San Francisco[5], especially in the older portion of the city, but example dimensions[6] are 310 x 670 ft (Richmond), 490 x 340 ft (downtown), and 275 x 658 ft (Hunter's Point). GIS data for blocks and lots were sampled in various parts of the city, Figure 7, arriving at an estimated average block size (i.e., sum of lots) of about 140,000 sq. ft. Typical street widths[7] were sampled from the GIS data as well as Google Earth, Figure 8, and vary from 60 ft. in downtown, to 70 and 75 ft. in many parts of the city, to 80 ft. in the Sunset. Of course, selected streets such as Market Street are much wider and constitute significant fire breaks (although in 1906 fire extended across even this broad street).

2.3 San Francisco Fire Department and Allied Resources

Data was collected on the San Francisco Fire Department's resources. SFFD protects the 46.7 square mile City and County of San Francisco (CCSF), whose 2009 resident population was estimated to be 815,000[8], and whose daytime maximum population may at times reach 1.5 million. CCSF includes the former military installations of the Presidio and Treasure Island. SFFD also provides protection at San Francisco International Airport, where it maintains three stations. In 2008 SFFD responded to 1,980 structural fires, Figure 10.

Table 4 and Figure 9 show locations of SFFD's 42 fire stations within the City. These stations were reviewed for seismic adequacy in the mid-1980s (EQE/AGS, 1989) and subsequently most of the stations were rebuilt or seismically retrofitted, so that today the

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[3] However, this represents only buildings under the purview of the Dept. of Building Inspection, and omits public and selected other buildings.

[4] Based on replacement cost data furnished by CAPSS.

[5] Even defining a 'block' is problematic, as many 'blocks' are bisected by alleys, and street patterns are extremely irregular in certain parts of the city, such as around Twin Peaks.

[6] Measured center of intersection to center of intersection, so therefore including a full street width on both length and width of the block dimension.

[7] Measured face of building to face of building.

[8] http://quickfacts.census.gov/qfd/states/06/06075.html

great majority of stations may be considered as seismically reliable in the four scenario events considered here.

Under normal operations, SFFD operates one engine from each station, as well as one truck and/or other apparatus and equipment from selected stations[9], for a total of 42 engines and 19 trucks. SFFD also has on average five reserve engines that would be put in service in an earthquake emergency[10], with some delay since they are not normally stocked with hose and equipment. SFFD also operates two dedicated fireboats, which are discussed further below.

SFFD has approximately 1750 uniformed firefighters, including Chief of Department, officers and firefighters. Each duty shift typically has about 325 officers and firefighters, not counting non-firefighter paramedics and EMTs on SFFD ambulances. SFFD also maintains a volunteer San Francisco Fire Reserve (http://sffd-fire-reserve.org/) that currently numbers approximately 30 personnel, and who are very useful at support tasks such as deploying 5" hose, portable hydrants, picking up hose, etc – however, they have no actual firefighting or rescue experience. Many firefighters live outside the City. In 1989 a general recall order was issued, and many SFFD personnel responded within several hours, including many who had not actually heard of the recall order.

SFFD also supports the Neighborhood Emergency Response Team (NERT, http://www.sf-fire.org/index.aspx?page=859) program. NERT is a free training program for individuals, neighborhood groups and community-based organizations in San Francisco, through which individuals learn the basics of personal preparedness and prevention. The training includes hands-on disaster skills that will help individuals respond to a personal emergency as well as act as members of a neighborhood response team. Since 1990 the NERT program has trained more than 17,000 San Francisco residents to be self reliant in a major disaster.

For comparison, in 1906 the San Francisco Fire Department protected approximately 400,000 persons occupying an urbanized area of approximately 21 square miles. The department consisted of a total of 585 full-paid fire force personnel resident within the city and on duty at all times , and deployed in 57 companies (38 engine, one hose, ten ladder, one hose tower, and seven chemical) The rated pumping capacity of the 38 first line and 15 relief and reserve engines totaled 35,100 gallons per minute (gpm). (NBFU, 1905). Table 5 compares the City and Fire Department in 1906 and today. While the population and area have more than doubled, the number of fire engines has barely increased (only fire engines are compared here, as they are the only apparatus that supplies water for fire suppression). However, when the capabilities of the City's two fireboats, and the AWSS (discussed below) are taken into account, the total pumping capacity has more than doubled, demonstrating their great value (and economy, as the staffing costs for these assets are relatively modest).

2.4 Water Supply and other Infrastructure

Water supply is critical to firefighting. A great irony is that San Francisco is surrounded on three sides by the largest body of water on earthquake, yet suffered one of the world's greatest conflagrations in 1906 due to lack of firefighting water. As a result of that

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[9] In fire service parlance, a fire engine or pumper supplements fire hydrant pressure to provide firefighting water for use by its crew, while a ladder truck, or simply truck, carries numerous ladders and other equipment and additional personnel that provide search and rescue, ventilation and other needs.

[10] This was done in the 1989 Loma Prieta earthquake, including putting in service an engine in the Fire Department's Museum. However, post-incident review indicated the capability and amounts of reserve engines, hose and other vital equipment were not satisfactory, and should be improved.

experience, San Francisco today has, in addition to the normal potable water supply system (herein termed the Municipal Water Supply System), an extensive system of firefighting-specific water supplies, the understanding of which is vital to an analysis of fire following earthquake risk in San Francisco. We first briefly discuss the potable water system, and then the other systems, referring the reader to citations for more detail.

Municipal Water Supply System

San Francisco's Municipal Water Supply System (MWSS) provides water from 18 different reservoirs and a number of smaller storage tanks. The water is stored at different levels, creating zones, or districts, where water is distributed within certain ranges of pressures. There are 23 different pressure districts, of which the Sunset and University Mound Reservoir Systems are the largest. Figure 11 shows a plan view of the Sunset Reservoir System, in which the trunk, or feeder, mains are indicated. The pipelines in this portion of the feeder main network range in diameter from 10 to 60 in., and vary in composition from riveted and welded steel to cast iron. There are approximately 300 mi. of feeder pipelines in the MWSS. Distribution pipelines are principally 4, 6, and 8 in. in diameter. They receive water from the feeder main network for delivery to hydrants and buildings. There are approximately 850 mi. of distribution piping in the MWSS.

In the 1989 Loma Prieta earthquake, damage was relatively low throughout the MWSS in areas outside the Marina, with a total of 30 breaks. Within the Marina, there were 123 repairs in an area with approximately 37,000 ft. of pipelines belonging to the MWSS (and 7,500 ft. of pipelines belonging to the AWSS) (O'Rourke, 1990).

Information on the MWSS for a detailed analysis was not available for this study. As an approximation, MWSS distribution piping was assumed to lie under all city streets, creating a 'proxy' system equivalent to about 1,200 miles of pipe, which approximately corresponds to the known total of 1,130. A relation for estimation of pipe breaks (O'Rourke and Ayala, 1993) was employed to estimate the number of pipe breaks for the Mw 7.9 San Andreas scenario (SA79). This 'proxy' analysis estimates there will likely be over 1,100 breaks in the MWSS, as shown in Figure 12 where estimated pipe breaks are shown in red overlaid on estimated SA79 peak ground velocity. 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. As can be seen in the figure, high concentrations of breaks can be expected in high hazard 'infirm' zones such as Mission and Islais Creeks, and a relatively low number of breaks on better soils in the northeast quadrant of the city. Of interest is the relatively large number of breaks spread over a broad area in the Richmond and Sunset, due to the high ground motions closer to the San Andreas fault. This number of breaks is likely to quickly result in much of the MWSS losing pressure, a situation similar to that in 1906 (in which over 28,000 breaks were sustained, including service line breaks).

Auxiliary Water Supply System

The need for a 'high pressure water supply system' was recognized in San Francisco prior to the 1906 earthquake, but had not yet been implemented due to its being deemed 'too expensive' (Tobriner, 1989, Dalessandro, 2005). Following the 1906 conflagration the need was obvious, and San Francisco built the high pressure Auxiliary Water Supply System (AWSS), which was largely completed by 1912. Space does not permit a detailed description of the AWSS here (see Scawthorn et al, 2006 for a detailed description). In summary, the AWSS consists of several major components (see Figure 13 and Figure 14):

- 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).

- Pump Stations: Because the Twin peaks supply may not be adequate under emergency conditions, two pump stations exist to supply salt 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 1970's.

- Pipe Network: The AWSS supplies water is conveyed to dedicated street hydrants by a special pipe network that, by the end of the 1980s, had a total length of approximately 120 miles (200 km). The pipe is bell and spigot, originally extra heavy cast iron (e.g., 1" or 25 mm wall thickness for 12" or 300 mm diameter), and more recent extensions are heavy ductile iron (e.g., .625" or 15mm wall thickness for 12" or 300 mm diameter). Restraining rods connect pipe lengths across joints at all turns, tee joints, hills and other points of likely stress.

- Fireboats: A major deficiency in 1906 was the lack of a fireboat to be able to pump large volumes from San Francisco Bay. Today, two powerful fireboats are provided, the *Pheonix* and the *Guardian*, capable of pumping 9,600 and 24,000 gpm (respectively, at 150 psi) into the AWSS system, in addition to the two pump stations. The pipe network has manifold connections located at several points along the City's waterfront in order to permit the City's two fireboats to act as additional "pump stations", drafting from San Francisco Bay and supplying the AWSS.

- Cisterns: San Francisco has 172 underground cisterns, largely in the northeast quadrant of the City but with newer cisterns in outer residential areas.

The AWSS is a remarkably well designed system for reliably furnishing large amounts of water for firefighting purposes under normal conditions, with many special features to increase reliability in the event of an earthquake. *A key aspect of San Francisco's ability to maintain and even extend this unique system is that fact that it is, by city charter, owned and operated by the fire department.* The AWSS is intended as an *auxiliary* system, to supplement the use of the municipal water supply system for fighting large fires, under non-earthquake as well as earthquake conditions. This is an important point – it does not sit around for decades, waiting for an earthquake. Rather, the department uses it at most greater alarm incidents, thereby gaining valuable experience, confirming its continued functionality and reliability, and justifying the system's existence. Another point is that the underground piping system was designed from the beginning to be highly earthquake resistant – the piping is extra heavy walled, and has restrained joints to resist pullout at numerous locations.

Following the 1906 earthquake, the significance of the 'infirm zones' was clearly recognized, and the AWSS was designed so that, while AWSS pipe passes through these zones, the system can be quickly isolated should pipelines in those zones fail. In modern times, the gate valves isolating the infirm zones have been motorized and can be remotely controlled via radio. As a result of the elevation of the Twin Peaks reservoir, and the capacity of the pumping stations and the fireboats, very high pressures, in excess of 300 psi, can be sustained in the AWSS. This pressure assures a high volume supply, but is too high for many applications, and can be reduced via Gleeson valves – a patented pressure reduction valve invented in the San Francisco Fire department shops. The Gleeson valve permits a firefighter to attach one or several handlines to an AWSS hydrant, and apply firestreams as if from a fire engine. Thus, the AWSS reduces the need for fire engines, and permits a continuous water curtain to be sprayed from a line of hydrants along a defensive line.

Designed almost a century ago with great foresight and skill, the San Francisco AWSS was intended to be a seismically reliable water supply system for fire protection. Even so, the 1989 Loma Prieta earthquake damaged a few components of the AWSS, which, coupled with human inaction, lowered pressure in the Lower Zone (the Upper Zone was not affected) and prevented the system from supplying water to the Marina fires, thus demonstrating that there is room for improvement.

A major enhancement to the AWSS was added in the 1980s with the addition of a Portable Water Supply System (PWSS), which greatly extends the reach of the AWSS. In the 1989 Loma Prieta earthquake, it was the PWSS working together with the fireboat *Pheonix* that finally provided the water that allowed the fire to be extinguished. Today, SFFD has four PWSS hose tenders, one of which is stationed on Treasure Island for the foreseeable future, so that only three may be available in the event of a large earthquake. Lastly, SFFD is currently researching and developing a prototype trailer-mounted hose and pump set, for possible use by NERT.

Recognizing that the AWSS was impaired during the 1989 Loma Prieta earthquake, a very modest earthquake relative to the scenario events considered in this study, the number of potential breaks that might occur in the AWSS were estimated for given the scenario events. Figure 16 shows the resulting 19 estimated breaks in red, overlaid on a map of SA79 PGV. While the number of breaks is relatively small when compared with the MWSS, these few breaks could significantly diminish, or even eliminate, the AWSS as a useful firefighting system in the event of a major earthquake. However, timely command decisions to close motorized gate valves and make up for break losses via use of the two pump stations and the fireboats, could maintain the utility of the AWSS immediately following the earthquake. This aspect should be the focus of specialized procedures and training by SFFD.

2.5 Windspeed

Windspeed is an important factor in fire spread. Data was collected on windspeed frequency in San Francisco and is shown in Figure 17.

3 Analysis and Results

This section presents a summary of the analyses performed for the four scenario events, and results. Because of the stochastic nature of the fire following earthquake process, there is not an exact solution as to where ignitions will occur, and the final burnt area. Rather, the analysis takes into account the variation or uncertainty on key parameters via random sampling of these parameters' underlying frequency of occurrence, and then employs the resulting set of randomly selected parameters in the model outlined above, to create one trial. This process is repeated numerous times, the result of which is a distribution of the frequency of ignitions, pipe breaks, fire spread and other parameters, and a distribution of the frequency of the overall burn area. For the analysis and main results here, typically 1,000 trials were performed for each scenario (this is discussed further below).

3.1 Ignitions

Based on methods developed for FEMA and the HAZUS program and documented in (SPA Risk, 2009), and employing data presented above, the total number of fire ignitions likely to occur given various patterns of ground shaking was estimated for each scenario. Sources of these would likely be similar to causes in the 1994 Northridge earthquake, which is the best US data set for recent fires following an earthquake – about half of all ignitions would be electrical related, a quarter gas-related, and the other due to a variety of causes, including chemical reaction, Table 6. It is worth noting that, although electric power often fails during the earthquake shaking in high intensity areas, electrically-caused ignitions still occur, due either to arcing before power fails, stored energy in electrical appliances and/or when power is restored. Also based on the Northridge experience, about half of all ignitions would typically occur in single family residential dwellings, with another 26% in multi-family residential occupancies – that is, about 70% of all ignitions occur in residential occupancies, Table 7. Educational facilities would be a small percentage of all ignitions (3% in Northridge), and most of these are due to exothermic reactions of spilled chemicals in chemistry laboratories.

Another issue for San Francisco is ignitions in highrise buildings, clearly a concern due (a) to the potential for large life loss, and (b) the high property values. While difficult to foresee, it is possible that fire department response to highrise fires will be to simply try to assure safe evacuation of occupants, and not to engage in aggressive fire attack (which simply put would require too many resources spread too thin). Recent earthquakes (1995 Kobe, 2010 Chile) did not see any highrise fires and, if fires do occur, they may in many cases not spread to a significant degree, due to modern fire protection features such as compartmentation and sprinklers. However, as seen in the 7WTC fire and collapse, these features may not protect a highrise in the absence of aggressive firefighting.

The actual number of ignitions varies with each trial of each ground shaking simulation, so that the frequency distribution of ignitions for the four scenarios is shown in Figure 18 and Table 8.

The results indicate that on average, about 95 fires would be expected following a Mw 7.9 San Andreas event, 73 fires following a Mw 7.2 San Andreas event, 57 following a Mw 6.5 San Andreas event, and 37 following a Hayward Mw 6.9 event.

However, these are mean averages (medians are quite similar), with considerable variation. For example, for the San Andreas Mw 7.9 event Table 8 shows that there is an 18% probability of the number of ignitions being less than 60, and a 25% probability of the number of ignitions being greater than 120 (and 10% chance of the ignitions being greater than 140).

3.2 Initial Response

Depending on the specific event, the hundred or so ignitions requiring fire department response will initially be responded to by citizens – as noted, they will be able to suppress some fires, which are not included in the overall estimate. When they realize the fire is beyond their capabilities, they will endeavor to call the fire department. Attempts to report via telephone will almost universally be unsuccessful, not so much due to damage to the telephone system as much as simple saturation of the system and emergency call centers.

Experience shows that citizens on scene will respond rationally (Van Anne, 1989) rescuing as many people as possible and protecting exposures. Water supply from mains (discussed below) will often be unavailable.

The initial response of fire companies and personnel in the region of the scenario will be to self-protect during violent shaking, and as soon as possible open the doors and remove apparatus from the fire stations. By this time, typically within five minutes, they will either have self-dispatched to an observed smoke column, responded to a citizen still alarm, or been instructed to mobilize with other companies into a strike team. . For the purposes of this study, a survey was conducted of over 60 SFFD fire officers. The survey found that, lacking communications with battalion or headquarters, more than half the officers would self-dispatch to the nearest fire. In any event, given situations when the number of fires outnumbers the number of engines (typically the case for the larger event scenarios considered here), SFFD fire service resources will be completely committed, and in need of assistance from outside the region. The primary needs will be personnel, additional hose, hard suction hose, foam, light equipment (gloves, hand tools, SCBA) and heavy equipment (cranes, bulldozers, backhoes). Additional fire apparatus (pumpers and ladder trucks) will not be the primary need, initially, but will still prove useful as extra-regional strike teams arrive. In the initial stage, personnel needs may be significantly supplemented by NERT teams, but will be more significantly strengthened by the recall of off-duty trained firefighters. Off-duty personnel can be expected to have doubled staffing within 3-6 hours, and tripled it within 12-24 hours. While responding, an issue will be how these personnel marry up with their companies, and there will be some inefficiencies as personnel join first available companies. Nevertheless, arrival of off-duty personnel will be very important, to spell on-duty personnel nearing their physical limits.

As noted above, emergency dispatch centers will be overwhelmed and doing as much as possible to triage events and dispatch resources. Reports of fires during the initial period will be haphazard. An anecdote demonstrates this – the first knowledge the San Francisco Fire Department Emergency Operations Center (EOC) had of the Marina fire in the 1989 Loma Prieta earthquake was from television news reports (despite several companies having responded). Quickly gaining accurate complete situational awareness is still a challenge. For purposes of this analysis, it has been assumed that all engines respond to fires, and that each engine responds to the fire nearest to them. The net result of this assumption is unclear – in reality, some engines will respond to non-fire emergencies (e.g., building collapse), and some department radio communications will probably be functional, allowing more efficient allocation of resources with some engines responding to fires other than the nearest.

3.3 Fire Growth and Spread

Depending on the specific event, only a fraction of San Francisco's initial ignitions will be responded to, and some fraction will grow in size and develop into conflagrations. Growth and spread varies with materials and density of construction, functionality of sprinklers where they exist, active fire suppression, wind speed and other factors. While physics-based models for fire spread are currently emerging (Cousins, 2003, Aoki, Himoto and Tanaka, 2008, Lee et al., 2008), their data demands are prohibitive, so that established empirical relations (Scawthorn et al., 2005) for fire spread were employed here.

3.4 Lifelines

The performance of lifelines, such as water supply, gas integrity, electric power, communications and transportation, is integral to the fire following earthquake process.

As discussed above, water supply may be severely impacted, depending on the scenario event. In addition, San Francisco has its unique AWSS. In order to estimate the availability of adequate water for firefighting, limited analyses were performed for both the MWSS and AWSS as discussed above. Additionally, number and proximity of suction connections and cisterns were considered, along with the capacity of SFFD's PWSS, to arrive at an overall Water Supply Factor (WSF) for each scenario. The WSF varies between 0 and 1 and is a measure of the availability of adequate firefighting water, with WSF = 0 indicating no water, and 1 indicating completely adequate water. Figure 19 shows a map of WSF (shades of blue) for the San Andreas Mw 7.9 event, with example MWSS breaks overlaid. Note that the darker the shade of blue the more adequate the water supply, and that WSF is estimated based on all sources of water (MWSS, AWSS pipe network, cisterns, suction connections, etc), not just MWSS.

The performance of the natural gas lifeline was not explicitly considered in this analysis, for the following reasons: (a) gas-related ignitions are included in the ignition algorithms; (b) while gas-related ignitions typically account for a significant portion of the total number of ignitions, these ignitions are probably not greatly affected by the performance of the gas pipelines. That is, while some ignitions have been caused by broken gas main flares in the street (e.g., Balboa Blvd. in the 1994 Northridge earthquake), most gas-related ignitions occur within buildings and are fueled by modest amounts of gas leaking in the building under residual pressure. However, the recent (9 September 2010) San Bruno transmission gas main explosion and fire, in which 8 persons died and 38 homes were destroyed (and others damaged) shows the potential damage arising from a broken gas main. While the San Bruno pipeline was a large high pressure transmission main, which in San Francisco is only in the southeast quadrant of the City, Figure 25, there are relatively high pressure distribution mains throughout the City. On the other hand, PG&E has done extensive work in the last several decades to upgrade its transmission and distribution system in the San Francisco Bay Area, and this will undoubtedly be beneficial.

Similarly, the performance of the electric power lifeline was not explicitly considered in this analysis, for the following reasons: (a) electric-related ignitions are included in the ignition algorithms; (b) while electric-related ignitions typically account for a significant portion of the total number of ignitions, many of these ignitions are 'prompt' ignitions, occurring in the very few seconds before electric power fails. Later ignitions, due to restoration of electric power, typically occur much later, are not included in the ignition algorithms used here, and have typically been easily dealt with by fire departments in past earthquakes. However, PG&E has done extensive work in the last several decades to upgrade its electric power system in the San Francisco Bay Area, and the effects of this on the fire following earthquake problem are unclear – if electric power continues through and after the earthquake, significantly more ignitions may occur very quickly in damaged buildings. Note that in the 1989 Loma Prieta earthquake, electric power failed very quickly in San Francisco, and was only gradually restored over several days, as sections of the gas and power systems were checked by PG&E.

As noted earlier, communications systems, particularly telephone, will sustain some damage but not enough to reduce functionality following the scenario event. However, saturation of the network and of emergency call centers will reduce relevant functionality to a great degree, for several hours or more. This lack of telephone service will result in delayed reporting, with consequences as discussed above.

The transportation system most relevant to fire following earthquake is the road network, which in San Francisco is highly gridded with few bottlenecks, so that performance of the network within the city is unlikely to be a significant factor. That is, while some roads will be blocked due to ground failure, or building or bridge collapse, bypasses should be generally available.

3.5 Final Burnt Area

Using the above methodology, one thousand trials were run for each of the four scenario events. Time of day, wind speed, ground motions, ignition rates and other relevant parameters were varied for each trial. Results are shown in Figure 20 and Figure 21, and Table 9, Table 10 and Table 11.

In summary, the mean (and 90th %) loss for the four scenario events is estimated to be (in millions of dollars), Table 2:

Table 2 Mean and 90% Dollar Losses to Buildings due to Fire Following Earthquake

Scenario	mean	90% P_e
San Andreas Mw 7.9	$7,674	$ 13,674
San Andreas Mw 7.2	$5,122	$ 9,551
San Andreas Mw 6.5	$3,387	$ 6,556
Hayward Mw 6.9	$2,947	$ 6,160

That is, for a repeat of an event similar to the 1906 earthquake, about $7.6 billion is expected to be lost due to fire following earthquake, with a 10% chance that the loss might be as high as $13.6 billion (denoted P_e; also note there is a corresponding lower bound, not shown here), and similarly for the other scenarios.

Another way to consider the range of losses is to identify the bounds within which the losses will fall half (i.e., 50%) of the time. That is, Table 3 shows the range within which ignitions, total dollar losses (billions $) and total burnt building floor area will be half the time. Correspondingly, half the time the losses will be outside (i.e., less or more) the ranges shown.

Table 3 50% Bounds for Losses to Buildings due to Fire Following Earthquake

	25% ~ 75% Confidence Range		
	Ignitions	**Loss** $ billions	**Total Burnt Building Floor Area** mill. Sq. ft.

San Andreas Mw 7.9	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

By way of reference, \$1 billion is approximately equivalent in replacement value to 2,000 single family houses, or five TransAmerica Pyramid highrises. As noted earlier, the significance of these results is not in their precision, but rather in their overall magnitude.

3.6 Validation

It is of value to validate these results, to the extent possible. San Francisco is a rather unique setting so that comparable settings and experience are almost non-existent. The most relevant data for validation is the 1989 Loma Prieta earthquake, in which the city was moderately shaken, had a few building collapses and deaths, and over two dozen fires. The Loma Prieta earthquake was therefore modeled using the above methodology, with the overall mean number of ignitions derived from a 1,000 trial simulation for the event estimated to be 15.7, as compared with 18 that occurred in San Francisco within 24 hours of the earthquake. Further results are shown in Figure 22 and Figure 23 – Figure 22 shows PGA as estimated by the USGS for the event overlaid with the actual ignitions that occurred within 24 hours of the earthquake (red triangles) and one distribution of ignitions drawn at random from a 1,000 trial simulation (squares). Ignitions that occurred after the first 24 hours are shown as smaller dots. One fire is estimated to, and did, occur in the Marina, and a roughly comparable distribution of estimated and real events can been seen throughout most of the City, with the exception of the Financial District, where more events are estimated than did occur. As noted by other observers, this disparity may be due to the rapid loss electric power in the event. Figure 23 shows the frequency of losses for the 1,000 trial simulation for this event, statistics of which are (millions \$):

<u>Loma Prieta Validation</u>

mean loss =	\$283
median loss =	\$122
stnd dev =	\$474
COV =	1.67

Accurate estimates of the fire following earthquake losses in the Loma Prieta event are not available, but the losses almost certainly did not exceed perhaps \$10 million. While the validation median results are significantly higher (\$122 million), note that the frequency distribution of losses is rather broad, and that the estimate indicates about a 35% probability of the losses being \$35 million or less.

3.7 Sensitivity of Results

Another issue of value to consider is the sensitivity of the above results to variation in key parameters. In a simulation, there are two aspects to sensitivity – the normal question of sensitivity to key inputs, and also the question of whether the 1,000 trials employed in the simulations were sufficient in number.

Regarding whether a sufficient number of trials was employed, Figure 24 examines the variation and robustness of results for the San Andreas Mw 7.9 scenario versus the total number of simulations, carried out to 10,000 trials. The top figure shows the average number of fires with increasing trials, and the bottom figure shows the average Total Burnt Area (th. sq. ft.). By both measures, simulation results clearly stabilize after several hundred trials.

Regarding sensitivity of results versus variation in key inputs, Table 12 shows results given variation in key parameters, using the Loma Prieta validation model. The most sensitive input is the time of day of the earthquake – Loma Prieta occurred at 5:04pm, which examination of national fire statistics (non-earthquake) shows is about the period of the day with the highest frequency of fire incidents. Conversely, early in the morning (e.g., 5am, as used in the sensitivity study) is the period of lowest frequency. The variation due to time of day is significant, as shown in the table, where it can be seen that it reduces the average number of ignitions, with a correspondingly much greater drop in Total Burnt Area (the effect is highly nonlinear, especially at the upper tail of ignitions – a few non-responded fires results in a major conflagration). The next most sensitive parameter is the Water Supply Factor – clearly, without water, most of the fires in San Francisco will turn into conflagrations.

Overall, the number of trials employed, and the robustness of the results to variation in key inputs, appears satisfactory.

3.8 Use of the Results

Use of the results presented above is fairly straightforward, although one point should be explained: The results are only for fire following earthquake losses, and are ‘independent’ of shake losses. Of course, a correlation exists between shake and fire following earthquake losses, but in general reasonable accuracy is satisfied by treating the shake and fire following earthquake losses as independent, due to the fact that both losses are typically a small fraction of the overall values at risk. The implication of their being regarded as independent is that the problem of ‘burning the rubble’ is more easily dealt with. That is, total losses due to shake and fire following earthquake can be estimated as:

$$Lt = Ls + Lf - Ls*Lf \qquad (1)$$

where Lt = total loss (expressed as a fraction of total values at risk)

Ls = shake loss (ditto)

Lf = fire following earthquake loss (ditto)

This formulation is equivalent to $A \cup B = A + B - A \cap B$ (i.e., the typical Venn diagram).

4 Mitigation of Fire Following Earthquake

Due to the stochastic nature of the fire following earthquake problem, there are many factors at play in determining the final result, and each of these factors offers opportunities for reducing, or mitigating, the problem. The current project does not permit an extended discussion of these opportunities (which, nevertheless, are vitally important for San Francisco), so that only brief comments are provided.

Opportunity	Comment
Improve reliability of water for firefighting	As discussed above, San Francisco's AWSS is unique, and a valuable legacy from the generation that suffered the 1906 earthquake and fire. Intervening generations have maintained and enhanced the AWSS, yet it is an aging asset, requiring constant maintenance. Nevertheless, Prop. B was recently approved by San Franciscans to further upgrade the AWSS, in recognition of its importance. Until recently, the AWSS had a 24/7 operator stationed at Jones Street Tank, and two operating engineers 24/7 at the Pump Stations, but these positions have been severely curtailed and in some cases eliminated. In the event of a major earthquake, minutes will count. The entire operation and staffing of the AWSS should be carefully reviewed for reliability, particularly with regard to human factors. Very recently, Firefighter Nate Hardy and others have led the effort to develop portable hose/monitor trailers for use by NERTs – sor tof a 'mini-PWSS'. This is an excellent development that SFFD has supported, and it should be carried forward with gusto. The MWSS is the only source of firefighting water in some parts of the City. The Department of Public Works (DPW) is in the midst of a multi-billion dollar upgrade of the entire Hetch Hetchy system. This upgrade should consider reliability of the MWSS for post-earthquake firefighting, particularly in areas where no other water source is available. An example would be installation of seismically reliable motorized gate valves on key parts of the MWSS, similar to those installed on the AWSS in the 1980s.
Improve fire command decision making	Good decision making under the pressures of an emergency are the specialty of fire chiefs, who do it every day. Nevertheless, a major earthquake is a once-in-a-lifetime experience, which is greatly complicated by the failure of some of everyday tools, such as communications and water supply. SFFD might consider forming a task force of key officers, to examine how best to deploy the department in the 'fog of earthquake', resulting in standard post-earthquake operating procedures and focused training for officers and firefighters.

Upgrade ability for NERT to suppress initial ignitions	NERT is a great resource that is doing a great job. However, their focus is currently on light rescue, and they receive little training in firefighting and/or SFFD equipment and procedures. A *NERT+* might be considered, that would move selected NERTs to a capability approaching the SFFD Fire Reserve. Additionally, the concept of neighborhood caches of equipment for NERTs has been developed, but not yet implemented, so funding for neighborhood caches should be pursued.
Require gas shut-off devices	Automated gas seismic shutoff devices have been a controversial issue in California for decades. Los Angeles City finally required them on all new construction and renovations, yet San Francisco, with much denser construction, still does not require them. This is doubly ironic, because they are not needed everywhere – they are really only needed in densely built up ‘conflagration breeder’ neighborhoods (such as in parts of San Francisco). Guidelines are needed for requiring such devices, based on their benefit/cost and, where warranted, then mandating them.
Water heat strapping	This is advocated by all, and may not be a problem. It is simply noted here, to see if statistics are available for San Francisco specifically.
Reinforce seismically deficient buildings	This is the central purpose of the CAPSS project, and is simply noted here because retrofitting such buildings also reduces the fire following earthquake problem.
Intumescent paint	DBI has investigated the benefits of this specialty item for some time. Its use would be beneficial from a fire following earthquake perspective.
Public school fire education (e.g., how to use a fire extinguisher)	Putting fire following earthquake on the school curriculum in San Francisco would clearly be beneficial.
Evacuation and safe route planning, and refuge signage	In selected areas such as Russian Hill, the potential for a horrific conflagration exists. Refuge areas should be identified, and street signage installed.
High school and other chem. Lab housekeeping	In past earthquakes, a surprising number of ignitions have occurred in high school chemistry laboratories, due to chemical reactions. Such laboratories, indeed all reactive chemical installations, should be the focus of improved housekeeping and other practices.
Breaking of water systems.	Much of the loss of water in 1906 was due to broken service connections to individual buildings. The concept of an excess flow valve being installed on the service line should be investigated.
Fire spread due to openings in buildings along property lines.	Much of San Francisco consists of contiguous housing built right to the property line, so that fire spread is very rapid. Use of fire shutters, fire resistant glazing and other features should be considered by DBI.

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Glossary and Acronyms

AWSS	Auxiliary Water Supply System
CAPSS	Community Action Plan for Seismic Safety
CCSF	City and County of San Francisco
DBI	Department of Building Inspection
DPW	Department of Public Works
EOC	Emergency Operations Center
gpm	gallons per minute
H69	Hayward / North & South Mw 6.9 CAPSS Scenario Event
Mw	Earthquake moment magnitude
MWSS	Municipal Water Supply System
NERT	Neighborhood Emergency Response Team
P_e	Probability of Exceedance
PGA	Peak ground acceleration
PWSS	Portable Water Supply System
SA65	San Andreas / Peninsular Mw 6.5 CAPSS Scenario Event
SA72	San Andreas / Peninsular Mw 7.2 CAPSS Scenario Event
SA79	San Andreas Mw 7.9 CAPSS Scenario Event
SFFD	San Francisco Fire Department
TBA	Total Burnt Area
TFA	Total Floor Area
WSF	Water Supply Factor

Tables

Table 4 San Francisco Fire Department fire stations and apparatus

Station	Address	Engine	Truck	Other
1	676 Howard St.	1	1	Rescue Squad
2	1340 Powell St.	1	1	Battalion 1 Chief
3	1067 Post St.	1	1	
5	1301 Turk St.	1	1	Division 2 Chief
6	135 Sanchez St.	1	1	
7	2300 Folsom St.	1	1	Division 3 Chief
8	36 Bluxome St.	1	1	Battalion 3 Chief
9	2245 Jerrold St.	1	1	Battalion 10 Chief
10	655 Presidio Ave.	1	1	
11	3880-26th St.	1	1	Battalion 6 Chief
12	1145 Stanyan St.	1	1	
13	530 Sansome St.	1	1	
14	551-26th Ave.	1	1	
15	1000 Ocean Avenue	1	1	Battalion 9 Chief
16	2251 Greenwich St.	1	1	
17	1295 Shafter St.	1	1	PWSS Hose Tender
18	1935-32nd Avenue	1	1	
19	390 Buckingham Way	1	1	
20	285 Olympia Way	1		
21	1443 Grove St.	1		
22	1290-16th Avenue	1		PWSS Hose Tender
23	1348-45th Avenue	1		
24	100 Hoffman St.	1		
25	3305-3rd Street	1		
26	80 Digby St.	1		
28	1814 Stockton St.	1		
29	299 Vermont St.	1		
31	441-12th Ave.	1		Battalion 7 Chief
32	194 Park St.	1		
33	#8 Capitol Ave.	1		
34	499-41st Ave.	1		Cliff Rescue Unit
35	Pier 22-1/2, Fireboats 1 & 2 (no Engine at present)			
36	109 Oak St.	1		Hazardous Materials Unit, Battalion 2 Chief
37	798 Wisconsin St.	1		
38	2150 California St.	1		PWSS Hose Tender, Battalion 4 Chief
39	1091 Portola St.	1		
40	2155-18h Ave.	1		Battalion 8 Chief
41	1325 Leavenworth St.	1		
42	2430 San Bruno Ave.	1		
43	720 Moscow St.	1		
44	1298 Girard St.	1		
48	Treasure Island (849 Ave. D)	1	1	PWSS Hose Tender
51	Presidio of S. F. (Lincoln Blvd.)	1		
Total		**42**	**19**	

Table 5 Comparison of San Francisco Fire Department, 1906 and today

	1906	**2010**
Population. Protected (thous.)	400	815
Area Protected (sq. mi.)	21	46.7
SFFD personnel[11]	585	1750
Engine companies	38	42
Fireboats	-	2
Auxiliary Water Supply System (AWSS)[12]	Proposed	Yes
Cisterns	23	172
Total SFFD Pumping Capacity (gallons per minute, gpm)		
Pumping Capacity (gpm)		
engines only	35,100	50,400
engines + fireboats	35,100	70,400
engines + fireboats + AWSS	35,100	90,400
Pump. Cap. Per capita (gpm pc)		
engines only	0.09	0.06
engines + fireboats	0.09	0.09
engines + fireboats + AWSS	0.09	0.11
Pump. Cap. Per Firefighter (gpm /ff) [13]		
engines only	60	29
engines + fireboats	60	40
engines + fireboats + AWSS	60	52

[11] In 1906 the 585 firefighters were virtually all resident in San Francisco, while today a significant number of SFFD personnel reside outside the City.

[12] The AWSS was proposed by Chief Dennis Sullivan and others in 1905, but was repeatedly turned down by the San Francisco Board of Supervisors as “too expensive” (see text).

[13] Based on all 1750 uniformed personnel today – if only on duty firefighters are considered, or on duty plus those likely to quickly return to duty in a major earthquake, the 52 gpm/ff would be more like 150~250 gpm/ff.

Table 6 General Sources of Ignition, LAFD Data, Northridge Earthquake (Scawthorn et al., 1998)

Source	Fraction
Electrical	56%
Gas-related	26%
Other	18%

Table 7 Property Use for 77 LAFD Earthquake-Related Fires 4:31 TO 24:00 hrs, January 17, 1994 (Scawthorn et al., 1998)

General Property Use	Fraction
One or Two Family Residential	45%
Multi-Family Residential	26%
Public Roadway	8%
Office	5%
Primary / Secondary School	3%
Vacant Property	3%
Restaurant	1%
Commercial	1%
Power Production/Distribution	1%
Other	5%
Unknown	1%

Table 8 Frequency Distribution of Ignitions, four Scenario Events

	SA Mw 7.9		**SA Mw 7.2**		**SA Mw 6.5**		**Hayward Mw 6.9**	
No. ignitions	**pdf**	**CDF**	**pdf**	**CDF**	**pdf**	**CDF**	**pdf**	**CDF**
0	0	0	0	0	0	0	0	0
20	0	0	0	0	0.00	0.00	0.01	0.01
40	0.01	0.01	0.05	0.05	0.16	0.17	0.64	0.64
60	0.16	0.18	0.30	0.36	0.42	0.59	0.35	1.00
80	0.20	0.38	0.27	0.63	0.34	0.93	0.01	1
100	0.19	0.57	0.22	0.85	0.07	1.00	0	1
120	0.18	0.75	0.14	0.99	0.00	1	0	1
140	0.14	0.89	0.01	1	0	1	0	1
160	0.10	0.99	0	1	0	1	0	1
180	0.01	1.00	0	1	0	1	0	1
200	0.00	1	0	1	0	1	0	1

pdf = probability density function, which in this context is a measure of the likelihood of having that number of ignitions;

CDF = Cumulative Distribution Function, which in this context is a measure of the likelihood of having that number, or a larger number, of ignitions

Table 9 Results for Final Burnt Area

Scenario →	San Andreas Mw 7.9				San Andreas Mw 7.2				San Andreas Mw 6.5				Hayward Mw 6.9			
	No. Fires	Vw (mph)	Tot Burnt Area (th sf)	TBA $ value (millions)	No. Fires	Vw (mph)	Tot Burnt Area (th sf)	TBA $ value (millions)	No. Fires	Vw (mph)	Tot Burnt Area (th sf)	TBA $ value (millions)	No. Fires	Vw (mph)	Tot Burnt Area (th sf)	TBA $ value (millions)
max of 1000 trials →	182	33.9	48,901	$ 22,472	129	29.8	39,525	$ 18,239	104	34.6	26,961	$ 12,508	65	35	24,755	$ 12,160

STATISTICS FOR ALL TRIALS

	San Andreas Mw 7.9		San Andreas Mw 7.2		San Andreas Mw 6.5		Hayward Mw 6.9	
mean Loss (mills sq ft)	16.7		11.1		7.3		6	
median TBA	**15.3**		**10.3**		**6.6**		**5.0**	
stnd dev TBA	**9.4**		**6.7**		**4.7**		**4.4**	
average No. Fires	95.1		73.1		57		37.8	
median No. Fires	92		72		56		37	
avg value psf	**$460**		**$461**		**$464**		**$491**	
mean $ Loss (mills $)	$7,674	3.74% of total value at risk	$5,122	2.50% of total value at risk	$3,387	1.65% of total value at risk	$2,947	1.44% of total value at risk
medan $ loss	**$7,035**		**$4,746**		**$3,040**		**$2,480**	
stnd Dev Dollar loss	**$4,325**		**$3,074**		**$2,182**		**$2,153**	
max $ loss	**$22,472**		**$18,239**		**$12,508**		**$12,160**	

Frequency Analysis of Total Dollar Loss ($ millions)

TBA $ (mills)		pdf	CDF	TBA $ (mills)		pdf	CDF	TBA $ (mills)		pdf	CDF	TBA $ (mills)		pdf	CDF
$ -	0	0	0	$ -	0	0	0	$ -	0	0	0	$ -	0	0	0
$ 2,000	56	0.056	0.056	$ 2,000	155	0.155	0.155	$ 2,000	301	0.301	0.301	$ 2,000	412	0.412	0.412
$ 4,000	169	0.169	0.225	$ 4,000	259	0.259	0.414	$ 4,000	351	0.351	0.652	$ 4,000	328	0.328	0.74
$ 6,000	172	0.172	0.397	$ 6,000	233	0.233	0.647	$ 6,000	223	0.223	0.875	$ 6,000	154	0.154	0.894
$ 8,000	179	0.179	0.576	$ 8,000	177	0.177	0.824	$ 8,000	90	0.09	0.965	$ 8,000	75	0.075	0.969
$ 10,000	142	0.142	0.718	$ 10,000	98	0.098	0.922	$ 10,000	27	0.027	0.992	$ 10,000	24	0.024	0.993
$ 12,000	110	0.11	0.828	$ 12,000	50	0.05	0.972	$ 12,000	5	0.005	0.997	$ 12,000	6	0.006	0.999
$ 14,000	86	0.086	0.914	$ 14,000	17	0.017	0.989	$ 14,000	3	0.003	1	$ 14,000	1	0.001	1
$ 16,000	43	0.043	0.957	$ 16,000	9	0.009	0.998	$ 16,000	0	0	1	$ 16,000	0	0	1
$ 18,000	25	0.025	0.982	$ 18,000	1	0.001	0.999	$ 18,000	0	0	1	$ 18,000	0	0	1
$ 20,000	12	0.012	0.994	$ 20,000	1	0.001	1	$ 20,000	0	0	1	$ 20,000	0	0	1
$ 22,000	3	0.003	0.997	$ 22,000	0	0	1	$ 22,000	0	0	1	$ 22,000	0	0	1
$ 24,000	3	0.003	1	$ 24,000	0	0	1	$ 24,000	0	0	1	$ 24,000	0	0	1
	0	0	1		0	0	1		0	0	1		0	0	1

pdf = probability density function, which in this context is a measure of the likelihood of having that loss;

CDF = Cumulative Distribution Function, which in this context is a measure of the likelihood of having that, or a larger, loss.

Table 10 Results Summary Statistics

Scenario →	San Andreas Mw 7.9	San Andreas Mw 7.2	San Andreas Mw 6.5	Hayward Mw 6.9
mean Loss (mills sq ft)	16.7	11.1	7.3	6
median TBA	15.3	10.3	6.6	5.0
Standard Deviation TBA	9.4	6.7	4.7	4.4
average No. Fires	95.1	73.1	57	37.8
median No. Fires	92	72	56	37
mean $ Loss (mills $)	$7,674	$5,122	$3,387	$2,947
mean loss (% total $ value)	3.74%	2.50%	1.65%	1.44%
median $ loss	$7,035	$4,746	$3,040	$2,480
Standard Deviation Dollar loss	$4,325	$3,074	$2,182	$2,153
max $ loss	$22,472	$18,239	$12,508	$12,160

Table 11 Frequency of Losses for four Scenario Events

	San Andreas Mw 7.9			San Andreas Mw 7.2			San Andreas Mw 6.5			Hayward Mw 6.9		
TBA $ (mills)	no.	pdf	**CDF**	no.	pdf	**CDF**	no.	pdf	**CDF**	no.	pdf	**CDF**
$ -	0	-	-	0	-	-	0	-	-	0	-	-
$ 2,000	56	0.06	0.06	155	0.16	0.16	301	0.30	0.30	412	0.41	0.41
$ 4,000	169	0.17	0.23	259	0.26	0.41	351	0.35	0.65	328	0.33	0.74
$ 6,000	172	0.17	0.40	233	0.23	0.65	223	0.22	0.88	154	0.15	0.89
$ 8,000	179	0.18	0.58	177	0.18	0.82	90	0.09	0.97	75	0.08	0.97
$ 10,000	142	0.14	0.72	98	0.10	0.92	27	0.03	0.99	24	0.02	0.99
$ 12,000	110	0.11	0.83	50	0.05	0.97	5	0.01	1.00	6	0.01	1.00
$ 14,000	86	0.09	0.91	17	0.02	0.99	3	0.00	1.00	1	0.00	1.00
$ 16,000	43	0.04	0.96	9	0.01	1.00	0	-	1.00	0	-	1.00
$ 18,000	25	0.03	0.98	1	0.00	1.00	0	-	1.00	0	-	1.00
$ 20,000	12	0.01	0.99	1	0.00	1.00	0	-	1.00	0	-	1.00
$ 22,000	3	0.00	1.00	0	-	1.00	0	-	1.00	0	-	1.00
$ 24,000	3	0.00	1.00	0	-	1.00	0	-	1.00	0	-	1.00
> $24,000	0	0	1	0	0	1	0	0	1	0	0	1

pdf = probability density function, which in this context is a measure of the likelihood of having that loss;

CDF = Cumulative Distribution Function, which in this context is a measure of the likelihood of having that, or a larger, loss.

Table 12 Sensitivity of Simulation for Loma Prieta Event to variation in Inputs

SAN FRANCISCO FIRE FOLLOWING EARTHQUAKE STUDY VALIDATION SENSITIVITY USING LOMA PRIETA MODEL											
Inputs	**BASE CASE**	**CHANGED VALUE OF VARIABLE (variables shown at left)**									
Average windspeed (m/s)	0	10									
Time of EQ	1700		500								
average dimension of single family dwelling (m)	16.6						12	20			
average separation of single family dwellings (m)	3.4						0	5			
average Fire Break Width (m)	24.4			29.28	19.52						
Water Supply Factor (WSF)	1					0					
initial delay (mins)	5								0		
Number of Engines	42									32	12
Change in input				20%	-20%					-24%	-71%
SUMMARY RESULTS											
mean Loss (millions sq ft) =	0.5	0.7	0.2	0.5	0.6	0.8	0.5	0.5	0.5	0.6	1.1
mean Dollar Loss (millions $) =	$ 258	$ 318	$ 79	$ 241	$ 278	$ 360	$ 258	$ 258	$258	$ 291	$482
average No. Fires =	15.7	15.7	13.5	15.7	15.7	15.7	15.7	15.7	15.7	16.1	15.9
EFFECT		23%	-70%	-7%	8%	39%	0%	0%	0%	13%	87%

Figures

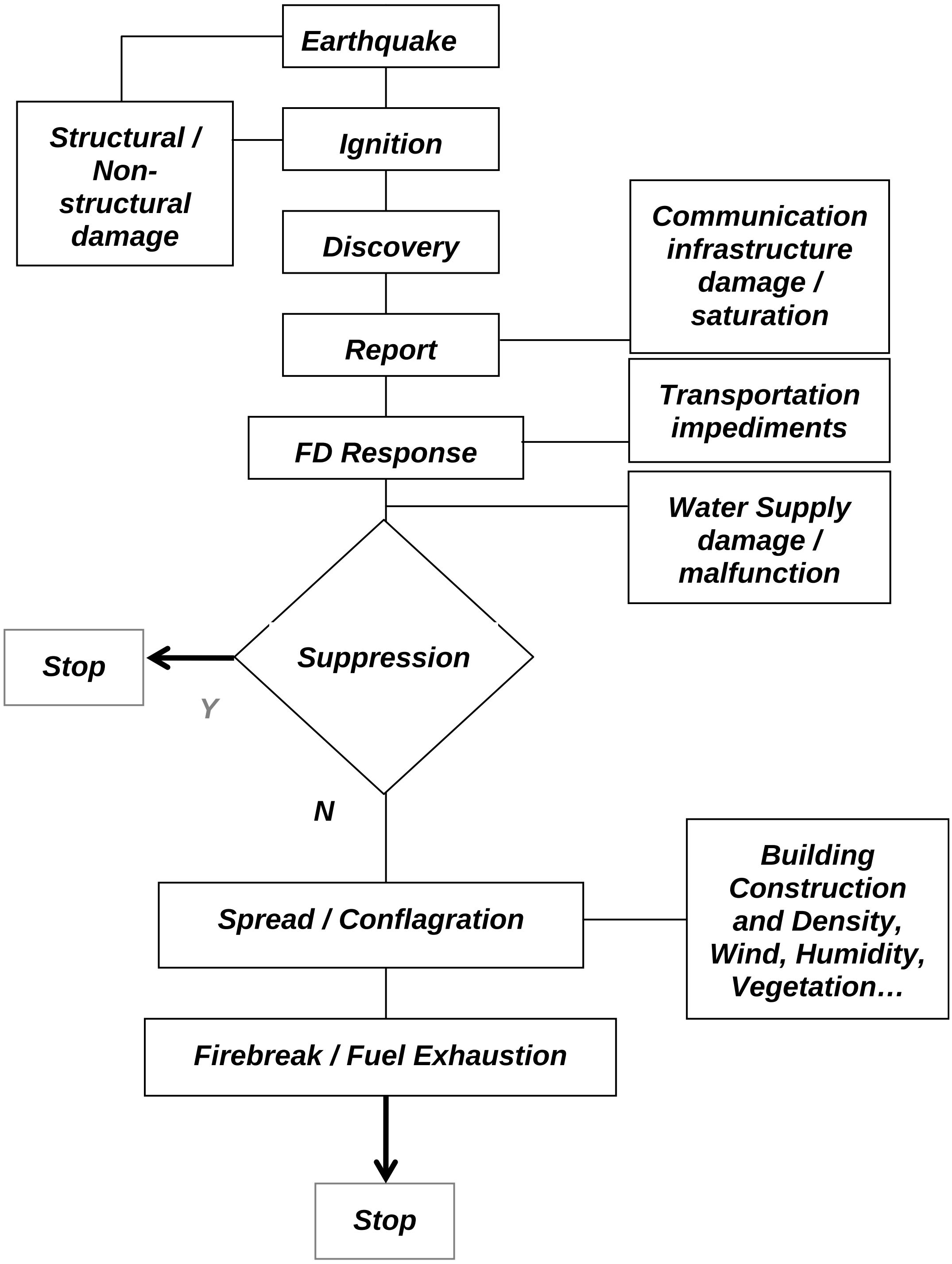


Figure 1 Fire following earthquake process (Scawthorn et al., 2005)

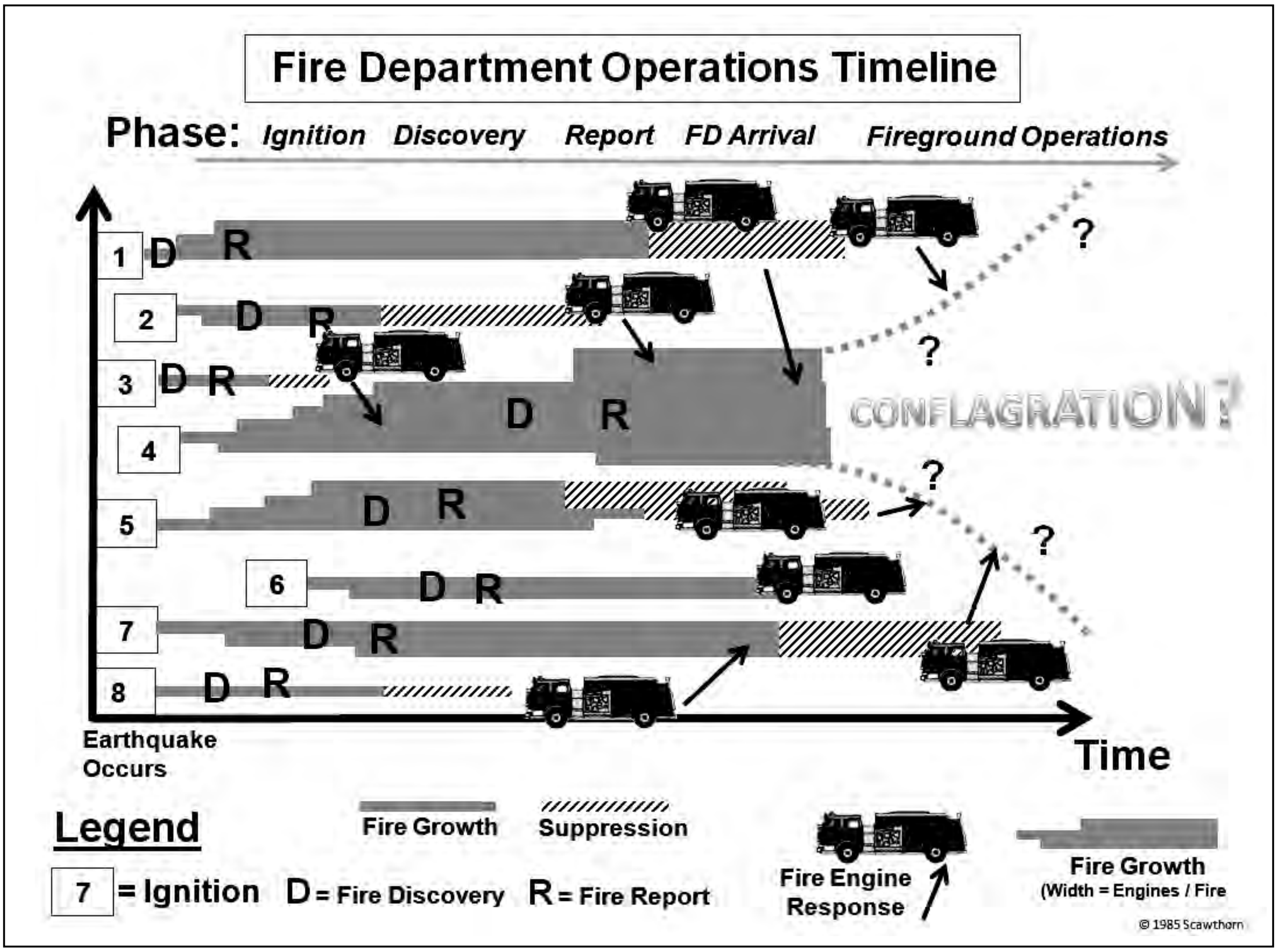
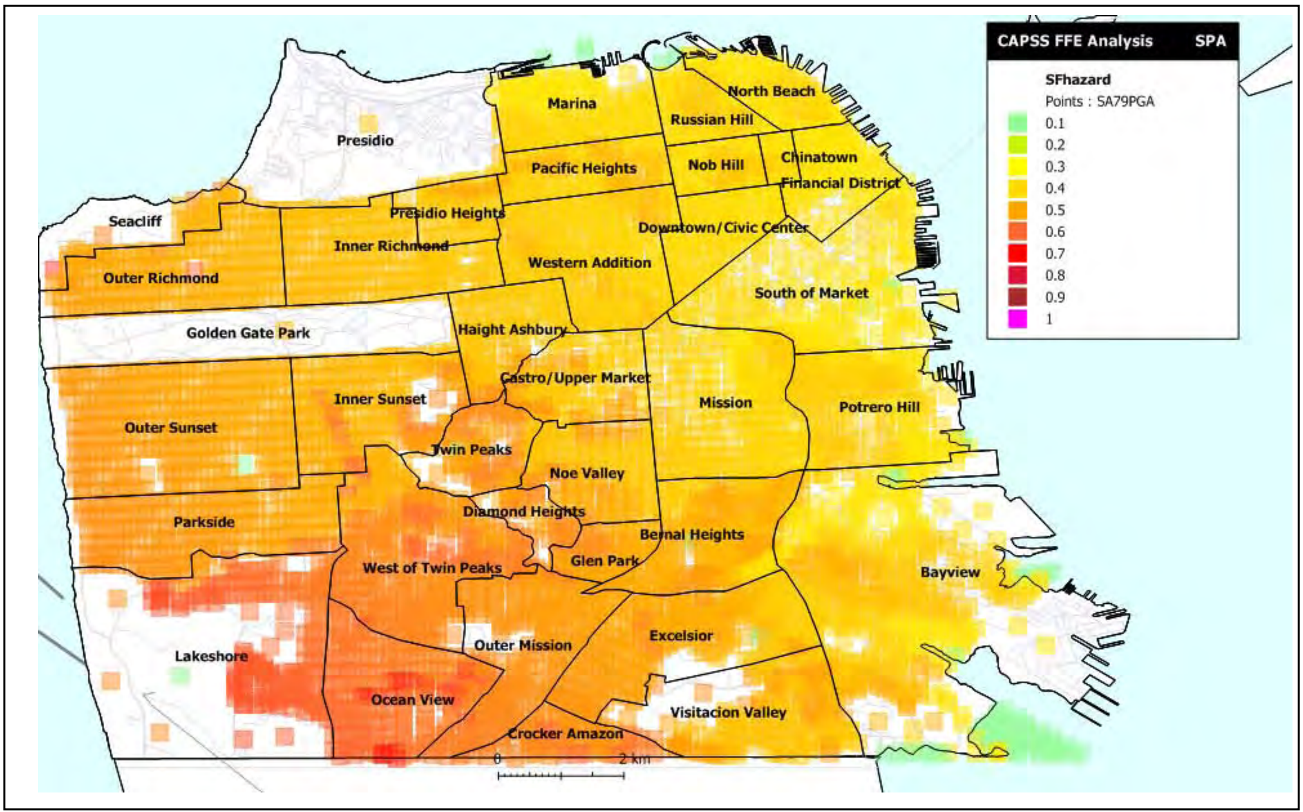


Figure 2 Fire department Operations Time Line (Scawthorn et al., 2005)



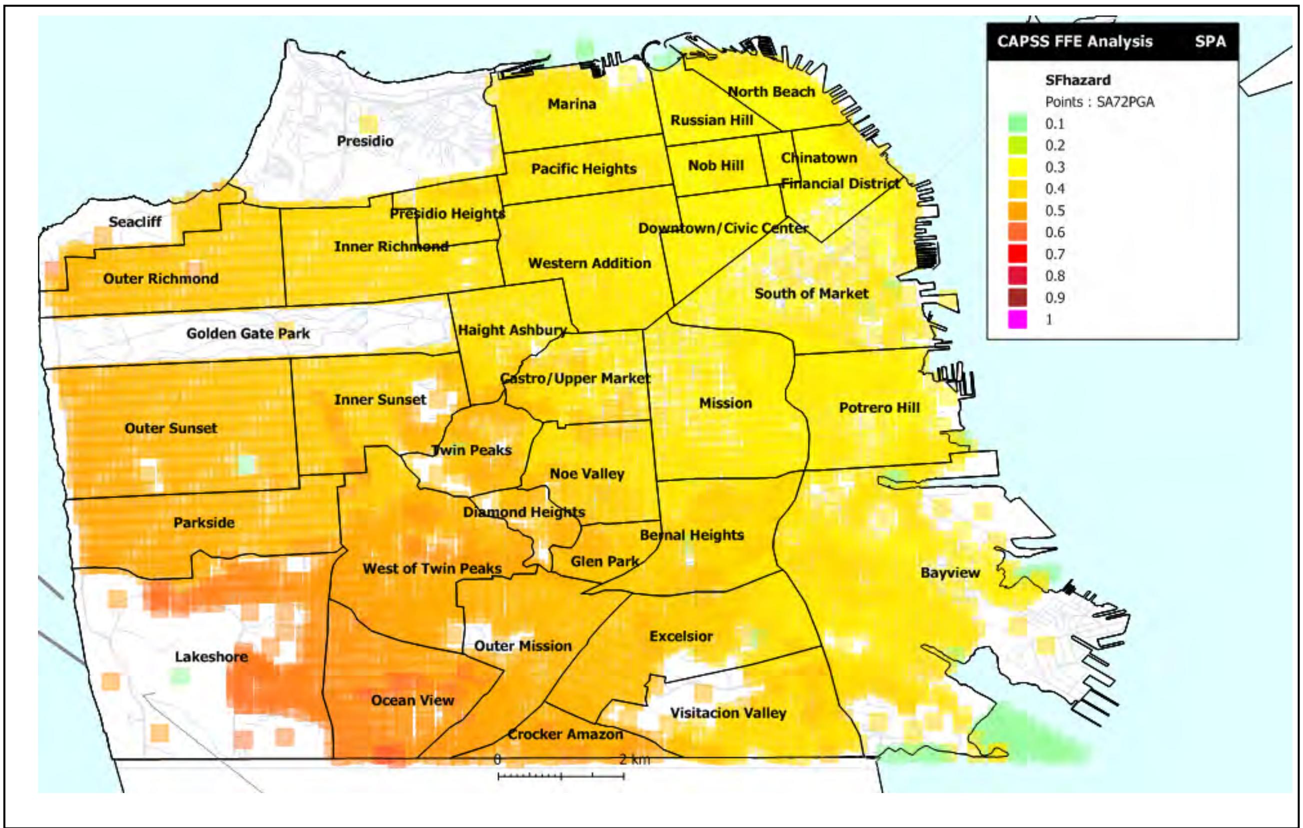
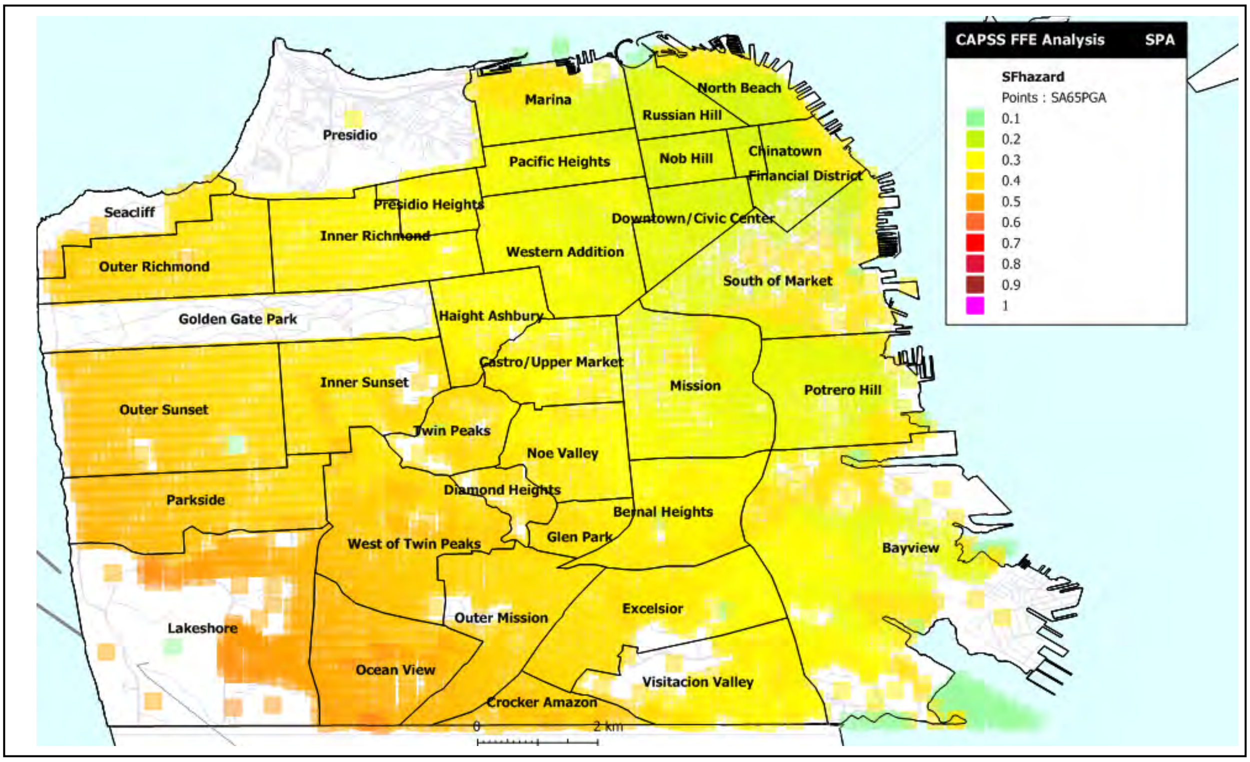


Figure 3 CAPSS Scenario Events, maps of Peak Ground Acceleration (PGA) (top) SA79; (bott.) SA72



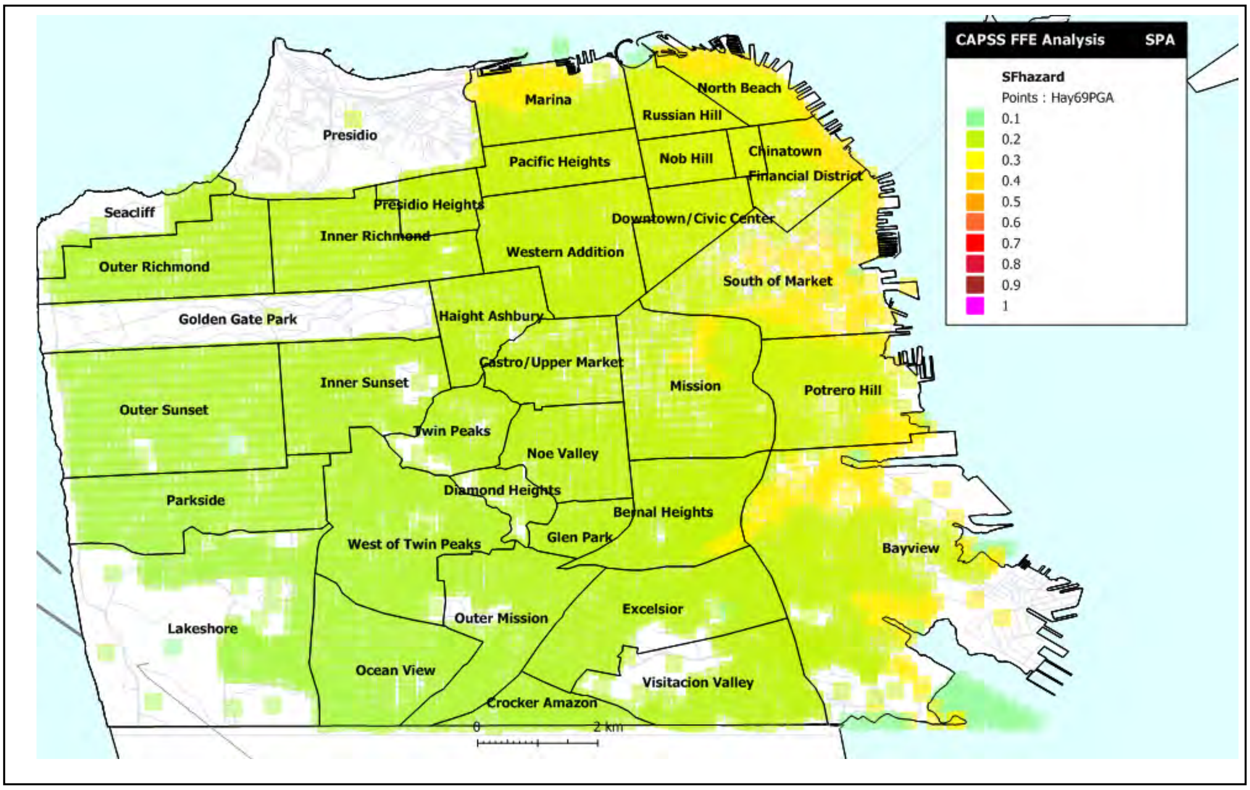
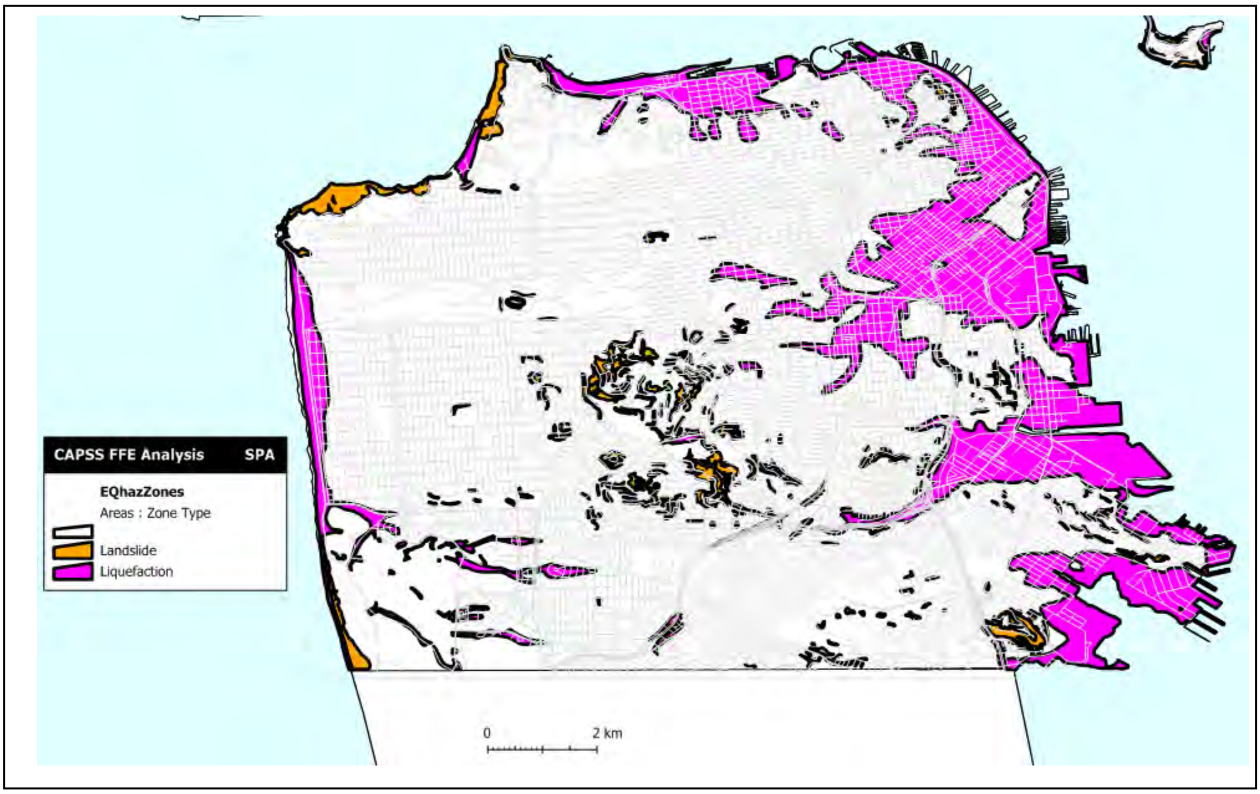


Figure 3 (cont.) CAPSS Scenario Events, maps of Peak Ground Acceleration (PGA) (top) SA65; (bott.) H69



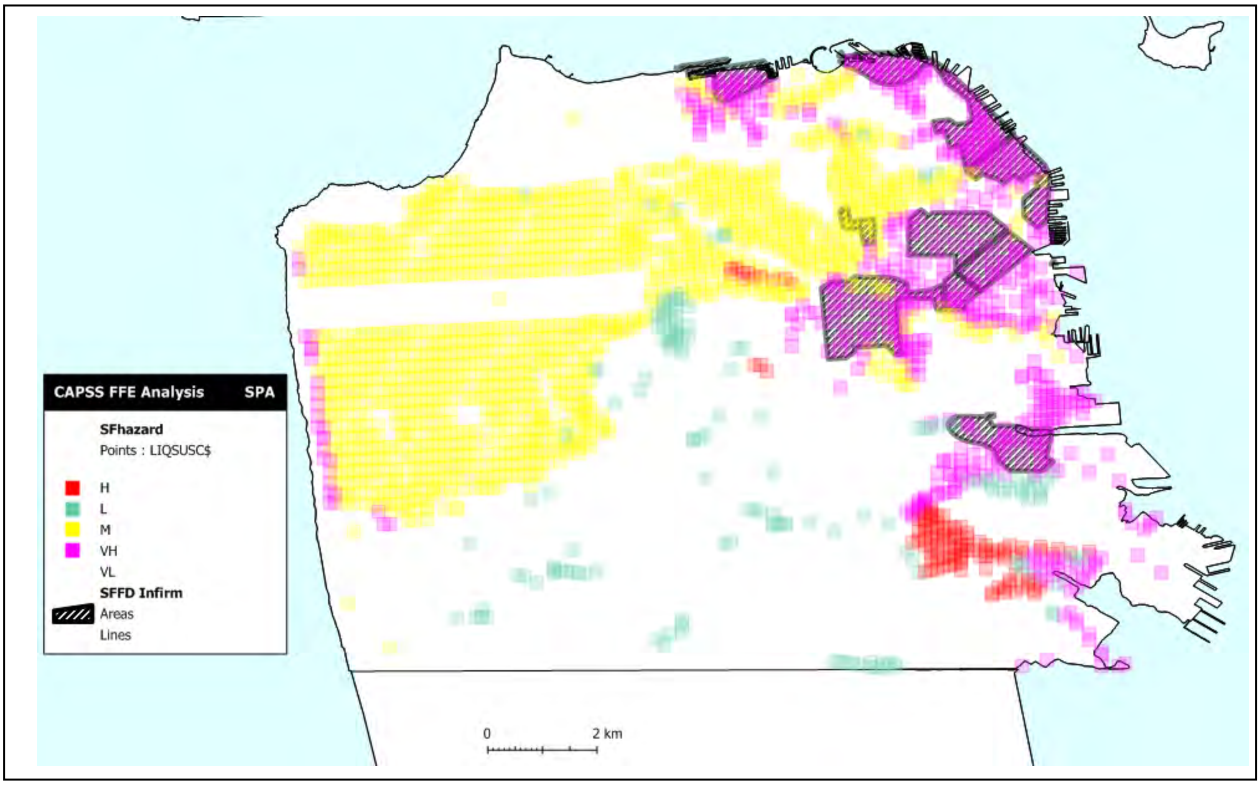


Figure 4 San Francisco Potential Ground Failure: (top) Earthquake Hazard Zones (source: http://gispubweb.sfgov.org); (bott) Liquefaction Susceptibility as furnished by the CAPSS project, overlaid with SFFD Infirm Areas.

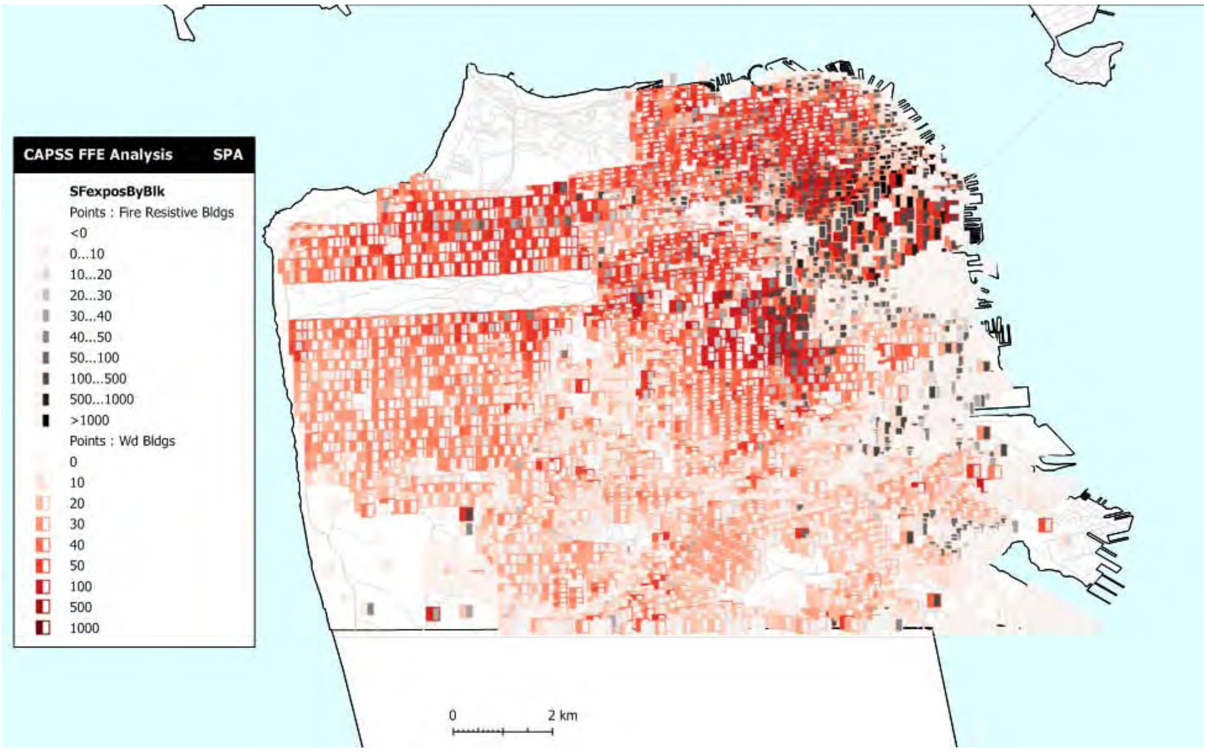


Figure 5 San Francisco building inventory, Total Floor Area (TFA) per block for wood (shades of red), and fire resistive (shades of gray) buildings. The more 'red' an area, the higher the TFA of wood buildings. Most of the City, especially north and east of Golden Gate Park, is clearly dense wood construction, while downtown has little wood.

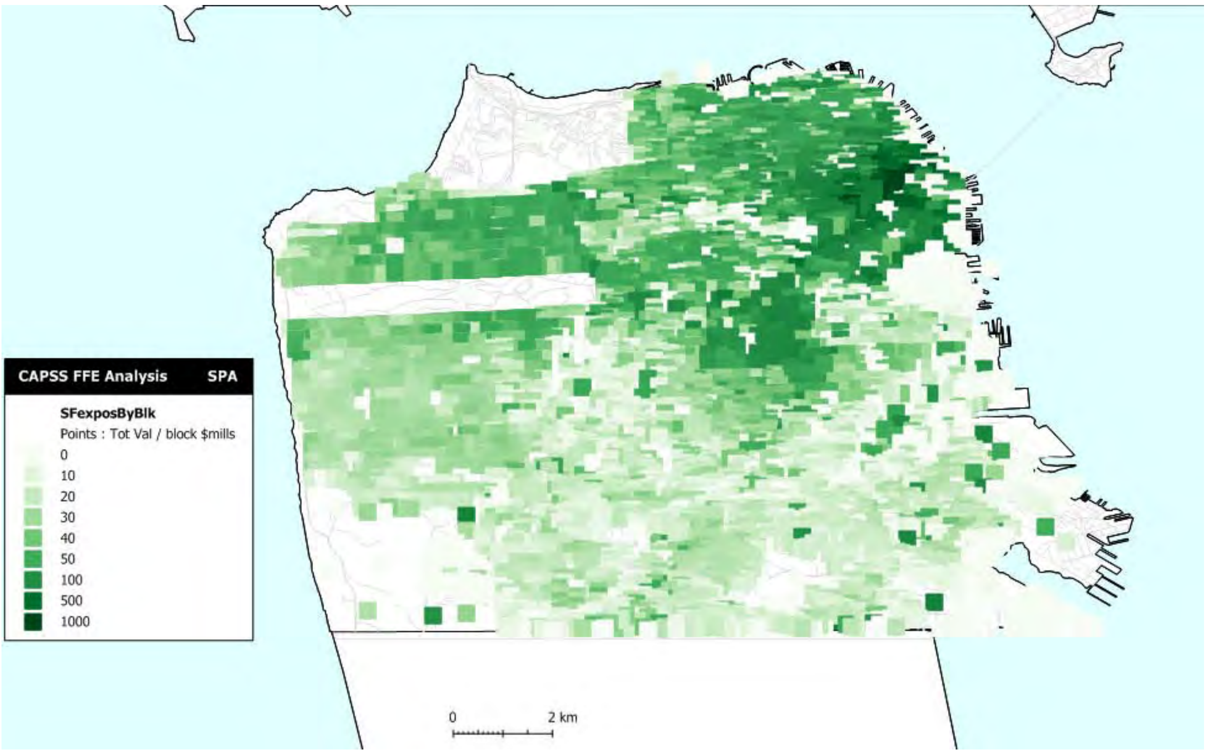


Figure 6 San Francisco building inventory, Total value (millions $)

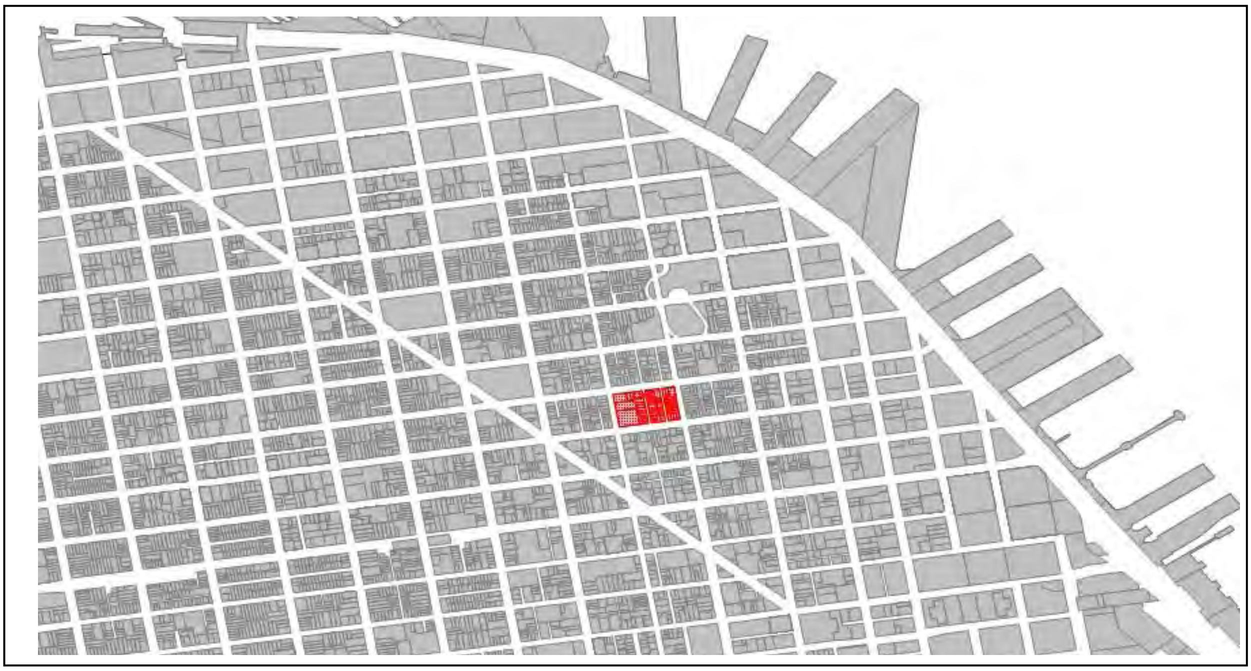


Figure 7 GIS data, block and lot, San Francisco.

Figure 8 Street width (building face-building face) sampled from Google Earth (example: 27th Ave between Moraga and Noriega).

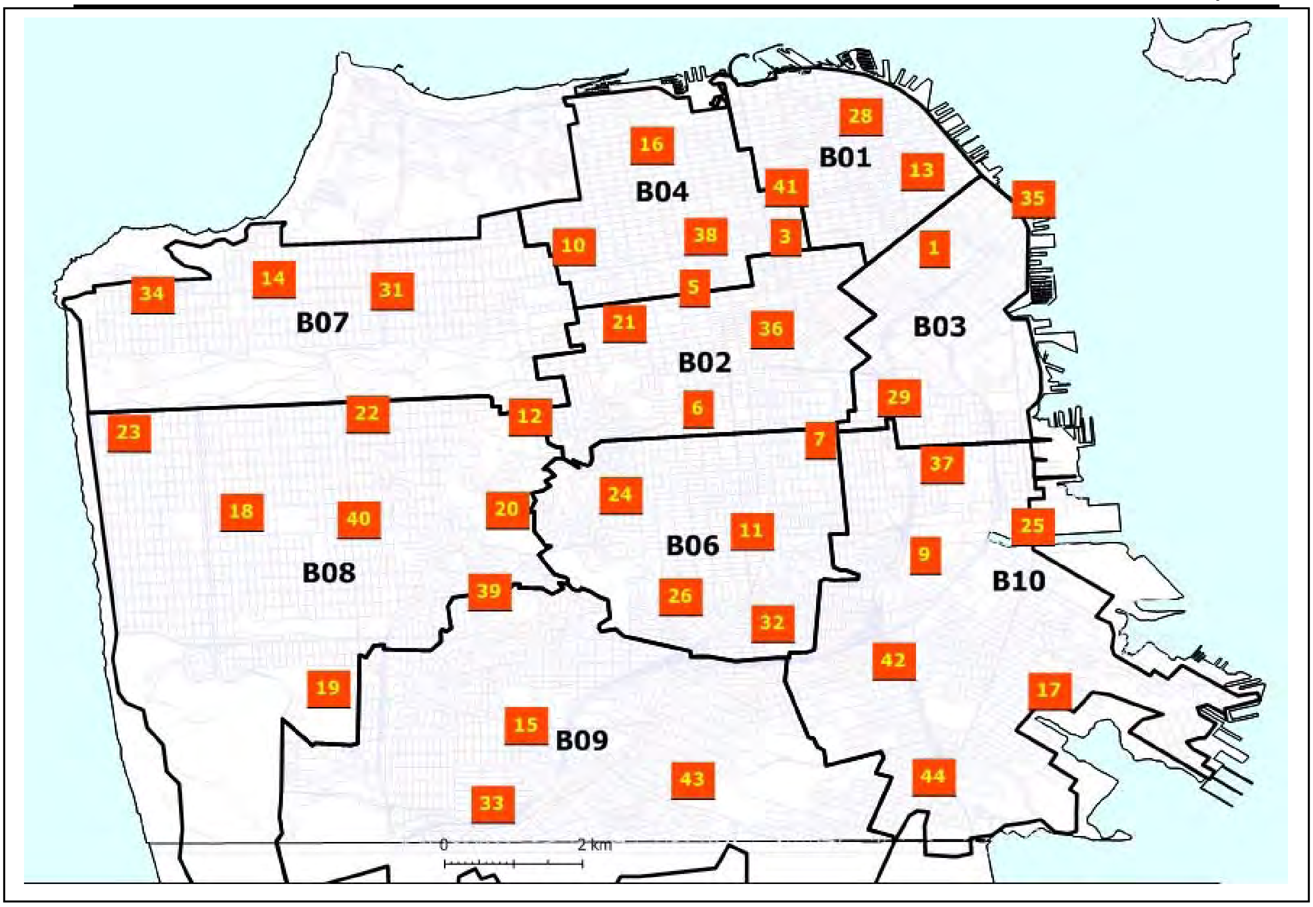


Figure 9 San Francisco Fire Department fire station locations and Battalion Districts

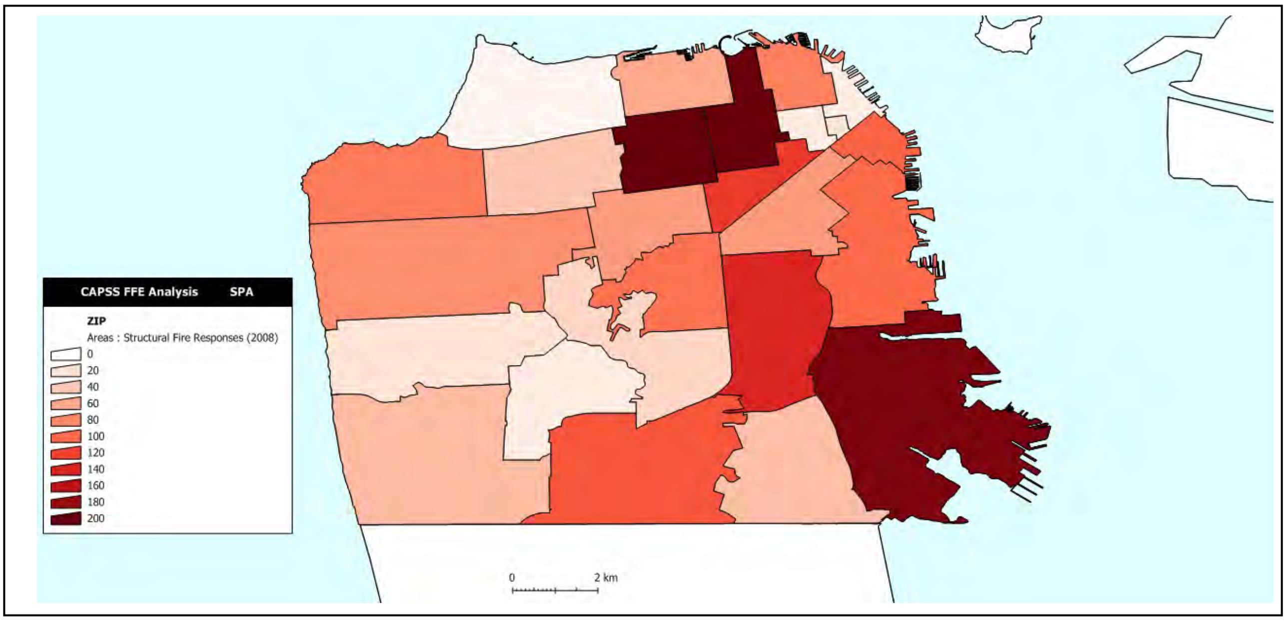


Figure 10 SFFD 2008 structural fire responses, by zip code (total responses 1,980)

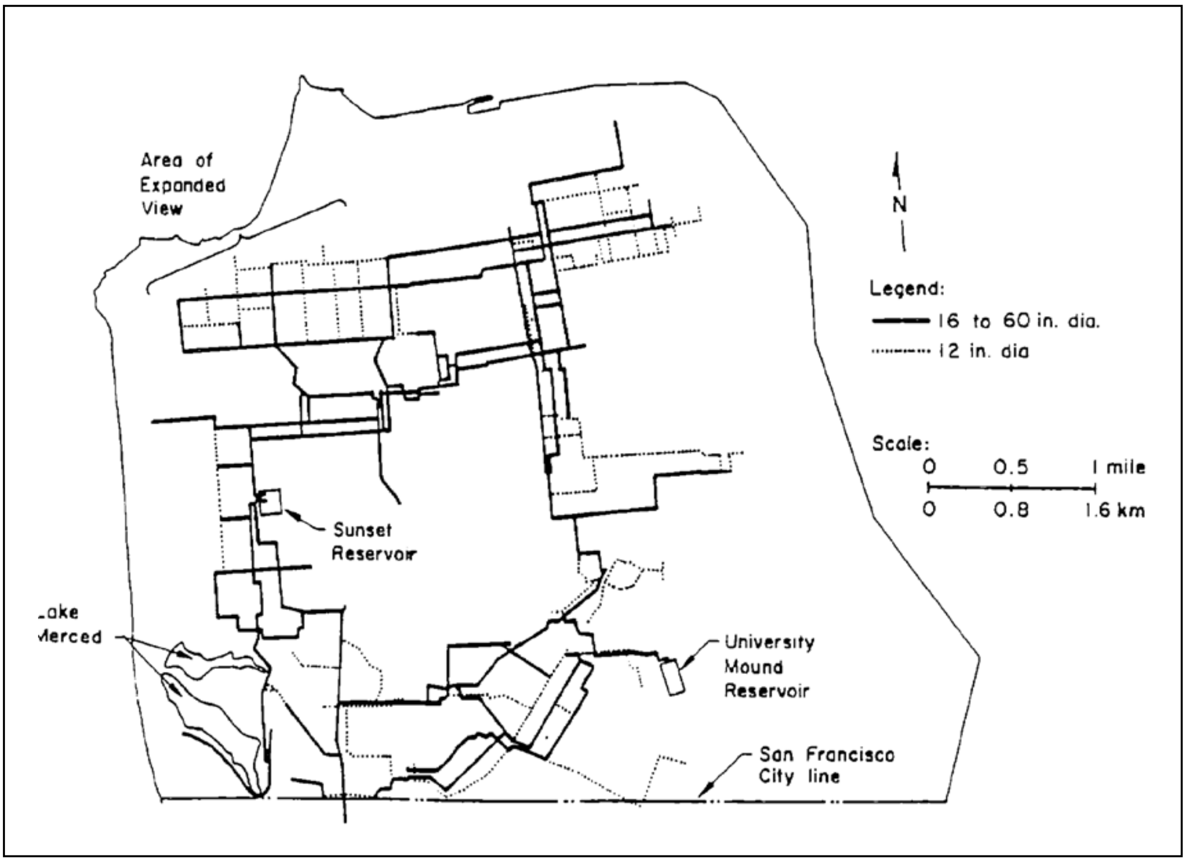


Figure 11 San Francisco Sunset portion (only) of MWSS (O'Rourke, 1990)

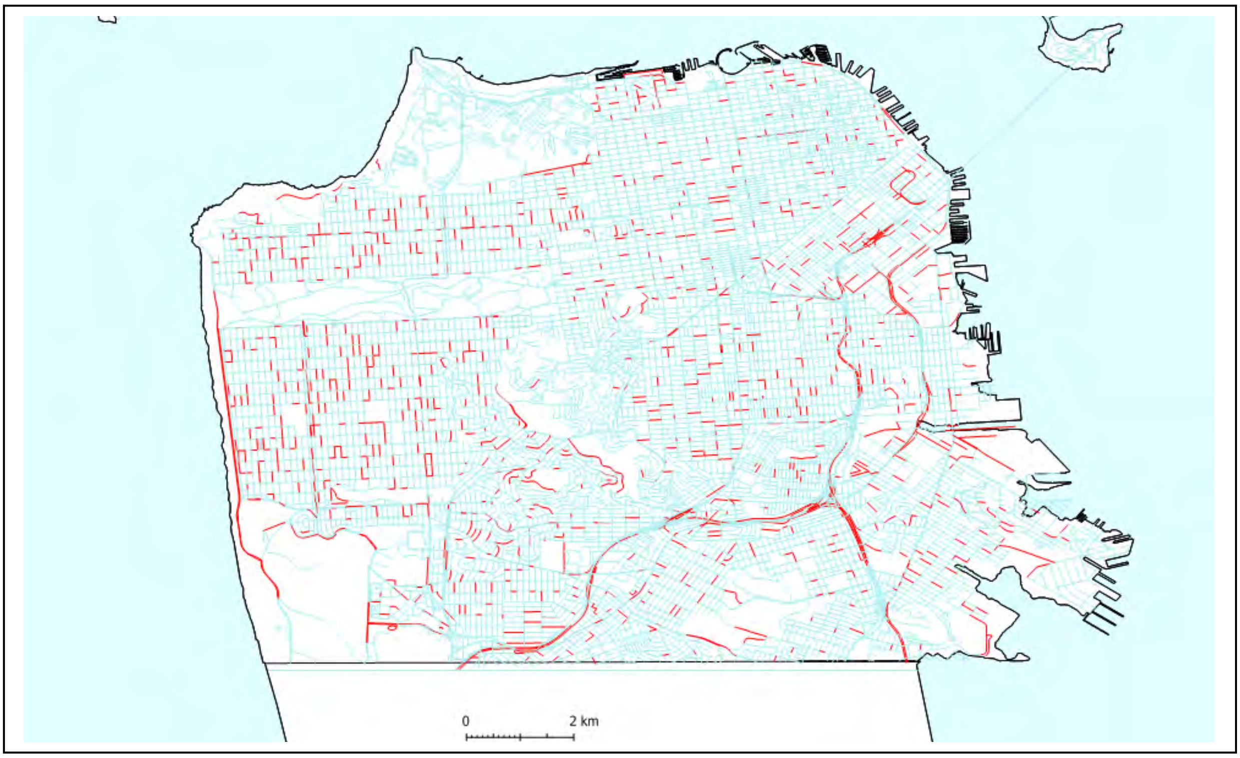


Figure 12 San Francisco proxy MWSS with estimated pipe sections with breaks shown in red, for SA79 scenario. Note that the estimation of the pipe breaks is a random process, so that only the general distribution, and not specific locations, of breaks are meaningful.

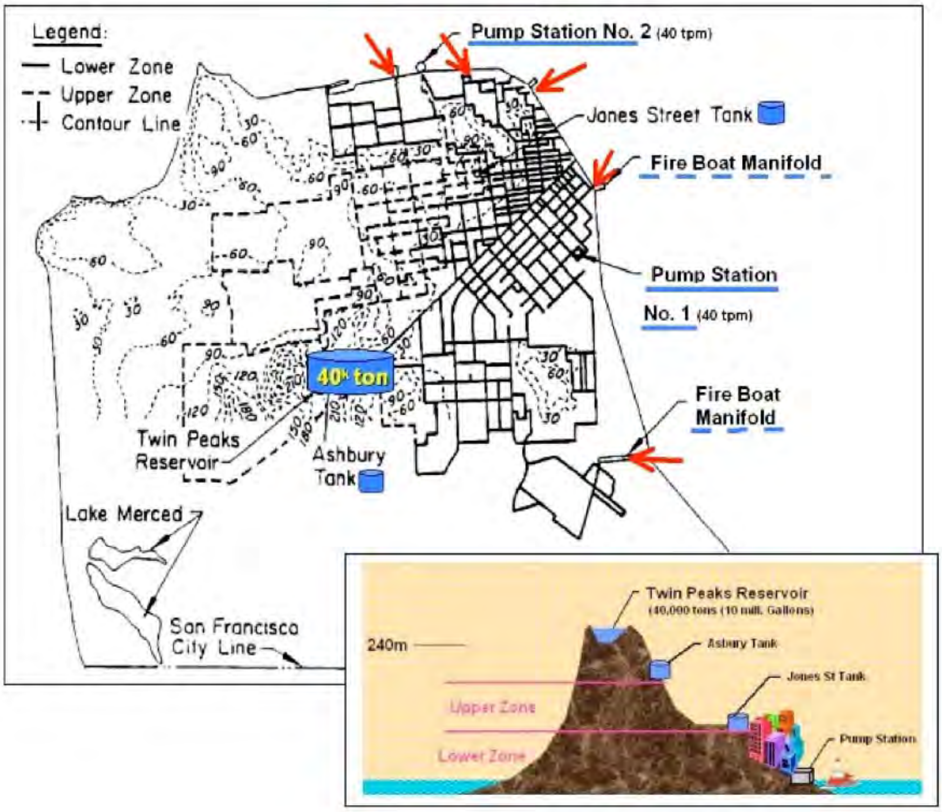


Figure 13 San Francisco AWSS overall Schematic

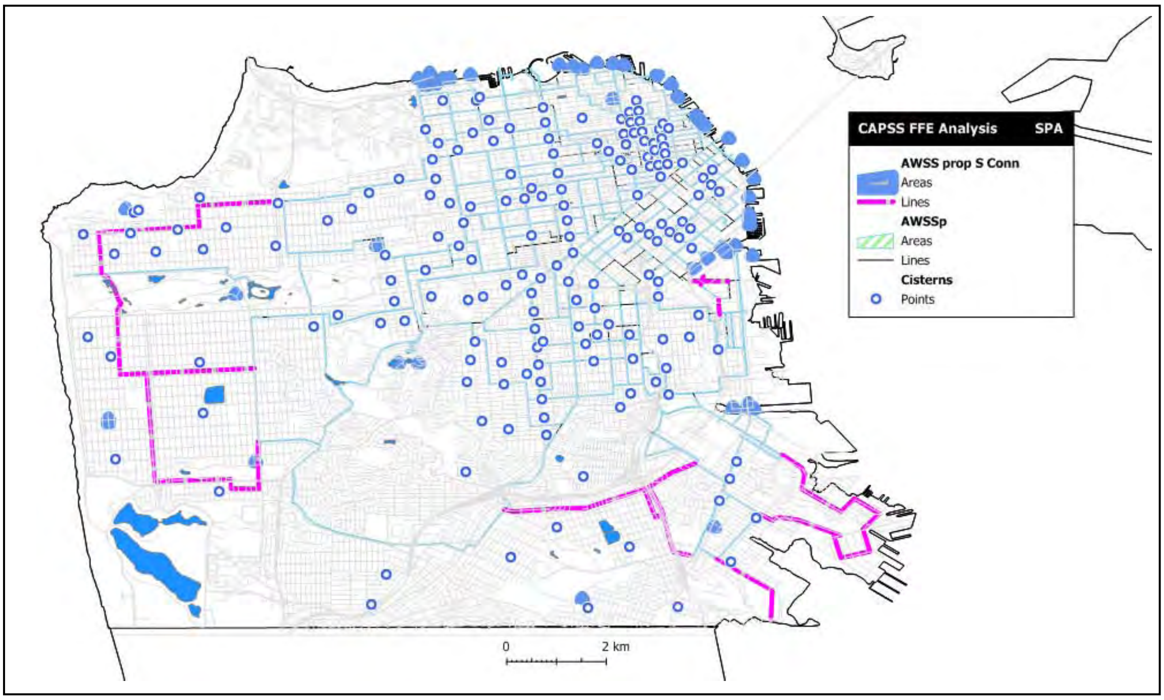


Figure 14 AWSS pipe network (magenta are proposed extensions that will be constructed with the 2010 Prop. B funding), suction connections (large blue 'blobs') and cisterns (smaller blue circles with white center).

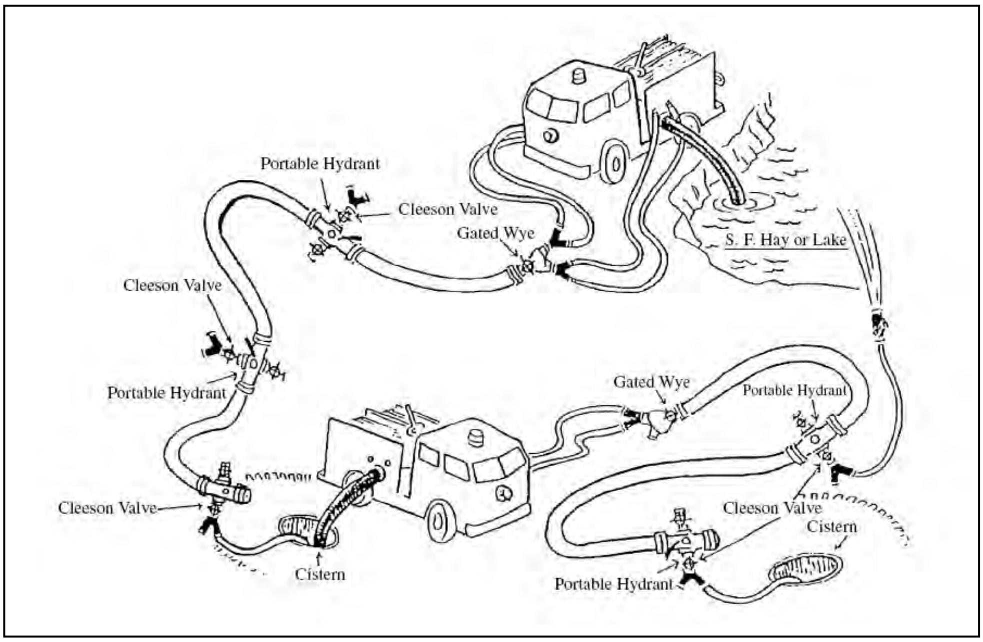


Figure 15 San Francisco Portable Water Supply System

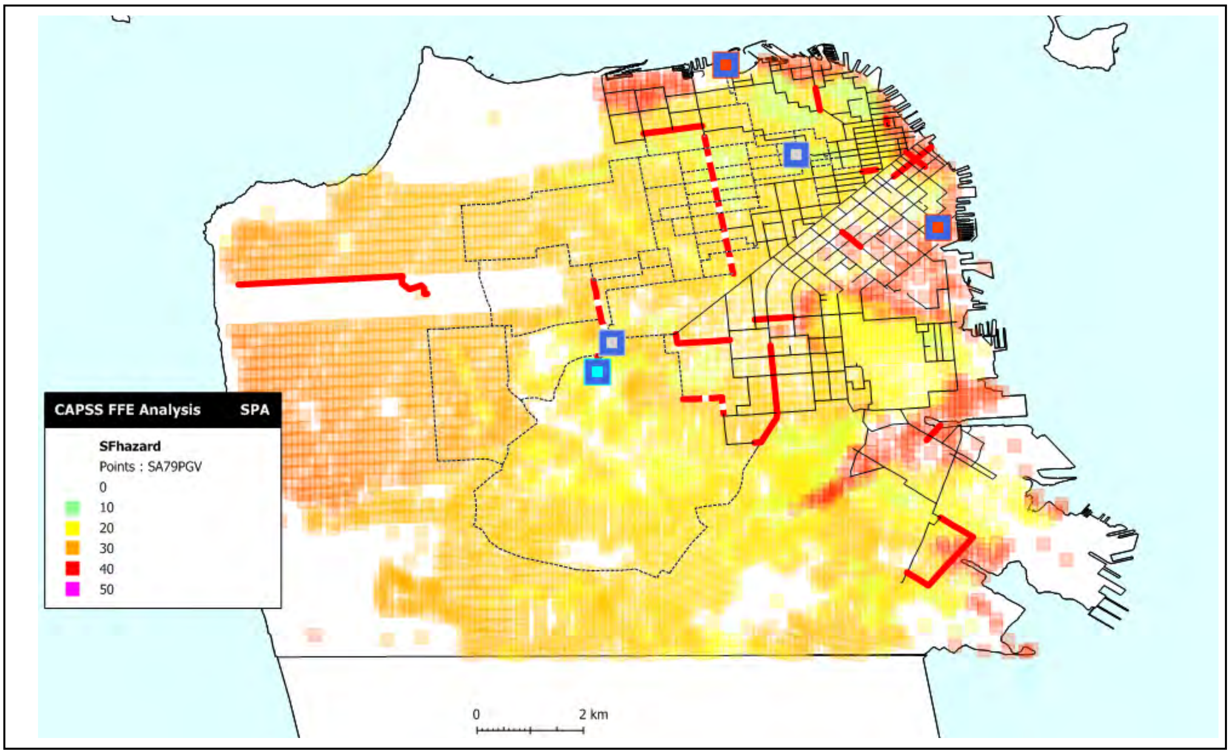


Figure 16 AWSS with estimated pipe breaks shown in red, overlaid on SA79 peak ground velocity. Note that the estimation of the pipe breaks is a random process, so that only the general distribution, and not specific locations, of breaks are meaningful.

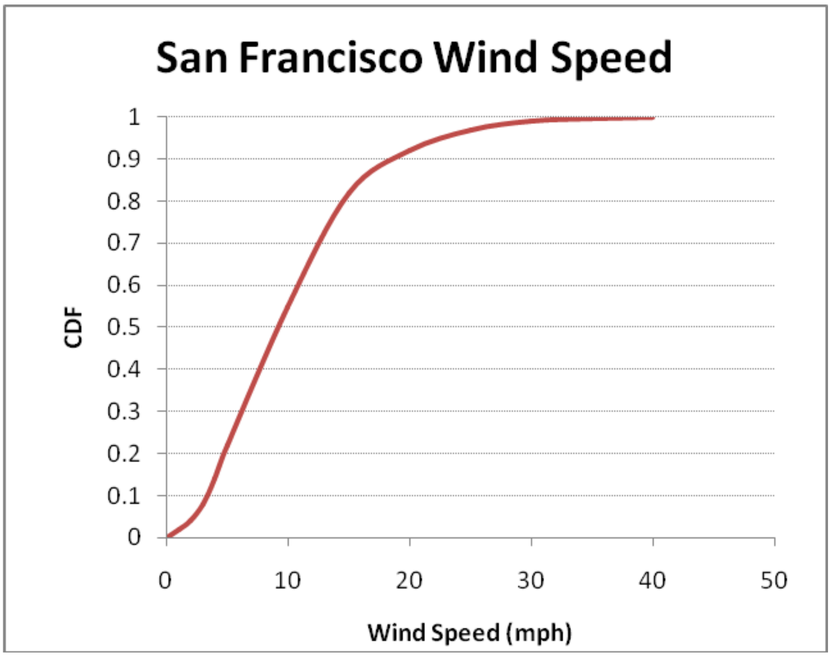


Figure 17 San Francisco Wind Speed

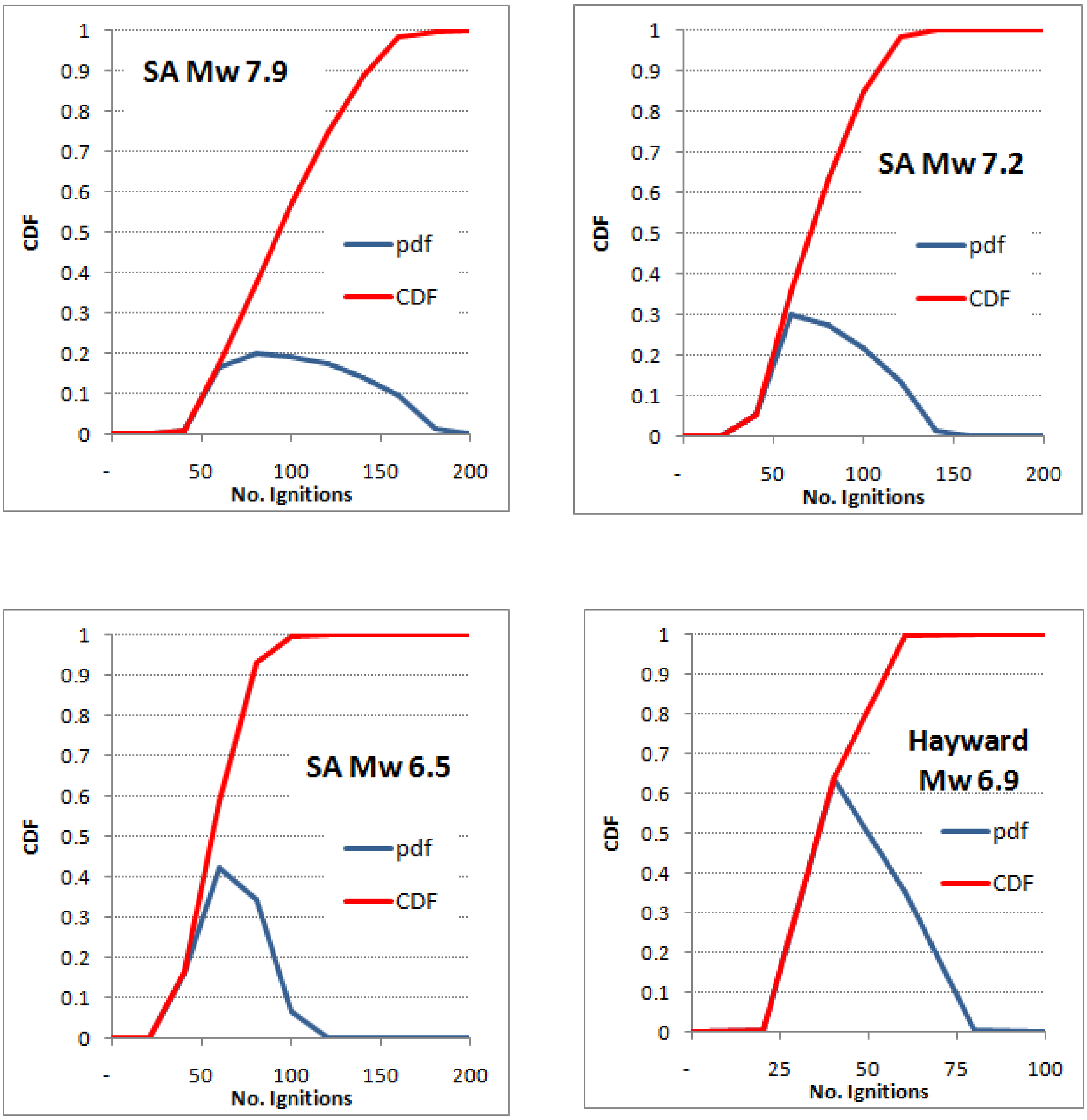


Figure 18 Frequency Distribution of Ignitions, four Scenario Events

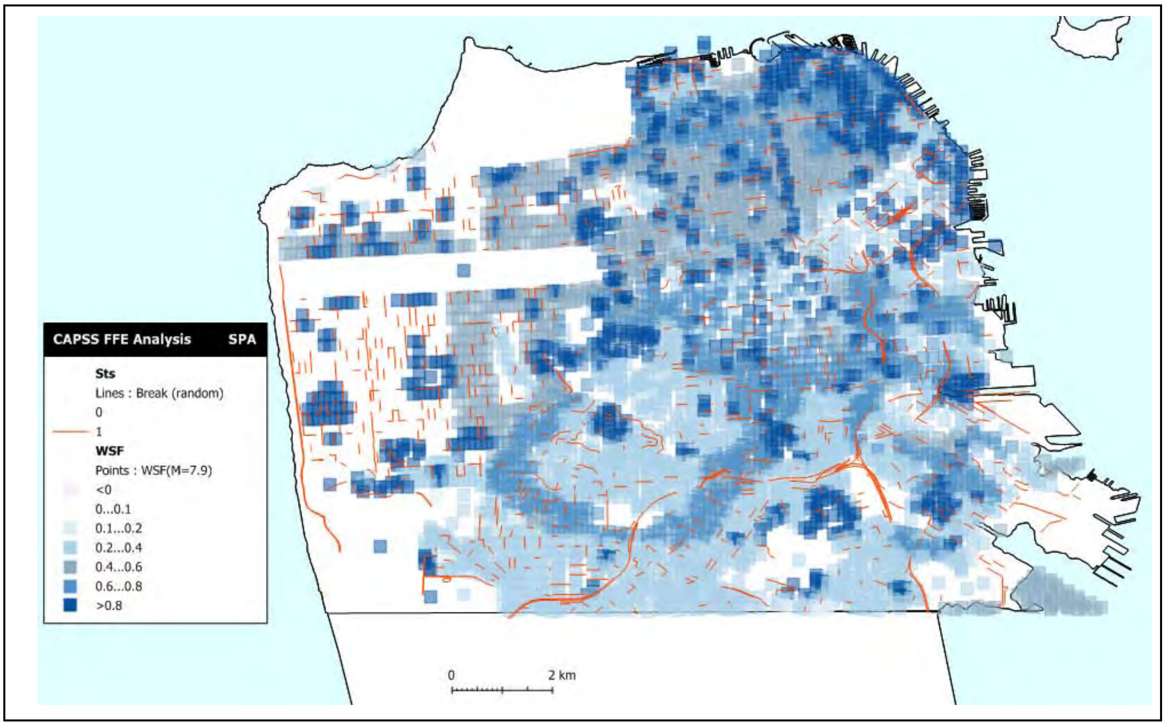
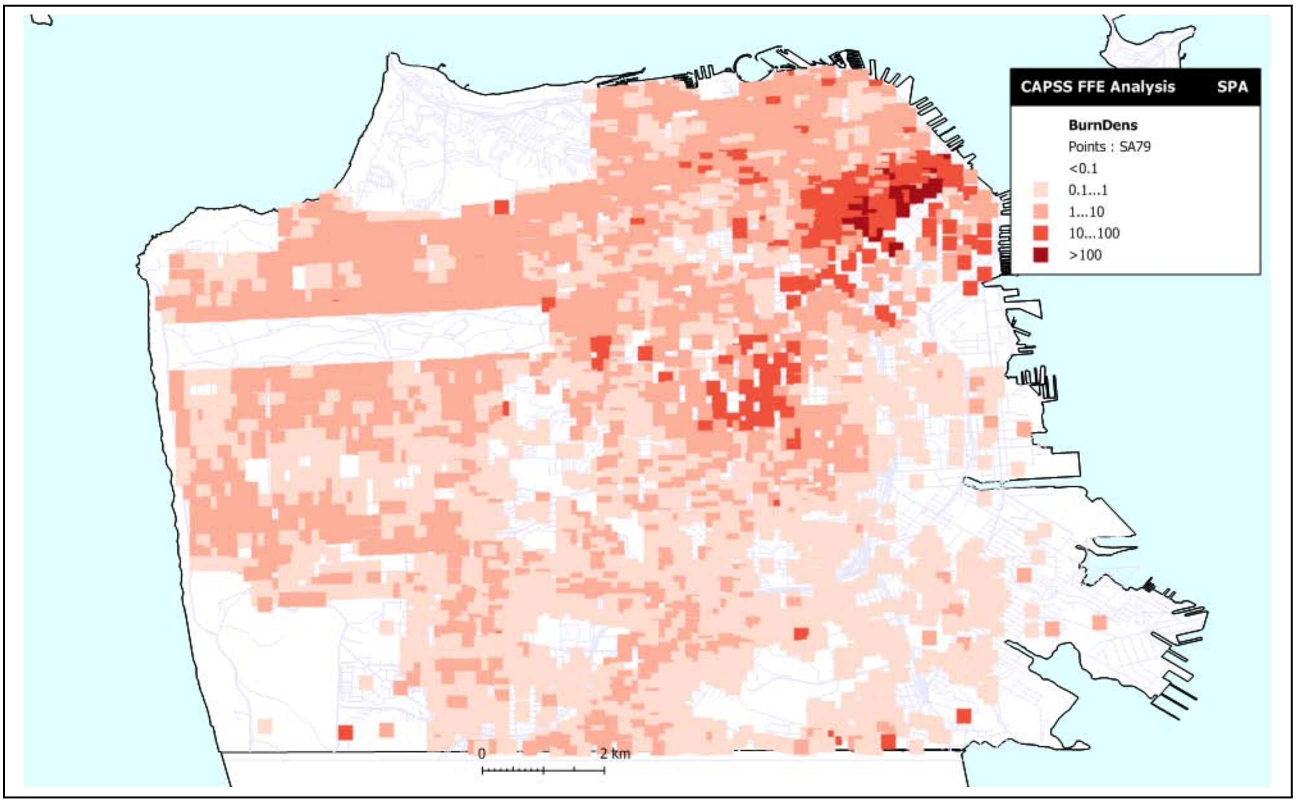


Figure 19 San Andreas Mw 7.9 event: example MWSS breaks overlaid on map of Water Supply Factor (WSF) for this scenario. WSF = 0 indicate no water (colored white), and 1 indicating completely adequate water (dark blue) – the darker the shade of blue the more adequate the water supply. Note that WSF is estimated based on all sources of water (MWSS, AWSS pipe network, cisterns, suction connections, etc). Presidio, Golden Gate and other parks not considered in the analysis.



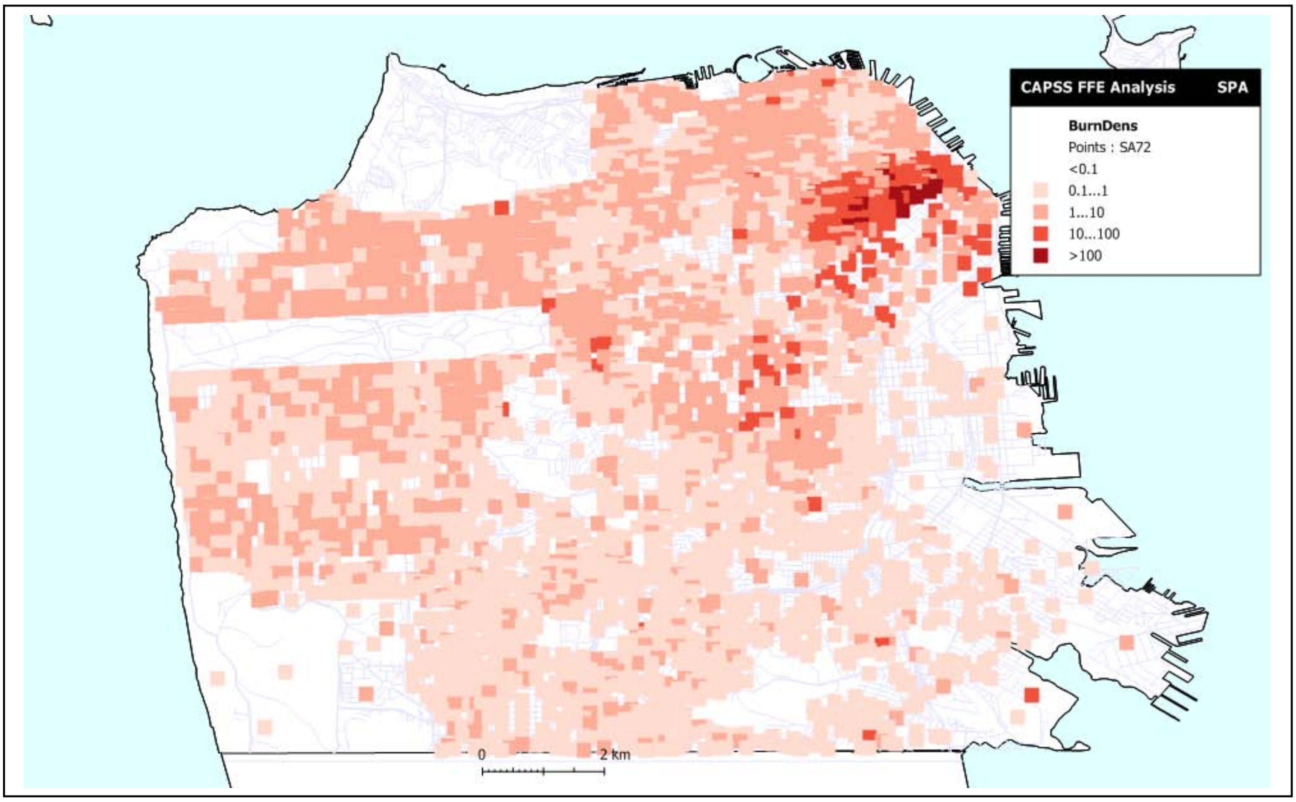
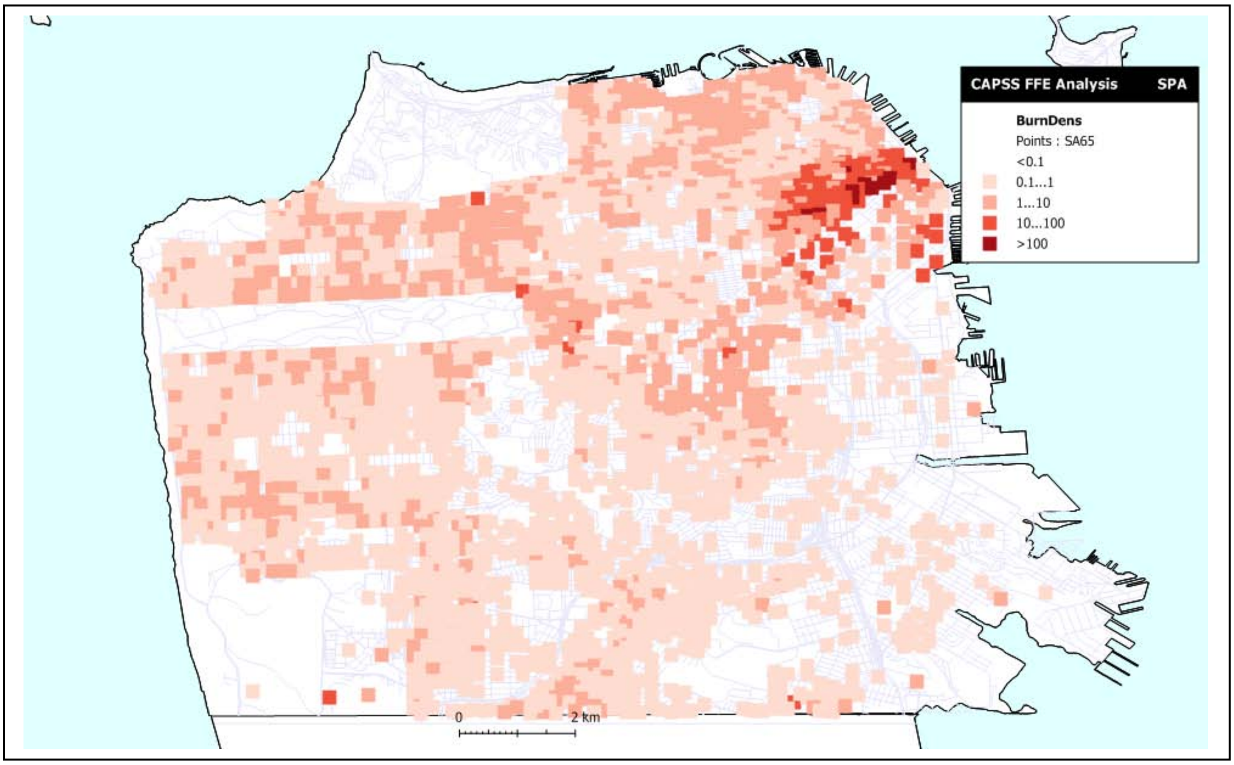


Figure 20 Distribution of Burn Density per block (millions $): (top) San Andreas Mw 7.9 Scenario; (bott.) San Andreas Mw 7.2 Scenario



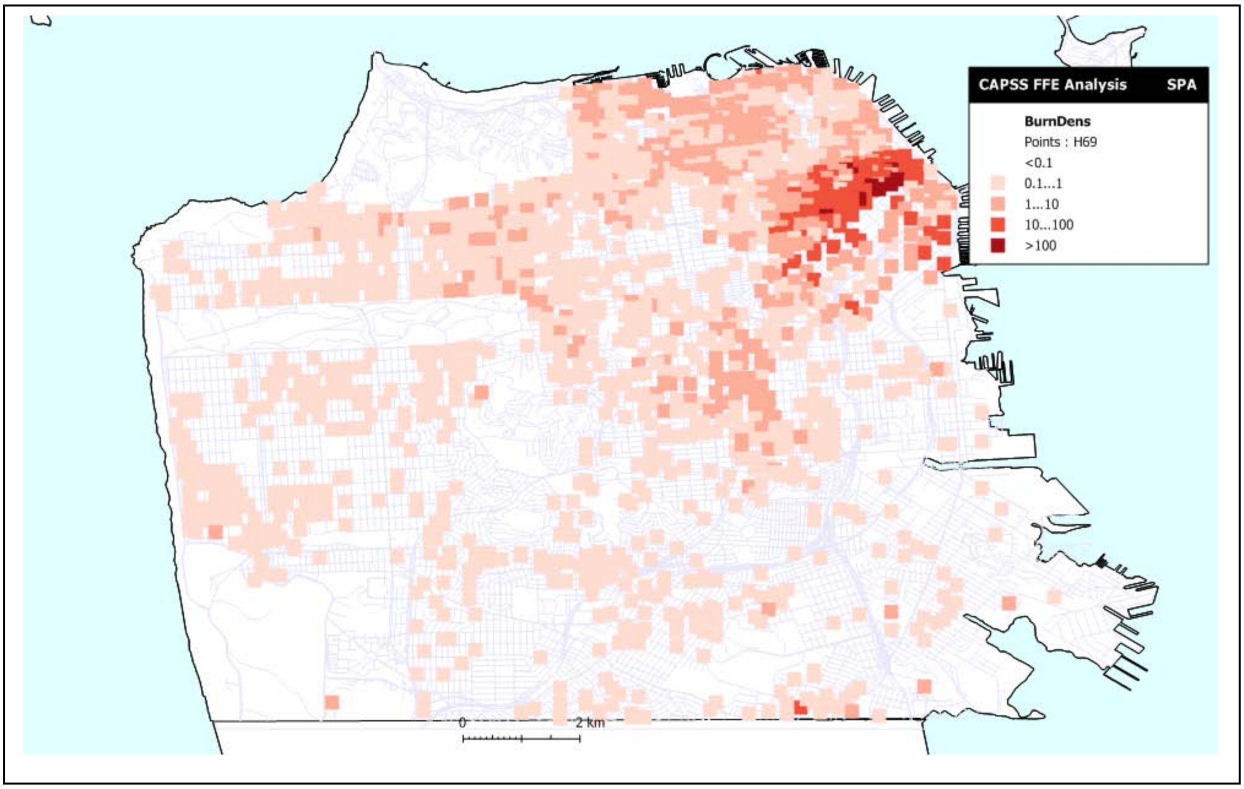


Figure 20 (cont.) Distribution of Burn Density per block (millions $): (top) San Andreas Mw 6.5 Scenario; (bott.) Hayward Mw 6.9 Scenario

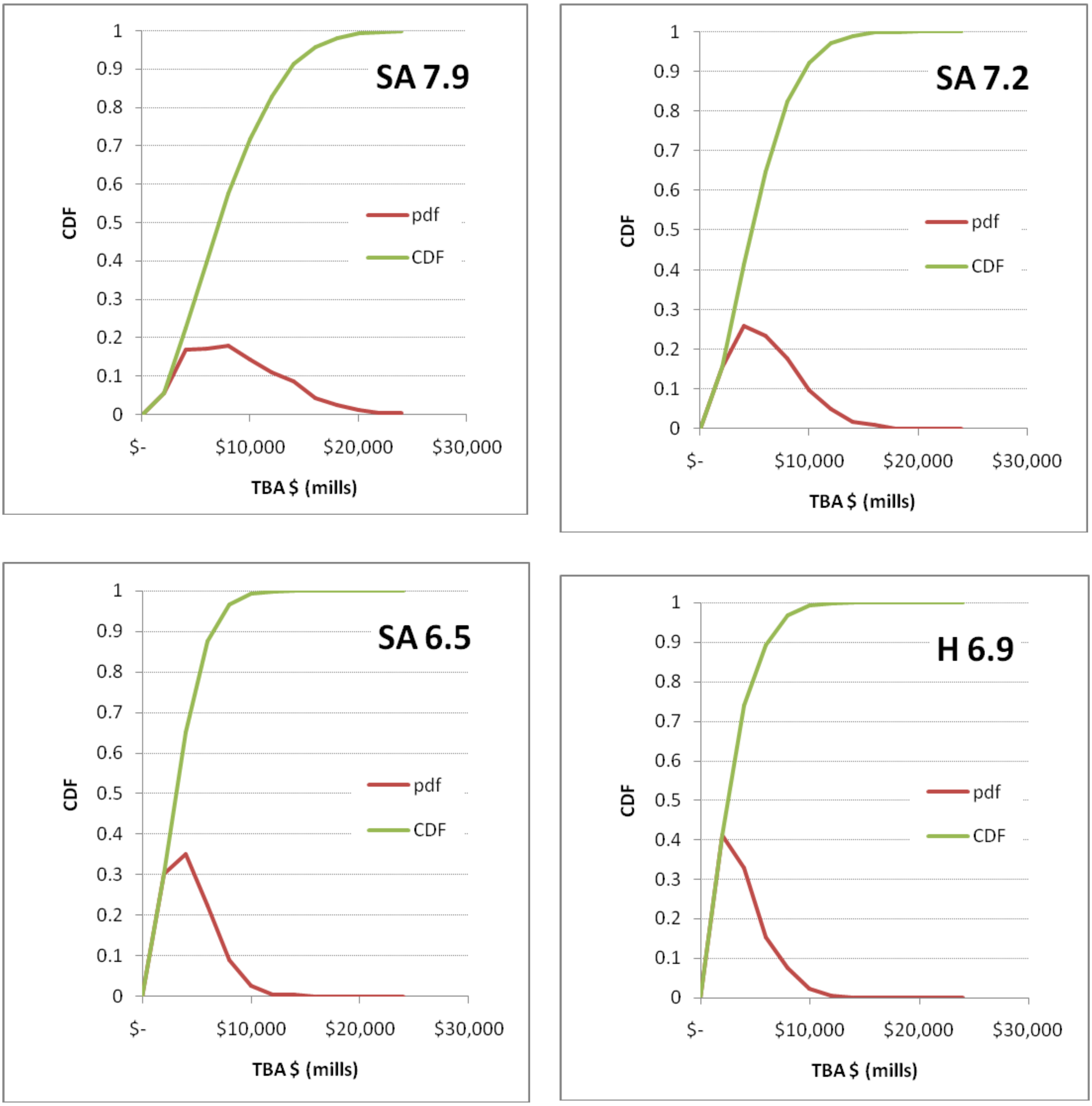


Figure 21 Frequency Distribution for final Total Burnt Area, four Scenario Events

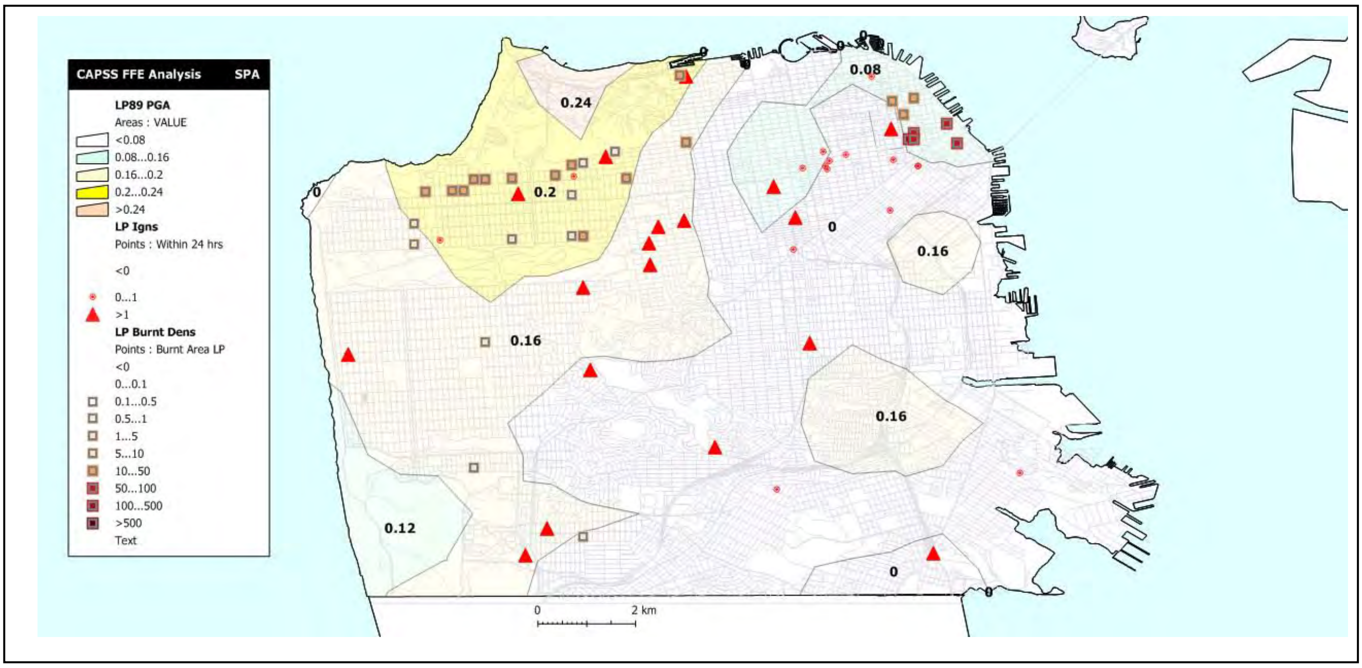


Figure 22 Loma Prieta Validation: Peak ground acceleration (PGA) estimated by the USGS are shown as colored zones, which are overlaid with the actual ignitions that occurred within 24 hours of the earthquake (red triangles) and one distribution of ignitions drawn at random from a 1,000 trial simulation (squares). Ignitions that occurred after the first 24 hours are shown as smaller dots. One fire is estimated to, and did, occur in the Marina, and a roughly comparable distribution of estimated and real events can been seen throughout most of the City, with the exception of the Financial District, where more events are estimated than did occur. As noted by other observers, this disparity may be due to the rapid loss electric power in the event.

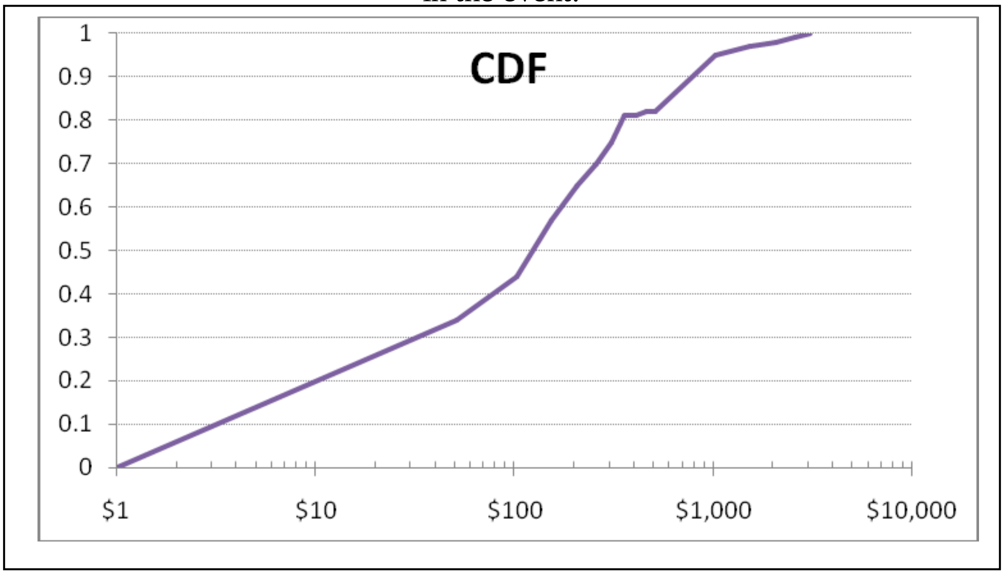


Figure 23 Loma Prieta validation: frequency of simulated losses, showing median loss of $122 million, and about a 35% probability of the losses being $35 million or less.

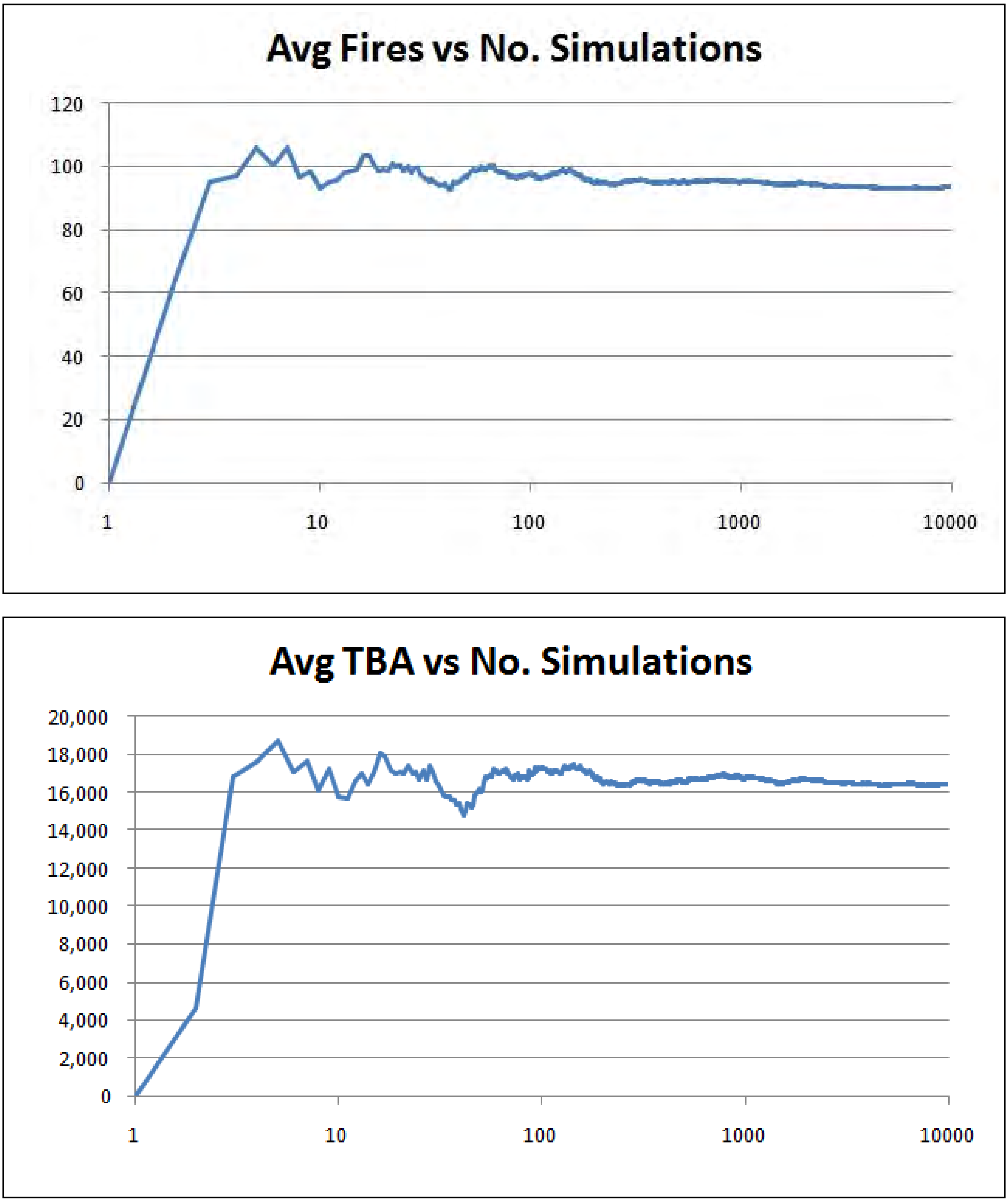


Figure 24 Examination of robustness of results for SA79 scenario vs. total no. of simulations: (top) average number of fires; (bott.) average Total Burnt Area (th. sq. ft.). By both measures, results clearly stabilize after several hundred trials.

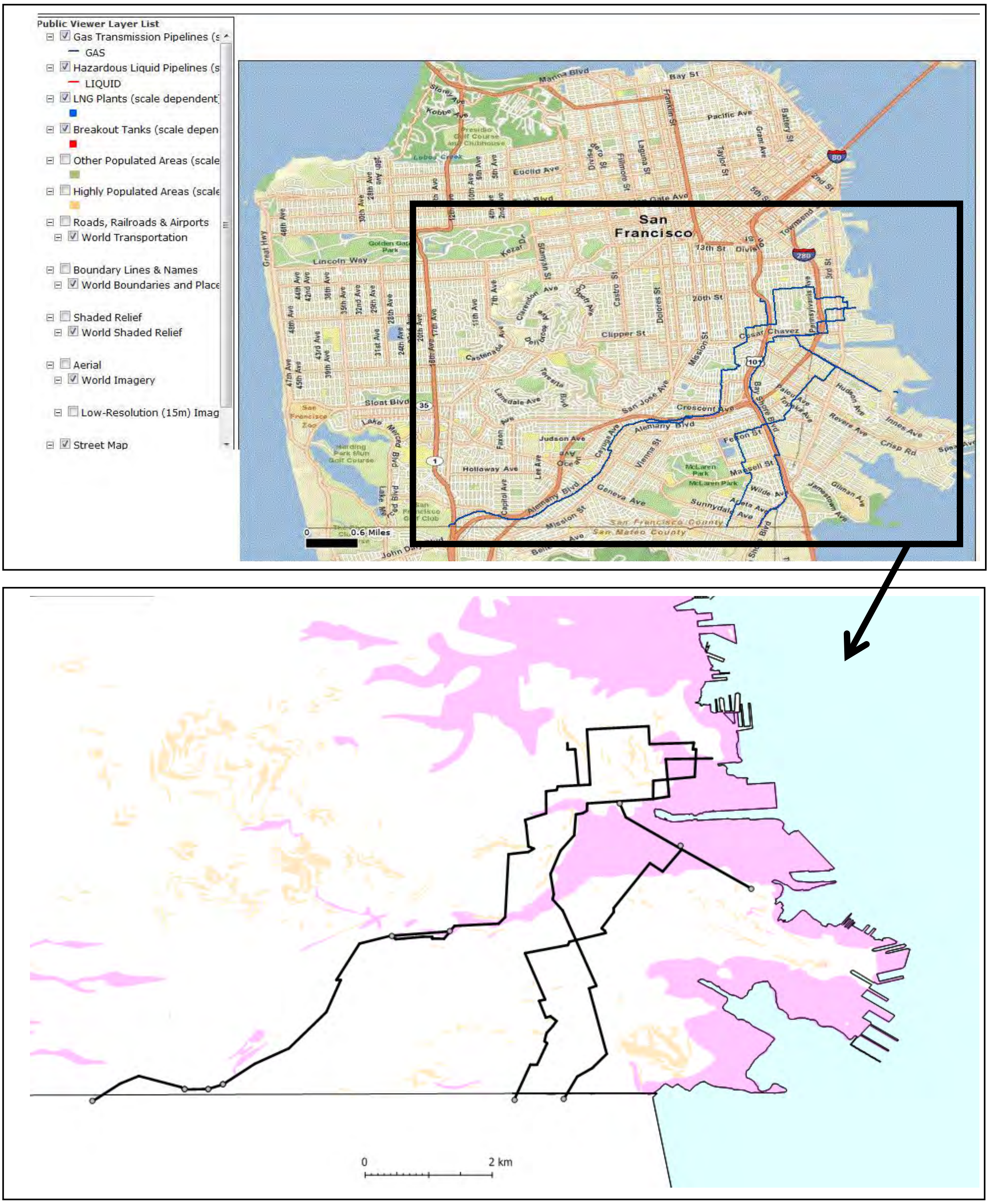


Figure 25 High pressure Gas Transmission lines in San Francisco, at bottom overlaid on geologic hazards (yellow is landslide hazard, purpose is liquefaction or other soft soil ground failure). (pipeline data taken from National Pipeline Mapping System (https://www.npms.phmsa.dot.gov/PublicViewer/composite.jsf?state=CA&county=06075)