SPA RISK

Fire Following Earthquake Water Requirements Study

Prepared for the
San Francisco Public Utilities Commission
David Myerson, P.E., Project Manager

by

Charles Scawthorn, S.E., D.Eng.
SPA Risk LLC

Under subcontract to

AECOM
Craig Smith

7 June 2021

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PO 3326 San Francisco CA 94119 USA • www.sparisk.com • +1-415-729-4939

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ABSTRACT

The purpose of this project has been the estimation of water required to suppress fires following a major earthquake affecting the city of San Francisco. This is required to determine if water supply sources and conveyance infrastructure meet the requirements for firefighting, or if additional sources and infrastructure are required. The model (SPA FFE) that has been employed to estimate the required water is the result of decades of research and development

Understanding that the water and fire services are co-equal members of the fire suppression team is crucial to the estimation of water requirements for fire suppression – one service complements the other in fire suppression. This co-dependence greatly affects the total demand on the water system – if a rapid and adequate fire department response is met with adequate readily available water at the fireground, the fire is relatively small and the total water demand modest. If the fire department response is delayed or water is a long time coming to the fireground, the fire rapidly grows to multi-alarm (or even multi-block) proportions, and the amount of required water is orders of magnitude greater. Thus, this analysis necessarily models the performance of both the fire and water service, as best we can estimate.

San Francisco has substantial assets at risk – the current population of about 880,000 is projected to grow by 2040 to more than 1.1 million, with an associated aggregate current structure and contents replacement value of about $530 billion that will grow by 2040 to perhaps $665 billion, in current dollars.

These assets are threatened by earthquakes and the fires that will follow. Two scenario earthquakes have been analyzed: (1) a Mw 7.9 event on the San Andreas fault like the 1906 event, and (2) a Mw 7 event on the Hayward fault in the East Bay, either of which will cause very strong ground motions in San Francisco. The Mw 7.9 San Andreas event is generally the more damaging event especially in the western portions of the City, which are only a few miles from the fault. The Hayward event is considered more likely to occur in the near future.

The San Francisco Fire Department (SFFD) will be challenged by a major earthquake – the Mw 7.9 San Andreas event will likely generate on average about 130 fires in the first 24 hours under current conditions (with growth increasing to perhaps 160 fires by 2050) – with mutual aid probably taking many hours to arrive. Lacking adequate water leads to continued fire growth and a larger demand for firefighting water than at first arrival, which has been considered in the analysis.

Results of the analysis of 21 Cases for current and future variations in EFWS and SFFD improvements shows that effective firefighting under current conditions is estimated to require flows of about 140,000 gpm (median, 75th percentile is 200,000+ gpm) after the first few hours, equivalent to a total volume of about 200+ million gallons in the first 24 hours after an earthquake. Results for various Cases show that future water requirements can remain about the same, or be much larger, depending on the improvements made to the EFWS and SFFD.

The main report is followed by Appendices that provide more detail. Detailed numerical and graphical results have been transmitted to SFPUC in the form of 46,930 electronic files totaling 122 mb.

TABLE OF CONTENTS

TABLE OF ABBREVIATIONS AND ACRONYMS

AC	Asbestos cement
AWSS	Auxiliary Water Supply System: the previous term for the existing high-pressure network, including pipes valving and hydrants (including currently motor operated valves), pump stations 1 and 2, Twin Peaks reservoir and Jones/Ashbury tanks. This network is now part of the EFWS.
BTCAR	Block Tree Canopy Area Ratio = tot. area tree canopy in block)/total area of the block
CAPSS	Community Action Plan for Seismic Safety (a City program, by the Department of Building Inspection)
CBD	Central Business District
CCSF	City and County of San Francisco
CDD	City Distribution Division
CGS	California Geological Survey
CI	Cast iron
Cisterns	Underground water tanks, typically circular with capacity of 75,000 gals.
csv	comma-separated variable (an electronic file format)
DEM	Digital elevation model
DI	Ductile iron
EFWS	Emergency Firefighting Water System: the complete set of water sources and systems for emergency firefighting – includes the high-pressure pipe network (with associated pump stations, tanks and Twin Peaks Reservoir), PEWFS, cisterns, fireboats, fireboat manifolds, pump stations, suction connections and other infrastructure.
FAR	Floor Area Ratio = TFA all buildings in city block)/total area of the block
FFEWRS	Fire Following Earthquake Water Requirements Study (this project)
GIS	Geographic Information System
GMPE	Ground motion prediction equation
gpm	gallons per minute
LDH	Large Diameter Hose
MCS	Monte Carlo Simulation
MMI	Modified Mercalli Intensity
MOV	Motor operated valve

MWSS	Municipal Water Supply System – that is, the normal potable water network
NERT	Neighborhood emergency response team
OES	Office of Emergency Services (Governor's Office, California)
PEWFS	Potable Emergency Water Firefighting System: a new system planned for the Richmond and Sunset and consisting of a pipe network from Lake Merced northwards to the Richmond and connecting to Sunset Reservoir, with pump stations at Lake Merced, Sunset Reservoir and perhaps at Sunset Pumping Plant. Will be operated as a potable trunk line supplied from Sunset Reservoir under normal conditions and switched to a high-pressure network (independent of the current high-pressure network) for firefighting when needed. When operating as a high-pressure network PEWFS if required may inject raw water from Lake Merced.
PGD	Permanent ground displacement
PGV	Peak Ground Velocity
SCADA	Supervisory control and data acquisition
SFFD	San Francisco Fire Department
SFPUC	San Francisco Public Utility Commission
SRTM	Shuttle Radar Topography Mission (ie, satellite DEM data)
STL	Steel
TFA	Total Floor Area (sq. ft., the sum of floor area on all floors of a building)
USGS	US Geological Survey
Vs30	Shear wave velocity, top 30 meters
WSF	Water supply factor

LIST OF FIGURES

LIST OF TABLES

REPORT

Purpose

The purpose of this project has been the estimation of water required to suppress fires following a major earthquake affecting the city of San Francisco. Estimation of required water is needed to determine if the current water supply sources and conveyance infrastructure meet the requirements for firefighting, or if additional sources and infrastructure are required. Water demands are key criteria for assessing the adequacy of the existing Emergency Firefighting Water System (EFWS) and planning EFWS's future expansion.

Water supply and fire suppression

The water and fire services are co-equal members of the fire suppression team. Understanding this is crucial to the estimation of water requirements for fire suppression – one service complements the other with regard to fire suppression. This co-dependence greatly affects the total demand on the water system – if a rapid and adequate fire department response is met with adequate readily available water at the fireground, the fire is fought while relatively small and the total water demand modest. If the fire department response is delayed or water is a long time coming to the fireground, the fire rapidly grows to multi-alarm (or even multi-block) proportions, and the amount of required water is orders of magnitude greater.

Fire following earthquake model

The model that has been employed for this project (SPA FFE) is the result of decades of research and development (Anderson et al. 2016; Davidson et al. 2012; Porter, Scawthorn and Sandink 2021; Porter et al. 2011; Scawthorn 2008; Scawthorn et al. 1982; Scawthorn 1987; Scawthorn 2020; Scawthorn, Cowell and Borden 1998; Scawthorn and et al 2018; SPA Risk 2009; TCLEE 2005) and has been employed on behalf of numerous fire, water and other government agencies including San Francisco's Department of Building Inspection (ATC-52-1A 2010), and also for the insurance industry.

All results presented here are estimates based on this model and inputs as described below. These results and the services to develop them were performed for the San Francisco Public Utility Commission through a contract with AECOM Technical Services, Inc. (collectively, the "Client") within the limits prescribed by the Client, in a manner consistent with that level of care and skill ordinarily exercised by other professional consultants under similar circumstances at the time the services are performed. Considerable uncertainty exists regarding the occurrence and circumstances of large earthquakes, which may affect the results of this model. No other representation, express or implied, and no warranty or guarantee are included or intended in this report or otherwise.

San Francisco's buildings at risk

San Francisco has substantial buildings at risk. The value of the buildings at risk in the City is exceptionally large and will only become larger. When originally built, San Francisco had a population of 400,000 and only the northeast quadrant of the City was significantly built up, with large parts of the western portion of the City still in a natural state. San Francisco as of 2021 has been fully built out with a population of about 880,000, Figure 4, and is projected to grow by 2040 to more than 1.1 million. The City had 400,000 housing units in 2019 (Planning Department 2020) and is required to add 82,000 housing units by 2031 (ABAG 2021), an increase of 20.5% by 2031. The current total floor area of all buildings in the City is estimated to be 885 million sq. ft., is quite dense and largely of wood construction, Figure 1 and Figure 2, and is expected to grow to 1.1 billion sq. ft. by 2040 and 1.25 billion sq. ft. by 2050. Depending on meteorological conditions, conflagration hazard is exacerbated by vegetation and the tree canopy, which is accounted for in the analysis, Figure 3. Approximately 24% of all floor area is in high-rise buildings, a significant fire in any one of which will challenge SFFD. The aggregate structure and contents replacement value of all buildings in the City is about $530 billion (2021 $) which by 2040 will grow to perhaps $665 billion, in current dollars. Beyond this potential loss in direct property damage, San Francisco is the financial and mercantile center of Northern California and its dysfunction will significantly impact larger economies, as occurred in 1906 (Odell and Weidenmier 2004).

Figure 1 Block Floor Area Ratio[1] per city block, showing density of buildings in the City.

[1] As used here, Block Floor Area Ratio = BFAR = (TFA all buildings in city block)/total area of the block

Figure 2 View of San Francisco residential neighborhood showing density of wood frame construction

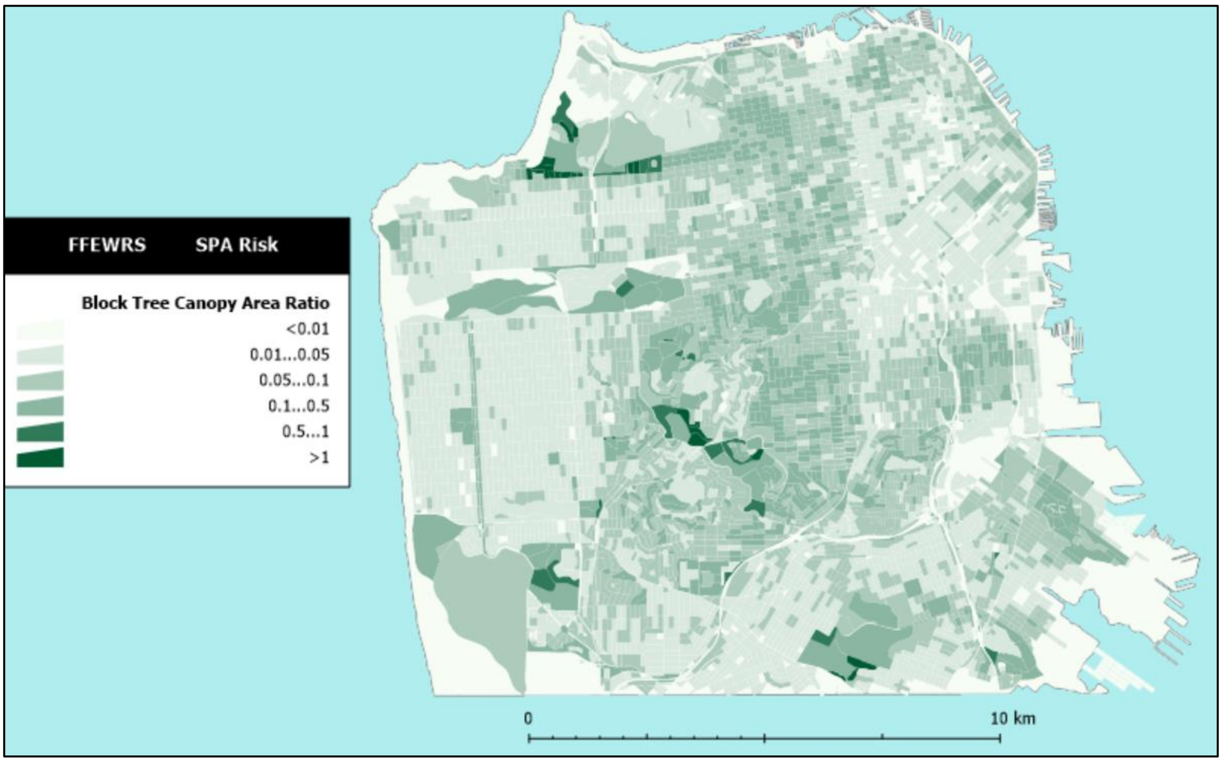


Figure 3 Block Tree Canopy Area Ratio[2] per city block, showing density of tree canopies in the City.

[2] As used here, Block Tree Canopy Area Ratio = BTCAR = (tot. area tree canopy in block)/total area of the block

San Francisco's earthquake risk

San Francisco is at major risk due to earthquake, with the City's downtown being equidistant from the San Andreas and Hayward faults, Figure 4. The study examined two major seismic events: (1) a Mw 7.9 event on the San Andreas fault like the 1906 event, and (2) a Mw 7 event on the Hayward fault in the East Bay. These two events were among those examined in the Department of Building Inspection's CAPSS study (ATC-52-1 2010).

Ground motions from either of these events will be very strong in San Francisco, with the Mw 7.9 San Andreas event being generally stronger, especially in the western portions of the City, which are only a few miles from that fault, Figure 5 (the Hayward event, while generally having similar or smaller ground motions than the San Andreas event, is considered more likely to occur in the near future).

To account for uncertainty in ground motions, a probabilistic Monte Carlo Simulation (MCS) was employed, and permanent ground displacements (PGD) due to liquefaction were accounted for using USGS data (Knudsen et al. 2000), see Figure 6.

Figure 4 San Francisco low and medium rise building total floor area per block. Arrows show distance Ferry Building equidistant from San Andreas and Hayward faults.

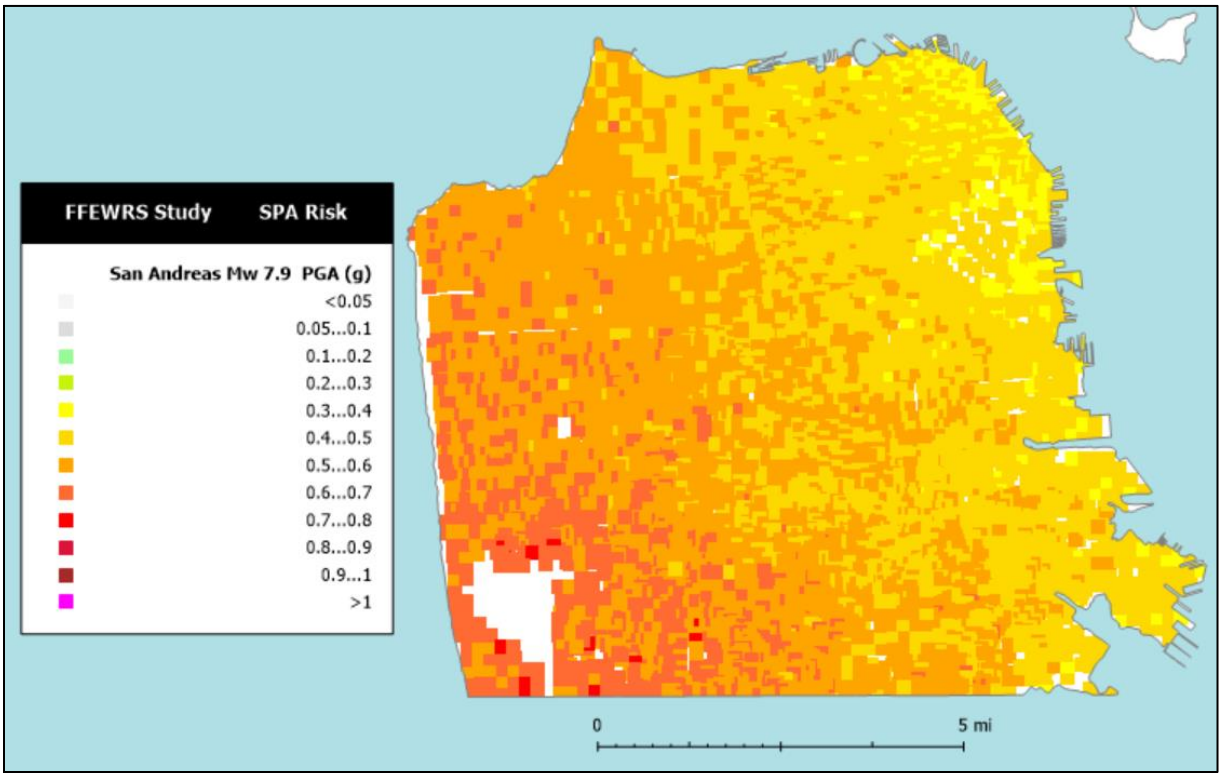


Figure 5 One realization of estimated ground motions due to a Mw 7.9 San Andreas earthquake.

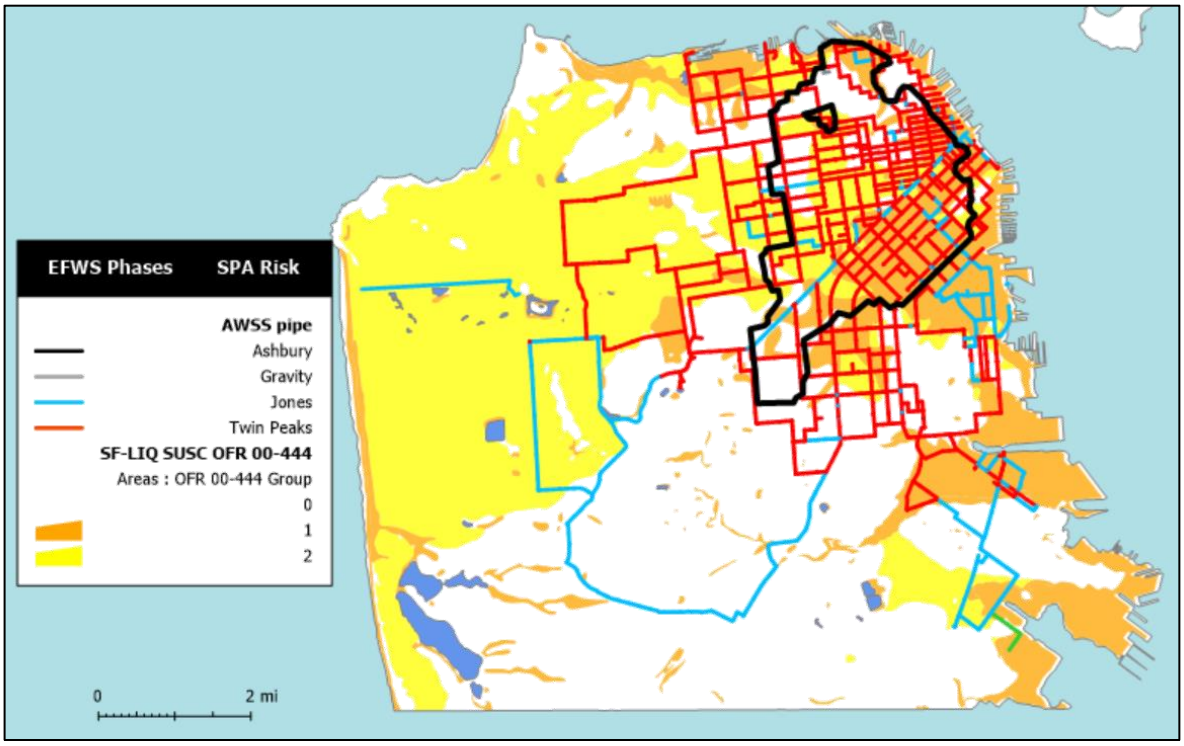


Figure 6 Existing EFWS high-pressure pipe network overlaid on liquefaction susceptibility areas, 1906 burnt area (black outline), colors show pipe materials (CI = cast iron, DI = ductile iron, ERDIP = earthquake resistant ductile iron pipe)

San Francisco Fire Department

The San Francisco Fire Department (SFFD) is the front line in protecting San Francisco against the risk of earthquakes and fires that may follow. SFFD is a first-class department that has historically been a leader in the fire service. However, SFFD will be extremely challenged by a major earthquake – while it has 1,449 personnel, it has only 44 stations and in-service engines (including one at Treasure Island, but not counting engines at San Francisco International Airport), 20 ladder trucks, 4 hose tenders, 3 fire boats and various other equipment.

A repeat of the 1906 earthquake will likely generate on average about 130 fires in the first 24 hours under current conditions, Figure 7 – this average will increase with the City's growth to about 160 by 2050. Due to the number of fires exceeding SFFD's available resources, some of these ignitions may grow to conflagration proportions well beyond SFFD's capability to fight. Mutual aid following a large earthquake will probably take many hours to arrive. Firefighter fatigue is a factor that will limit firefighting over time (the analysis assumes responding off-duty firefighters offset this).

Most significantly, SFFD can do little to fight fires if it has no water. Under non-earthquake conditions, SFFD accesses firefighting water from either the Municipal Water Supply System (MWSS, that is, the low-pressure potable water mains) and/or the EFWS high-pressure pipe network. The MWSS is not designed for earthquake and is anticipated to have hundreds of water main breaks and leaks in a major earthquake, such that large portions will lose pressure, resulting in dry MWSS hydrants.

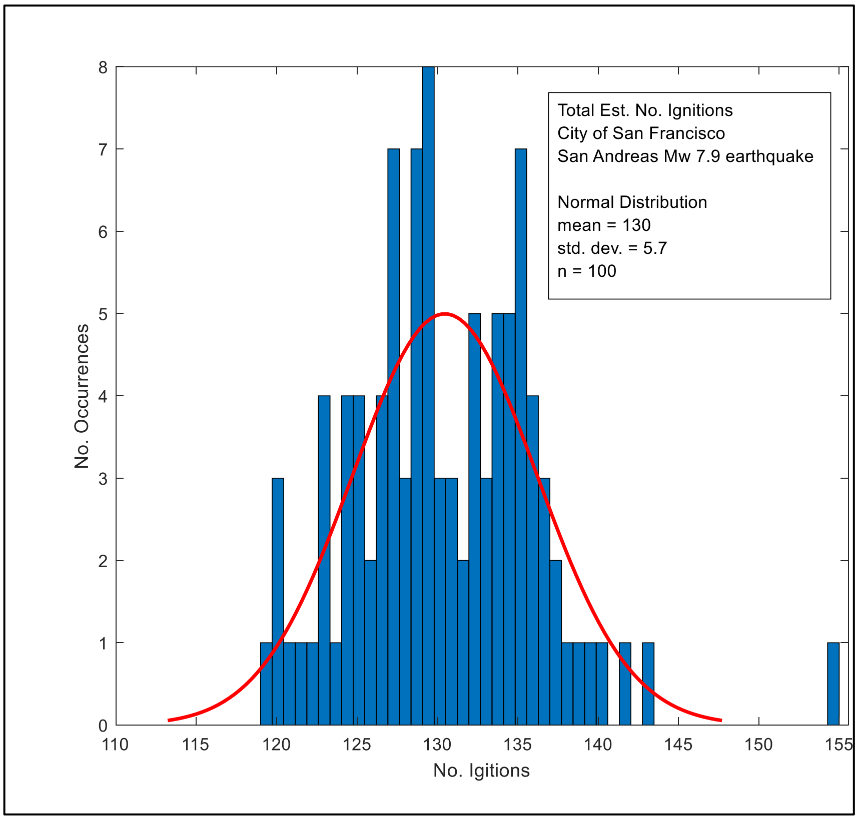


Figure 7 Histogram of estimated total number of ignitions for Mw 7.9 San Andreas event under current conditions. Current mean of 130 ignitions will grow to about 160 ignitions by 2050.

Emergency Firefighting Water System

The Emergency Firefighting Water System (EFWS) is the backup to the MWSS for firefighting. EFWS is the aggregation of all the City's water sources and systems for emergency firefighting, including the high-pressure pipe network, cisterns, fireboats, fireboat manifolds, pump stations, suction connections, and other infrastructure. The EFWS high-pressure pipe network was initially constructed following the 1906 earthquake and fire and at that time covered only the built-up northeast quadrant of the City, Figure 8. The system was designed to provide large volumes of water for firefighting, particularly after a major earthquake, and be independent of the potable water supply system which had hemorrhaged water in 1906 due to many breaks in mains and 28,000 service line leaks. San Francisco has continued to invest in expanding the high-pressure system (to the Mission and Western Addition in the 1930s, and elsewhere in the 1970s and 80s), Figure 8 and Figure 9. Due to its age, much of the existing high-pressure pipe is cast iron, Figure 8, which is a relatively brittle material and subject to breaks in an earthquake. Moreover, the system still does not extend to the western or southern portions of the City although some protection for those districts is provided by cisterns, Figure 10, which however are limited in their capacity (typically, 75,000 gallons equivalent to one hour's supply for one fire engine). That is, cisterns can provide sufficient water for an initial attack and thus would allow the fire department to suppress some fires at an early stage (if the fire engines arrived at that stage), but are probably insufficient for greater alarm fires, not to mention conflagrations.

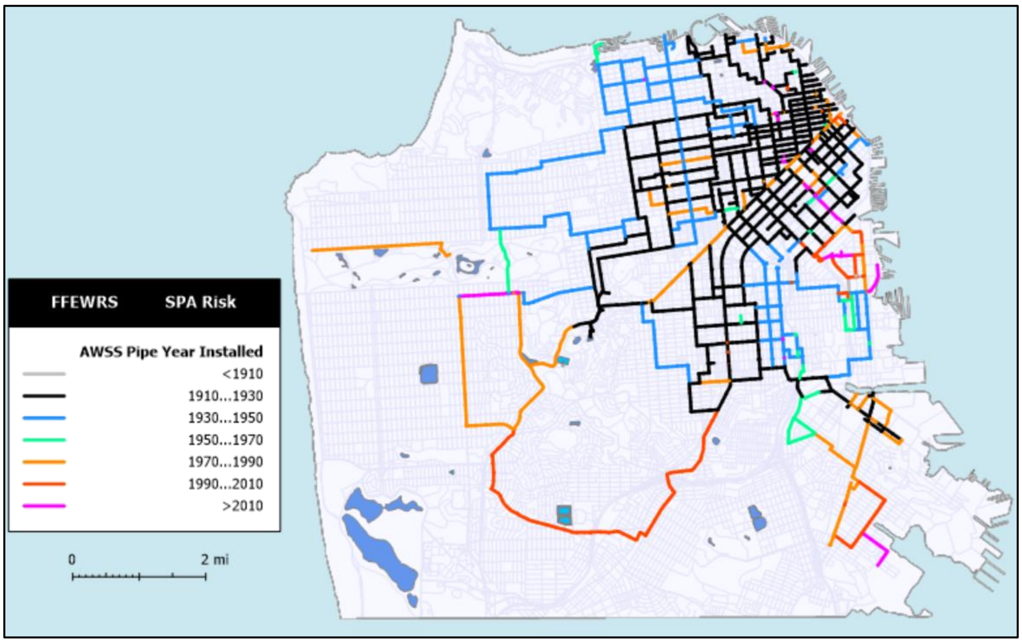


Figure 8 Existing EFWS high-pressure pipe network, colors show year installed, with black lines showing the original 1912 high-pressure pipe network

This analysis considers a phased expansion in the EFWS, including construction of the Potable Emergency Water Firefighting System (PEWFS) to be built in the Richmond and Sunset districts as well as extensions and improvements to the high-pressure pipe network. Three phases of EFWS expansion are considered, with timing of the phase's dependent on funding.

Demands for these phases are based on projected population and building inventories for 2030, 2040 and 2050. The specific buildouts corresponding to each phase that were used for future projections in this study are shown in Figure 11 – note specific alignments of pipe and other features is likely to change as the design of the EFWS progresses.

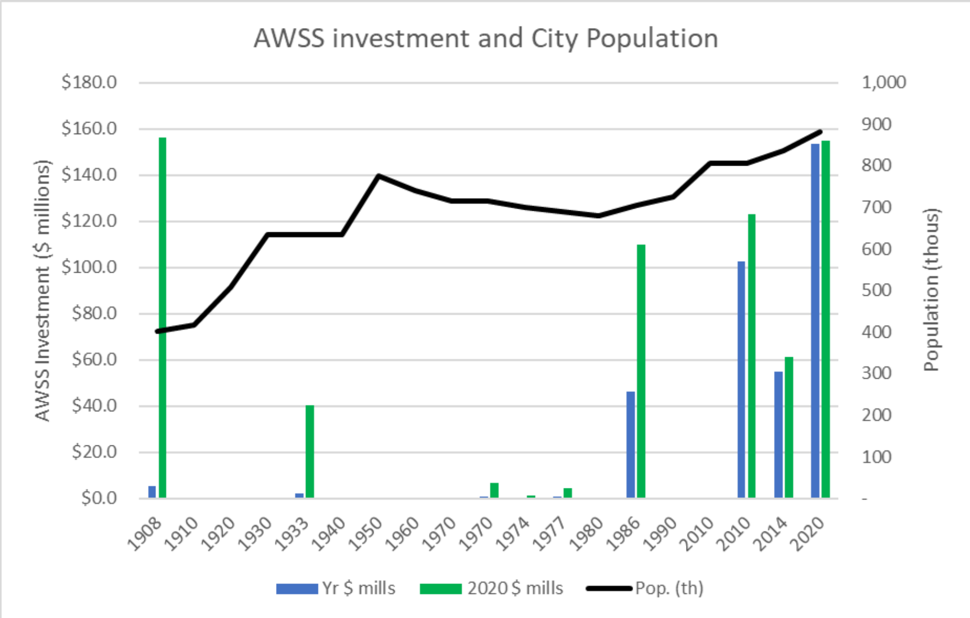


Figure 9 EFWS investment in both $ for that year (blue column) and 2020$ (green column), and City's population (black line)

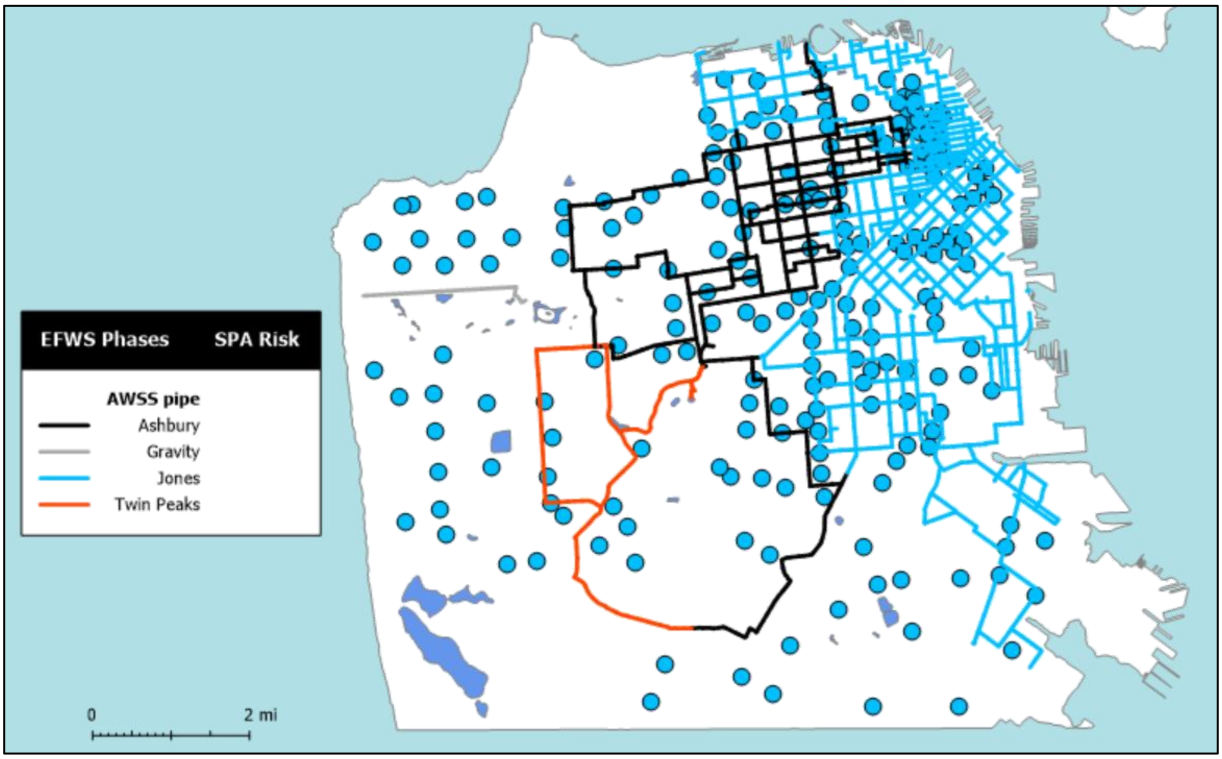


Figure 10 Existing EFWS high-pressure pipe network, colors show pressure zones, circles are cisterns

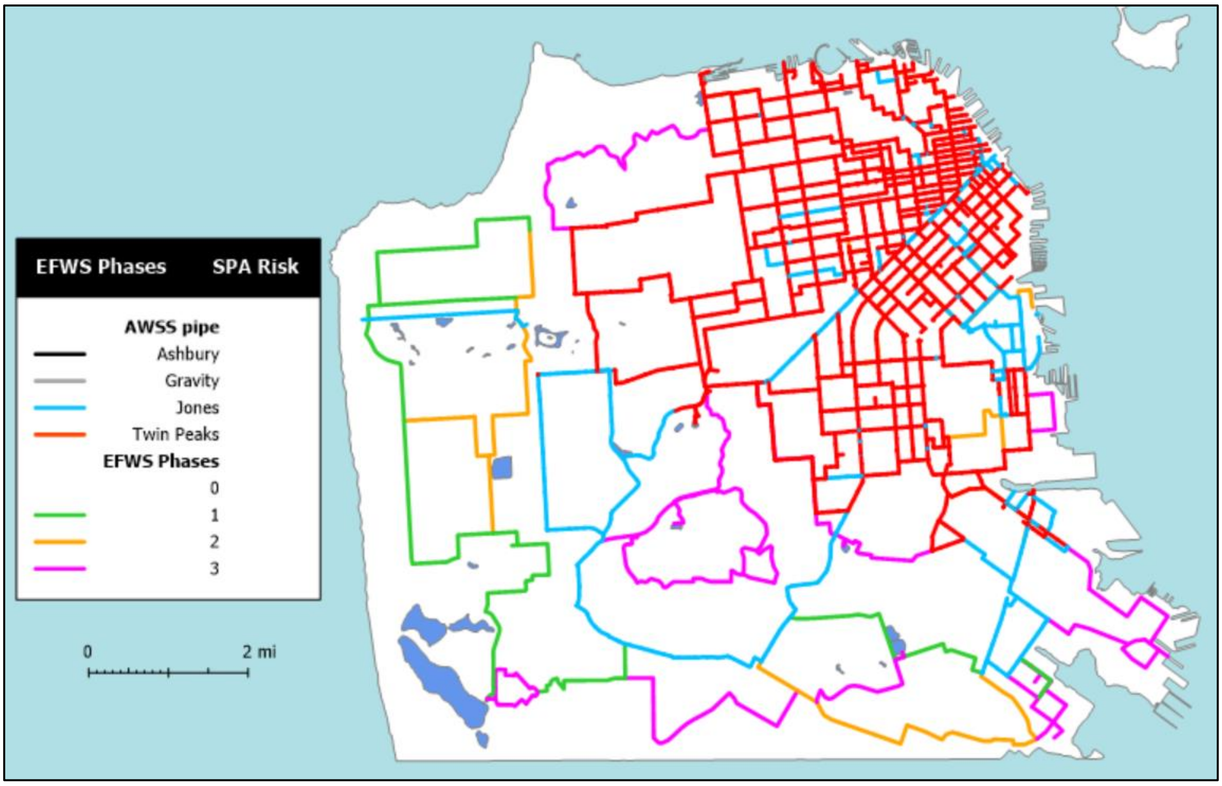


Figure 11 Existing EFWS high-pressure pipe network (Ashbury, Gravity, Jones and Twin Peaks pressure zones) and Phases 1, 2 and 3 preliminary EFWS future buildouts – note specific alignments of pipe and other features is likely to change as the design of the EFWS progresses.

Analysis of fire following earthquake

Fire following earthquake involves considerable uncertainty and is modeled as a stochastic process. Time is of the essence for fires following earthquakes. Figure 12 shows a Fire Department Operations Timeline, in which 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).

Analysis of firefighting water demands is complex and consists of modeling the following steps (see Figure 13):

- *Occurrence of the earthquake* –earthquake shaking causes damage to buildings and contents, even if the damage is as simple as knocking things (such as candles or lamps) over. For this study, two scenario earthquakes are examined, a Mw 7.9 event on the San Andreas fault, and a Mw 7.0 event on the Hayward fault, with both events epicenters assumed close to San Francisco. Ground motions for the events are estimated using a suite of appropriate ground motion prediction equations in a probabilistic format accounting for spatial correlation. Ground failure is estimated based on liquefaction susceptibility maps.

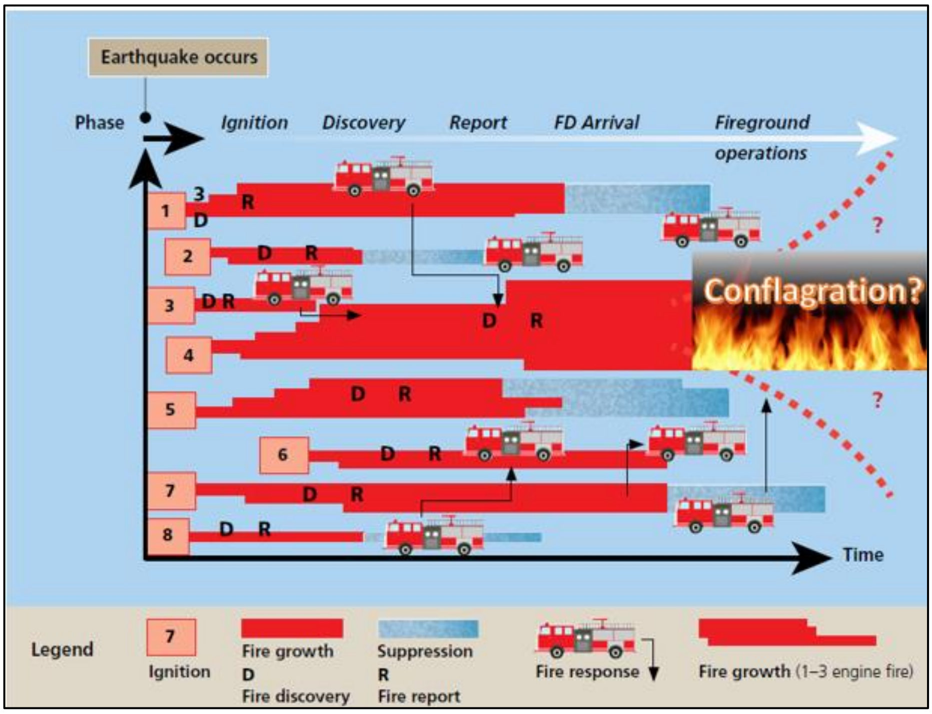


Figure 12 Fire department operations time line. Horizontal axis is time, beginning at time of earthquake. Horizontal bars depict development of fires, from ignition through growth or increasing size (size is indicated by width or number of horizontal bars).(Scawthorn 1987)

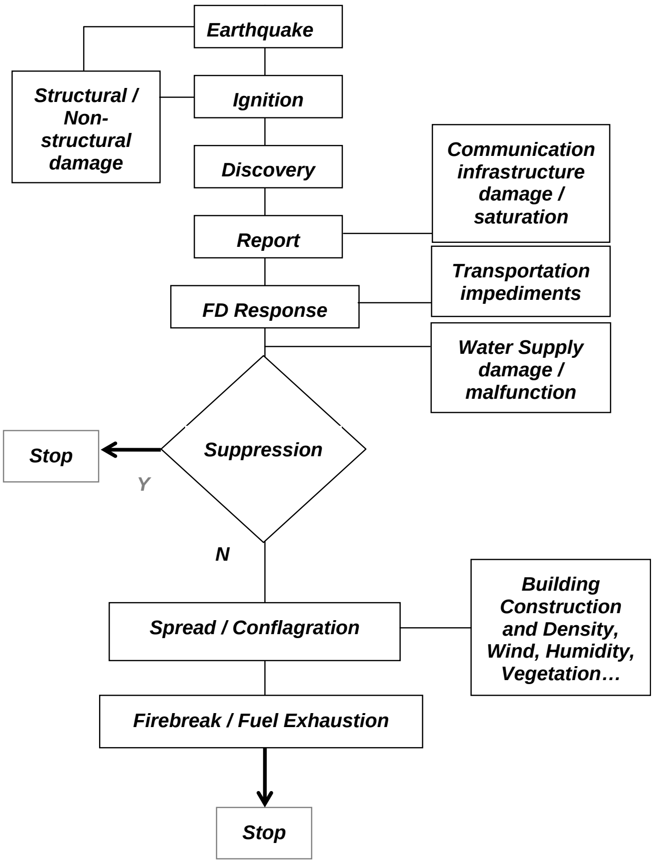


Figure 13 Flow chart of fire-following-earthquake process (TCLEE 2005)

- *Assets at risk* – a database or building inventory for the City was compiled based on a variety of sources, including projections of future growth and traffic patterns. The spatial database consists of a record for each building in the City, with fields specifying location (block, latitude and longitude), date of construction, type of occupancy, primary construction material, number of stories, total floor area, building footprint shape and area.
- *Ignition* – whether a building has been damaged or not, ignitions can 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. For this study, ignitions are based on correlations with ground motion developed by this author for FEMA and used in the national earthquake model Hazus-MH (FEMA 2003). The correlations are empirical – that is, based on observations of past events – and no adjustment has been made here for future projections. While to some extent older construction in San Francisco will be replaced by more modern buildings, the lack of adjustment is based on several factors: (i) a lack of observed change over time in the normalized ignition rate for past events; (ii) post-earthquake ignitions are only partially correlated with structural performance, and are due more to appliances and contents sources, which are likely to more slowly change over time; (iii) while San Francisco's energy policies are shifting away from natural gas, this will entail a shift towards electric power, another ignition source; (iv) a rapidly increasing trend toward rooftop solar and home storage (e.g., Tesla Powerwall), which represent a new post-earthquake ignition source. The conclusion was that a future trend in post-earthquake ignitions may arguably be increasing or decreasing over the next few decades, and no specific adjustment could be justified. Lastly, given the disparity between the number of estimated ignitions and SFFD capability, any reasonable adjustment was unlikely to significantly change the overall results.
- *Fire growth* – fires grow very rapidly, the growth depending on many factors primary of which are the available fuel and oxygen supply, and how soon the fire is fought. As fires increase in size, building compartmentation, inter-building spacing, fenestration, cladding and windspeed are all important factors. An unfought fire in a densely built-up residential neighborhood can progress from a candle-sized to sofa-sized to room flashover within a very few minutes. Room-to-room and then building-to-building (and then block-to-block) fire spread are modeled based on a large body of data (TCLEE 2005) that incorporates radiative, convective and ember effects on building cladding, interiors and also the City's tree canopy. Weather (wind speed and direction, temperature, precipitation, relative humidity) are all considered probabilistically.
- *Discovery* – at some point, the fire resulting from the ignition will be discovered. In the confusion following an earthquake, the discovery may take longer than otherwise.
- *Report* – if it is not possible for the person or persons discovering the fire to immediately extinguish it, fire department response will be required. Only fires that require fire department response are modeled in this study. For the fire department to respond, a Report to the fire department typically has to be made, but the possibility of fire companies directly observing a fire and self-dispatching is considered in the analysis. Communications system dysfunction and saturation may delay some reports.
- *Response* – the fire department then has to respond but may be impeded by non-fire emergencies they may also have to respond to (e.g., building collapse) as well as

transportation disruptions. In this study the assumption however is that fires are the first priority for all available fire engines (i.e., pumpers). Fire trucks (i.e., ladders) are a vital type of apparatus crucial to normal firefighting, but don't actually carry hose or a pump, so that fire engines are the critical element considered in the analysis. Initially, 43 fire engines are considered available (the apparatus on Treasure Island and at San Francisco International Airport are not considered available within the Peninsular City). SFFD has five fully equipped engines in ready reserve and the analysis assumes off-duty personnel would respond such that these engines would be in service two hours following a major earthquake, so that 48 engines are available at hour 2 following the earthquake. Additionally, there are five more engines that the analysis assumes would be equipped and in service four hours following the earthquake (ie, 53 engines at hour 4). A factor examined but not explicitly included in this analysis is the prevalence of overhead wires, both for Muni and electrical distribution. Some of these wires will come down due to shaking and ground failure, and pose two problems – they will impede traffic, particularly because motorists will not know if the wires are energized and thus will proceed with caution, and because they will require urgent SFFD response.

- *Mutual aid* – Regarding mutual aid, the analysis assumes no mutual aid for the first 12 hours. Thereafter, mutual aid strike team arrive every two hours for the period 12-24 hours, following which as many engines as needed are available. Aerial attack by tanker aircraft as typically used in wildland fires, is unlikely in San Francisco and is not considered in the analysis. These resource and operational aspects of the modeling were reviewed with SFFD senior Chiefs.
- *Water supply* – upon arrival at the fireground, water is needed for fire suppression. Fire engines typically have a 500-gallon tank, which can be used for quick attack and suppression of small fires but is inadequate if a fire is much beyond one room in size. The first choice for water supply will be a fire hydrant – an EFWS hydrant if available, otherwise a potable water hydrant supplied by the MWSS. However, earthquake shaking and PGD effects will cause pipe breaks and leaks in both the EFWS and MWSS. The MWSS is likely to have hundreds of breaks and leaks, such that large portions of the system will lose all pressure, resulting in dry hydrants. The EFWS has been designed and constructed to minimize earthquake damage, but much of the EFWS high-pressure pipe network, particularly the older portions, are likely to sustain some breaks and leaks such that the Lower or Jones Street Zone of the high-pressure pipe network (see Figure 10), which serves a large part of the City, may lose pressure. This is what occurred in the 1989 Loma Prieta earthquake, and the potential for this remains today although the SFPUC has made several improvements to the existing EFWS. Performance of the EFWS is accounted for in the analysis by considering damage to the pipe network and the probability of system operations being able to maintain functionality (Porter 2018). Cisterns and other sources of water (Bay suction connections, fireboats, Stowe Lake and other bodies of water, swimming pools) are included in the calculation of the probability of water be supplied at the fireground. Affecting this probability is distance from the water source to the fireground. Longer distances require longer lays of hose which may require more than one engine for relay purposes. SFFD's hose tenders, each carrying about 4000 ft. of Large Diameter Hose (LDH, typically 5-inch diameter) are a major asset in this regard and considered in this analysis.
- *Suppression* –the analysis models fire department suppression, beginning with the assumption that all fire engines are in their assigned fire station at the time of the earthquake,

and all fire engines and personnel are immediately available for service. As discussed above, as fire reports are received or fires detected directly by engine companies, the fire engines travel directly to the fire nearest to their fire station. If a second fire is in the neighborhood, since the fire engine has committed to the first fire, a different fire engine is required to respond to the second fire, which requires a longer travel time resulting in the fire being larger on arrival than it would have been if there had only been one fire.

- o <u>If sufficient water is available</u> at the fireground, the fire is fought. If the first engine is insufficient for full suppression, additional engines are assigned, and travel to the fire, which requires more time. During this time, the fire continues to grow, albeit somewhat abated due to the firefighting by on-scene fire engines. This process continues, with more and more engines arriving and slower and slower fire growth, until growth is contained. The flow of water required (in gallons per minute, gpm) during these activities is calculated based on empirical and theoretical models. As the fire is suppressed or fuel is exhausted, fire engines remain at the fireground for some time, both for overhaul and equipment and hose retrieval. As soon as possible, fire engines are released to go to other fires.

  The total amount of water employed at the fire may be calculated in various ways with the measure used here being Required Water, which is the water flow that is required to suppress the fire at that moment, taking into account fire department suppression activities up to that time (other measures are Actual Water, Available Water and Theoretical Water, see Appendices for details, but Required Water is the most relevant measure for our purposes).

- o <u>If no water is available</u> at the fireground, even considering hose relays, hose tenders and other resources, the first arriving engine remains on scene for an assumed period, typically to assure life safety. No further engines are assigned to the fire, which continues to grow. When the fire has grown and spread to a neighboring block, an assessment is made again regarding water availability – if water is available, then the process described in the preceding paragraph is followed, if not, then the fire grows unabated and the Required Water is substantially more than if water had been available.

- o Whether water is available or not, there will be cases where the fire grows to sufficient size to spread to another block – that is, cross a street or other intervening distance. Data on street widths, parks and other "gaps in fuel" are employed in the analysis, and the probability of "crossing", in four directions, is considered for each block in which an ignition occurs, considering whether or not active suppression is present.

- At each ignition, if the engine company or companies achieve suppression (not just control, but suppression), they move on to the next incident after a limited amount of time (less than usual) for overhaul to avoid rekindles. Until control is accomplished, on scene engine companies (including further arriving companies, as available) continue to attempt to contain the fire but it spreads albeit at a slower rate and may still become a conflagration. Success or failure hinges on numerous factors including fire engine availability, water supply functionality, building construction and spacing, wind and humidity conditions, etc. If the fire cannot be contained, the process ends when the fuel is exhausted – that is, when the fire fails to cross a firebreak, such as a city street or large area (e.g., park). Probability of crossing a firebreak is based on the size of the fire, windspeed, the width of the firebreak and nature of the fuels on both sides of and within the firebreak (including tree canopy).

Uncertainty

To account for uncertainty, the Monte Carlo Simulation (MCS) method was employed in the analysis. MCS is a widely used method for incorporating uncertainty due to a stochastic process. Simply put, MCS consists of assigning probability distributions to those variables in a process that have significant uncertainty (i.e., the random variables) and using random numbers to independently assign a point value to each random value for a specific trial. Each random variable having a point value permits calculation of the process and its result, which is termed a realization. Repeating the use of new random numbers to assign a new point value to each random value for the next trial yields a new realization. N repetitions yields N realizations, which approximates the probability distribution of the result of the random process. The number of realizations required depends on the desired confidence in the result and can vary from dozens to millions depending on the process and associated uncertainties, and desired confidence. MCS was employed for this analysis, with the following variables having uncertainty:

- Ground motion: uncertainty as determined by the suite of NGA-West2 ground motion prediction equation (Gregor et al. 2014), with inclusion of spatial correlation.
- Weather (temperature, humidity, wind speed and direction, precipitation) randomly sampled from five years of hourly data
- Ignition location and frequency based on random sampling of a function of total floor area database for San Francisco using relationships employed in Hazus-MH (SPA Risk 2009)
- Damage to and serviceability of the EFWS based on (Porter 2018) approach using data on ground motion, pipe diameter and material
- Water supply based on random sampling of serviceability of and distance to the EFWS and alternative water sources
- Fire growth and spread based on randomness in ignition location, neighboring buildings, inter-building spacing, tree canopy, building material of construction, temperature, relative humidity, recent precipitation, windspeed and wind direction, number of fire engines on scene and availability of water for firefighting.

A study was conducted as to a reasonable minimum number of MC simulations required for stable median, mean and variance results, finding that 50 simulations per case was a reasonable minimum. Results presented here are based on 100 simulations.

Analysis Cases

The Monte Carlo Simulation was applied to a number of cases which are denoted

“Phx v1v2v3v4v5”

where

Phx refers to Phasesx, where x= 0 is the situation as of 2020, and x= 1, 2 and 3 refers to succeeding stages of EFWS buildout and City growth.

v1 denotes whether and how **system damage** is considered – that is, v1 = D denotes EFWS pipe breaks and leaks are included in the analysis, v1 = N considers the system to be undamaged, and v1 = P triggers a probabilistic weighting of damage occurrence.

v2 denotes whether and how EFWS **system operational efficiency** is considered – that is, v2 = L denotes a slow operational response to EFWS damage, with some time required to assess damage and respond with valve closures and other measures, v1 = M denotes a moderate operational response, v3 = H denotes good situational awareness (e.g., via a high-resolution SCADA) and rapid response (e.g., via a dense network of automatic or remotely operable motor operated valves, MOVs), and v3=E denotes efficient system operations, significantly exceeding v3=H such that the system is fully functional almost without interruption.

v3 denotes whether EFWS **system improvements** have been implemented – that is, v3 = Y denotes EFWS system expansion and improvements for that Phase have been implemented, while v3 = N denotes no improvements (i.e., same as in 2020).

v4 denotes whether **SFFD resources have been increased** – that is, v4 = C denotes the current number of SFFD fire engines (initially 43, as described above) are what is available for that Phase, while v4 = A considers SFFD has been increased in size with additional engines and hose tenders commensurate with the population growth for that Phase.

v5 denotes whether **City growth** is considered – that is, v5 = B the current population and building inventory, while v5 = F denotes population and growth projections for 2030 (Phase 1), 2040 (Phase 2) and 2050 (Phase 3) were employed. Use of these specific years is not meant to imply that EFWS expansion will occur by that year.

Thus, for example, **Ph0 DLNCB** denotes an analysis for Ph0 (i.e., the current EFWS) considering Damage to the system, Low system operational response to that damage, No system improvements, Current SFFD resources and current (i.e., 2020) City growth, the latter three variables being consistent with Ph0. Another example: Ph3 PHNAF denotes Phase 3, Probabilistic weighting of damage, High system operational response to that damage, No system improvements, a larger SFFD with more resources and Future (i.e., 2050) City growth.

Feasible combinations of Phases and v1 to v5 are 91 in total, Table 1.

Table 1 Case List

Case	Ph	sysDmg	sysEff	sysImpr	SFFD	Growth
1	0	D	L	N	C	B
2	0	D	M	N	C	B
3	0	D	H	N	C	B
4	0	N	E	N	C	B
5	0	P	L	N	C	B
6	0	P	M	N	C	B
7	0	P	H	N	C	B
8	1	D	L	Y	C	F
9	1	D	L	Y	A	F
10	1	D	L	N	C	F
11	1	D	L	N	A	F
12	1	D	M	Y	C	F
13	1	D	M	Y	A	F
14	1	D	M	N	C	F
15	1	D	M	N	A	F
16	1	D	H	Y	C	F
17	1	D	H	Y	A	F
18	1	D	H	N	C	F
19	1	D	H	N	A	F
20	1	N	E	Y	C	F
21	1	N	E	Y	A	F
22	1	N	E	N	C	F
23	1	N	E	N	A	F
24	1	P	L	Y	C	F
25	1	P	L	Y	A	F
26	1	P	L	N	C	F
27	1	P	L	N	A	F
28	1	P	M	Y	C	F
29	1	P	M	Y	A	F
30	1	P	M	N	C	F
31	1	P	M	N	A	F
32	1	P	H	Y	C	F
33	1	P	H	Y	A	F
34	1	P	H	N	C	F
35	1	P	H	N	A	F
36	2	D	L	Y	C	F
37	2	D	L	Y	A	F
38	2	D	L	N	C	F
39	2	D	L	N	A	F
40	2	D	M	Y	C	F
41	2	D	M	Y	A	F
42	2	D	M	N	C	F
43	2	D	M	N	A	F
44	2	D	H	Y	C	F
45	2	D	H	Y	A	F
46	2	D	H	N	C	F
47	2	D	H	N	A	F
48	2	N	E	Y	C	F
49	2	N	E	Y	A	F
50	2	N	E	N	C	F
51	2	N	E	N	A	F
52	2	P	L	Y	C	F
53	2	P	L	Y	A	F
54	2	P	L	N	C	F
55	2	P	L	N	A	F
56	2	P	M	Y	C	F
57	2	P	M	Y	A	F
58	2	P	M	N	C	F
59	2	P	M	N	A	F
60	2	P	H	Y	C	F
61	2	P	H	Y	A	F
62	2	P	H	N	C	F
63	2	P	H	N	A	F
64	3	D	L	Y	C	F
65	3	D	L	Y	A	F
66	3	D	L	N	C	F
67	3	D	L	N	A	F
68	3	D	M	Y	C	F
69	3	D	M	Y	A	F
70	3	D	M	N	C	F
71	3	D	M	N	A	F
72	3	D	H	Y	C	F
73	3	D	H	Y	A	F
74	3	D	H	N	C	F
75	3	D	H	N	A	F
76	3	N	E	Y	C	F
77	3	N	E	Y	A	F
78	3	N	E	N	C	F
79	3	N	E	N	A	F
80	3	P	L	Y	C	F
81	3	P	L	Y	A	F
82	3	P	L	N	C	F
83	3	P	L	N	A	F
84	3	P	M	Y	C	F
85	3	P	M	Y	A	F
86	3	P	M	N	C	F
87	3	P	M	N	A	F
88	3	P	H	Y	C	F
89	3	P	H	Y	A	F
90	3	P	H	N	C	F
91	3	P	H	N	A	F

In consultation with SFPUC and AECOM it was determined that not all 91 possible cases need be analyzed, so that 21 cases were analyzed, consisting of Cases:

1) 1 Ph0 DLNCB
2) 2 Ph0 DMNCB
3) 3 Ph0 DHNCB
4) 4 Ph0 NENCB
5) 20 Ph1 NEYCF
6) 22 Ph1 NENCF
7) 48 Ph2 NEYCF
8) 50 Ph2 NENCF
9) 64 Ph3 DLYCF
10) 65 Ph3 DLYAF
11) 66 Ph3 DLNCF
12) 67 Ph3 DLNAF
13) 68 Ph3 DMYCF
14) 69 Ph3 DMYAF
15) 72 Ph3 DHYCF
16) 73 Ph3 DHYAF
17) 74 Ph3 DHNCF
18) 75 Ph3 DHNAF
19) 76 Ph3 NEYCF
20) 77 Ph3 NEYAF
21) 78 Ph3 NENCF

These 21 cases were run for both the San Andreas Mw 7.9 and Hayward Mw 7 scenario events, so in total 42 cases were run.

Results

This section presents summary results for the 21 Cases for the San Andreas Mw 7.9 and Hayward Mw 7 scenarios. Results for both scenario events are presented in greater detail in Appendix section 5, and complete results have been uploaded to SFPUC SharePoint website in a zip file containing 46,930 electronic files totaling 122 mb, the structure of which is detailed in Appendix section 5.3.

Format of results

Results for each case in the zip file are contained in folders which consist of 100 simulations, each of which is contained in a subfolder which contains comma-separated variable (csv) files an example of which is shown in Figure 14. Each csv file provides Required Water, Area Burned etc for each time step. For example, the Required Water ("reqWater") timeline is shown in Figure 14 (note the view is split in four quadrants) and shows for each of 91 ignitions (the number of ignitions for this simulation – the number varies with each simulation; note that each row represents an ignition) the Required Water flow (gpm) at minute 0 (col A), minute 10 (col B) and so on to minute 1500 (col ET), each column being a 10 minute timestep. Total Required Water per fire in gallons is simply the summation of a row (times 10) and total water flow (gpm) for a trial at any 10-minute time step is simply the summation of that column.

	A	B	C	D	E	F	G	H	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET
1	0	181	147	125	107	92	79	67	0	0	0	0	0	0	0	0	0	0	0
2	0	269	215	181	155	133	114	98	0	0	0	0	0	0	0	0	0	0	0
3	66	50	42	36	31	26	23	19	0	0	0	0	0	0	0	0	0	0	0
4	82	61	51	43	37	32	27	23	0	0	0	0	0	0	0	0	0	0	0
5	87	67	56	48	41	35	30	26	0	0	0	0	0	0	0	0	0	0	0
6	0	102	83	70	60	51	44	38	0	0	0	0	0	0	0	0	0	0	0
7	39	31	26	22	19	16	14	12	0	0	0	0	0	0	0	0	0	0	0
8	0	343	246	203	173	148	128	110	0	0	0	0	0	0	0	0	0	0	0
9	53	371	309	264	227	195	167	142	0	0	0	0	0	0	0	0	0	0	0
10	120	86	71	60	52	45	38	33	0	0	0	0	0	0	0	0	0	0	0
11	86	62	51	43	37	32	27	23	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	13	10	8	5	3	1	0	0	0	0	0
84	0	0	0	0	0	0	0	0	12	10	8	6	4	2	1	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	132	106	90	77	66	57	48
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500
91	0	0	0	0	0	0	0	0	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500

Figure 14 Example contents of file "reqWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57" (note the view is split in four quadrants)

Ignitions

The scenario events cause a large number of ignitions – on average 130 ignitions for the San Andreas event and 42 for the Hayward event, as shown in Figure 15 and Figure 16.

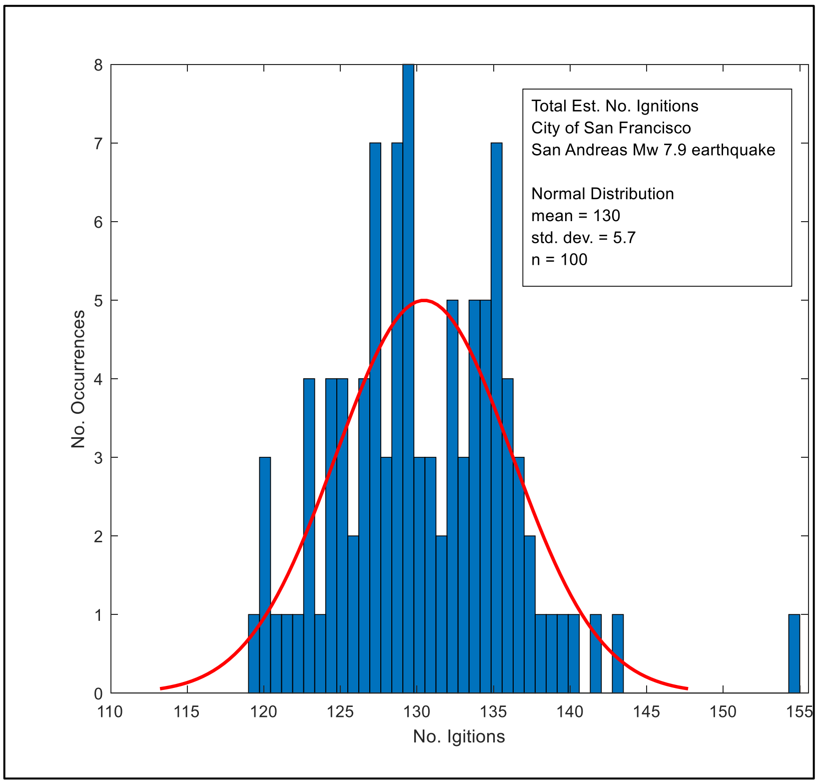


Figure 15 Histogram of estimated total number of ignitions for Mw 7.9 San Andreas event under current conditions. Current mean of 130 ignitions will grow to about 160 ignitions by 2050.

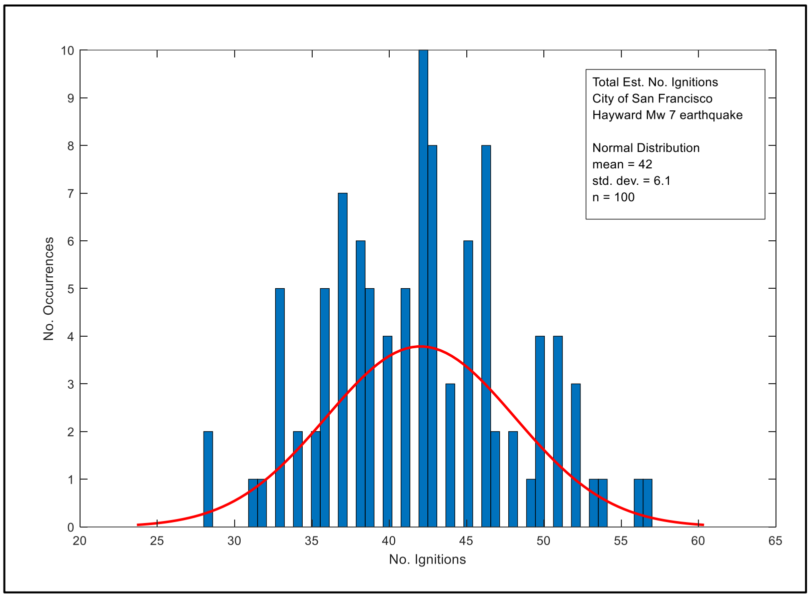


Figure 16 Histogram of estimated total number of ignitions for Mw 7 Hawyard event under current conditions. Current mean of 42 ignitions will grow to about 60 ignitions by 2050.

Number of ignitions grows with the City's population of course, and on average by 2050 will be about 160 for the San Andreas event and 60 for the Hayward event.

Required Water

Table 2 presents summary Required Water (flow in gpm and total volume in millions of gallons) and Burnt Total Floor Area (TFA, millions of sq. ft) for all 21 cases, for the 24th hour for the San Andreas Mw 7.9 event, and Table 3 similarly for the Hayward Mw 7 event.

Appendix section 5.3 presents similar results for hours 1, 2, 4, 8, 12 and 24. Also shown in both tables are the minimum and maximum values of all cases. Note that Table 2 contains results for a variety of conditions and for Phases 0 to 3, so direct comparison (and averaging) across all 21 cases is not valid, although comparison of two or more cases with similar conditions or Phases is valid.

As noted earlier in re the ground motions, the San Andreas event is far more severe than the Hayward event, and subsequent discussion here will only address the San Andreas event.

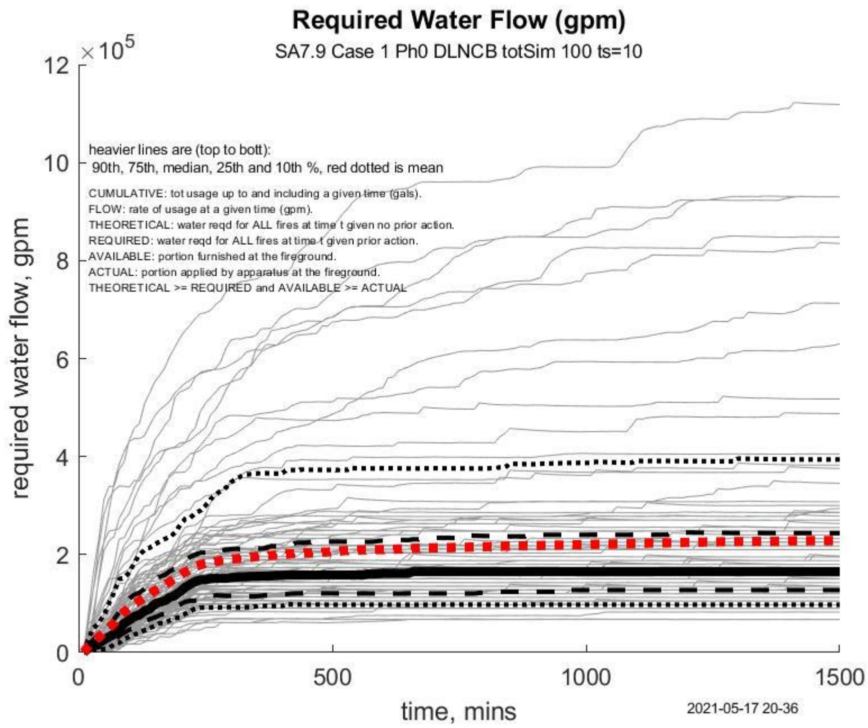
Table 2 Summary estimated Required Water demands (total water, millions of gallons) and flows (gpm), and total Burnt TFA, means, medians and 75th percentile, for 24th hour, for 21 cases

Case		Total Required Water Flow (millions gallons)			Required Water Flow (gpm)			Burnt TFA (millions sq ft)		
		median	mean	75%	median	mean	75%	median	mean	75%
1	SA7.9 Ph0 DLNCB	218	284	309	165,059	228,439	243,896	19	19	20
2	SA7.9 Ph0 DMNCB	176	225	266	131,445	180,384	218,535	18	18	20
3	SA7.9 Ph0 DHNCB	162	205	246	120,072	166,243	195,212	17	18	19
4	SA7.9 Ph0 NENCB	141	194	223	112,510	159,258	184,002	17	18	18
20	SA7.9 Ph1 NEYCF	143	205	256	112,621	167,254	202,586	25	26	27
22	SA7.9 Ph1 NENCF	161	209	241	128,048	169,887	202,599	25	26	28
48	SA7.9 Ph2 NEYCF	143	213	221	113,026	178,722	176,621	34	35	36
50	SA7.9 Ph2 NENCF	142	194	216	112,719	159,024	173,056	33	35	35
64	SA7.9 Ph3 DLYCF	216	282	340	165,368	233,123	274,085	48	49	52
65	SA7.9 Ph3 DLYAF	254	332	366	191,502	262,908	285,350	46	48	50
66	SA7.9 Ph3 DLNCF	198	276	317	154,152	226,830	255,097	46	49	51
67	SA7.9 Ph3 DLNAF	275	334	360	210,124	262,226	281,481	45	47	50
68	SA7.9 Ph3 DMYCF	155	233	269	124,100	194,487	210,338	43	45	48
69	SA7.9 Ph3 DMYAF	219	313	365	165,176	249,334	288,888	42	45	46
72	SA7.9 Ph3 DHYCF	140	192	232	108,835	160,093	188,237	42	44	46
73	SA7.9 Ph3 DHYAF	216	306	371	165,255	245,180	289,105	42	44	45
74	SA7.9 Ph3 DHNCF	136	204	245	105,150	170,313	191,507	42	44	46
75	SA7.9 Ph3 DHNAF	208	254	305	157,598	198,034	237,922	42	43	44
76	SA7.9 Ph3 NEYCF	150	215	241	120,181	180,760	198,990	42	44	45
77	SA7.9 Ph3 NEYAF	208	294	334	161,549	237,548	262,762	42	45	46
78	SA7.9 Ph3 NENCF	144	193	236	112,664	162,089	195,184	42	44	45
	Min all Cases	**136**	**192**	**216**	**105,150**	**159,024**	**173,056**	**17**	**18**	**18**
	Max all Cases	**275**	**334**	**371**	**210,124**	**262,908**	**289,105**	**48**	**49**	**52**

Figure 17 presents the timeline of estimated Required Water for Case 1 Ph0 DLNCB (San Andreas event) from the time of the earthquake to the 1500th minute (25th hour). It can be seen that median flow grows initially and then stabilizes at about 165,000 gpm as SFFD is fully committed, and that the median total amount of Required Water is about 218 million gallons. There is quite a bit of variation about these medians, as shown by the spread of the light gray lines (representing individual trials), with outliers several multiples of medians.

Figure 18 is for Case 72 Ph3 DHYCF (San Andreas event) – median flow is about 108,000 gpm and the median total amount of Required Water is now about 140 million gallons. That is, Required Water is less, despite population growth of 25%. Why? The EFWS now extends to all parts of the City and its operational efficiency is now High rather than Low (i.e., wider coverage, greater resilience, restores functionality faster, more rapid application of water on fire). SFFD capability is the same in both Phases. Improving SFFD's capability (Case 73 Ph3 DHYAF) results in more water usage but about the same total burnt area.

Following the figures are results for the Hayward scenario, Table 3. Comparable results and plots are provided for all Cases, for Required Water and a number of other parameters, in the electronic files.



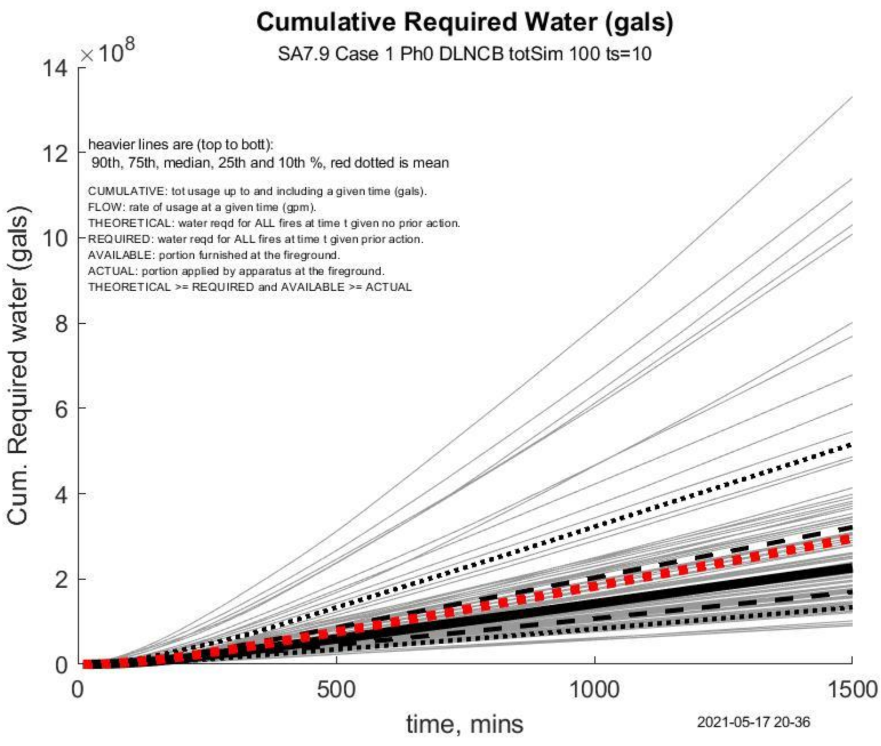
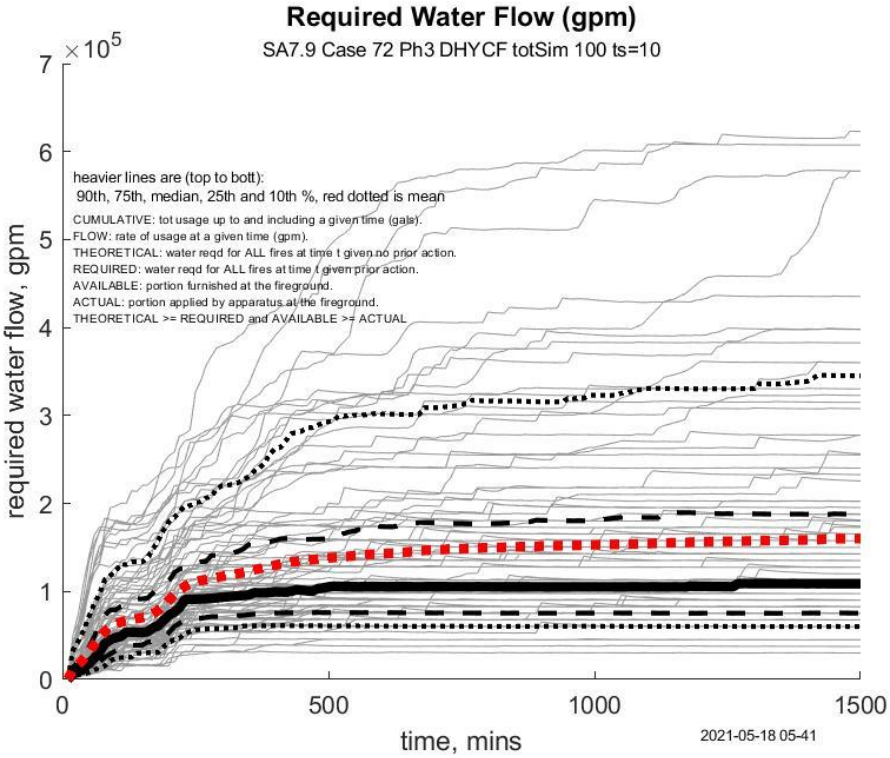


Figure 17 Case 1 Ph0 DLNCB San Andreas Mw 7.9 event current conditions estimated Required Water timelines: (top) water flow, gpm; (bott) total water required (gallons), from time of earthquake to 1500th minute. Heavy solid black line is median of 100 trials, dotted red is mean, dashed and dotted heavy black lines are 75th and 90th percentiles, and light gray solid lines are all 100 simulations.



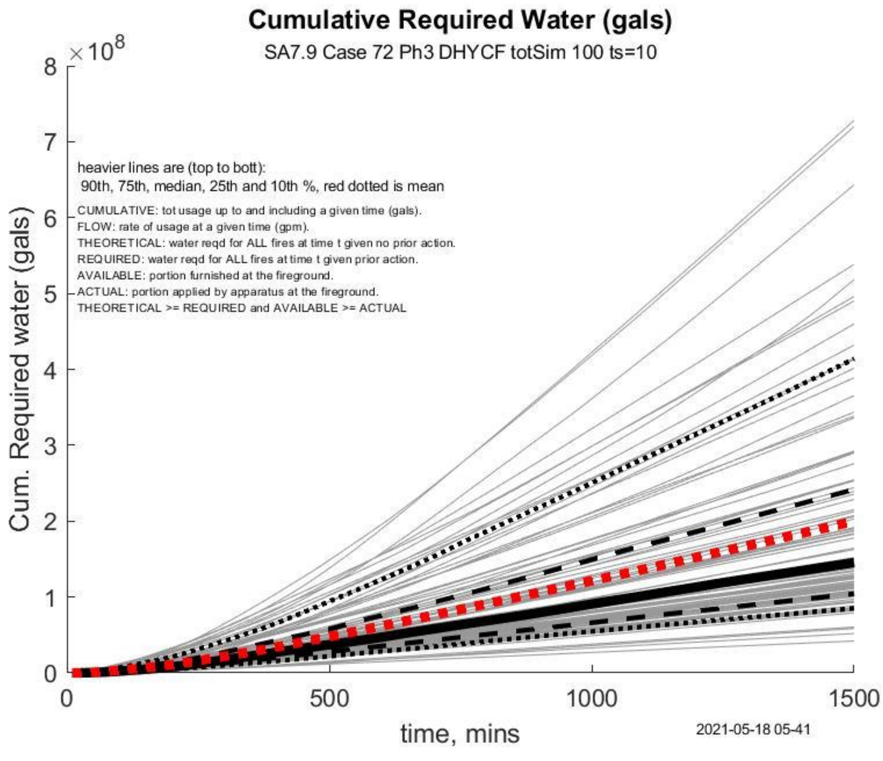


Figure 18 Case 72 Ph3 DHYCF San Andreas Mw 7.9 event current conditions estimated Required Water timelines: (top) water flow, gpm; (bott) total water required (gallons), from time of earthquake to 1500th minute. Heavy solid black line is median of 100 trials, dotted red is mean, dashed and dotted heavy black lines are 75th and 90th percentiles, and light gray solid lines are all 100 simulations.

Table 3 Summary estimated Required Water demands (total water, millions of gallons) and flows (gpm), and total Burnt TFA, means, medians and 75th percentile, for 24th hour, for 21 cases

Case		Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
		median	**mean**	**75%**	**median**	**mean**	**75%**	**median**	**mean**	**75%**
1	H7.05 Ph0 DLNCB	21	38	48	15,013	31,255	41,897	6	7	9
2	H7.05 Ph0 DMNCB	11	20	29	7,707	16,058	22,529	5	6	6
3	H7.05 Ph0 DHNCB	10	32	31	7,518	25,387	22,662	5	6	6
4	H7.05 Ph0 NENCB	10	27	40	7,540	22,335	30,065	5	6	6
20	H7.05 Ph1 NEYCF	19	45	50	15,011	36,615	37,500	9	10	12
22	H7.05 Ph1 NENCF	21	42	41	15,022	34,248	37,692	9	10	13
48	H7.05 Ph2 NEYCF	32	58	71	30,000	45,248	52,762	18	18	22
50	H7.05 Ph2 NENCF	38	68	78	30,005	55,465	60,009	18	17	22
64	H7.05 Ph3 DLYCF	63	104	127	48,873	79,984	97,637	30	30	35
65	H7.05 Ph3 DLYAF	57	88	107	41,442	71,182	83,318	30	30	33
66	H7.05 Ph3 DLNCF	73	109	132	60,007	85,505	108,963	31	31	35
67	H7.05 Ph3 DLNAF	50	79	91	37,696	63,664	67,585	30	29	33
68	H7.05 Ph3 DMYCF	59	102	140	45,190	80,284	113,948	28	28	33
69	H7.05 Ph3 DMYAF	50	90	111	37,604	69,738	86,269	28	27	31
72	H7.05 Ph3 DHYCF	60	102	133	45,167	80,181	101,264	28	28	31
73	H7.05 Ph3 DHYAF	40	82	108	30,072	64,857	82,530	25	26	30
74	H7.05 Ph3 DHNCF	51	97	109	41,375	76,808	90,151	28	27	31
75	H7.05 Ph3 DHNAF	41	72	83	30,133	56,278	63,988	26	26	29
76	H7.05 Ph3 NEYCF	60	92	116	45,068	72,299	90,715	27	27	31
77	H7.05 Ph3 NEYAF	50	75	97	37,686	61,132	82,501	28	26	30
78	H7.05 Ph3 NENCF	69	97	125	52,871	76,020	97,500	27	27	31
	min	**10**	**20**	**29**	**7,518**	**16,058**	**22,529**	**5**	**6**	**6**
	max	**73**	**109**	**140**	**60,007**	**85,505**	**113,948**	**31**	**31**	**35**

Discussion

The above has provided a glimpse of the large set of results from this study. This dataset provides rich detail, which is discussed at more length in Appendix section 5. A few observations:

- Figure 19 shows the median and 75th % Required Water flow (gpm) averaged across all cases. Averaging over all cases mixes many things, including the different phases of EFWS buildout, so that the figure is only of limited value. Nevertheless, it can be seen that the Required Water flow is several times current capacity.
- Figure 20 parses Figure 19 by Phase of EFWS building, finding that 75th % Required Water demand remains about the same or slightly decreases from current conditions (Phase 0) through 2050, despite the City's very significant projected population growth during this period.
- It is of interest to compare the current study's results with those provided in 2012 for CS-199. Comparison is difficult due to the 2012 results being for only the first 120 minutes, not considering fire department response etc, but Figure 21 provides some useful insight – in summary, this study's results at minute 60 are somewhat less than the results in 2012 due to this study considering fire department response (and 2012 not doing so), but after that time the general trend of the 2012 study is in line with this study's results.

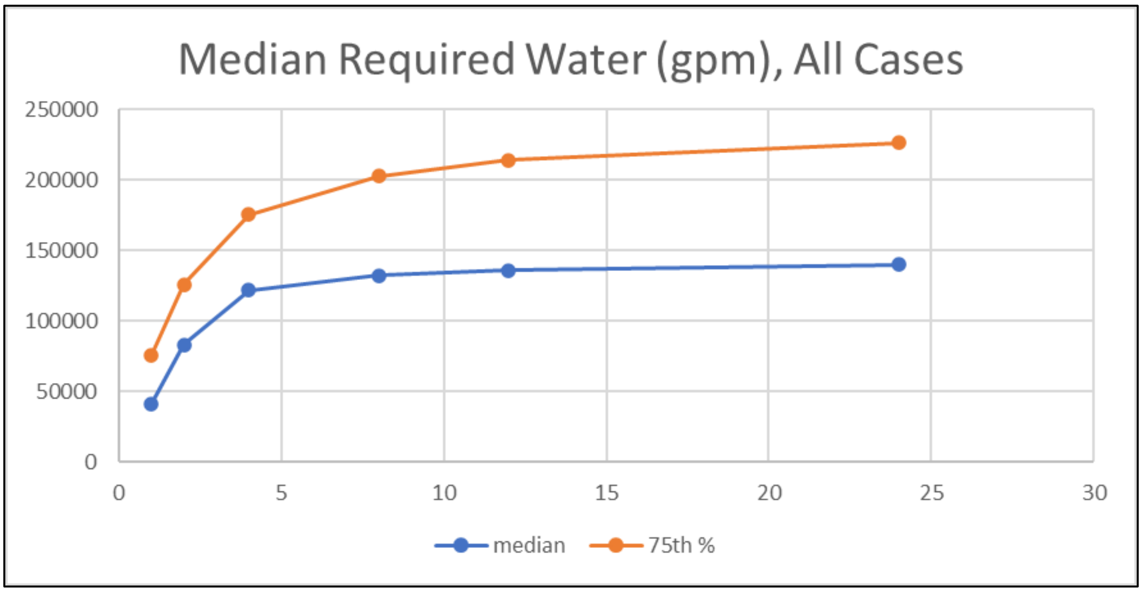


Figure 19 Median and 75% estimated Required Water flow (gpm), averaged over all Cases

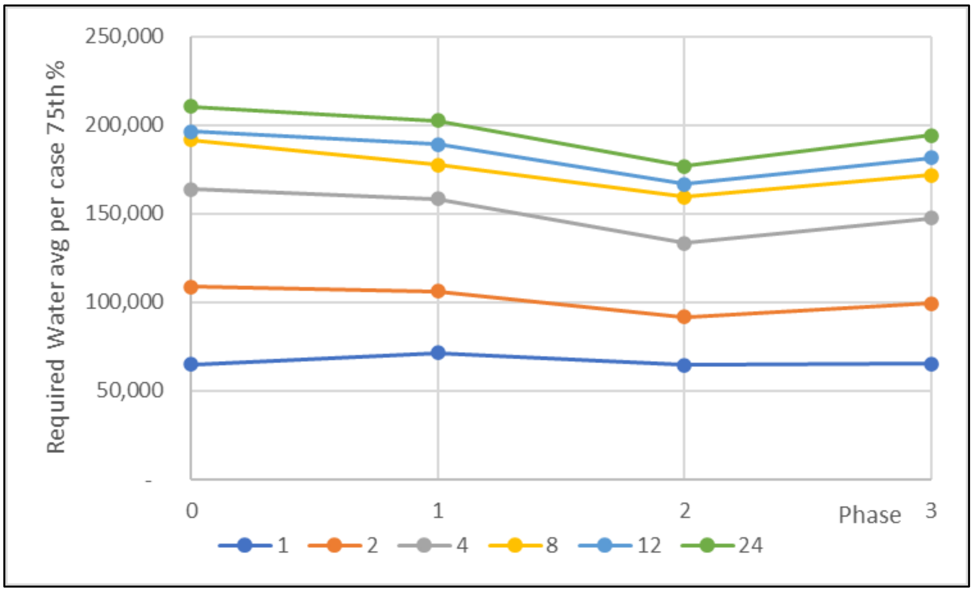


Figure 20 Variation of estimated Required Water demands vs. Phases, for hours 1, 2,4, 8, 12 and 24. In all cases, demand modestly decreases despite City's significant growth of population.

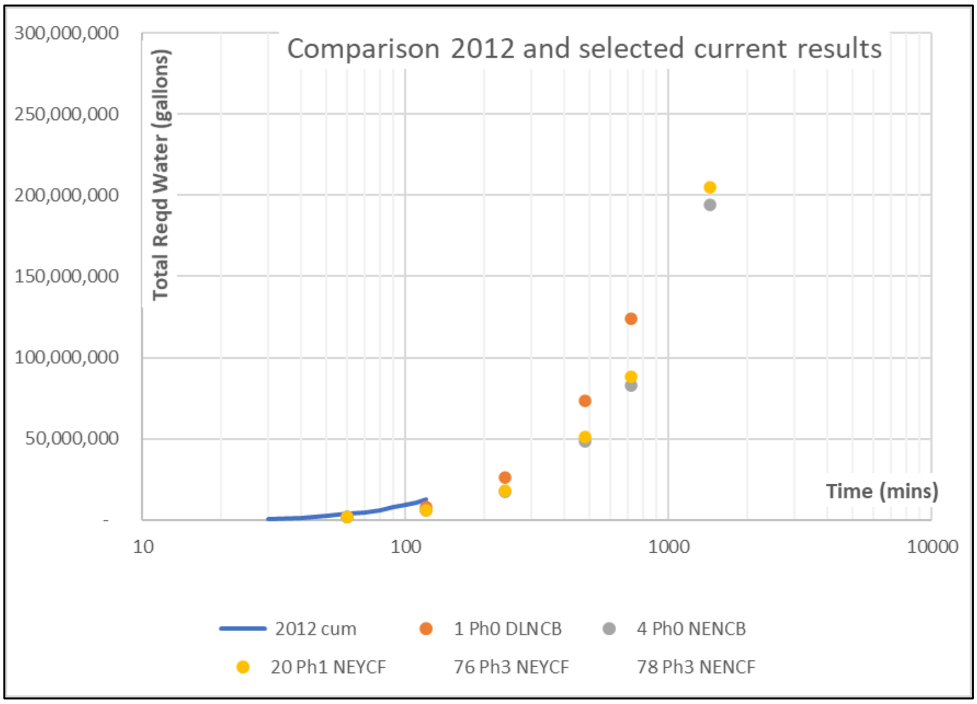


Figure 21 Comparison of estimated water demands from 2012 analysis (solid blue line) vs. selected current estimates (points). The 2012 analysis (see Appendix D) was only for the first 2 hours and had several limitations. The current estimates are selected cases – see text for description. The overall trends are (a) water demands increase exponentially with time; (b) there is relatively little variation in water demands no matter what the Phase is, or assumptions regarding system damage and operation; (c) the 2012 results, although limited, appear to have the same trend as current estimates.

Concluding Remarks

Water demands for fighting fires following a major earthquake affecting San Francisco have been estimated based on a detailed model of fire service operations and water system performance. The model employs several large datasets, including data for each building in the City, detailed ground motion models, hourly weather data, tree canopy data, pipe network data and other data. Uncertainty on many of these data is considered in the analysis.

A key point emerging from the analysis is that effective suppression of fires following a major earthquake requires a balance of fire service and water supply resources – that is, copious amounts of water are superfluous if the fire department's resources are not adequate to the task, and conversely an abundance of fire department resources is largely useless if the water supply isn't adequate to the task. Moreover, rapid and adequate fire department response with adequate water readily available at the fireground greatly reduces the total water demand.

Regarding water requirements, under current conditions, the first 25 hours following a major earthquake are estimated to require 200+ million gallons of water provided to firegrounds for effective firefighting. This demand can be reduced or remain about the same through 2050, depending on EFWS improvements and SFFD capability. Further study is probably required to determine how SFFD can most effectively use this water.

The fundamental result is that depending on Case, estimated Required Water flow will be 100,000 to 200,000 gpm in the median, and 200,000+ gpm at the 75th percentile. It is important to understand that the system should be designed for an upper percentile of required flows, rather than the median – if designed for the median, then by definition 50% of the time flows will be inadequate for fire suppression, thus an upper percentile should be a design target. Figure 17 shows that the 75% flow is about the same as the mean (i.e., arithmetic average) flow, at about 230,000 gpm, while the 90th percentile flow is over 300,000 gpm. Designing for the 75th percentile is equivalent to having sufficient water for fire suppression in 3 out of 4 repetitions of the scenario event.

What does 200,000 gpm mean in physical terms? Well, to use a popular measure, an Olympic size swimming pool[3] would be filled in 3 minutes at this rate. Or, Twin Peaks Reservoir (10 million gallons) would be emptied in 50 minutes.

More relevantly, if all 43[4] SFFD first line and 7 reserve engines (i.e., total of 50 engines), and all three Fireboats (Pheonix,10,000 gpm; Guardian, 22,000 gpm and St. Francis, 18,000 gpm, all at 150 psi) and both EFWS Pump Stations (two at 10,000 gpm each, at 150 psi), are all pumping at full capacity, the total is 144,600 gpm[5]. If the 75th percentile is the goal, the shortfall of 200,000 – 144,600 = 55,400 gpm might be provided by Twin Peaks Reservoir for 180 minutes. This capacity is useful if the EFWS can convey all this water to the fireground.

However, "if the EFWS can convey all this water to the fireground" is the issue. At present, the EFWS ability to convey large amounts of water to some locations is limited by the pipe sizes leading to those locations and, in any case, the EFWS doesn't currently extend to all parts

[3] Defined as 25m x 50m x 2m equivalent to 660,000 gallons.

[4] Apparatus on Treasure Island and at San Francisco International Airport are not included.

[5] Note that this is only for illustration and its simple addition involves double counting since if fire engines are drawing from the EFWS then their pumping capacity is against and not in addition to the pumping capacity of the fireboats or pump stations.

of the City. In those parts of the City not covered by the EFWS, there are a significant number of cisterns. However, the effective radius over which a cistern provides protection is only a few blocks. Hose tenders extend this radius, and SFFD is in the process of acquiring a larger number of modern hose tenders.

In conclusion, depending on the expansion of the EFWS and capacity of SFFD, there may or may not be adequate amounts of water at some fires when fire engines arrive, which would lead to continued fire growth and a larger demand for firefighting water than at first arrival. The analysis has considered this in the various Analysis Cases and estimation of Required Water.

Appendices to this report provide additional detail.

APPENDICES

1 INTRODUCTION

The project purpose, background and scope of work are presented.

1.1 PURPOSE

The purpose of this project has been the estimation of water required to suppress fires following a major earthquake affecting the city of San Francisco. Estimating the required water assumes all fires are fought by the San Francisco Fire Department (SFFD) with aid from other fire departments some time following the earthquake. Estimation of required water is needed to determine if the current water supply sources and conveyance infrastructure meet the requirements for firefighting, or if additional sources and infrastructure are required.

1.2 NOMENCLATURE

The many specialized terms and abbreviations used in this report are defined in the Table of Abbreviations and Acronyms, but a few terms are worth discussion:

The **Emergency Firefighting Water System (EFWS)** refers to the aggregation of the high-pressure network[6], PEWFS and other pipelines, connections to reservoirs, pump stations and infrastructure planned to protect the city from major fires. The high-pressure network is an earthquake-resistant pipe network and facilities built following the 1906 San Francisco earthquake and includes not only the pipe network but also the Twin Peaks 10-million-gallon reservoir, Pump Stations 1 and 2, and other critical equipment including cisterns, fireboat manifolds and other appurtenances. The original pipe network protected the Central Business and nearby districts and in subsequent decades was extended to the Mission and other areas. Future pipes and appurtenances connected to the current network (e.g., Infirm Area backbones, Presidio line, lines in southern part of city) are included unless otherwise noted.

The **Potable Emergency Water Firefighting System (PEWFS)** is a new system in the planning stage that will protect the Richmond and Sunset districts. It will consist of a pipe network from Lake Merced northwards to the Richmond and connecting to Sunset Reservoir, with pump stations at Lake Merced, Sunset Reservoir and perhaps at Sunset Pumping Plant. It will be operated as a potable trunk line supplied from Sunset Reservoir under normal conditions and switched to a high-pressure network (independent of the current high) for firefighting when needed. When operating as a high-pressure network PEWFS if required may inject raw water from Lake Merced.

1.3 Background and Scope of Work

During 2011-2014 the San Francisco Public Utilities Commissions and its consultant AECOM/AGS JV reviewed the existing EFWS high-pressure pipe network and made recommendations on pipelines, control systems, seawater intake tunnels, and cisterns to optimize benefits from repairs and improvements to the network, given the potential for seismic activity in the area (CS-199 2014). As part of that work estimates were made of the water required for post-earthquake firefighting (Scawthorn 2012). These estimates had several limitations – (a) they were based on early 2000s data that had been employed for the previous CAPSS study (ATC-52-1 2010), (b) they were only for the first 2 hours following the earthquake, (c) they did not take into account SFFD firefighting response (and were thus an

[6] The high-pressure network was termed the Auxiliary Water Supply System (AWSS) but is now part of the larger EFWS

overestimate of water requirements) and (d) they were a "snapshot" of needs in July 2012 as opposed to what the needs of the city would be in the future.

Because the estimates left room for improvement, discussions with SFPUC in late 2018 resulted in agreement on a scope of work for updating the fire following earthquake water demands, termed the Fire Following Earthquake Water Requirements Study project (FFEWRS). To avoid frequent future updates of these results, it was decided to make projections of future San Francisco growth through 2050 and provide estimates of firefighting water needs at several future stages or "phases" of infrastructure buildout. The specific scope of work consisted of the following tasks:

1. "Project initiation and work plan: this is a modest task to meet with SFPUC and present the project work plan. The work plan will be based on this scope of work, with actual schedule dates and specific meetings, and identification of needed SFPUC liaison with other departments. Deliverable: Document the task and results in a Technical Memo.
2. "Kickoff and stakeholder input: this task consists of one to several meetings with stakeholder City agencies to outline the project and receive stakeholder input. If possible, a workshop will be held to facilitate simultaneous input from multiple stakeholders. Deliverable: Document the task and results in a Technical Memo.
3. "Collect and review San Francisco exposure and growth data: Working with SFPUC personnel, arrange and attend meetings with relevant persons in San Francisco PUC, Planning Department and Fire Department, to identify and receive relevant future growth projection data. If deemed useful, meet with Metropolitan Transportation Commission and other agencies (e.g., ABAG) for similar purposes. Included in this task is collection of data related to exposures in city parks (e.g., Golden Gate, McLaren and other parks) and in the Presidio (to be confirmed). Review and employ this data to develop LMH growth projections. This task will include receiving most current building stock inventory from the Planning Department. Deliverable: Document the task and results in a Technical Memo.
4. "Data processing and preparation: with approved LHM projections, building stock projections will be developed and prepared for use in the fire following earthquake model. This is a project internal task and no TM will be prepared.
5. "Seismic hazard: this task will review current seismic hazard estimates affecting San Francisco, to assure up-to-date ground motion data will be employed (the ground motion estimates employed in 2012 are out of date). Two major seismic events will be considered: an Mw 7.9 event on the San Andreas fault similar to the 1906 event, and a Mw 7 event on the Hayward fault (based on the recently published Haywired study. The question of whether and how to include effects of aftershocks will be addressed. To account for uncertainty, ground motions will be characterized in a suite of hazard maps, probably using the method of Miller and Bakeriii. Deliverable: Document the task and results in a Technical Memo.
6. "Analysis and post-processing: this task consists of estimating ignitions, corresponding fire department response and water requirements for typical seasonal weather conditions, for city block other areas in the contiguous portion of San Francisco county, for one-minute steps for the first two hours following the earthquake. Effects of

vegetation in city parks and the Presidio will be considered. This task does not require a TM.

7. "Results delivery and report: Data on water demands will be delivered in a format like that employed in 2012, together with a Report documenting the methods and data employed. The Report will provide guidance on use of the data, including given actual growth data available in the future. Deliverable: Document the task and results in a final project Report.
8. "Project management: This is a modest task consisting of project management, status reports and related activities. "

The Fire Following Earthquake Water Requirements Study project (FFEWRS) began and was amended in October 2019 for two tasks regarding optimization of the pipe network.

2 SAN FRANCISCO, ITS EARTHQUAKE RISK AND THE EMERGENCY FIREFIGHTING WATER SYSTEM

San Francisco's development, seismicity, fire following earthquake risk and infrastructure for mitigating this risk are provided as background and context for this study. These topics are not addressed in depth, and the reader is referred elsewhere for more detail.

2.1 San Francisco and its development

Prior to the Gold Rush, San Francisco was hardly a village, with a population of just a few hundred. Even after 1849, while growth was rapid, the City hardly extended beyond today's Financial District, Figure 22, although the density of construction was rather high, Figure 27. Much of the rapidly expanding city was built of wood, which led to a number of conflagrations in the 1850's and a vigilance against fire that continued thereafter. By the turn of the century, San Francisco had grown to a population of 400,000, with a major fire risk, Figure 23.

A survey of San Francisco 1905 by the National Board of Fire Underwriters (NBFU 1905) provides a detailed snapshot of the city, whose built-up extent is shown in Figure 24, while Figure 25 shows the western portions (today's Richmond and Sunset districts) were still sand dunes. The grew rapidly and was largely built out by WW2, with only a few remnant sand dunes remaining, Figure 26.

Figure 22 San Francisco 1857
Source: US Coast and Geodetic Survey map, David Rumsey Map Collection www.davidrumsey.com

Figure 23 San Francisco 1905

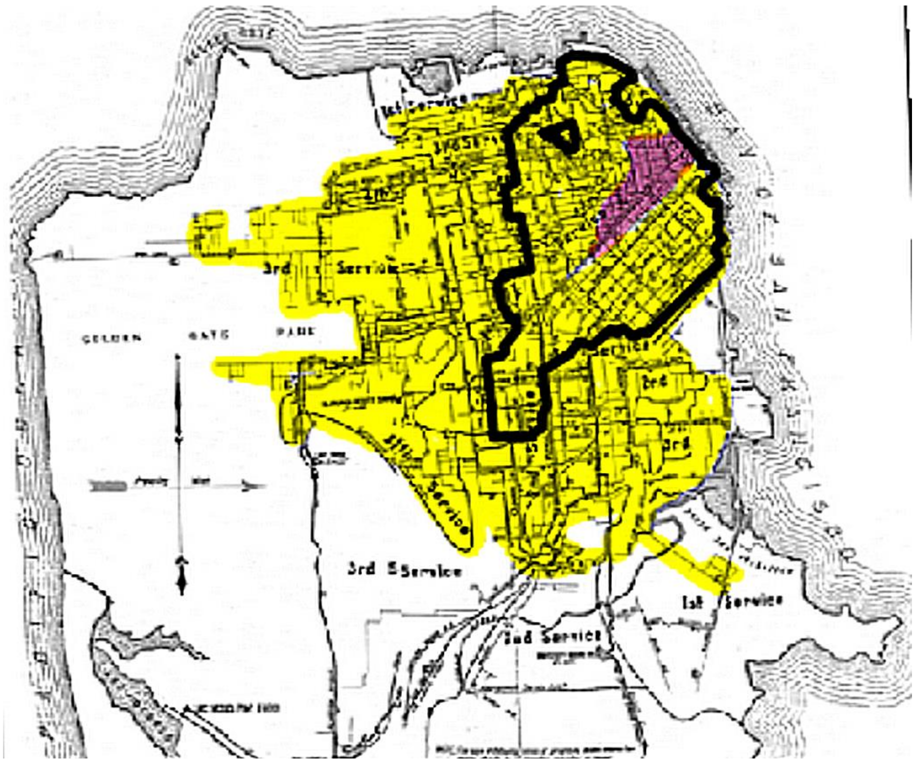


Figure 24 San Francisco water distribution network, 1905
– built-up area shown in yellow and congested area in pink, outline of 1906 burnt area in black
Source: adapted from (NBFU 1905)

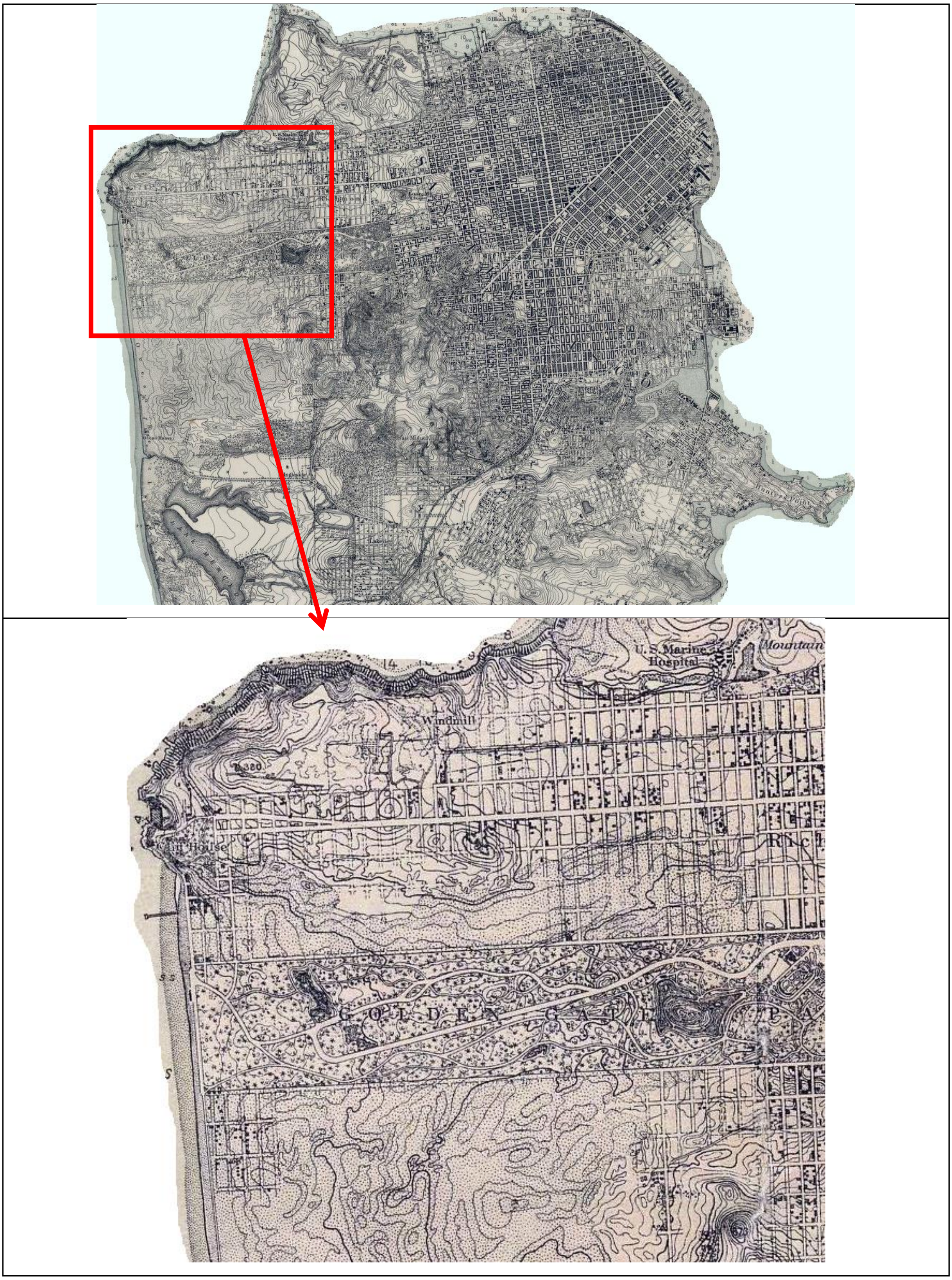


Figure 25 San Francisco 1905 – note sparsity of buildings N and S of Golden Gate Park
Source: US Coast and Geodetic Survey map, David Rumsey Map Collection www.davidrumsey.com

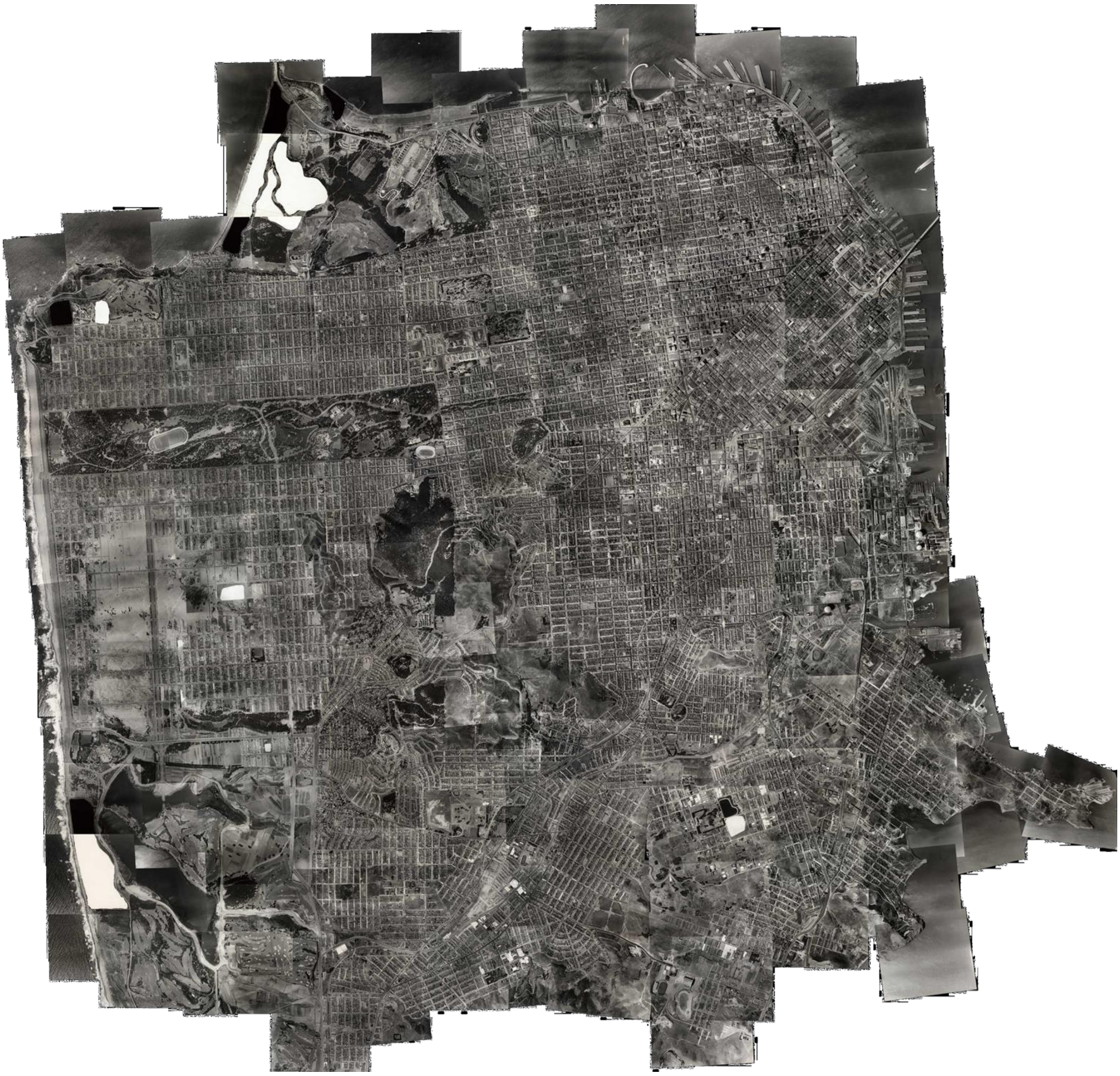


Figure 26 San Francisco composite aerial views by H. Ryker, 1938. City is almost entirely built out with remnant sand dunes in Sunset District west of Sunset reservoir
Source: David Rumsey Map Collection www.davidrumsey.com

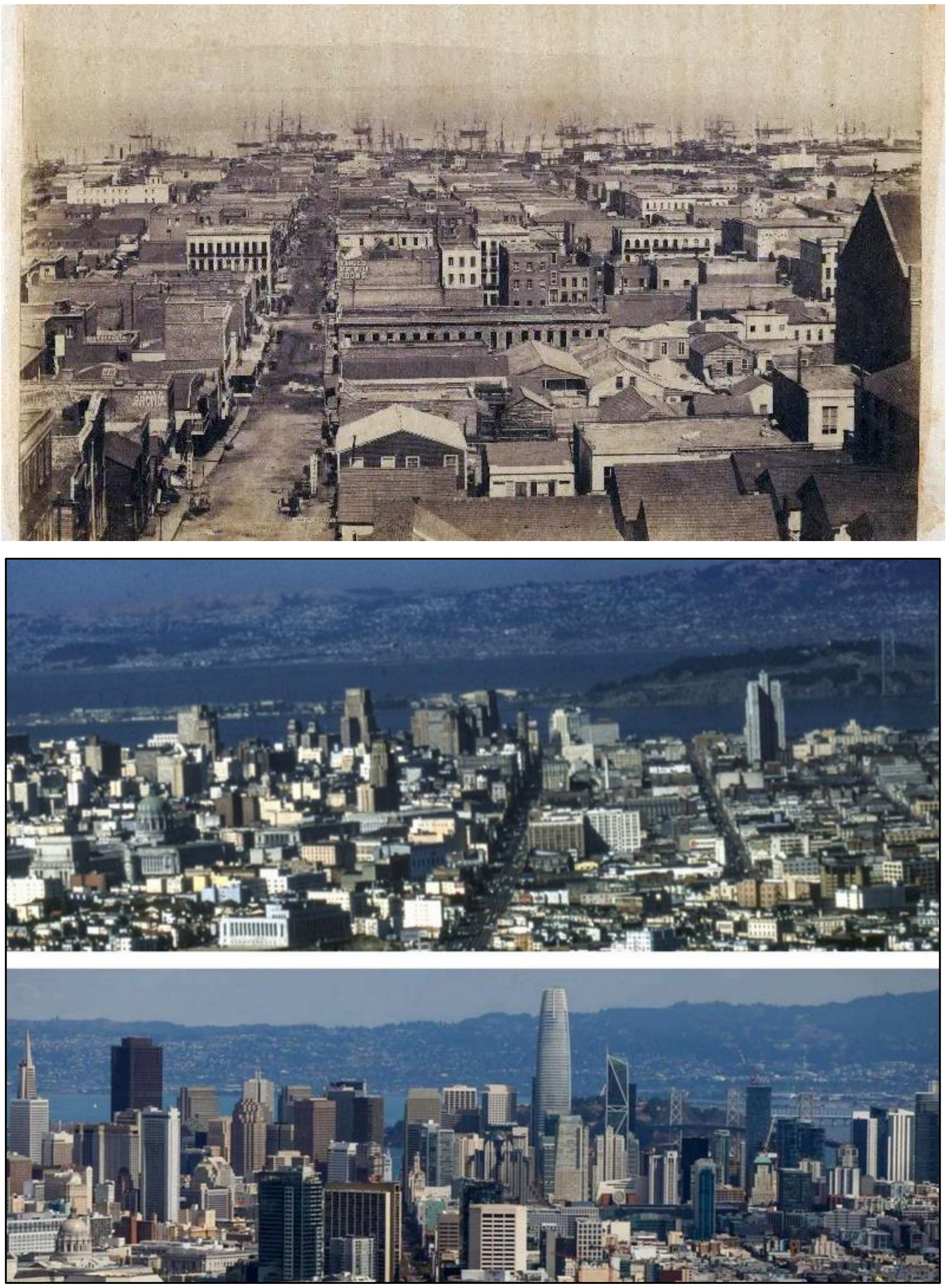


Figure 27 San Francisco: 1856, 1954 and 2018

Sources: https://sf.curbed.com/maps/old-photos-photographs-san-francisco-gold-rush and https://www.sfgate.com/bayarea/article/san-francisco-tallest-buildings-skyscrapers-height-13532960.php#photo-16804791

The rapid growth of San Francisco, continuing today, is clearly shown in Figure 27 and Figure 28. While many new high-rises have risen downtown, and there's been some densification in residential areas with multi-family buildings replacing single-family homes, by number much of San Francisco's buildings pre-date WW2 (67%) and even pre-1906 (13%), while 94% of all buildings are of wood construction (ATC-52-1 2010), Figure 2.

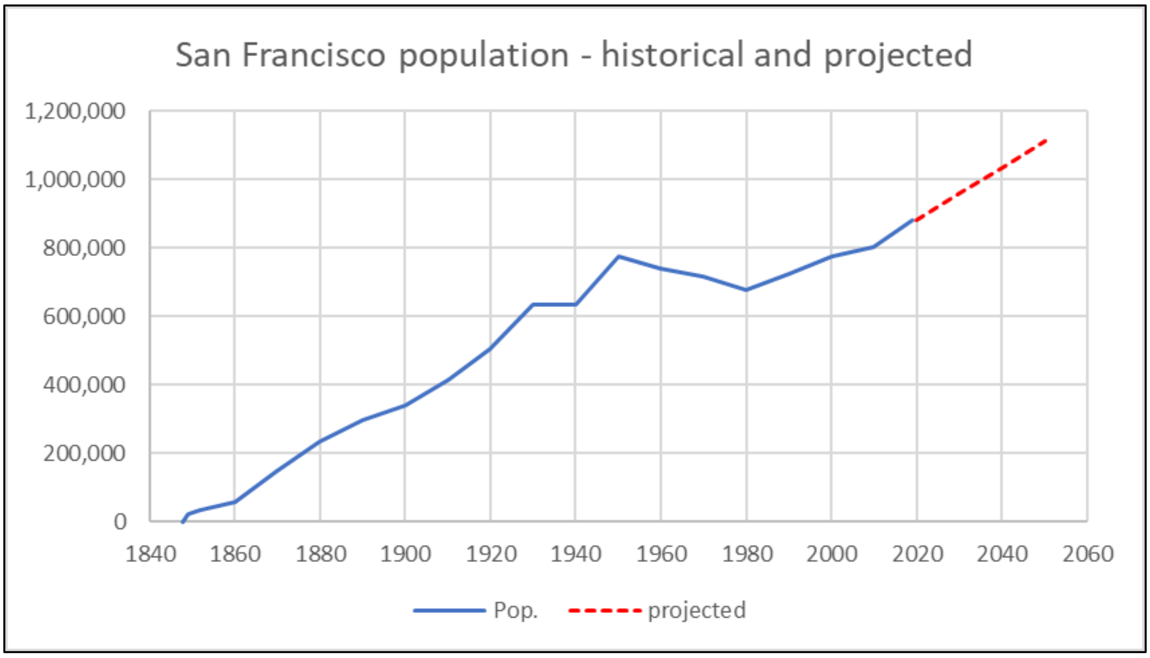


Figure 28 San Francisco historical and projected population by decade

2.2 SAN FRANCISCO'S SEISMIC HAZARD

There is not much need to dwell on San Francisco's earthquake risk – it's well known and real. The city is athwart the North American – Pacific plate boundary, with the San Andreas fault and the Hayward faults 10 miles equidistant from the Ferry Building, Figure 29. Virtually all of the city has the potential for very strong ground shaking, with USGS for the next 30 years estimates being 72% for a Mw 6.7, 51% for a Mw 7.0 and 20% for a Mw 7.5 event in the Bay Area, Figure 30.

Based on a review of seismicity, this study employs two scenario earthquakes: (1) a Mw 7.9 event on the San Andreas fault like the 1906 event, and (2) a Mw 7.05[7] event on the Hayward fault in the East Bay. These two events were also examined in the CAPSS study (ATC-52-1 2010). Ground motions for these events is discussed in section 3.2.3 but it should be noted that the ground motions from either of these events will be very strong in San Francisco, with the Mw 7.9 San Andreas event being generally stronger, especially in the western portions of the City, which are only a few miles from that fault. The Hayward event, while generally having similar or smaller ground motions than the San Andreas event, is considered more likely to occur in the near future.

[7] The two digit precision for the Hayward event is due to the USGS Haywired project (Detweiler, S.T., and A.M. Wein (Eds.). 2017. *The HayWired earthquake scenario—Earthquake hazards (ver. 1.1, March 2018):*. Washington: U.S. Geological Survey Scientific Investigations Report 2017–5013–A–H, available at https://pubs.er.usgs.gov/publication/sir20175013v1. Such precision for earthquake magnitude is somewhat illusory, and hereafter the Hayward event magnitude will be denoted at Mw 7.

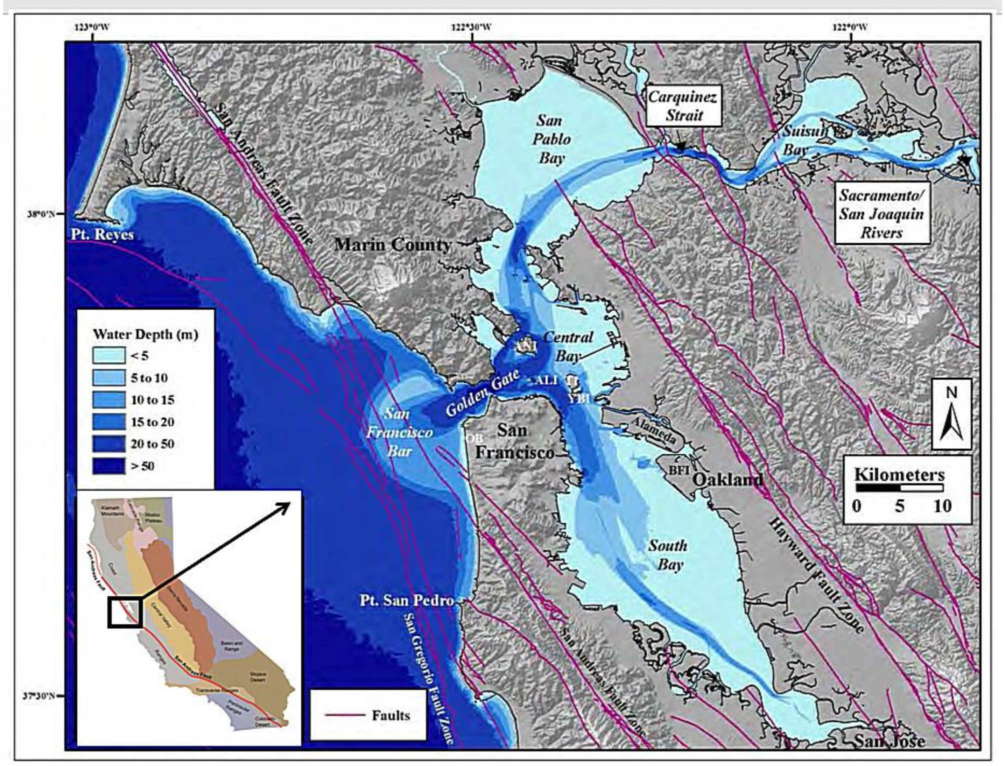


Figure 29 Bay Area map with shaded relief and faults in magenta. Inset is the state of California main geomorphic figures, particularly the San Andreas fault shown in red.
Source: adapted from (Johnson and Bartow 2018) who source it as (Barnard et al., 2013)

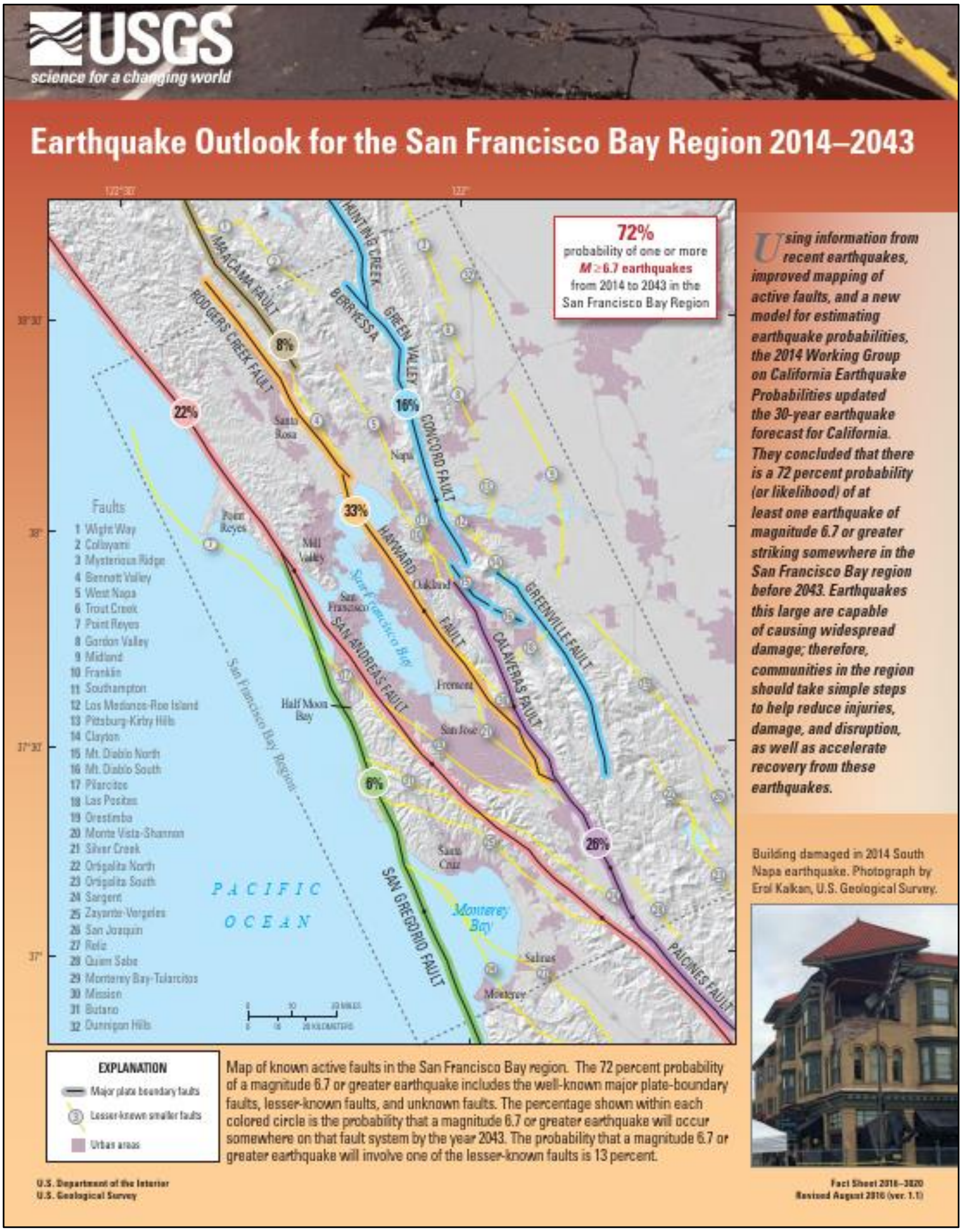


Figure 30 USGS estimated event probabilities 2014-2043

Geology strongly influences earthquake ground motions, and the city has large areas of very soft soils in what was once the Bay or marshes, and virtually the entire western half of the city being on what were a century ago sand dunes, Figure 31.

Figure 31 Geologic map of San Francisco illustrating Quaternary units (Graymer et al., 2006). Franciscan Complex Bedrock is not shown. Units include: Gray= Artificial Fill (AF), Pink= Landslide and hillslope deposits (Qsl), Yellow = Sand dunes (Qd), Orange = Colma Formation (Qc), green = older Quaternary Alluvium (Qpa); Merced Formation = light blue. Also shown is location of the shoreline in 1850 (blue dashed line) and the extent of historic marshes from 1898 (blue cross hatch pattern) Note: Young Bay mud is covered by artificial fill in San Francisco.
Source: (Johnson and Bartow 2018) who source it as (Sowers et al., 2007)

2.3 SAN FRANCISCO AND FIRE FOLLOWING EARTHQUAKE

Nineteenth century urban America was a very flammable place – for example conflagrations in nine different cities from 1835 to 1905 each involved the destruction of at least 1,000 buildings (TCLEE 2005). San Francisco was no exception, with several conflagrations in its early years[8], and an appreciation by 1905 that there was a very high risk of a major conflagration. In that year, the city was rated by the National Board of Fire Underwriters (NBFU, 1905) who found its fire department efficient, well organized and, in general, adequate. The NBFU however concluded that

> "...In fact, San Francisco has violated all underwriting traditions and precedent by not burning up. That it has not done so is largely due to the vigilance of the fire department, which cannot be relied upon indefinitely to stave off the inevitable."

Prophetic words, indeed.

2.3.1 Comparison of 1906 and today

It is worth comparing the situation in 1906 and today. The San Francisco Fire Department in 1905 protected approximately 400,000 persons occupying an urbanized area of approximately 21 square miles, Figure 24. The department consisted of a total of 585 full paid fire force personnel (resident within the city and on duty at all times), commanded by Chief Dennis T. Sullivan and deployed in 57 companies (38 engine, 1 hose, 10 ladder, 1 hose tower, and 7 chemical) (NBFU, 1905). The distribution of these companies was well conceived, being centered about the congested high value district (i.e., the Central Business District or CBD, known in San Francisco as the Financial District), with 24 engine, 8 ladder, 1 water tower and 7 chemical companies within 2 miles of the center of the CBD. All but two of the 38 steam engine companies dated from 1890 or later and were rated at an average of 680 gallons per minute (gpm), although the eight engines tested in 1905 averaged only about 70% of their rated capacity, and the "*ability of the men handling the engines was in general below a proper standard*". The rated pumping capacity of the 38 first line and 15 relief and reserve engines totaled 35,100 gpm. Table 3 shows this SFFD capacity in 1906 and today (many specialized types of apparatus are omitted).

Table 4 SFFD on duty staffing over the years

Year	Engines	Pumping Capacity (gpm)		Ladder trucks	Total Fire Personnel	Total On-duty Fire Personnel[9]
		Tot.	Per thous. popul.			
1906	38	35,100	88	16	585	585
2020[10]	43 + 5 R	72,000	82	20	1449	268

[8] "Several" is an understatement: Two multi-building fires in 1849, one of which caused a million dollars in damage; 4 in 1850 with one causing $4 million in damage; and two in 1851, one causing $12 million and another $3 million in damage (http://sfmuseum.org/hist1/fire.html).

[9] All personnel in 1906 resided in San Francisco and were on-call at all hours if needed. Today, many firefighters reside outside the City.

[10] Engine count includes 5 reserve engines, does not include Treasure Island or San Francisco International Airport. Pumping Capacity in 2020 based on 1500 gpm per engine.

2.3.2 1906 earthquake and fire

One of the largest earthquakes to strike North America occurred at 5:12 AM on April 18, 1906. Much has been written about it, and only a brief review is presented here.

Within moments after the earthquake, Chief of Department Dennis T. Sullivan was fatally injured due to a neighboring building collapsing onto the fire station where he was sleeping – he lingered for four days. Ten fire stations sustained major damage (Tobriner, personal communication) although the earthquake did not seriously damage any engines, which all went into service (Reed 1906). Street passage was in general not a problem, and a number of fires were quickly suppressed, although many more could not be responded to. The NBFU (Reed 1906) reported that:

> "…fires in all parts of the city, some caused directly by earthquake, some indirectly, prevented an early mobilization of fire engines and apparatus in the valuable business district, where other original fires had started and were gaining headway".

The numbers of fires and/or explosions after the earthquake have been estimated as between 50 (Reed 1906) and 52 (Scawthorn and O'rourke 1989), Figure 32

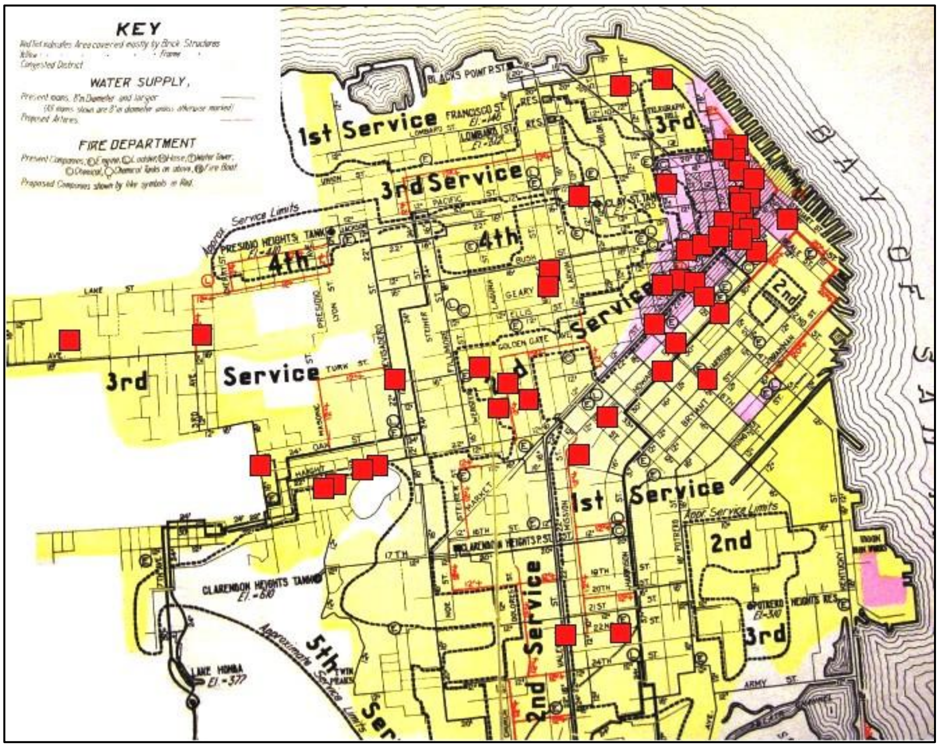


Figure 32 San Francisco in 1906: Black lines are 8 inch and larger water mains (thicker the line, larger the diameter). Yellow area is primarily wood frame construction, while pink is primarily masonry – crosshatched pink area downtown is the 'congested area' – that is, the Central Business District. Ignitions following the 1906 earthquake are shown as red squares. (adapted from NBFU, 1905)

The NBFU concluded that even under normal conditions the multiple simultaneous fires would probably have overwhelmed a much larger department, such as New York's, which had three times the apparatus. Nevertheless, Bowlen (see Scawthorn and O'Rourke, 1989) concluded that by 1 PM (i.e., about 8 hours after the earthquake)

> "the fire department, except that it was without its leader, was in fairly good shape, that is the men and horses were in good trim for firefighting, the apparatus was in shape and could be worked where there was water. There is not one report of an engine or man going out of commission during the early hours of the fire, and the department was hard at work all the time, even though there was little to show for its effort"

The final burnt area is shown in Figure 33.

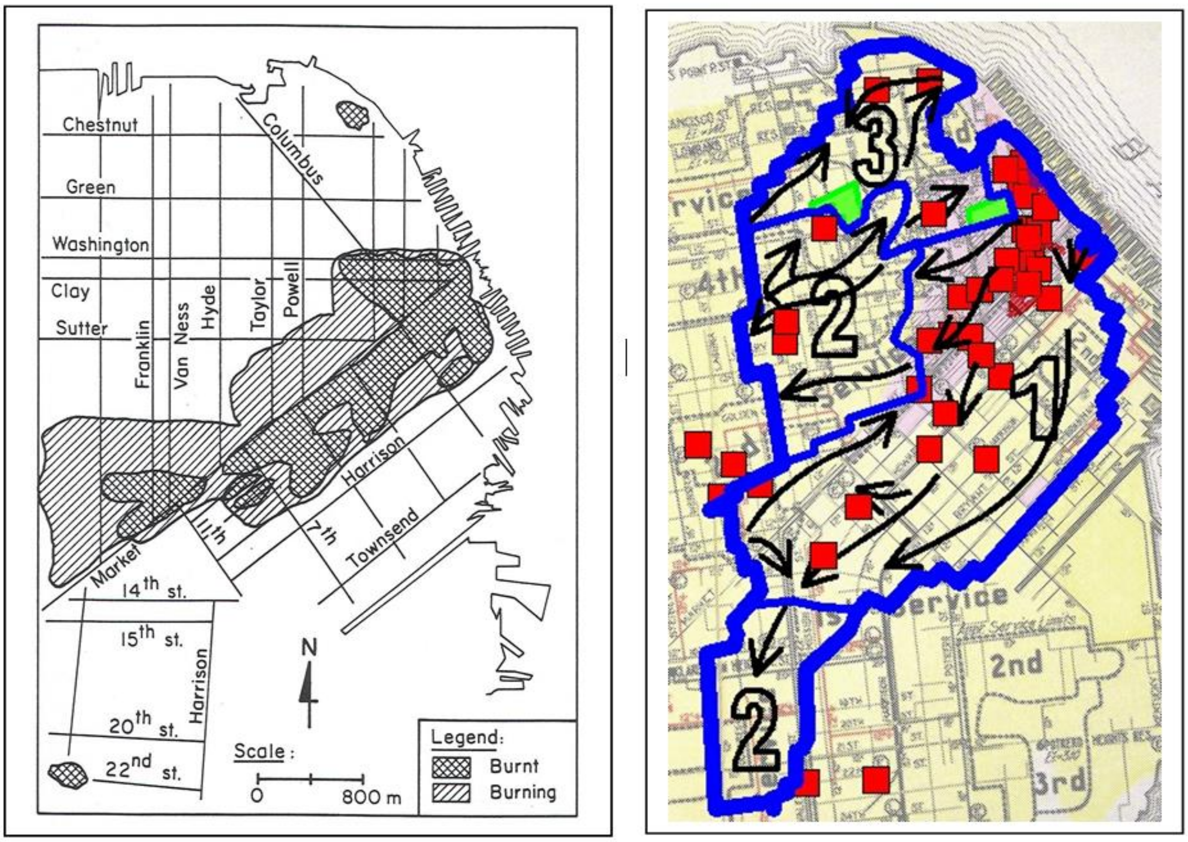


Figure 33 (left) Fires at about midnight April 18 (Source: Scawthorn and O'Rourke, 1989); (right) Final burnt area outlined in heavy line – arrows show fire path of fire spread, with general areas burned in days 1, 2 and 3/4 indicated by numerals and divided by thinner lines. Green areas were not burnt.

2.3.3 1906 earthquake and water supply

The real impairment was not to the fire department but to the water service. At the time of the earthquake, there was a combined volume of 88.7 billion liters in San Francisco's reservoirs on the San Francisco Peninsular. Within the city limits, there were approximately 711 km of distribution piping at the time of the earthquake, of which roughly 18,5 and 66.5 km were wrought and cast iron trunk lines, respectively, mostly constructed during the years of 1870 to 1906. Figure 24 shows the 1906 water supply within the San Francisco City limits, where nine reservoirs and storage tanks provided a total capacity of 354 million liters. All trunk lines, 400 mm or larger in diameter, are also plotted, as well as zones of lateral spread caused by soil liquefaction.

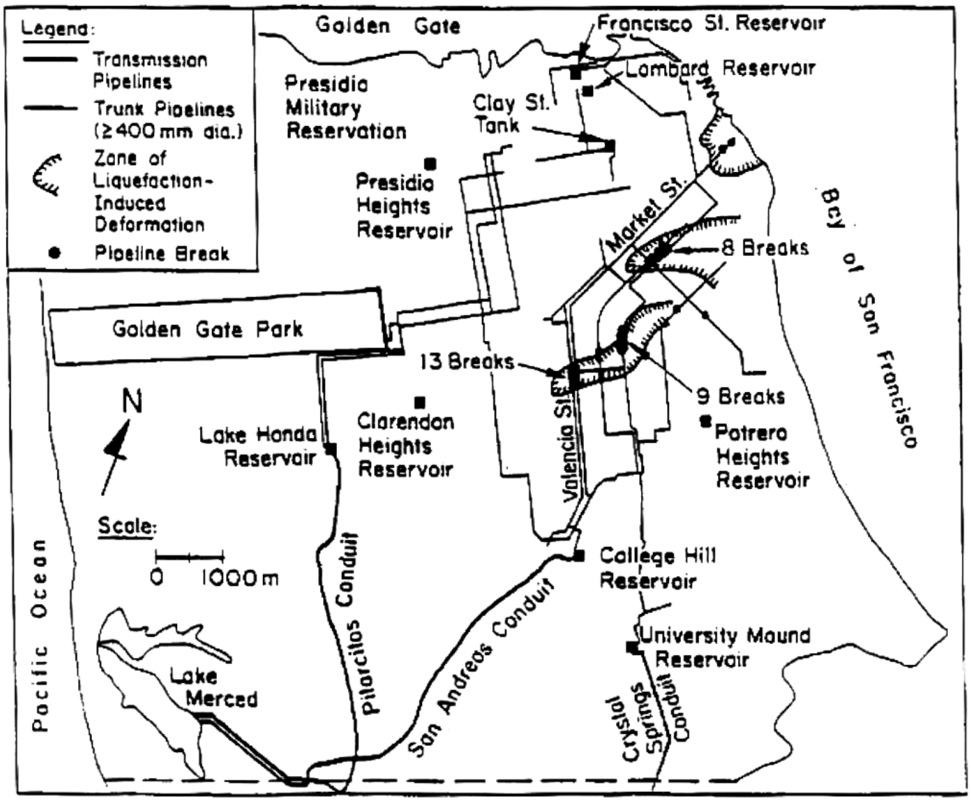


Figure 34 San Francisco Water Supply and effects of permanent ground deformation (Scawthorn and O'rourke 1989)

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. Liquefaction induced lateral spread and settlement ruptured two pipelines, 400 and 500 mm in diameter, across Valencia Street north of the College Hill Reservoir, which emptied the reservoir of 53 million liters, thereby depriving fire fighters of water for the burning Mission District of San Francisco. With the College Hill and University Mound Reservoirs cut off, only the Clay Street Tank and the Lombard and Francisco Street 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 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 spatial relationship between unburnt districts in San Francisco and availability of water implies that pipeline system integrity played a key role in limiting the spread of fire, and that areas suffering from ruptured pipelines fared poorly. This inference must be made with caution, however, since the development of the fire south of Market by mid-afternoon had resulted in a burning perimeter or flame front on the order of 7.5 km. Effective defense along this flame front would require on the order of one to two hundred handheld lines, or virtually the entire steam engine force of the fire department. Even if effective, this ignores branding (i.e., fire spread by burning debris, flying over defense lines and causing fires behind the fire line) and does not consider whether the water supply system, if intact, could have furnished the required water (25,000 to 50,000 gpm). Even if this defense had held, the firefighters, fully occupied south of Market, would have been outflanked by the "Ham and Egg fire "[11], which did indeed sweep down from the west during the second period, outflanking the defending line along Market.

Figure 35 presents a bar graph showing the reservoir storage in San Francisco as a function of time after the earthquake. The amounts of water corresponding to Day 1 represent the quantities available roughly two hours after the earthquake struck. After four days, less than one-tenth of the initial capacity of the College Hill, University Mound, and Lake Honda Reservoirs still was available. Two factors were critically important in preserving flow. Sixteen hours after the earthquake, water was pumped from Lake Merced into the Pilarcitos Conduit to supply Lake Honda. This action provided an additional 25 million liters/day, thereby maintaining capacity in Lake Honda for distribution to the western parts of the city. After repairs of the San Andreas Conduit over three days, approximately 30 million liters/day were conveyed to the College Hill Reservoir for distribution in the South Mission area of the city. By Day 5, approximately 55 million liters of water were flowing into the city, in addition to the 25 million liters still available in the reservoirs.

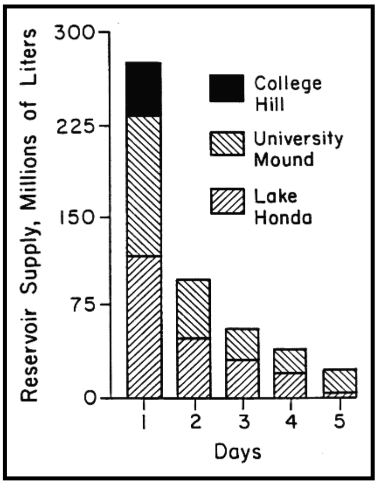


Figure 35 Reservoir Storage in San Francisco as a Function of Time After the Earthquake
Source: (O'Rourke, Beaujon and Scawthorn 1992)

2.3.4 Recent estimates of potential fire following earthquake losses

Since 1906 the insurance industry of course has had a profound interest in San Francisco and its potential for losses due to a future earthquake and fire – the impact on the industry had been huge (Whitney 1906) and interest continues to this day (LMA 2010). Freeman (Freeman 1932) was the first to seriously address estimation of fire following earthquake risk, and discusses San Francisco while not however providing estimates of potential loss. Steinbrugge (Steinbrugge 1968) highlighted the fire following earthquake problem in the San Francisco Bay Area and

[11] Following the earthquake, a person "started a fire in a stove to cook breakfast, about 9 o'clock. The chimney had been rendered defective by the earthquake, and fire broke out. This fire [may] have burned over more territory than any other single fire." (http://www.sfmuseum.org/1906/kennedy.html)

collected data (Steinbrugge et al. 1971) but San Francisco's fire following earthquake was only first quantified in 1987 (Scawthorn 1987).

Most recently, the City's Community Action Plan for Seismic Safety (CAPSS) examined potential losses, with findings as shown in Table 5 and Table 6. As can be seen, the CAPSS study examined four different earthquake scenarios, two of which are comparable to the scenarios examined in this study.

Table 5 Estimated Number of Fires and Size of Burned Area Following Four Scenario Earthquakes Source: (ATC-52-1 2010)

Scenario	Average Number of Fires[a]	Size of Burned Area[b] (Million Square Feet)		
		Good Conditions[c]	Average[d]	Bad Conditions[e]
Hayward Fault, Magnitude 6.9	38	3.6	6.0	11
San Andreas Fault, Magnitude 6.5	57	4.7	7.3	14
San Andreas Fault, Magnitude 7.2	73	7.7	11	19
San Andreas Fault, Magnitude 7.9	95	11	17	28

a. This table shows the average estimated number of fires requiring professional response for the many analyses with varying circumstances. There would be additional small fires extinguished by residents or self-extinguished. Many more or fewer fires could occur.
b. These numbers represent the size of building floor space that is burned. Some of these buildings will also have suffered damage from earthquake shaking.
c. This estimate has a 75 percent chance of being exceeded. Under extremely favorable conditions, the burned area could be smaller.
d. This is the average estimate for the many analyses with varying circumstances.
e. This estimate has a 25 percent chance of being exceeded. Under extremely unfavorable conditions, the burned area could be larger.

Table 6 Average Cost of Damage Caused by Fire Following the Scenario Earthquakes
Source: (ATC-52-1 2010)

Scenario	Shaking Damage ($ Billions)[a]	Average Additional Damage Due to Fire[b] ($ Billions)	Shaking Plus Fire Damage[c] ($ Billions)
Hayward Fault, Magnitude 6.9	$14	$2.7	$17
San Andreas Fault, Magnitude 6.5	$20	$3.0	$23
San Andreas Fault, Magnitude 7.2	$30	$4.3	$34
San Andreas Fault, Magnitude 7.9	$48	$5.8	$54

a. These figures include direct damage to buildings from shaking and ground failure, in 2009 dollars.
b. These figures are averages for the many analyses with varying circumstances and do not double count shaking damage (i.e., burning rubble). Results are in 2009 dollars.
c. In 2009 dollars. Numbers in table have been rounded, which can make totals differ from sum of columns or rows.

2.4 San Francisco's Emergency Firefighting Water System

2.4.1 EFWS high-pressure network

Following the experience in 1906, Marsden Manson (San Francisco City Engineer) in 1908 proposed the high-pressure network that Chief Sullivan had advocated during the prior decade. Its construction was funded with a $5.2 million bond issue and largely completed by 1912, see Figure 36.

This original AWWS is now part of the City's large EFWS (Emergency Firefighting Water System), which is still being expanded.

In summary, the EFWS high-pressure network consists of several major components, see Figure 37.

- Static Supplies: The main source of water under ordinary conditions is a 10-million-gallon (40 million liter) reservoir centrally located on Twin Peaks, the highest point within San Francisco (approximately 227m or 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 (667 l/s) at 300 psi (20.7 bar) capacity. Both pumps were originally steam powered but were converted to diesel power in the 1970's.

- Pipe Network: The EFWS high-pressure network supplies water 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.

Figure 36 Manson map of 1908 showing plan for an auxiliary water system for fire protection (Manson et al. 1908)

- Fireboats: A major deficiency in 1906 was the lack of a Fireboat to be able to pump large volumes from San Francisco Bay. Chief Sullivan in 1905 had proposed that the City purchase a Fireboat, but the request was denied. With the construction of the high-pressure network in 1912, two powerful steam fireboats were provided, each capable of pumping 10,000 gpm (40,000 l/s) into the high-pressure network 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 high-pressure network.

- Cisterns: SFFD in 1906 was finally able to establish a water supply along Van Ness Avenue, a natural east-west fire break as it is 150 feet wide. Water supply was from US Navy ships and tugboats at the foot of Van Ness Ave. The successful experience of cisterns in 1906 led to the construction between 1912-1940 of 128 75,000-gallon capacity cisterns (200,000 liters, about one hour supply for a typical fire department pumper), every three blocks from SF Bay to Market Street and at other locations. Van Ness Ave remains today as the major fire break in the Northeast section of the city. Today, San Francisco has 172 underground cisterns, largely in the northeast quadrant of the city but with newer cisterns in outer residential areas.

The significance of this fire break is important, since the building stock west of Van Ness, to and including Pacific Heights is mainly wood frame, and virtually intact as it was in 1906 – large wood frame buildings of 3 to 4 stories in height, a conflagration hazard. The area east of Van Ness Ave, to Stockton Street, including Telegraph hill was completely burned off in 1906. In the rush to rebuild, it was reconstructed virtually as it was, recreating the conflagration hazard that previously existed. With occasional high winds, narrow streets and densely built wood frame building of 3 to 4 stories in height, this section of San Francisco today is as significant a conflagration hazard as it was in 1906.

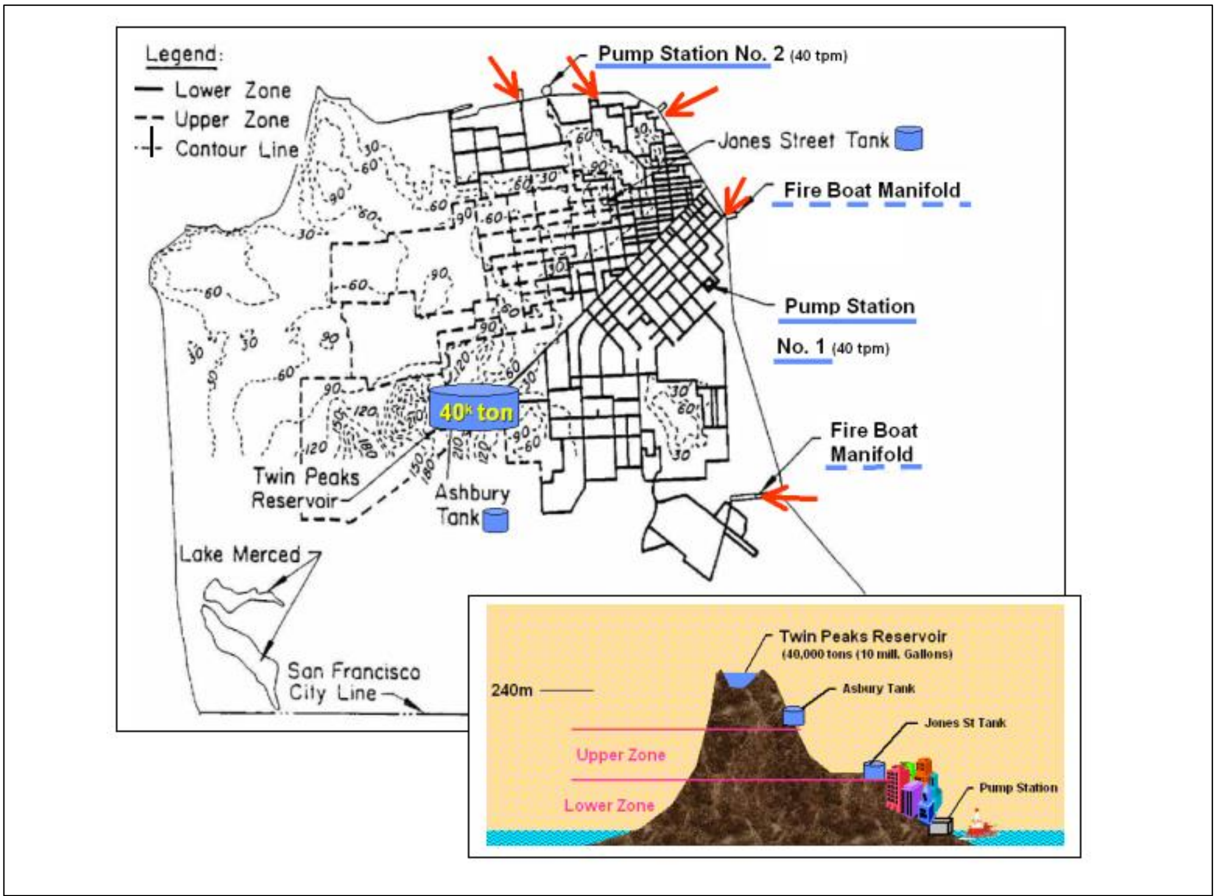


Figure 37 San Francisco EFWS high-pressure network

The EFWS high-pressure network 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 EFWS high-pressure network 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.

While the original portions of the high-pressure network were built during 1908-1912, the City has continued to invest and expand the system, as shown in the following tables and figures.

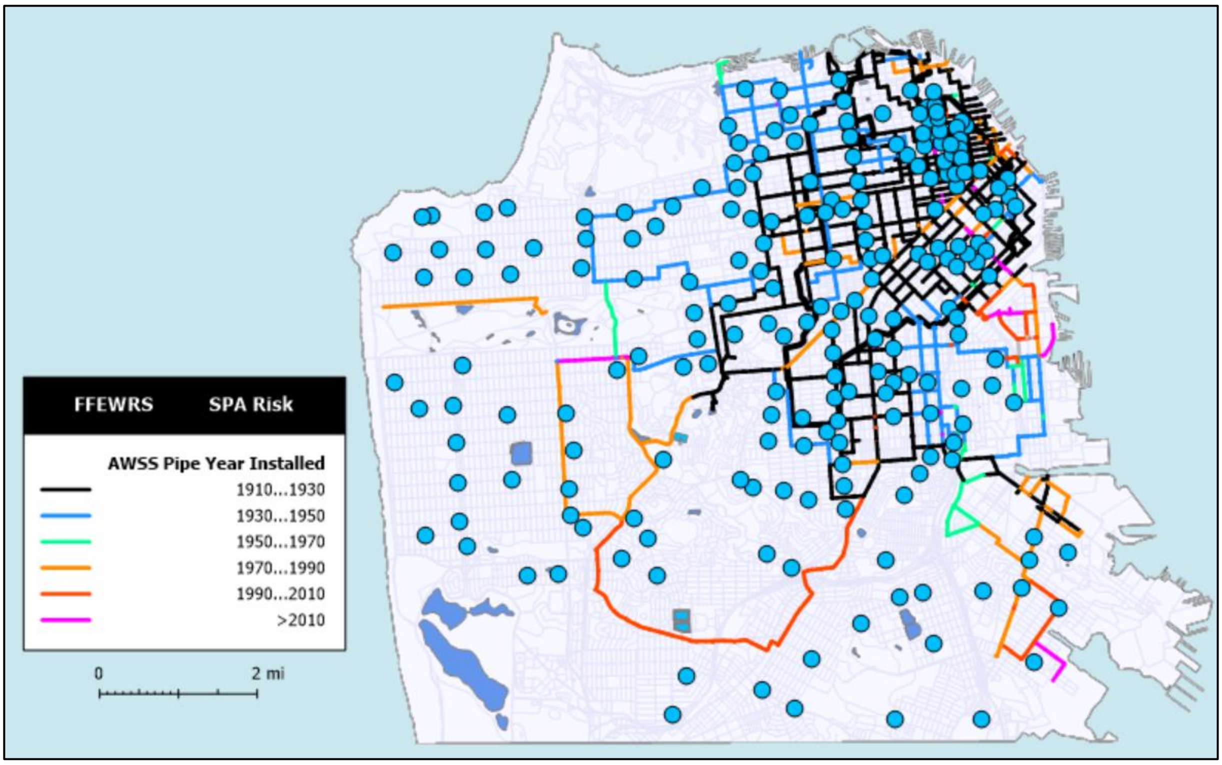


Figure 38 EFWS high-pressure network construction by era, Circles are cisterns.

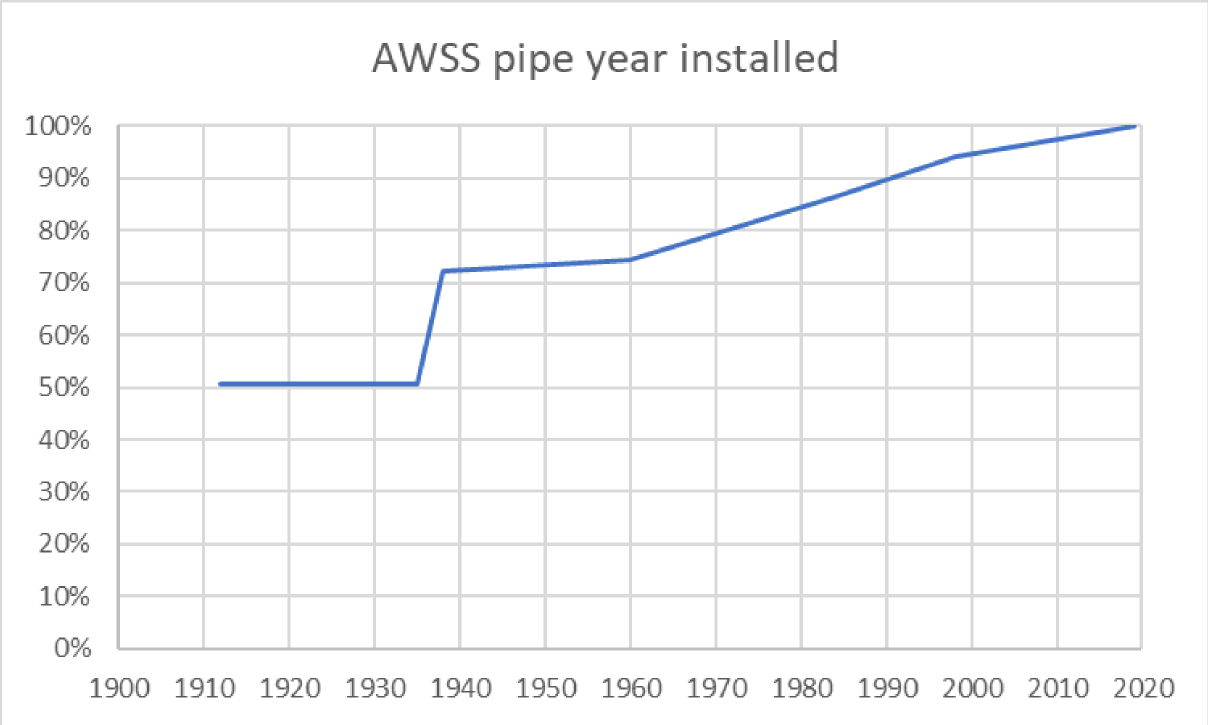


Figure 39 Fraction of EFWS high-pressure network pipe by year of installation

Table 7 San Francisco's capital investments in the EFWS

Yr	**Yr $ mills**	**2020 $ mills**	**Pop. (th)**	**cum 2021 $ / cum(p-yrs)**	**Notes**
1908	$5.2	$156.4	402		original cost
1933	$2.0	$40.4	634	$12.07	+ Marina, W Addition, Mission
1970	$1.0	$6.9	716	$5.68	estimated portion of larger bond issue
1974	$0.2	$1.1	701	$5.60	adds 3rs St. Crossing; est. of larger bond
1977	$1.0	$4.5	690	$5.44	no specifics; est. of larger bond
1986	$46.2	$109.8	706	$4.84	+ cisterns + Ocean Ave ext + MOVs
2010	$102.4	$123.1	805	$5.18	+ cisterns + renovations
2014	$55.0	$61.2	836	$6.74	investments to be determined
2020	$153.5	$155.0	882	$7.00	investments to be determined
2021	$0.0	$0.0	882	$9.08	includes 2020 bond $
No. Yrs.	Tot Yr $	Tot 2020 $			
113	$367	$658			

Note 1: 2021$ are current value of Yr $ ref: https://www.multpl.com/cpi/table/by-year

Note 2: San Francisco population data from https://en.wikipedia.org/wiki/Demographics_of_San_Francisco

Note 3: does not include operating and maintance costs

Note 4: No information could be found re 1960's bond issue, so data and amount are estimated

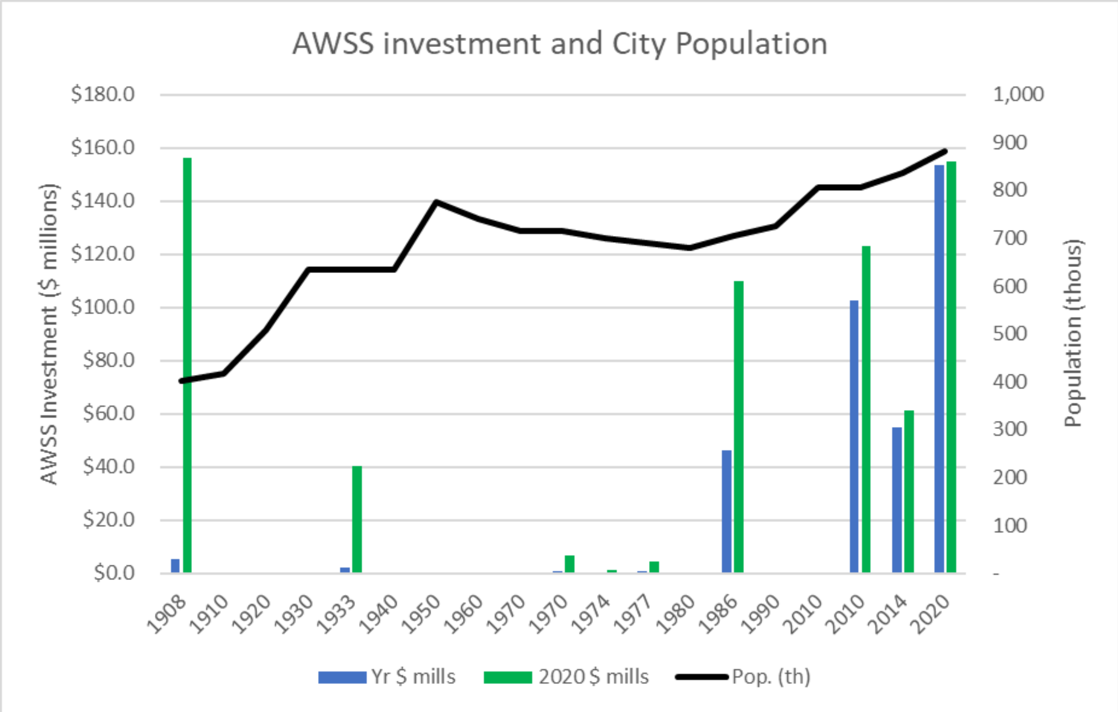


Figure 40 EFWS high-pressure network investment in both $ for that year (blue column) and 2020$ (green column), and City's population (black line)

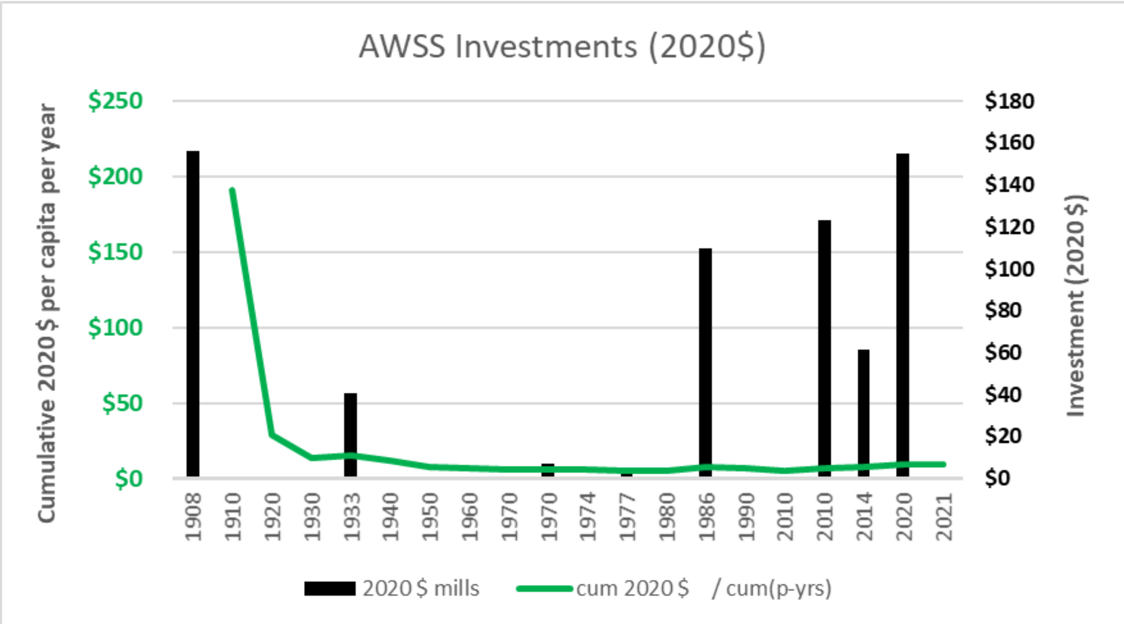


Figure 41 EFWS high-pressure network investment in 2020$ (black column) and cost per capita per year (green line). By 1933 the initial 1908 $5.2 million high-pressure network construction ($156 million in today's dollars) averaged $12 per capita per annum. The trend of averaged succeeding investments declined to less than $6 pc pa, while investments since 2010 have reversed this trend with total investments today averaging about $8 pc pa.

2.4.2 "Infirm Areas"

San Francisco has areas of highly liquefiable soils – these were observed to fail in 1906 and to correlate with damage to underground piping. These locations were mapped with other areas of concentrated damage as 'infirm zones', Figure 43, and the system designed so that, while EFWS high-pressure network pipe passes through these zones, Figure 42, 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 EFWS high-pressure network. 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 1 high-pressure network hydrant, and apply fire streams as if from a fire engine. Thus, the EFWS high-pressure network 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 EFWS high-pressure network was intended to be a seismically reliable water supply system for fire protection. Most of the original pipeline was extra heavy cast iron pipe with more recent installations using thick-walled ductile iron pipe with restrained joints at high thrust locations. It has been maintained for almost a century and embodies the key attributes of redundancy in supply and layout, reliability via layout and seismic design of components, flexibility in application, economy via reducing the need for fire engines and apparatus, and integration in the fire department's day-to-day operations. Even so, the 1989 Loma Prieta earthquake damaged a few components of the EFWS high-pressure network, which, coupled with human inaction, drained the Lower Zone (Scawthorn 1990a)and prevented the system from supplying water to the Marina fires; thus, demonstrating that there is room for improvement.

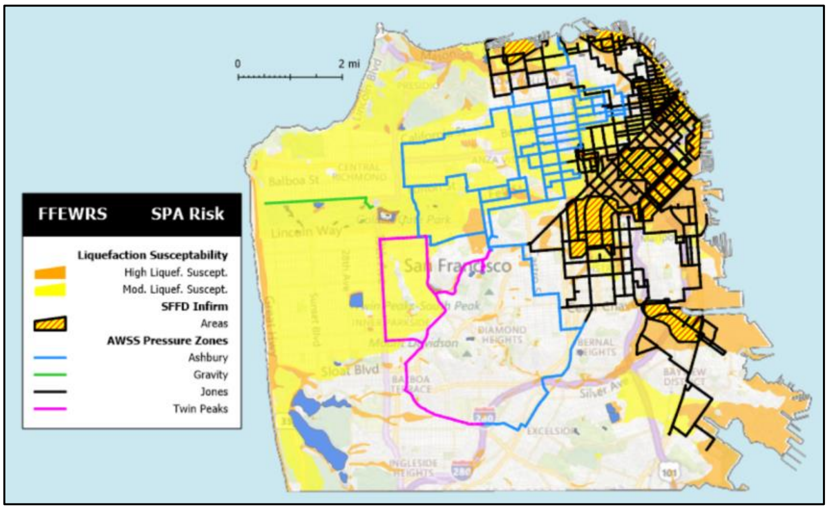


Figure 42 Current EFWS high-pressure network showing pressure zones overlaid on liquefaction susceptibility and SFFD Infirm Areas (red and yellow hatched areas). Twin Peaks Zone (magenta) is primarily to west of Twin Peaks; Ashbury or Upper Zone (blue) is intermediate between Twin Peaks and Jones or Lower Zones (black). A Gravity system (green) is an independent pipeline fed from Stowe Lake and runs west along Fulton St.

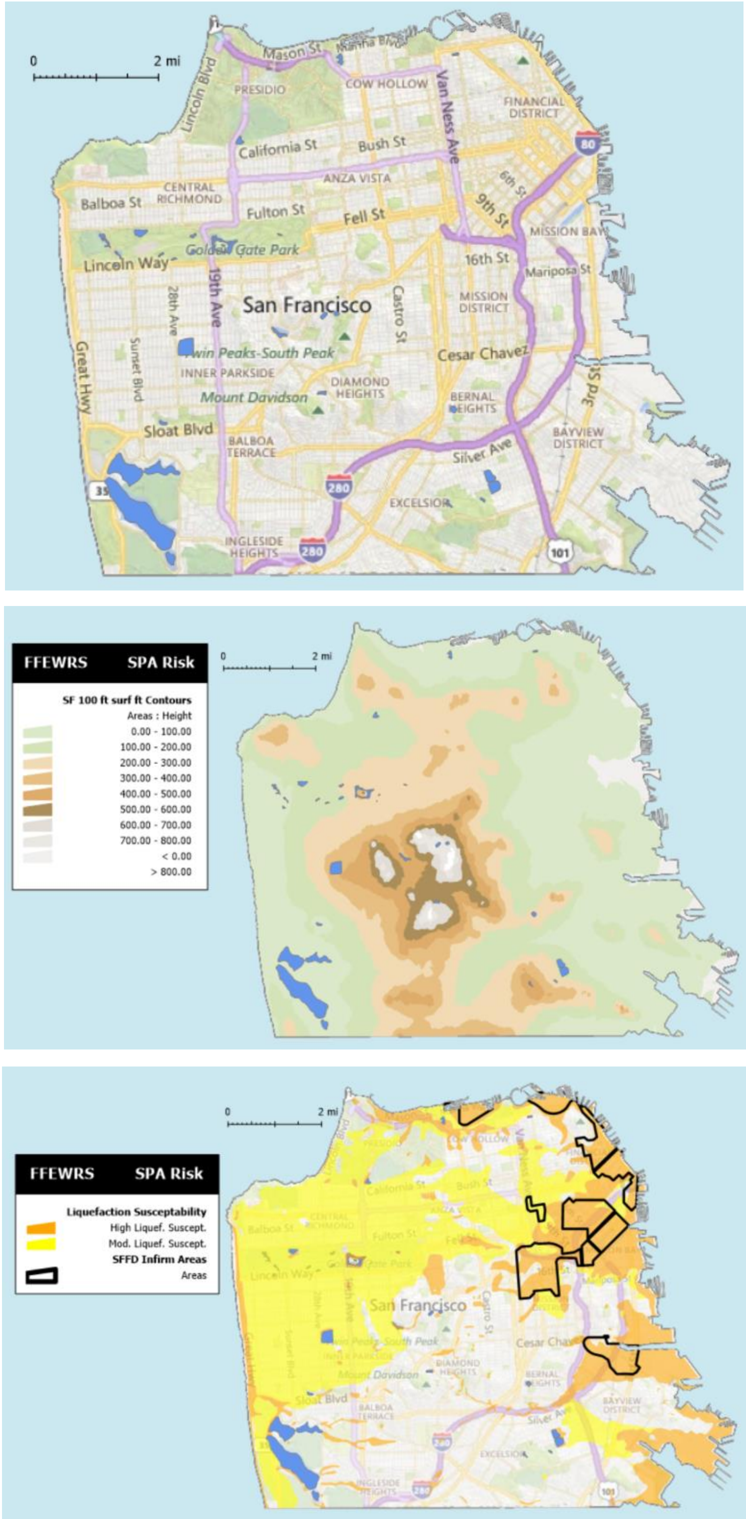


Figure 43 (top) City; (mid) Elevations; (bott) Liquefaction susceptibility and SFFD Infirm Areas

3 DATA

A large amount of data was collected and employed in this project. Data included exposure including detailed information on buildings and tree canopy, data on earthquake ground motions and permanent ground displacement, fire resources, water supply, streets and access, and weather.

3.1 INTRODUCTION

This section discusses the data used for analysis.

3.2 Exposure

3.2.1 Current buildings at risk

Data on San Francisco's buildings, both present and projected in the future, was collected from a number of sources, primarily the Planning Department and its GIS portal. Commensurate with current population, the current total floor area of all high-rise buildings in the City is estimated to be approximately 215 million square feet, and all low- and medium-rise buildings 670 million square feet, with an aggregate structure and contents replacement value of about $530 billion (2020 $)[12]. Figures below show selected data on land use, gross square footage and building height, building footprints and materials of construction.

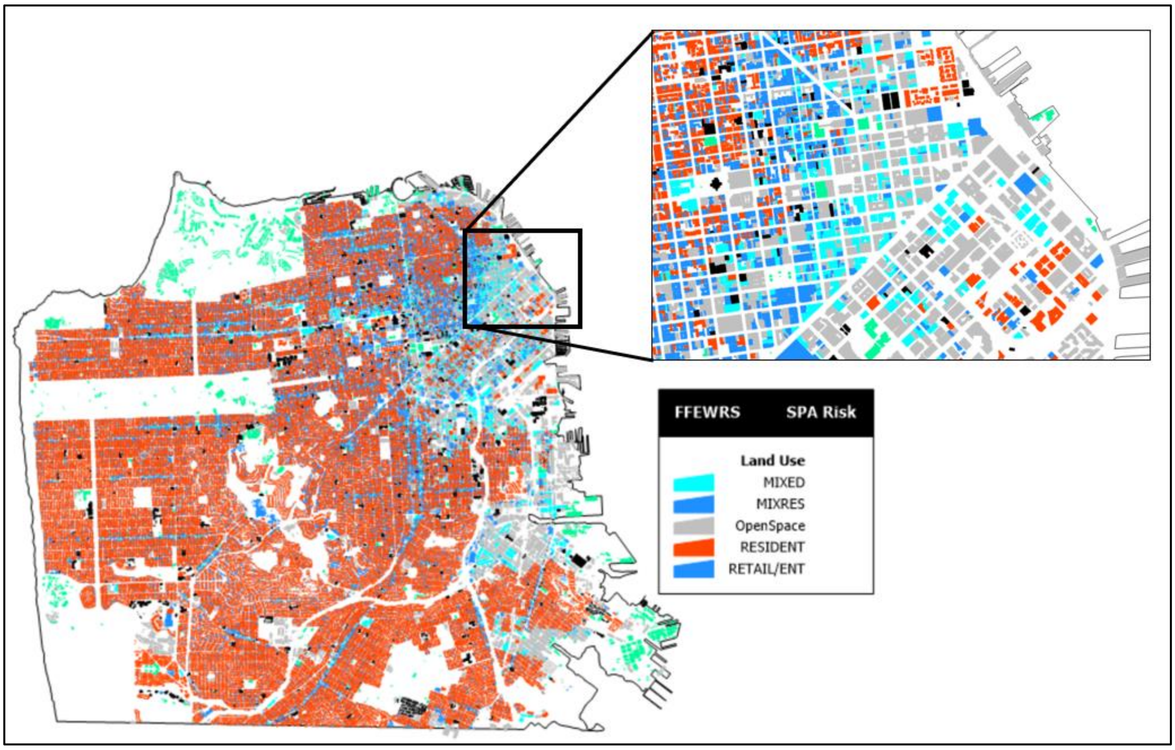


Figure 44 Land Use

[12] $600 per square foot, in 2021$, is used as average replacement value for buildings and their contents.

Figure 45 (left) Total Floor Area (TFA, sq. ft.) per block, for Low and Medium Rise buildings; (right) TFA per block for High Rise buildings.

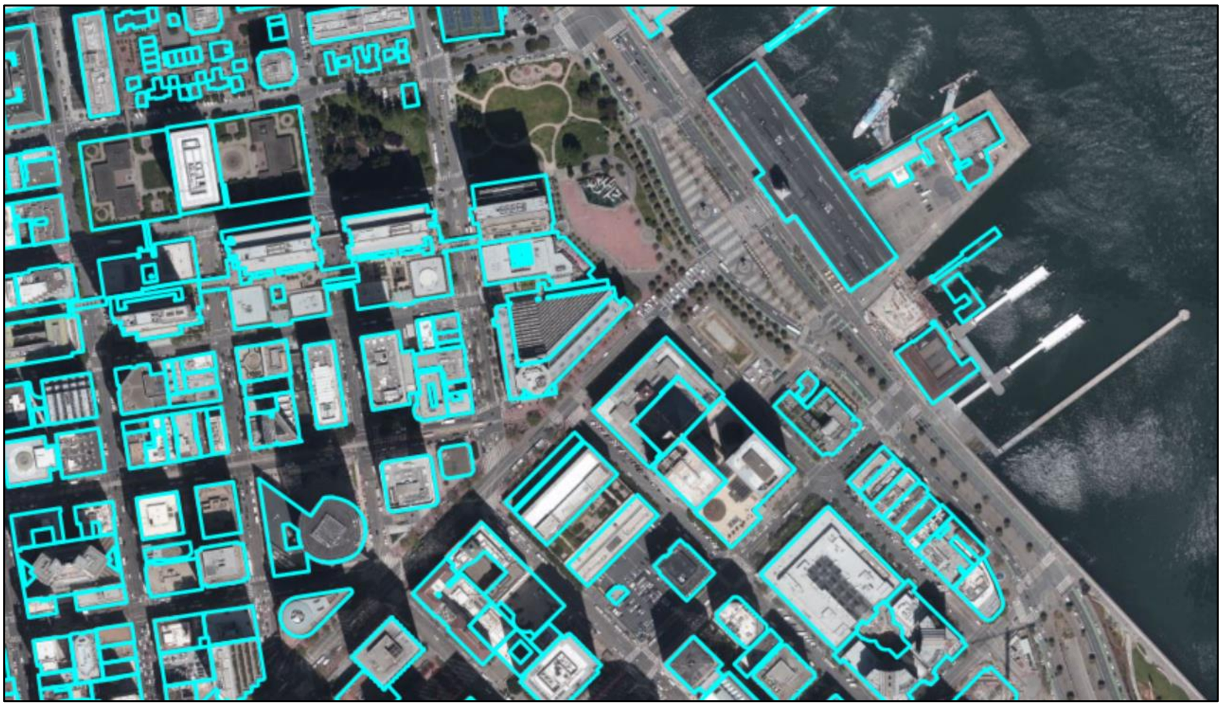


Figure 46 Building footprints

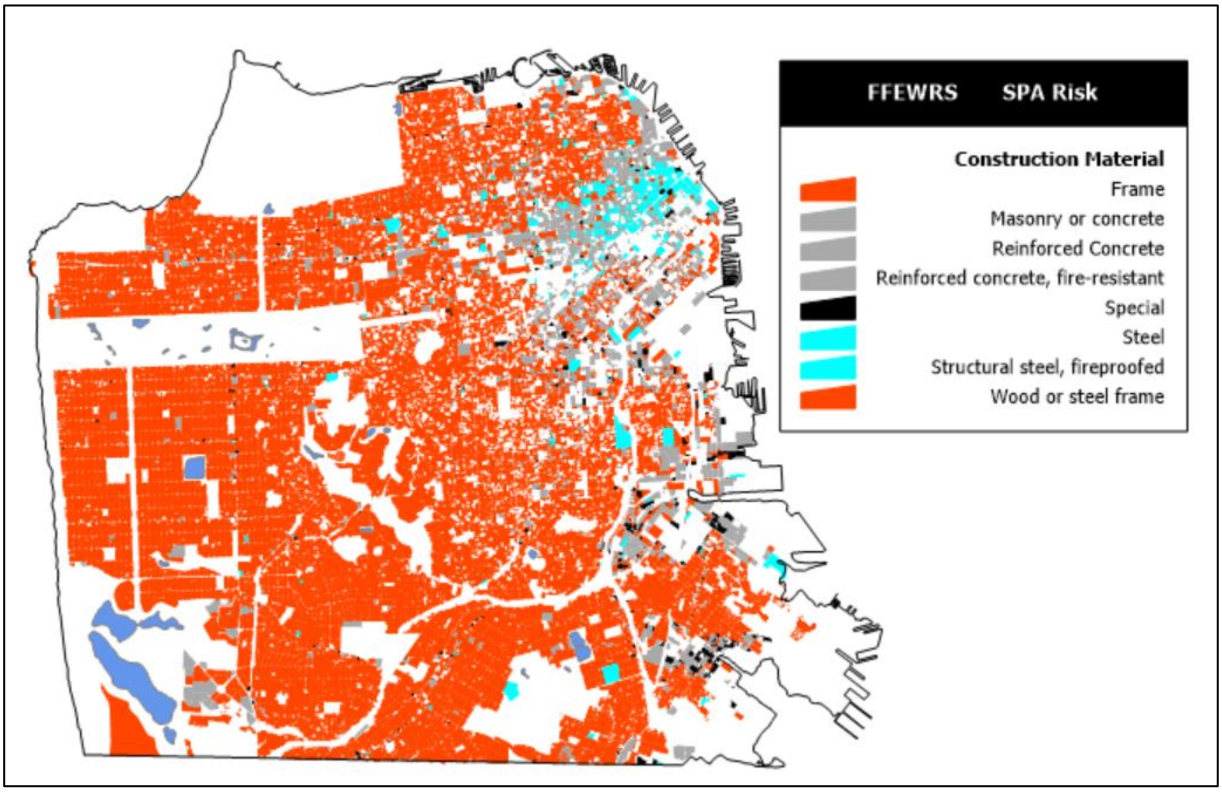


Figure 47 Materials of construction

Exposure data was also obtained for the Presidio, with processing of this and data for other large non-homogeneous occupied tracts of land currently listed as one "city block" in the City's databases. These large tracts of land are highlighted in red in Figure 55, which shows all city blocks (outlined in gray) and every building in the City (outlined in blue), with a detail for the Presidio.

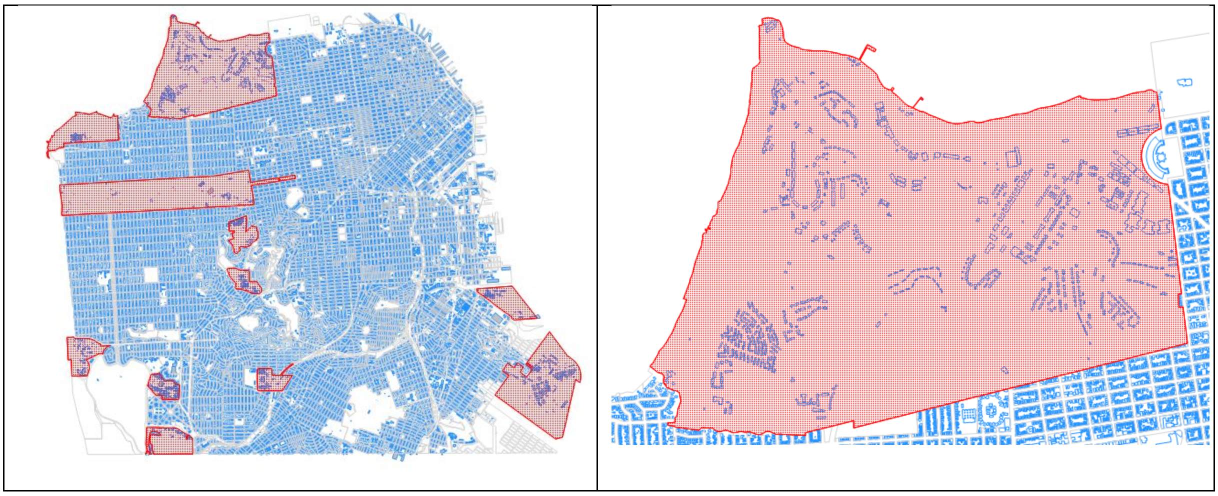


Figure 48 (left) large tracts of land highlighted in red with all city blocks outlined in gray and every building in the City outlined in blue; (right) detail for the Presidio.

Fire following earthquake analysis analyzes fire spread in several stages – within a building, within a city block, and then at firebreaks (e.g., city streets). City blocks are typically densely and homogeneously occupied by buildings of a similar nature, which however is not the case in the Presidio or these other large tracts.

To account for this, the current Presidio and other large tracts have been divided into "new blocks", each of a similar nature, as shown in Figure 49 for the Presidio. In summary, the one Presidio "block" has been subdivided into 47 "new blocks", and a total of 79 "new blocks" were created from the large tracts shown in Figure 48.

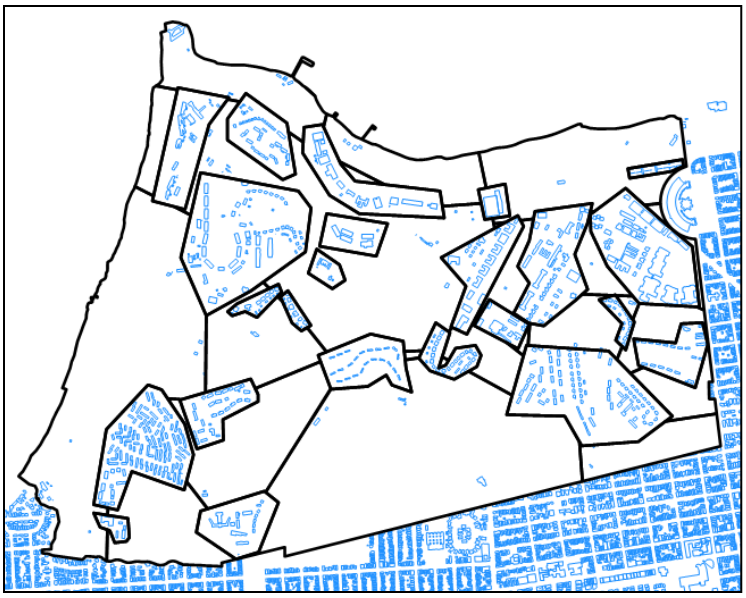


Figure 49 "new blocks" created in Presidio

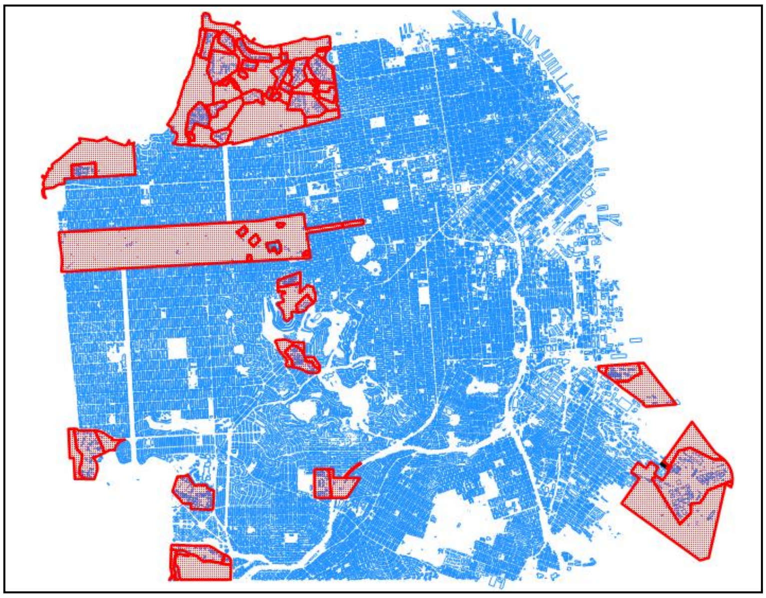


Figure 50 "new blocks" created from large tracts

3.2.2 Future building exposure

As discussed in section 2.1, San Francisco is expected to continue to grow, with today's population of 880,000 growing by 2040 to 1.1 million. Based on population and traffic projections, the total floor area of all buildings in the City is estimated to grow to 1.1 billion sq. ft. by 2040 and 1.25 billion sq. ft. by 2050, with an aggregate structure and contents replacement value of $665 billion in 2040, in 2021 dollars. Much of this growth will occur in eastern portions of the City, as shown in Figure 51 to Figure 53.

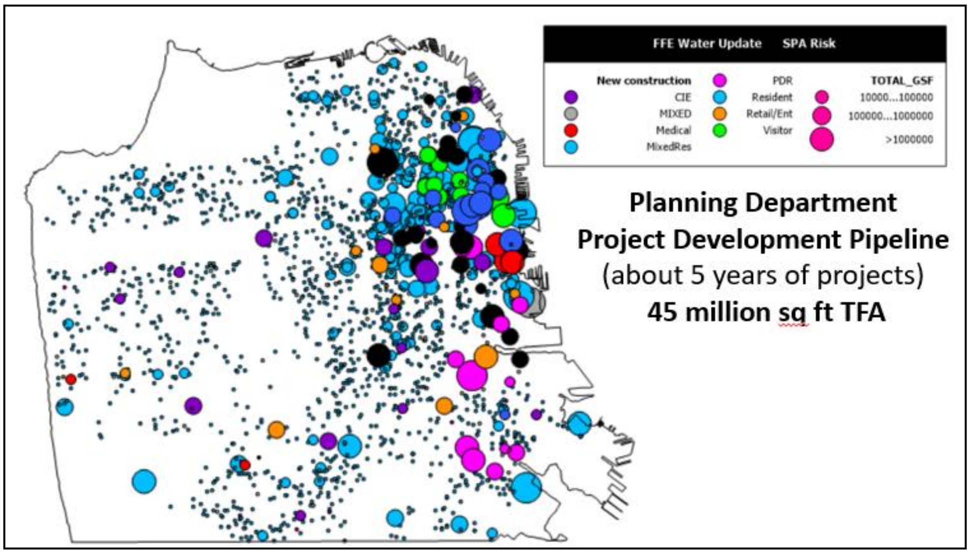


Figure 51 San Francisco "in pipeline" building projects, totaling about 45 million sq ft. of new construction. (Source: San Francisco Planning Department)

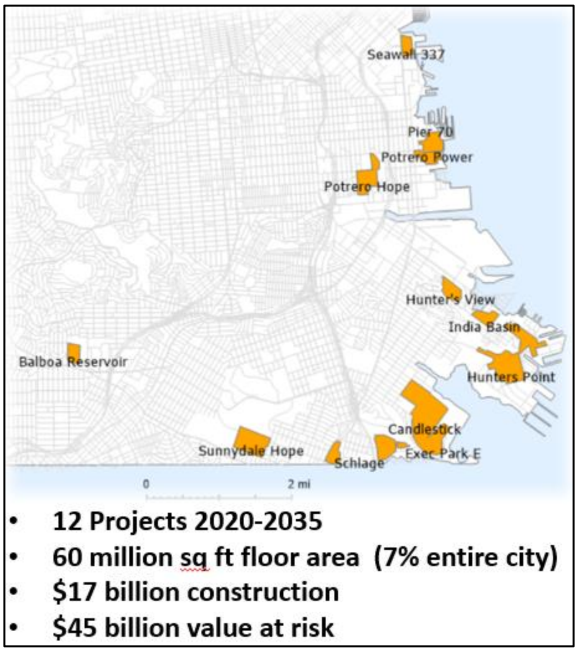


Figure 52 Known specific larger developments in various stages of planning or construction, totaling about 60 million sq. ft. of new construction. (Source: AECOM)

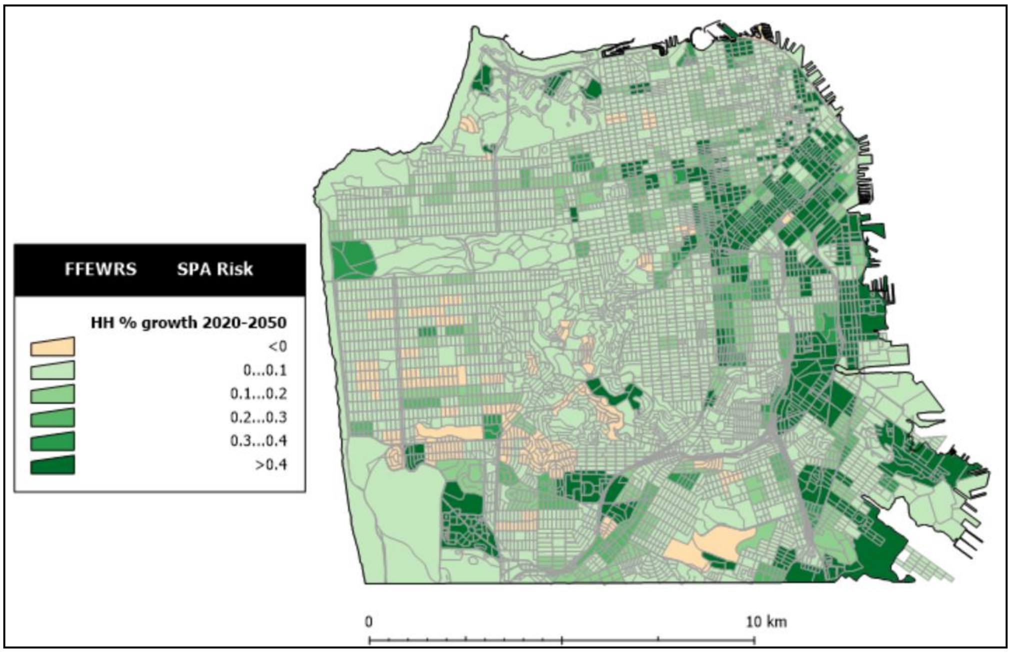


Figure 53 Percentage growth in Households (HHs) 2020-2050

3.2.3 Tree canopy

Vegetation, particularly larger trees, can play a significant role in firespread, especially in hot dry weather conditions. Two databases for trees exist for San Francisco – those are trees in public lands (including those lining streets), and those in private lands (e.g., backyards). These were merged into a single database of 290,000 records, and a detail of that database is shown in Figure 54. Inclusion of the tree canopy in the overall analysis is important in order to account for San Francisco's large green spaces, such as the Presidio, Golden Gate, McLaren, Lincoln, Sigmund Stern Grove and Glen Canyon parks and Mt. Davidson.

Figure 54 Detail of tree canopy data employed for this study.

3.3 SCENARIO EARTHQUAKES AND GROUND MOTIONS

3.3.1 Scenario events

This study has assessed two scenario earthquakes: (1) a Mw 7.9 event on the San Andreas fault like the 1906 event, and (2) a Mw 7.05[13] event on the Hayward fault in the East Bay. Comparable events were among those also examined in the CAPSS study (ATC-52-1 2010). Ground motions from either of these events will be very strong in San Francisco, with the Mw 7.9 San Andreas event being generally stronger, especially in the western portions of the City, which are only a few miles from that fault. The Hayward event, while generally having similar or smaller ground motions than the San Andreas event, is considered more likely to occur in the near future (Detweiler and Wein 2017).

3.3.2 Ground motions

Estimates of ground motion are needed as an input for the estimation of post-earthquake ignitions (Lee et al. 2008; Scawthorn 2018b; TCLEE 2005). This study applies four of the NGA-West2 ground motion prediction equations (GMPEs) to predict ground motion in the shallow crustal earthquake scenarios (EQ3 and EQ4), the specific GMPEs being (Abrahamson, Silva and Kamai 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Youngs 2014). Each of the GMPEs is assigned equal weight for predicting both the peak ground acceleration (PGA) and peak ground velocity (PGV).

Soil stiffness is an important influence on the intensity of ground motions, and a common measure is the shear wave velocity of the upper 30 meters of the soil column, denoted Vs30. Vs30 data for San Francisco was acquired from (Wills et al. 2015) and is shown in Figure 55. This data was georeferenced to each city block, as shown in the same figure.

For both scenarios, the Jayaram and Baker (Jayaram and Baker 2009) model for spatial correlation of ground motion was applied. This model gives the correlation coefficient (ρ) for the within-event residuals of ground motion at two locations as a function of their separation distance. Jayaram and Baker (2009) did not study PGV directly. However, it is generally accepted that the spatial correlation of PGV is similar to that of spectral acceleration at a period of 1 second, and we apply this rule of thumb to obtain correlation coefficients for PGV. This use of spatially correlated ground motions for infrastructure performance and loss estimation is still rather innovative, and a novel contribution of this study.

To generate a spatially correlated field of ground motion for a given scenario, we took the sum of (i) the logarithmic median predicted by the GMPE(s) on a per-location, per-realization basis, (ii) a random sample of the between event residual, which is normally distributed with zero mean and variance τ^2 given by the GMPE(s), on a per-realization basis, and (iii) spatially correlated samples of the within event residual, which is normally distributed with zero mean and variance φ^2 given by the GMPE(s), on a per-location, per-realization basis. We generate 100 realizations of each scenario for both PGA and PGV.

[13] The two digit precision for the Hayward event is due to the USGS Haywired project (Detweiler, S.T., and A.M. Wein (Eds.). 2017. *The HayWired earthquake scenario—Earthquake hazards (ver. 1.1, March 2018):*. Washington: U.S. Geological Survey Scientific Investigations Report 2017–5013–A–H, available at https://pubs.er.usgs.gov/publication/sir20175013v1.. Such precision for earthquake magnitude is somewhat illusory, and hereafter the Hayward event magnitude will be denoted at Mw 7.

The Jayaram and Baker (2009) model for the spatial correlation of ground motion depends on whether site conditions in the region of interest are clustered or not. We assume that the site conditions in San Francisco are clustered based on Figure 56, which shows a semivariogram of the $V_{S,30}$ data used in this study, which shows a clear relationship. See Jayaram and Baker (2009) for examples of the clustered and unclustered cases.

Median PGA for the two scenarios are shown in Figure 57 to Figure 58. As discussed above, there is considerable variation in actual ground motion – for example Figure 59 shows three of the one hundred realizations of spatially correlated ground motion, for the two scenarios. It can be seen from these figures that the Mw 7.9 San Andreas scenario is by far the more severe event, and that only in the eastern-most portion of the City are the two events comparable.

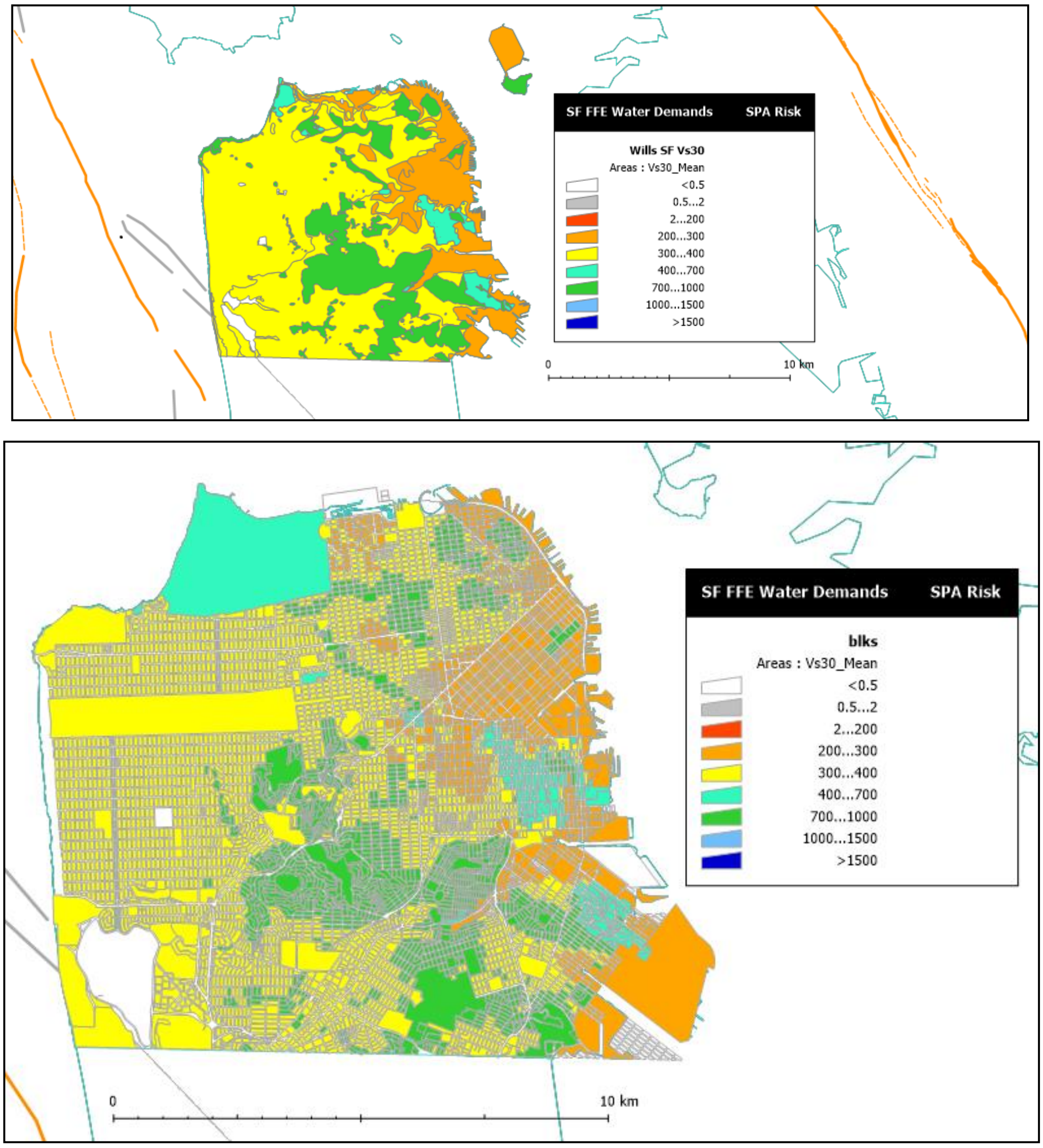


Figure 55 Wills Vs30 data

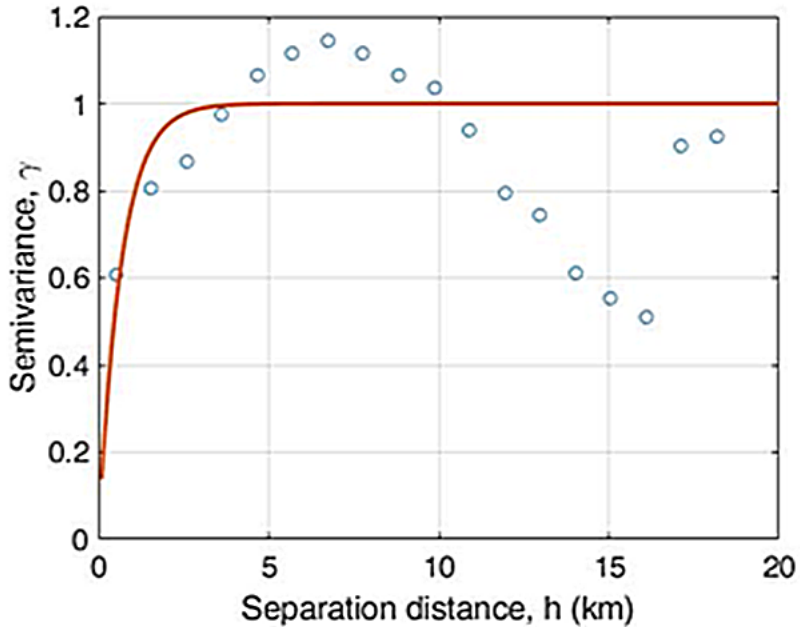


Figure 56 Empirical semivariogram of the site conditions (Vs30) in San Francisco .

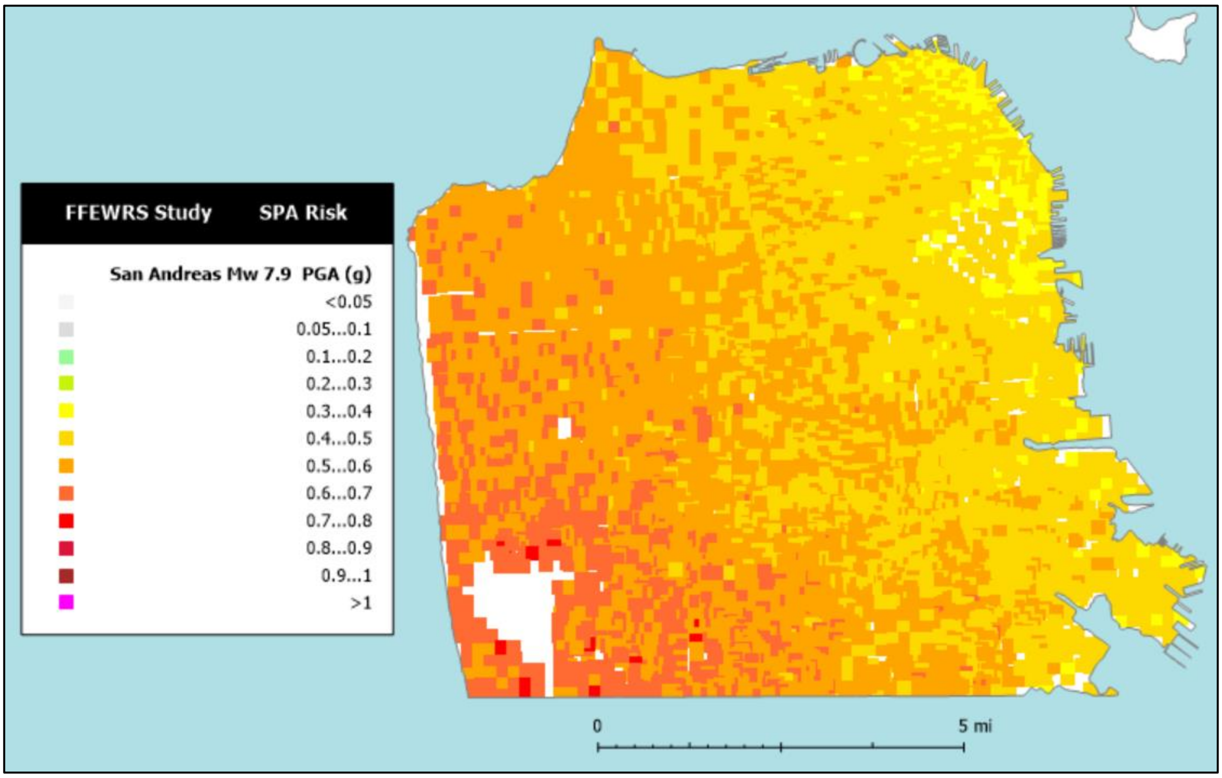


Figure 57 Median Peak Ground Acceleration (g), Mw 7.9 San Andreas event

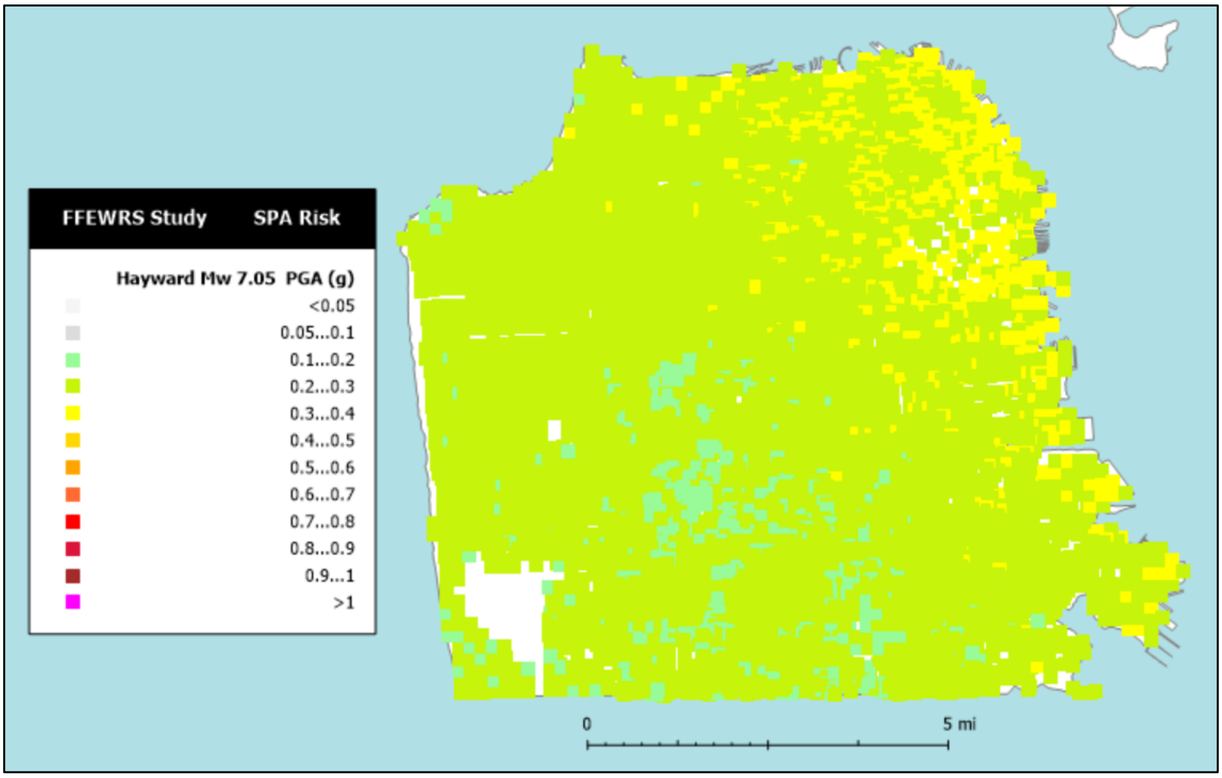
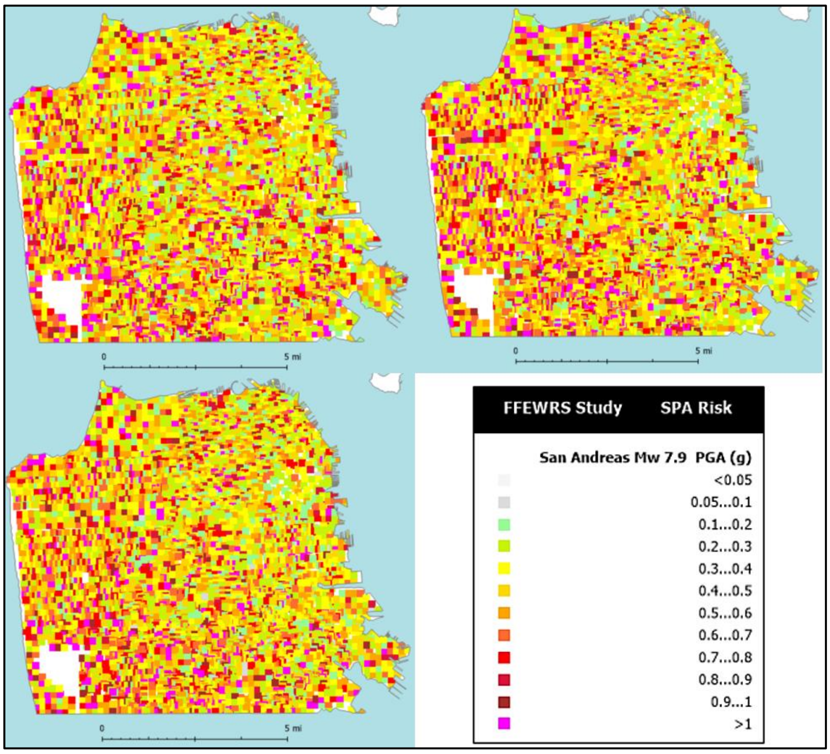


Figure 58 Median Peak Ground Acceleration (g), Mw 7 Hayward event



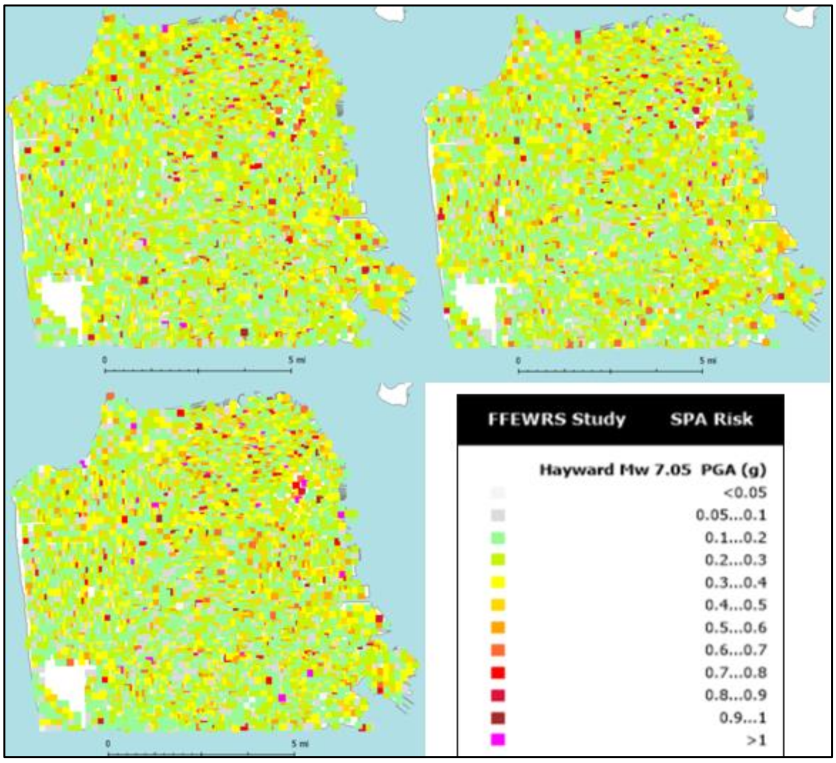


Figure 59 Three of one hundred realizations considering spatial correlation for mean Peak Ground Acceleration (g): (top) Mw 7.9 San Andreas; (bott) Mw 7 Hayward events

3.3.3 Permanent Ground Displacement

Permanent ground displacement (PGD) is relevant to fire following earthquake due to the damage and loss of service it will cause to buried water and gas pipelines, thus reducing availability of firefighting water while simultaneously increasing the presence of flammable gas and potential for fire and explosion. Permanent ground displacements can occur due to a number of mechanisms: abrupt relative displacement such as at the surface expression of a fault or at the margins of a landslide, or in spatially distributed PGD which can result for example from liquefaction-induced lateral spreads or ground settlement due to soil consolidation. In this study, we consider soil liquefaction and landslide due to earthquake, as they are anticipated to be a major influence on buried water, particularly South of Market.

Liquefaction is generally associated with saturated cohesionless uniformly graded soils that contain few fines, and results from seismic shaking that is of a sufficient intensity and duration to cause soils to undergo volume reduction upon shaking. Under these conditions, cohesionless soils will tend to densify when subjected to cyclic shear stresses from ground vibrations but will be temporarily prevented from doing so at depth due to restricted drainage. As a result, excess pore pressures accumulate, effective stresses decrease, and soils lose strength and may become liquefied (Seed and Idriss 1982). Because the capacity of soils to withstand loads (including their own self-weight) is directly related to their strength, liquefied soils may undergo permanent displacements both vertically and horizontally, so that liquefaction poses a serious hazard to constructed structures whether above ground or buried. The first step in quantifying the potential for liquefaction and PGD is mapping surficial soils and their relative vulnerability.

Estimation of the probability of liquefaction follows established procedures (DHS 2003) and is based on published mapping of liquefaction susceptibility data, Figure 60 (Knudsen et al. 2000).

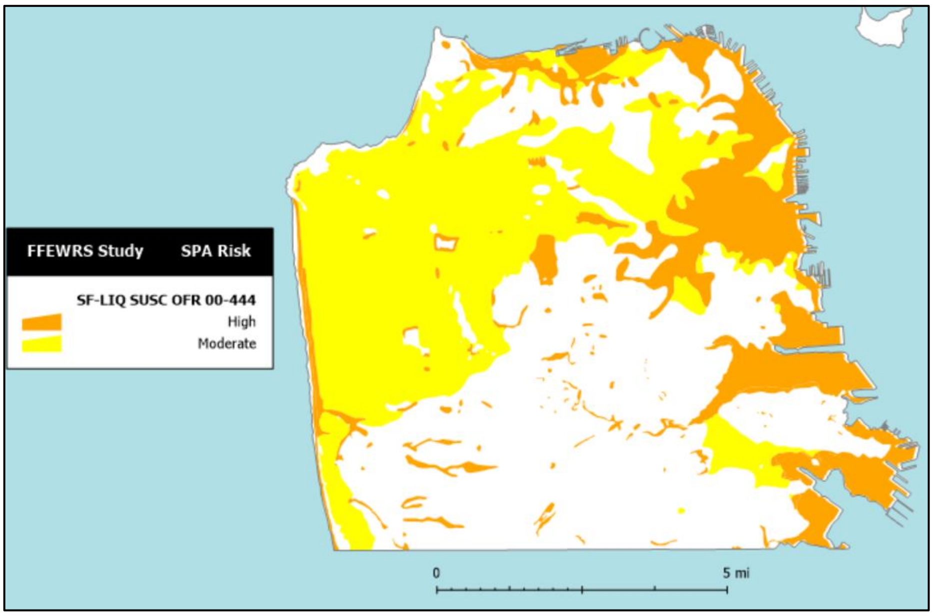


Figure 60 liquefaction susceptibility
Source: (Knudsen et al. 2000)

3.4 Fire resources – SFFD and mutual aid

3.4.1 SFFD resources

The San Francisco Fire Department provides primary fire protection for the City and is considered as the first and only responder for the initial fires following the scenario events. SFFD also provides protection to the Presidio, Treasure Island (both within CCSF) and San Francisco International Airport, where it maintains three stations. Data was collected on SFFD's resources

Figure 61 and Table 8 show locations of SFFD's 44 fire stations within the City, and associated fire engines[14]. 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 great majority of stations may be considered as seismically reliable in the four scenario events considered here.

[14] Stations also house other apparatus, such as ladder trucks, but fire engines apply the water and are the critical apparatus for this analysis. A complete inventory of SFFD apparatus is available at www.ufsws.org .

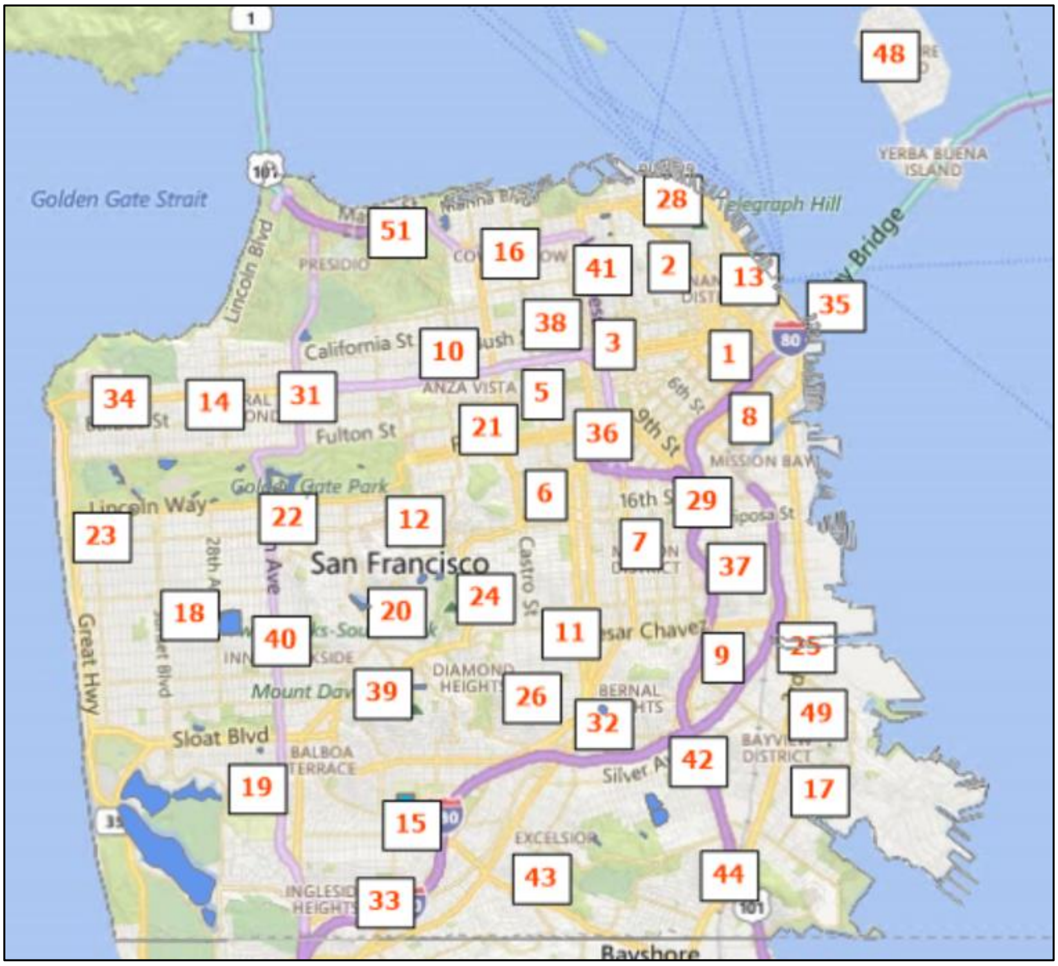


Figure 61 SFFD fire station numbers and locations

Under normal operations, SFFD operates one engine from each station, as well as one truck and/or other apparatus and equipment from selected stations[15], for a total of 44 engines and 20 ladder trucks. SFFD also has on average five ready reserve engines that would be put in service in an earthquake emergency[16], and typically five other spare engines that would be put in service with some delay since they are not normally stocked with hose and equipment. SFFD also operates two dedicated fireboats, which are discussed further below.

[15] 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.

[16] 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.

Table 8 SFFD Fire stations and apparatus

Fire Station No. and address	Year station built / re-built	Engine No. and apparatus
	1st Battalion	
FS 2 - 1340 Powell Street (Chinatown)	1916 / Re-built 1955	Engine 2 - 2019 Ferrara Igniter (1500/500)
FS 13 - 530 Sansome Street (Financial District)	1975 / Remodeled 2002	Engine 13 - 2017 Ferrara Igniter (1500/500) (SN#H-6112)
FS 28 - 1814 Stockton Street (North Beach)	1913 / Remodeled 1999	Engine 28 - 2002 HME / Ferrara (1500/500/50F) (SN#540)
FS 41 - 1325 Leavenworth Street (Nob Hill)	1910 / Remodeled 1957	Engine 41 - 2017 Ferrara Igniter (1500/500) (SN#H-6113)
	2nd Battalion	
FS 1 - 935 Folsom Street (SOMA)	2013	Engine 1 - 2017 Ferrara Igniter (1500/500) (SN#H-6116)
FS 6 - 135 Sanchez Street (The Castro)	1967	Engine 6 - 2014 Spartan ERV Metro Star (1500/500)
FS 29 - 299 Vermont Street (Potrero Hill)	1955	Engine 29 - 2017 Ferrara Igniter (1500/500) (SN#H-6115)
FS 36 - 109 Oak Street (Hayes Valley)	1961	Engine 36 - 2017 Ferrara Igniter (1500/500) (SN#H-6119)
	3rd Battalion	
FS 4 - 449 Mission Rock Street (Mission Bay)	2015	Engine 4 - 2014 Spartan ERV Metro Star (1500/500)
FS 8 - 36 Bluxome Street (South Beach)	1939	Engine 8 - 2014 Spartan ERV Metro Star (1500/500)
FS 35 - Pier 22½, 380 The Embarcadero (Embarcadero)	1915	Engine 35 - 2002 HME / Ferrara (1500/500)
FS 48 - 800 Avenue I, Treasure Island (Treasure Island)	2015	Engine 48 - 2006 American LaFrance Eagle (1500/500/20A/20B)
	4th Battalion	
FS 3 - 1067 Post Street (Tenderloin)	1916 / Re-built 1974	Engine 3 - 2017 Ferrara Igniter (1500/500) (SN#H-6117)
FS 16 - 2251 Greenwich Street (Marina District)	1956 / Re-built 2018	Engine 16 - 2017 Ferrara Igniter (1500/500) (SN#H-6118)
FS 38 - 2150 California Street (Pacific Heights)	1960	Engine 38 - 2017 Ferrara Igniter (1500/500)
FS 51 - 218 Lincoln Boulevard (Presidio)	1917 / Re-built 2015	Engine 51 - 2005 Pierce Dash (1500/1000)
	5th Battalion	
FS 5 - 1301 Turk Street (Fillmore District)	1956 / Re-built 2018	Engine 5 - 2013 Spartan ERV Metro Star (1500/500)
FS 10 - 655 Presidio Avenue (Presidio Heights)	1956	Engine 10 - Spartan Gladiator / Crimson (1500/500)
FS 12 - 1145 Stanyan Street (Haight-Ashbury)	1956	Engine 12 - 2006 American LaFrance Eagle (1500/500/20A/20B)
FS 21 - 1443 Grove Street (Panhandle)	1958	Engine 21 - 2014 Spartan ERV Metro Star (1500/500)
	6th Battalion	

Fire Station No. and address	Year station built / re-built	Engine No. and apparatus
FS 7 - 2300 Folsom Street (Mission District)	1954	Engine 7 – 2014 Spartan ERV Metro Star (1500/500)
FS 11 - 3880 26th Street (Noe Valley)	1958	Engine 11 - 2013 Spartan ERV Metro Star (1500/500)
FS 24 - 100 Hoffman Avenue (Dolores Heights)	1914	Engine 24 - 2006 American LaFrance Eagle (1500/500/20A/20B)
FS 26 - 80 Digby Street (Glen Park)	1968	Engine 26 -
FS 32 - 194 Park Street (Bernal Heights)	1942	Engine 32 - 2002 HME / Ferrara (1500/500)
7th Battalion		
FS 14 - 551 26th Avenue (Central Richmond)	1958 / Remodeled 1998	Engine 14 - 2014 Spartan ERV Metro Star (1500/500)
FS 22 - 1290 16th Avenue (Inner Sunset)	1962	Engine 22 - 2006 American LaFrance Eagle (1500/500/20A/20B)
FS 31 - 441 12th Avenue (Richmond District)	1913 / Remodeled 1957 and 1969	Engine 31 - 2006 American LaFrance Eagle (1500/500/20A/20B)
FS 34 - 499 41st Avenue (Outer Richmond)	1928 / Re-built 1957	Engine 34 - 2014 Spartan ERV Metro Star (1500/500)
8th Battalion		
FS 18 - 1935 32nd Avenue (Sunset District)	1951	Engine 18 - Spartan Gladiator / Crimson (1500/500)
FS 20 - 285 Olympia Way (Midtown Terrace)	1963	Engine 20 - Spartan Gladiator / Crimson (1500/500)
FS 23 - 1348 45th Avenue (Outer Sunset)	1912 / Remodeled 1957	Engine 23 -
FS 40 - 2155 18th Avenue (Golden Gate Heights)	1931 / Remodeled 1956	Engine 40 -
9th Battalion		
FS 15 - 1000 Ocean Avenue (Ingleside)	1957	Engine 15 - 2010 Spartan Metro Star / Crimson (1500/500/20F)
FS 19 - 390 Buckingham Way (Lakeside)	1953	Engine 19 - 2014 Spartan ERV Metro Star (1500/500)
FS 33 - 8 Capitol Avenue (Oceanview)	1974	Engine 33 - 2018 Ferrara Igniter (1500/500)
FS 39 - 1091 Portola Drive (Forest Hill)	1923 / Remodeled 1955	Engine 39 - 1998 Spartan Gladiator / 3D (1500/500) (Ex-Engine 2)
FS 43 - 720 Moscow Street (Excelsior)	1970	Engine 43 - 2017 Ferrara Igniter (1500/500) (SN#H-6114)
10th Battalion		
FS 9 - 2245 Jerrold Avenue (Bayview)	1974	Engine 9 -
FS 17 - 1295 Shafter Avenue (Bayview)	1956 / Remodeled 1996	Engine 17 - 2018 Ferrara Igniter (1500/500)
FS 25 - 3305 3rd Street (India Basin)	1927 / Remodeled 1998	Engine 25 -
FS 37 - 798 Wisconsin Street (Potrero Hill)	1914 / Remodeled 1997	Engine 37 -

Fire Station No. and address	Year station built / re-built	Engine No. and apparatus
FS 42 - 2430 San Bruno Avenue (Portola)	1912 / Remodeled 1953	Engine 42 -
FS 44 - 1298 Girard Street (Vistacion Valley)	1913	Engine 44 - Spartan Gladiator / Crimson (1500/500)

SFFD has approximately 1450 uniformed firefighters, including Chief of Department, officers and firefighters. Each duty shift typically has about 300 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, https://sf-fire.org/nert) 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.

The Hose Tender provides an above ground portable water supply system. This system can be strategically placed to provide adequate flow and pressure for firefighting when other sources of water supply fail or are not available.

Figure 62 Typical SFFD (top) fire engine; (bott) hose tender
Source: (SFFD 2009)

3.4.2 Mutual aid

Mutual aid is the lending of firefighting assistance across jurisdictional boundaries when circumstances require. SFFD has agreements to provide and receive mutual aid from neighboring jurisdictions, and this has occurred for example when SFFD responded to Oakland in the 1991 East Bay Hills fire.

In a large disaster such as the scenarios of this study, SFFD would receive mutual aid but most likely not from nearby departments, since most departments in the Bay Area would be fully committed within their own jurisdictions. Therefore, mutual aid would from the Central Valley and Southern California, after a number of hours, coordinated by the Governor's Office of Emergency Services (OES), who are well practices in this. This delay would be due not only to the distance but because transportation routes would be likely to sustain some partial dysfunction due both to damage as well as congestion.

As discussed above, this study assumed no mutual aid for the first 12 hours with mutual aid strike team arrivals every two hours for the period 12-24 hours, and as many engines as needed after 24 hours. Aerial attack by tanker aircraft as typically used in wildland fires, is unlikely in San Francisco and is not considered in the analysis. These resource and operational aspects of the modeling were reviewed and approved by SFFD senior Chiefs.

3.5 WATER SUPPLY

This section discusses the various sources of water that SFFD would access for firefighting purposes.

3.5.1 Potable water system

Under normal circumstances at a fireground, SFFD accesses water from a fire hydrant, either an EFWS high-pressure network or a potable water system hydrant. The potable system, termed the 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. 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 Municipal System. 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 Municipal System.

In the 1989 Loma Prieta earthquake, damage was relatively low throughout the Municipal System 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 Municipal System (and 7,500 ft. of pipelines belonging to the EFWS high-pressure network) (O'Rourke 1990).

As discussed in the CAPSS technical documentation (ATC-52-1A 2010), the MWSS is likely to suffer numerous breaks and leaks such that substantial numbers of its hydrants will be without water for firefighting. For this reason, the MWSS was not considered as a source of water for firefighting for this study. The precise serviceability of the MWSS given a major earthquake is a vital question for San Francisco and should be investigated.

3.5.2 EFWS

The EFWS was described above and currently consists of the high-pressure network (i.e., the static supplies, pump stations and pipe network), cisterns, suction connections and fireboats. In future, the EFWS may include additional pipes and pump stations in other parts of the City. For purposes of this analysis, after considerable study, a phased construction of additions was identified, as reasonably representing what is required. These additions were to occur in three phases, as shown in Figure 63 and Figure 64. It is emphasized that these phases are a reasonable postulate of how the EFWS might be expanded, and that the expansion of the EFWS could take many other forms.

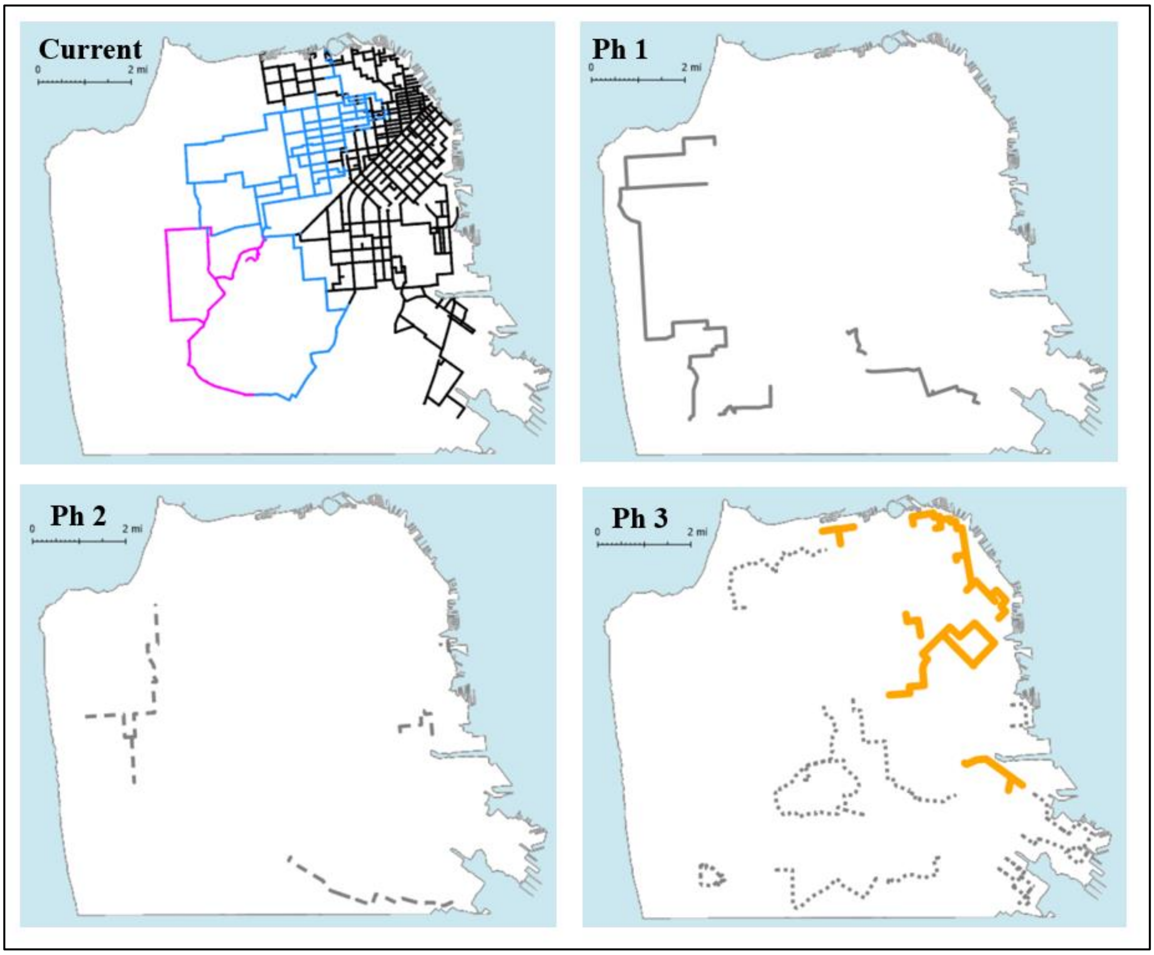


Figure 63 EFWS current and future phases: (top left) current; (top right) phase 1; (lower left) phase 2; (lower right): phase 3.

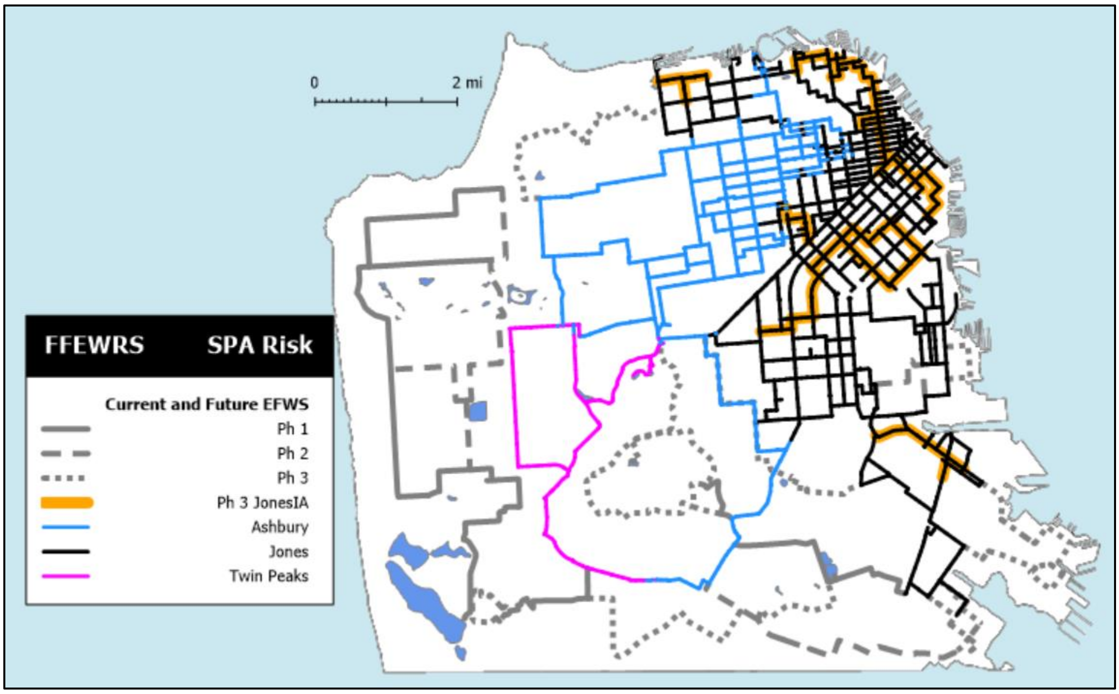


Figure 64 EFWS all phases combined

3.5.3 Alternative water supplies

In addition to the MWSS and EFWS high-pressure network, a number of alternative water supplies exist in the City, which SFFD in extremis might employ for firefighting, as shown in Figure 65, and include various lakes, reservoirs and suction connections. All of these were included in the analysis.

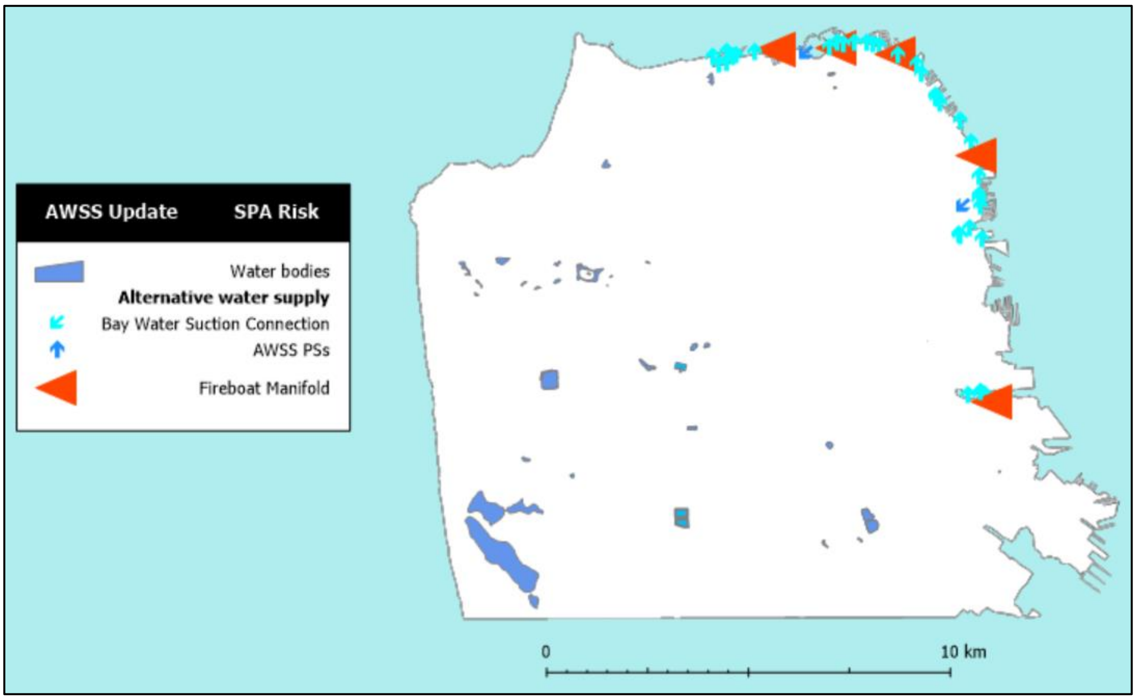


Figure 65 Alternative water supplies

3.5.4 Presidio

Data on the Presidio water system was acquired and georeferenced, as shown in Figure 66 below.

Figure 66 Presidio water system georeferenced with hydrants shown as blue-yellow triangles.

3.6 Streets and access

SFPUC personnel will have to travel to locations of EFWS damage, and SFFD must travel to fires, so data was gathered on the City's streets, Figure 67 and Figure 68.

A particular issue is that San Francisco has a large number of streets with overhead wires, such as the overhead trolley lines in Figure 69, which may fall and block streets, hindering emergency response. Streets with overhead SFMTA lines are shown in Figure 70 and streets where overhead electric distribution lines have been "undergrounded" are shown in Figure 71.

The issue of overhead wires was examined but is not explicitly incorporated in this study's modeling and may deserve further attention.

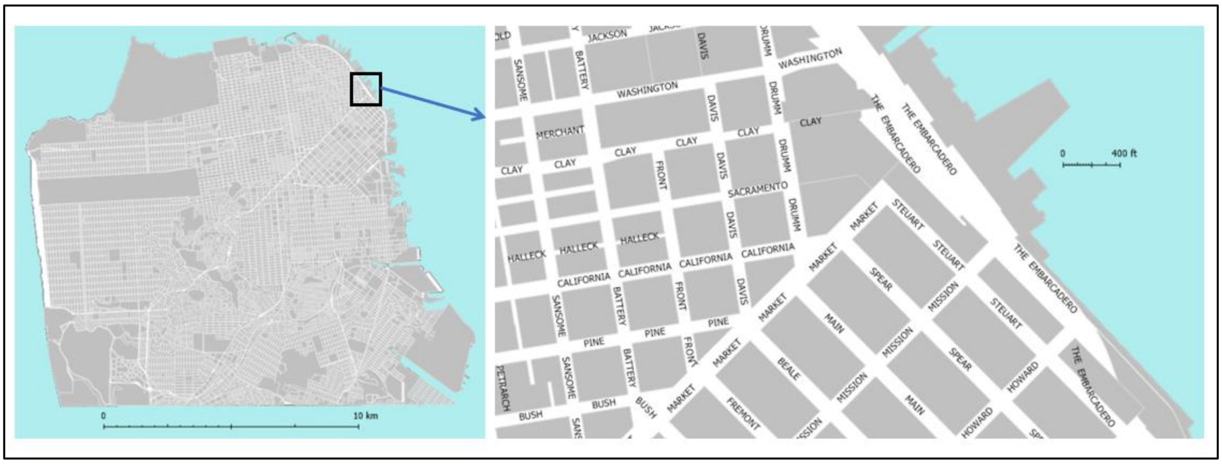


Figure 67 Street data

Figure 68 Street width (building face-building face) sampled from Google Earth (example: 27th Ave between Moraga and Noriega).

Figure 69 Example of complex overhead wire arrangement, Castro District
(Source: Google Street View)

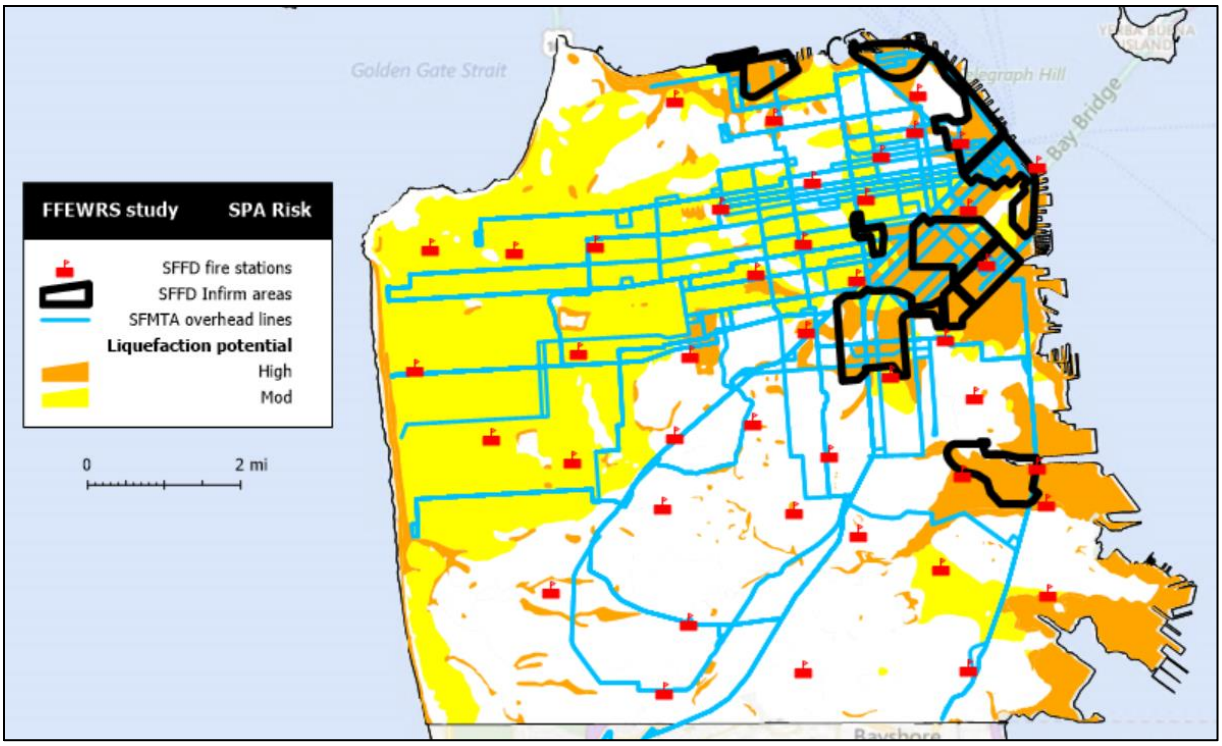


Figure 70 SFMTA overhead wires shown in blue and SFFD fire stations (red symbols) overlaid on liquefaction potential and SFFD Infirm Areas.

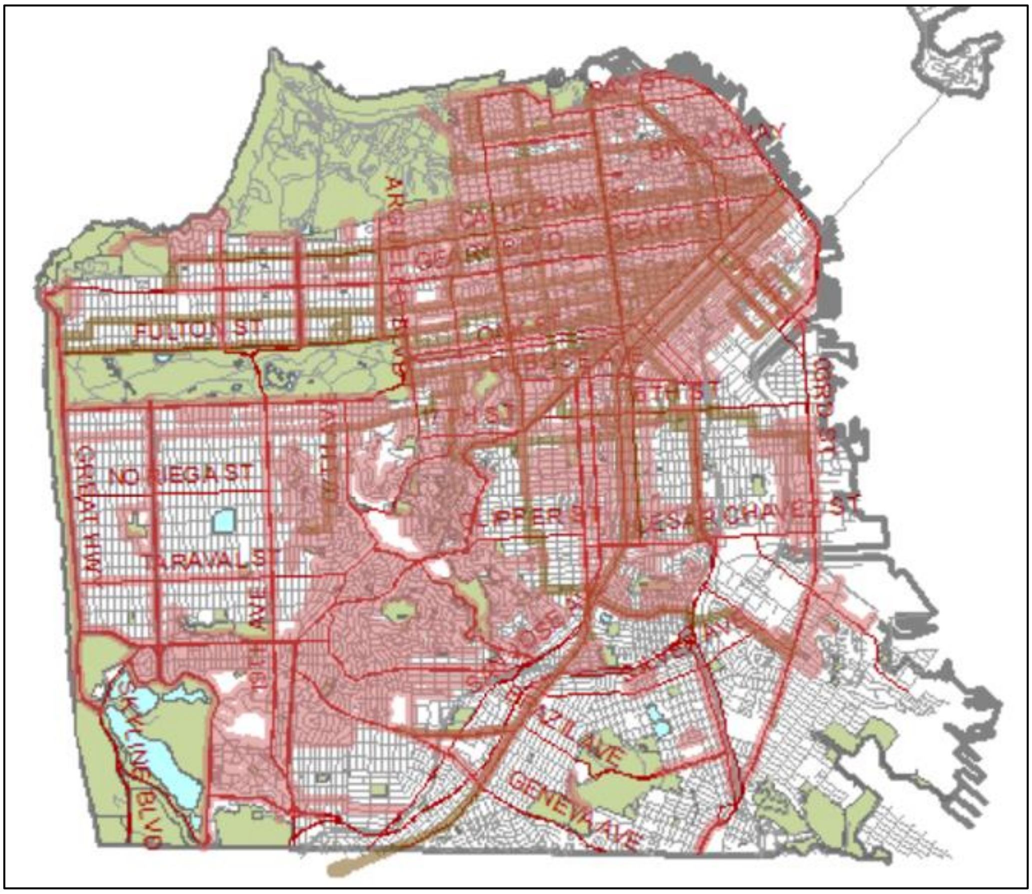


Figure 71 San Francisco ‘undergrounded’ streets shaded in red (i.e., streets in red have no overhead electric distribution lines) Source: https://bsm.sfdpw.org/mapviewer/

3.7 Weather

Weather is an important factor in firespread, so data was collected from a variety of sources for San Francisco temperature, windspeed and direction, relative humidity and precipitation. The primary dataset was hourly observations of humidity, temp, pressure and wind for the five-year period 2012-2017. This was supplemented with total daily precipitation for the period 1921-2019. Figure 72 to Figure 74 summarize the data.

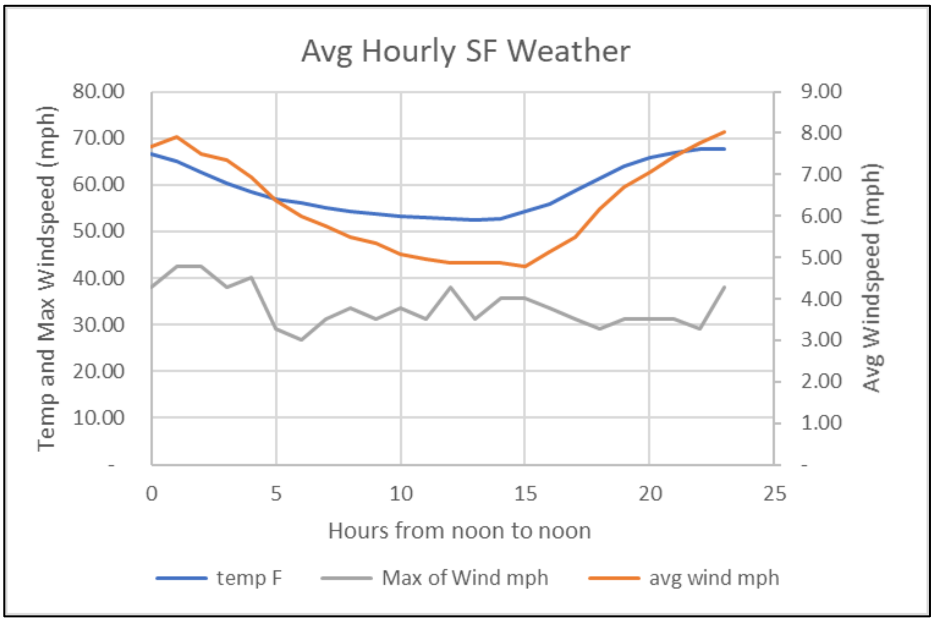


Figure 72 Variation of San Francisco mean temperature, maximum windspeed and mean windspeed, hourly observations 2012-2017 (n = 44,489)

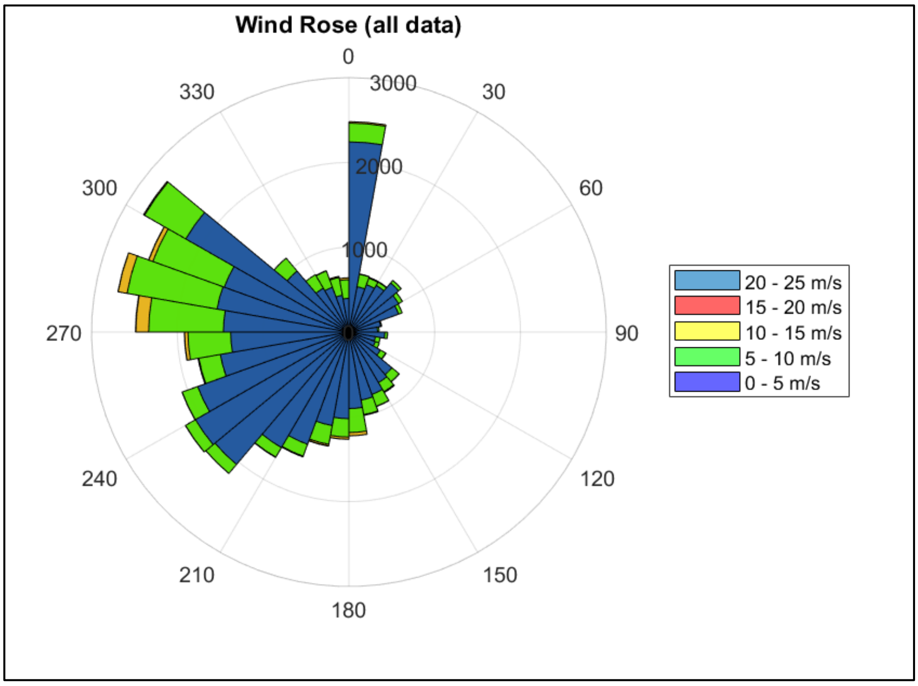


Figure 73 Wind rose of San Francisco winds, all hours

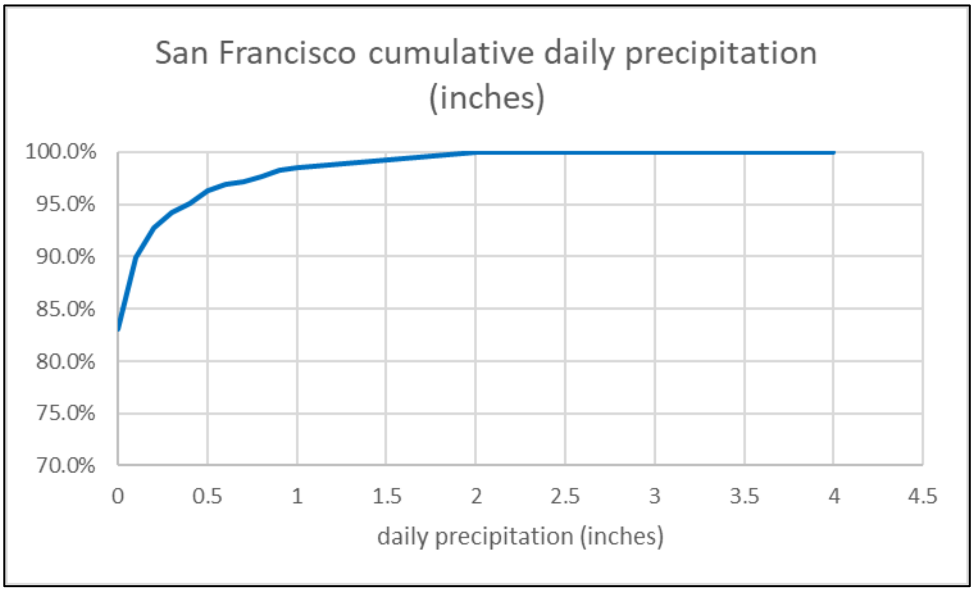


Figure 74 Cumulative distribution of San Francisco daily precipitation (inches). About 82% of days there is no precipitation.

4 FIRE FOLLOWING EARTHQUAKE: ANALYSIS AND MODELING

Methods and algorithms employed in the project are summarized.

4.1 INTRODUCTION

The modeling of ignition, growth and spread of fires, and firefighting to suppress those fires, has been performed within a Monte Carlo simulation framework for this study. The Monte Carlo method evolved in the 1930s and 40s as part of the work on atomic energy, is well documented (Zio 2013) and essentially consist of numerous repetitions of a stochastic model, with each replication of the model using fixed values of the stochastic variables. The fixed values of the variables are determined by randomly sampling each variable's underlying probability distribution function. The essence of the approach then is developing a model and deciding which variables in the model are uncertain and thus require sampling. This section first provides an overview of the underlying model for analysis of fire following earthquake, and then discusses specifics of the modeling performed in this study.

4.2 Analysis of fire following earthquake

4.2.1 Overview

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, Yamada and Iemura 1981) and has been applied to major cities in western North America (Scawthorn 1992). An American Society of Civil Engineers' monograph (Scawthorn, Eidinger and Schiff 2005) details the state of the art in modeling fire following earthquake. Previously, fire following earthquake was modeled for the CAPSS project where the focus was on property loss, not water use. Given these sources, only a brief review of the general modeling of fire following earthquake is presented here, with additional detail as needed related to water use. In summary, the steps in the process are shown in Figure 75:

- *Occurrence of the earthquake* –causing damage to buildings and contents, even if the damage is as simple as knocking 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 to 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 76, which is a Fire Department Operations Timeline. 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.

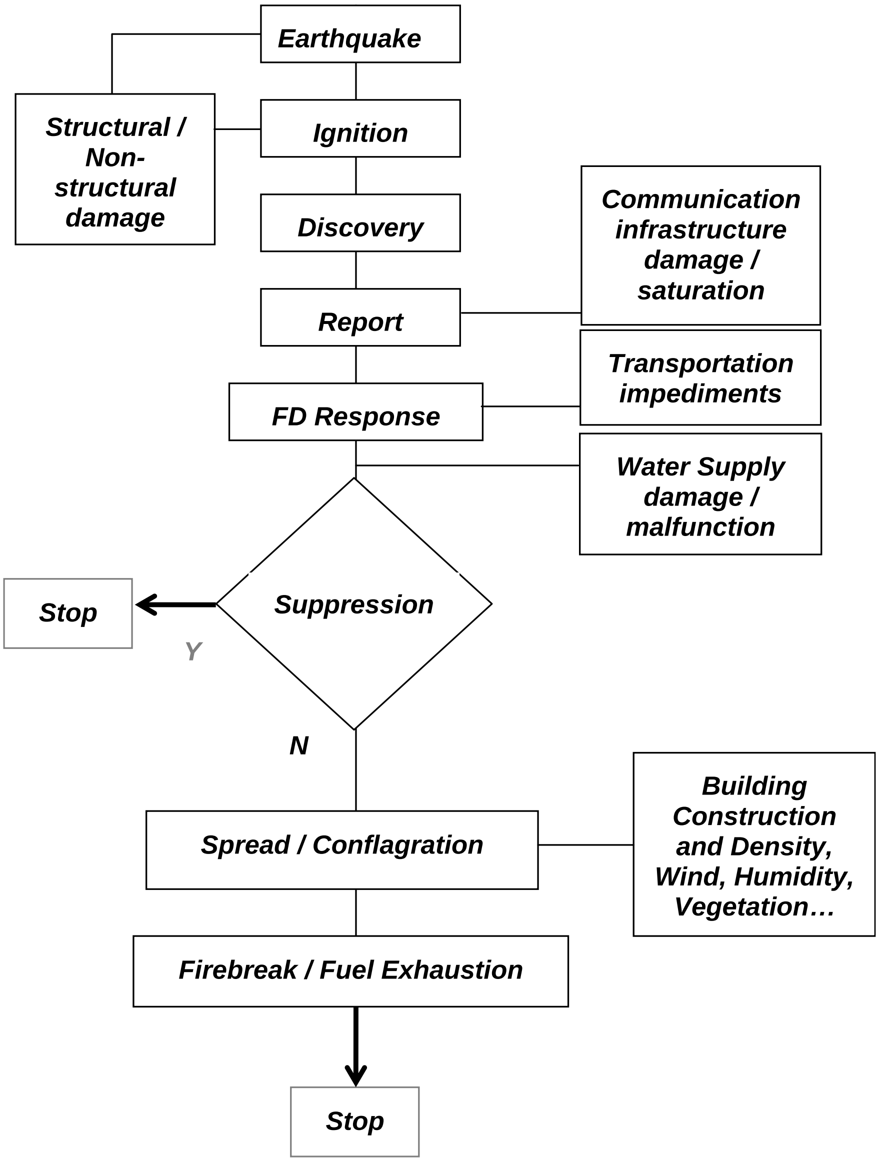


Figure 75 Flow chart of fire-following-earthquake process (TCLEE 2005)

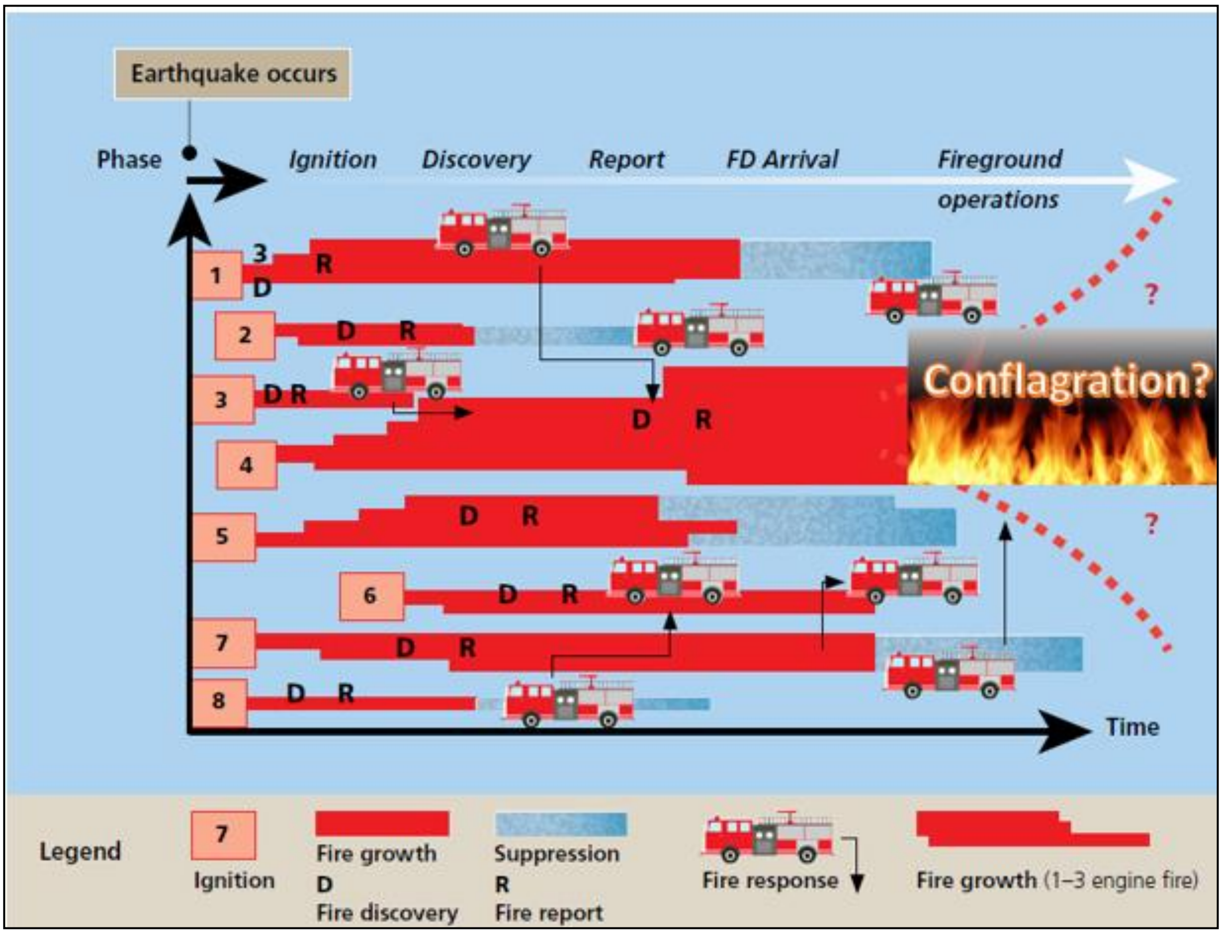


Figure 76 Chart of fire department operations time line. Horizontal axis is time, beginning at time of earthquake. Horizontal bars depict development of fires, from ignition through growth or increasing size (size is indicated by width or number of horizontal bars).(Scawthorn 1987)

4.2.2 Ignitions

The number and pattern of ignitions are estimated for each block in the city based on intensity of ground motion, TFA and ignition relationship shown in Figure 77 which is based on methods in (SPA Risk 2009) which are further discussed in (Scawthorn 2018a). Figure 78 compares the relationship with a model by Davidson. The cause of these ignitions will 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, 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. 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.

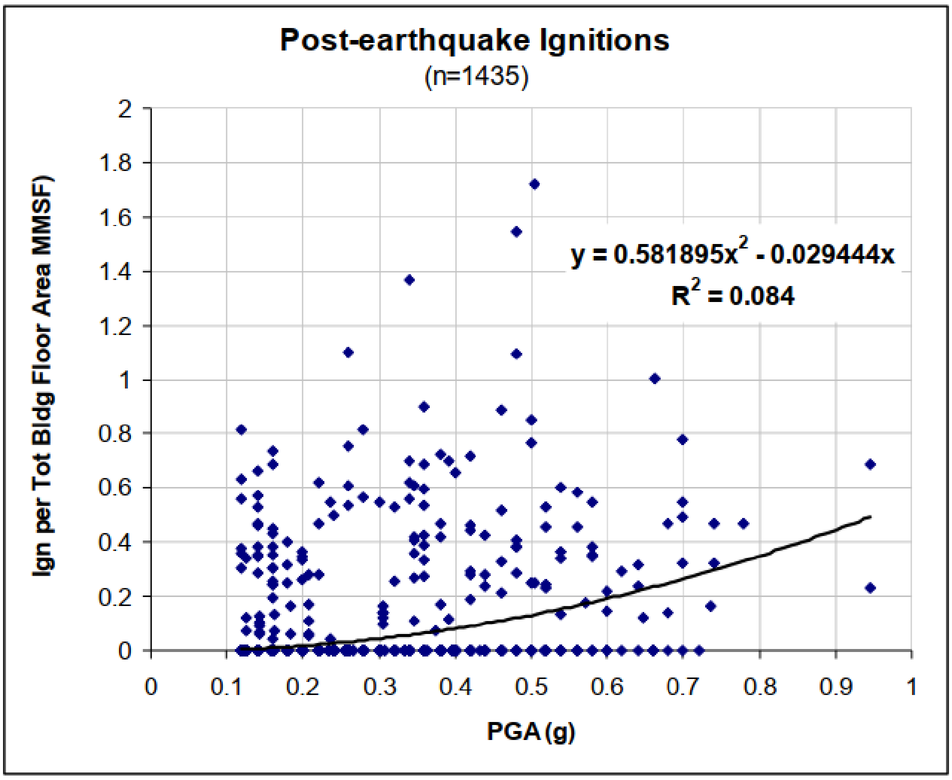


Figure 77 Ignition models, taken from (SPA Risk 2009) (MMSF is millions of square feet).

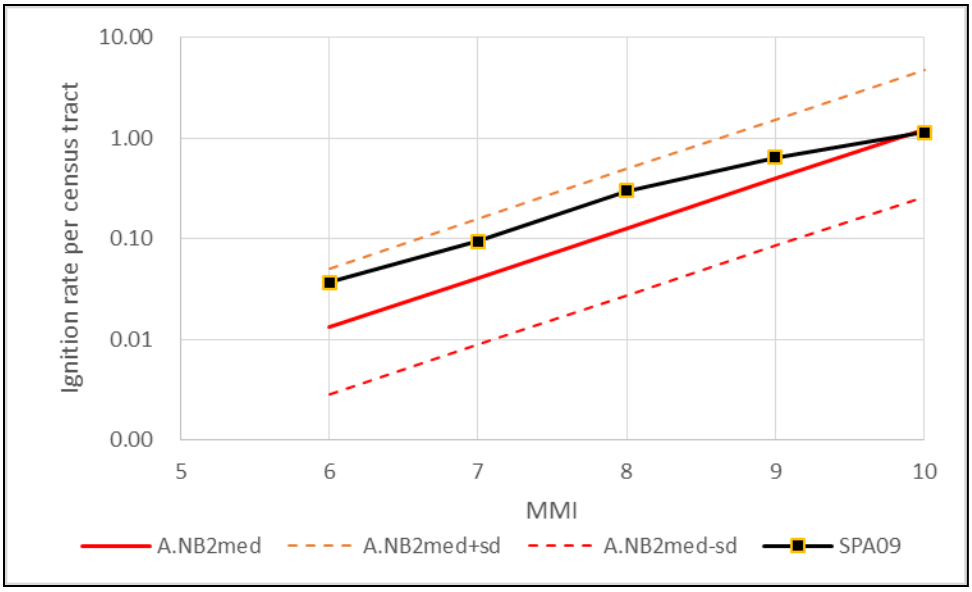


Figure 78 Ignition models, comparison of ignition regression models (1) [Davidson 2009] and (3) [SPA 2009] using median values per census tract. Dotted lines are equation (1) plus and minus one standard deviation. Abscissas in the figure are Modified Mercalli Intensity (MMI), but analysis for this study employed peak ground acceleration (PGA) as the hazard measure.

4.2.3 Initial Response

4.2.3.1 Citizen response

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 estimates of fires. When citizens realize the fire is beyond their capabilities, they will endeavor to call the fire department, by telephone since fire alarm street pull boxes have largely disappeared from the North American urban landscape. Attempts to report via 911 will almost universally be unsuccessful, not so much due to damage to the telephone system as much as simple saturation of the system, and 911 call centers. Citizens will then go by auto to the nearest fire station, but such 'still alarms' will be largely unneeded, since the fire companies will have already responded to the nearest fire ("self-dispatched"), if not dispatched by 911.

Experience shows that citizens on scene will respond rationally (Van Anne, Scawthorn and Mileti 1994) rescuing as many people as possible and protecting exposures. Water supply from mains may be unavailable.

4.2.3.2 Reporting

As noted above, 911 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. Most fire departments do not have their own helicopters, and TV helicopter news reporting will be a valuable resource for a few major incidents, but not most. An anecdote demonstrates this – the first knowledge the San Francisco Fire Department EOC had of the Marina fire in the 1989 Loma Prieta earthquake was from television news reports (despite several companies having responded). Quickly gaining an accurate complete situational awareness is still a challenge.

4.2.3.3 Fire Service initial response

The initial response of fire companies and personnel in the study area will be to protect themselves during violent shaking, and as soon as possible open the doors and remove apparatus (e.g., pumpers and ladder trucks) from the fire stations. Different departments have somewhat varying earthquake procedures but in general companies will remove apparatus to a pre-designated location, often simply in front of the fire station, check the station for damage and perform a radio check. 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.

Debris, downed wires and other damage may block some roads and impede access to fire sites, although San Francisco's street pattern is sufficiently redundant such that added travel time will be limited to a few minutes (Kiran and Corcoran 2017), typically less than time lost due to delayed reporting.

Local fire service resources will be completely committed, and in need of mutual aid. The primary needs will be personnel, additional hose, hard suction hose (that is, hose that does not collapse when used to draft water from a source that is not already under pressure), foam, light equipment (gloves, hand tools, self-contained breathing apparatus [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 Neighborhood Emergency Response Teams (NERT) 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.

Time of arrival at the fire by a fire engine is then based on the time of ignition following the earthquake, plus a period for reporting taken as the travel time (vehicular travel) from the fire to the nearest fire station, plus the same travel time back to the fireground by the fire engine. If the fire engine assigned to that fire station has already committed to another fire, the travel time is then taken as that of the nearest available engine.

4.2.4 Water supply performance

The availability of water for firefighting is crucial and is discussed here.

4.2.4.1 Water Supply Factor

The availability of water at a fireground is determined based on the stochastic variable WSF (Water Supply Factor), which varies from 0 (no water) to 1 (sufficient water for firefighting). The WSF is determined as the probabilistic combination of constituent WSF_i where i = EFWS high-pressure network (HP), Cisterns and Alternative Water Supplies. That is,

$$WSF = 1 - \prod (1 - WSF_i)$$ Equation 1

Determination of WSF_{HP} based on the approach in Hazus (DHS 2003) as enhanced by Porter (Porter 2018), where serviceability *s(r)* is a function of pipe repair rate *r* normalized by pipe length *L*, ln denotes natural logarithm, r/L denotes the average break rate (r main breaks per L kilometer of pipe), q and b are model parameters, and Φ is the standard normal cumulative distribution function:

$$s(r) = 1 - \Phi\left(\frac{\ln\left((r/L)/q\right)}{b}\right)$$ Equation 2

That is, $WSF_{HP} = s(r)$, and its determination reduces to estimating pipe repair rate of the EFWS high-pressure network pipe for the scenario earthquake. The EFWS high-pressure network overlaid on areas of high likelihood PGD is shown in Figure 79, and the number and pattern of repairs and breaks are shown in Figure 80 and Figure 81, respectively.

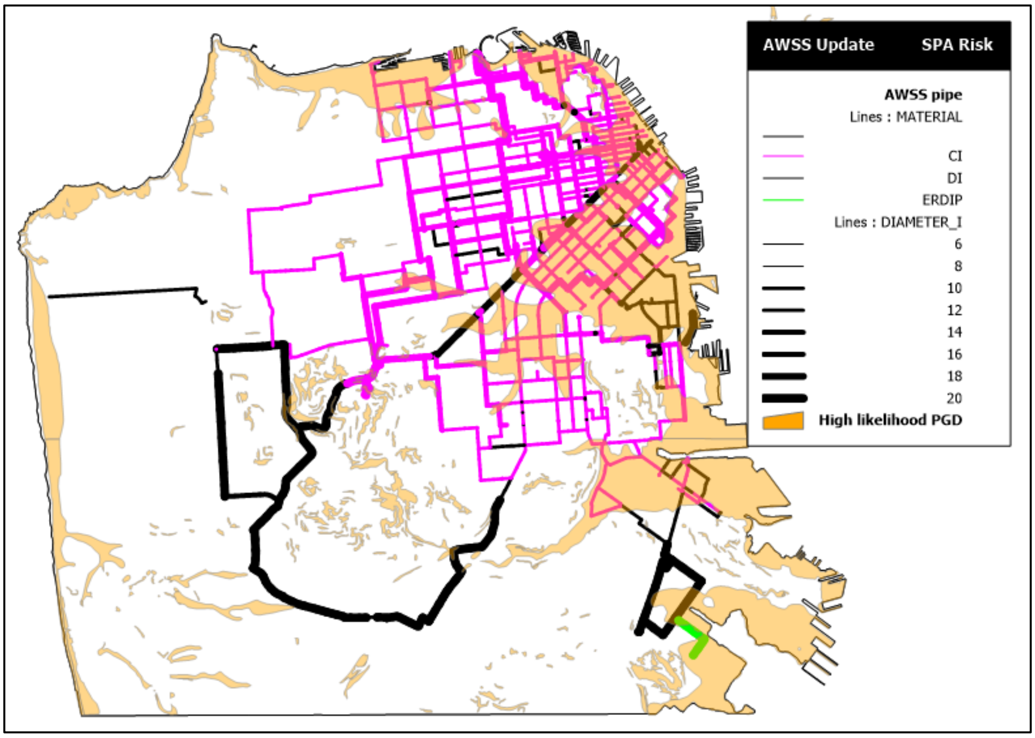


Figure 79 EFWS high-pressure network pipe network overlaid on areas of high likelihood PGD

For details of this approach, and the values of q and b, and methods for estimating pipe repairs and breaks, see (Porter 2018). For each trial of a Monte Carlo simulation then, Equation 2 is used to estimate the serviceability of each zone of the EFWS high-pressure network. This serviceability is then multiplied by a factor based on distance from the pipeline, to account for the probability of SFFD ability to access the EFWS high-pressure network hydrant (the further from the hydrant, the less likely SFFD will be able to convey water from the hydrant to the fireground, under post-earthquake conditions).

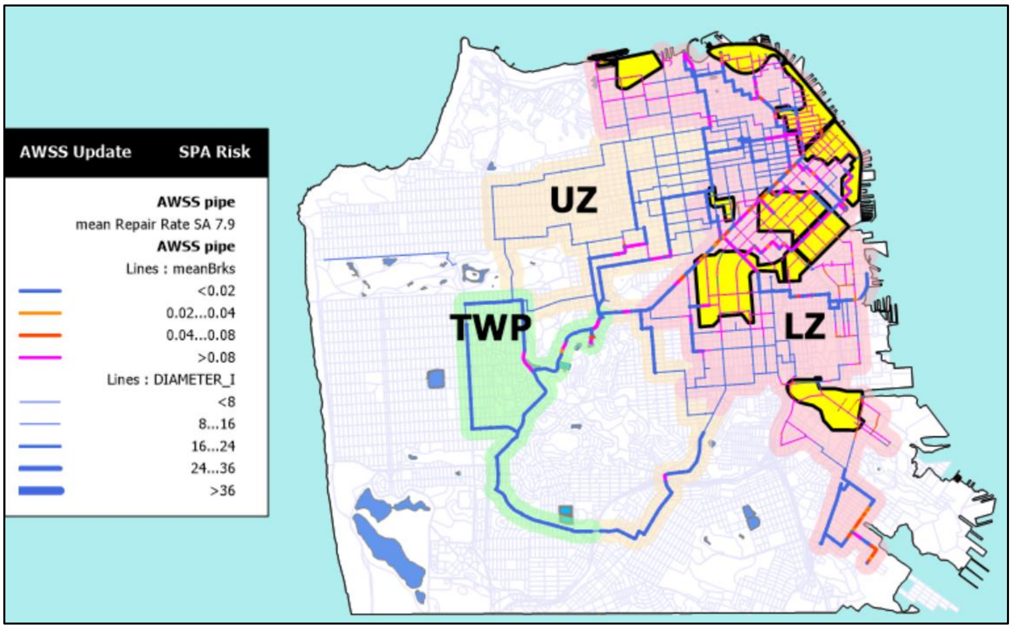


Figure 80 Mean **repair** rate for SA 7.9 event – mean number of repairs is 105, of which 52 are within the SFFD identified Infirm Areas – that is, 53 will not be isolated by current seismically actuated motorized gate valves. LZ denotes the Lower Zone, UZ the Upper Zone and TWP the Twin Peaks Zone.

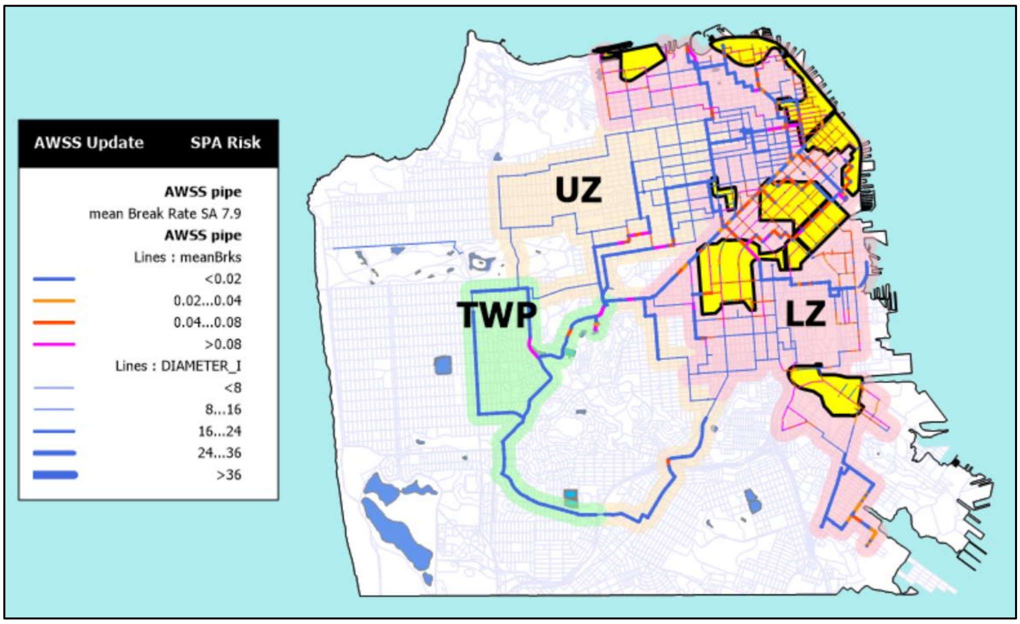


Figure 81 Mean **break** rate for SA 7.9 event – mean number of breaks is 52, of which 26 are within the SFFD identified Infirm Areas– that is, 26 will not be isolated by current seismically actuated motorized gate valves.

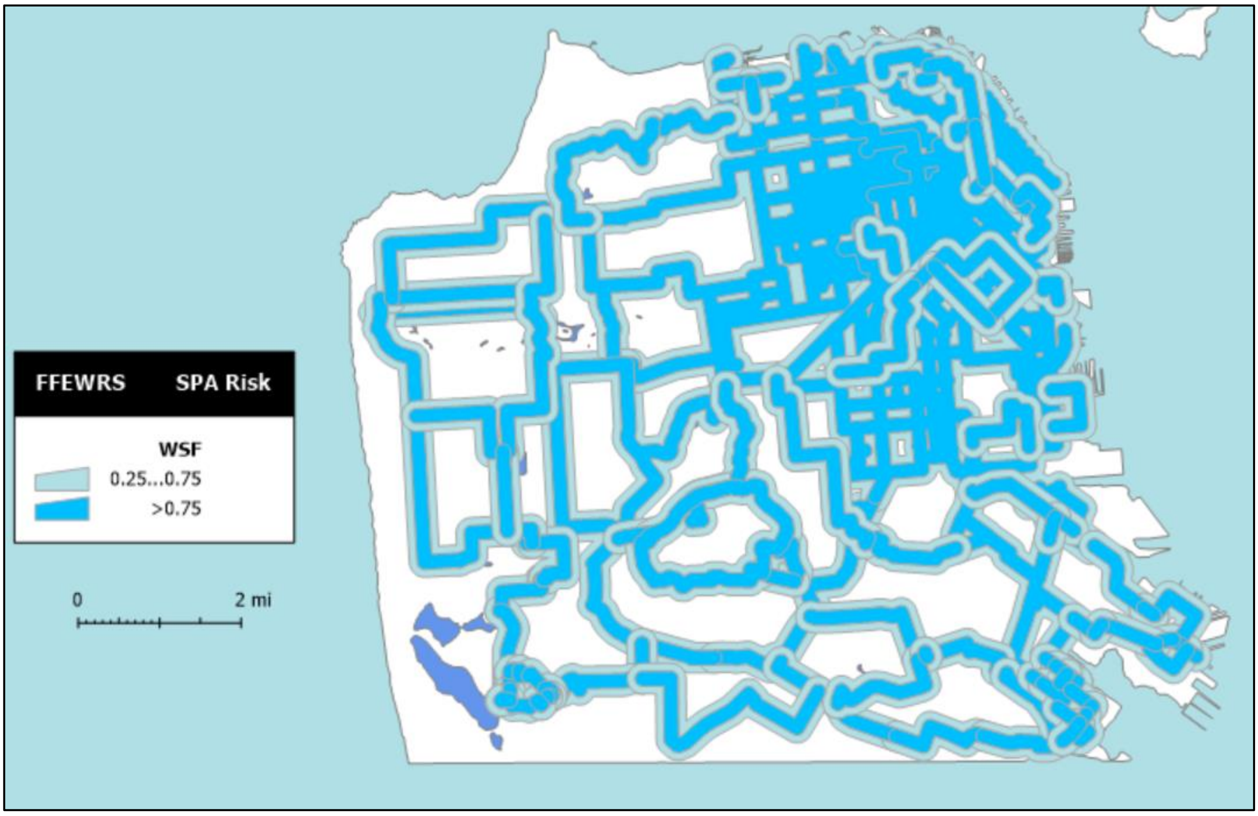


Figure 82 EFWS WSF, at Phase 3 buildout

The above accounts for the physical serviceability of the EFWS high-pressure network. However, as seen in 1989, the physical serviceability can be further affected by operational factors. That is, the potential exists for EFWS high-pressure network operators to rapidly isolate damage to the network and maintain system functionality or, on the other hand, respond more slowly, which may allow the system to dewater, resulting in a prolonged delay until pressure can be restored. The latter is what happened in the 1989 Loma Prieta earthquake – operators had only about 20 minutes to respond (Scawthorn 1990b).

To account for this operational aspect, the WSF_{HP} as determined above is modified as a function of time following the earthquake by two factors, *sysEFF* and t_{REC}. That is, system serviceability (i.e., $WSF_{HP} = S(t)$) is modeled using a generalized logistic function:

$$S(t) = S(0) + \frac{1 - S(0)}{[1 + \exp\,(-sysEff * t]^{t_{Rec}}}$$

Equation 3

where

S(t) is Serviceability at time *t*

sysEFF is system efficiency (ie, ability to restore serviceability following earthquake) which varies from 0 (very poor) to 1 (excellent recovery)

t_{REC} is time to near-complete recovery. Reasonable times to recovery for Low, Moderate and High are shown in the table below. Note that $t_{REC} = 6/sysEff$.

Three levels of EFWS system efficiency are considered in the analysis, Table 9, with consequences as shown in Figure 83:

Table 9

System Efficiency	EFWS system command and control	*sysEff*	t_{REC} (hrs)
Low	unable to gain situational awareness in timely manner and/or make and implement decisions to improve EFWS performance. Effectively, pre-event configuration unchanged for significant period (cannot isolate breaks)	0.25	24
Moderate	Gains situational awareness over time (e.g., via reports) and can isolate EFWS damage and compensate via valving and other measures such that hydrants have water over some period of time.	0.5	12
High	Immediately acquires situational awareness (eg., via SCADA), identifies and can isolate EFWS damage and compensate via valving and other measures such that hydrants have water.	0.75	6

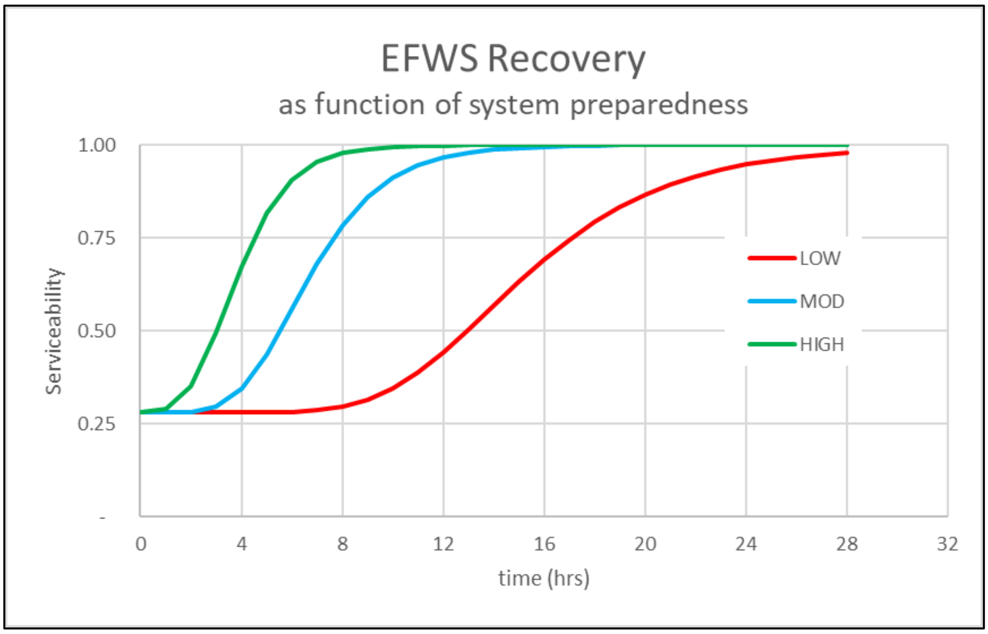


Figure 83 System recovery for Lower Zone of EFWS under three scenarios of system serviceability

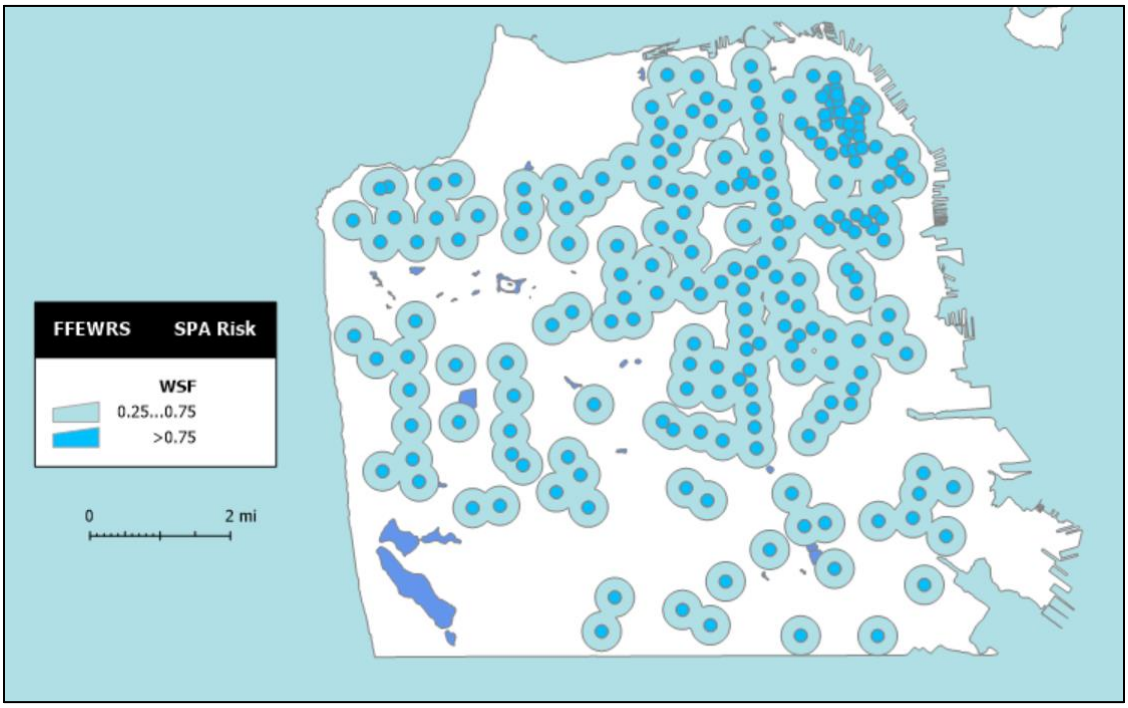


Figure 84 Cisterns WSF

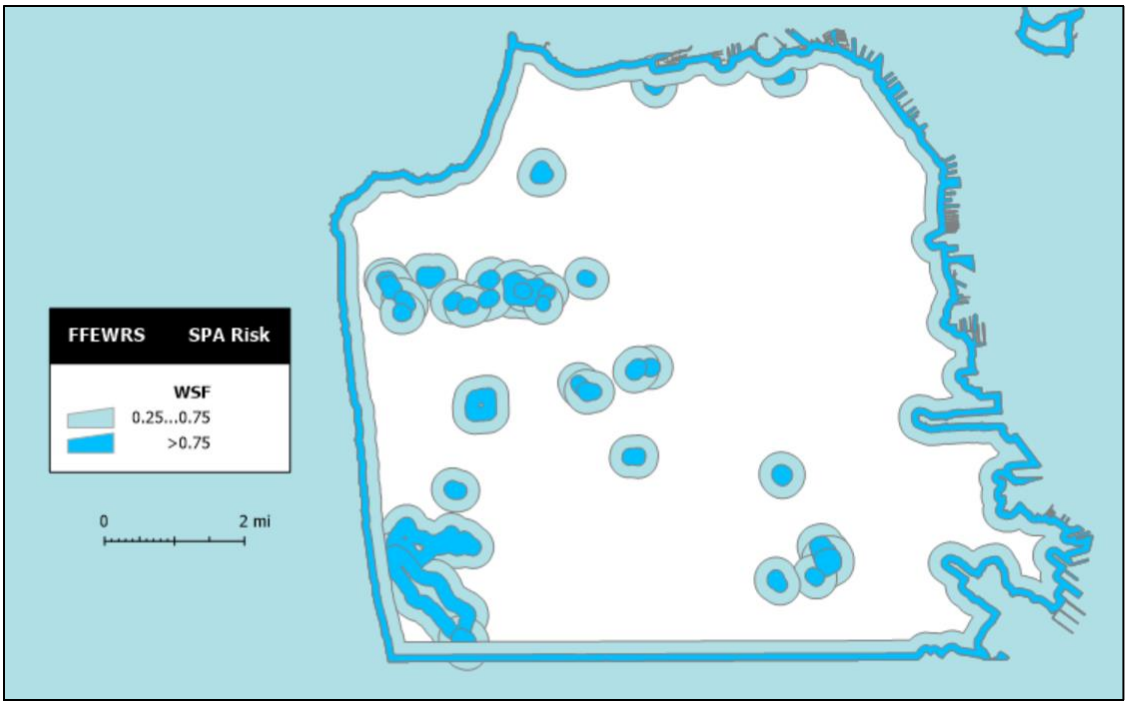


Figure 85 Alternative Water Supplies' WSF

A similar but somewhat less complex process is used to determine $WSF_{cistern}$ and WSF_{AWS} given distance from the fireground to the water source, see Figure 84 and Figure 85. The aggregate pattern of WSF for each city block is shown in Figure 86, given the Phase 3 buildout.

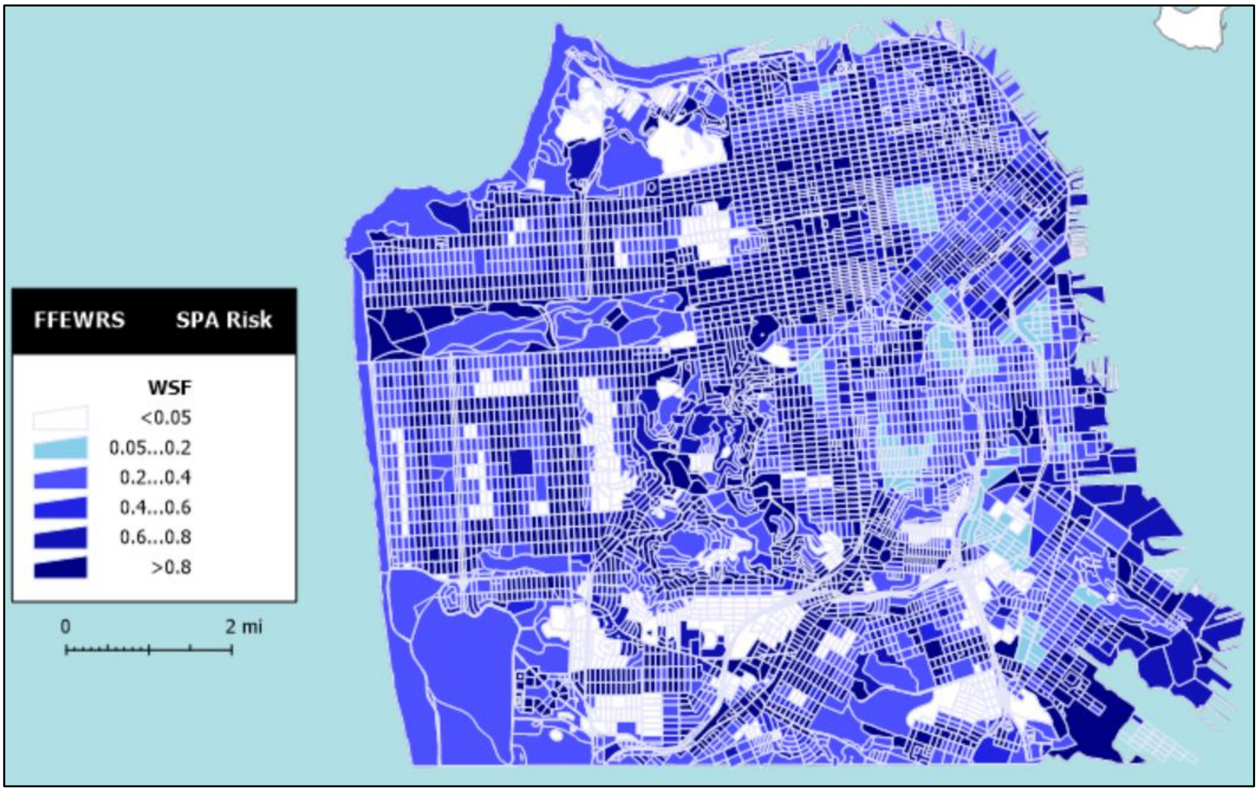


Figure 86 Water Supply Factor (WSF) given EFWS Phase 3 buildout

4.2.5 Fire Spread

The analysis assumes all fire service resources will initially focus on firefighting, leaving search and rescue, hazmat response and other emergencies until fires are brought under control. The initial ignitions will not all develop into large fires. Nevertheless, the normal structural fire response time will hardly be met. Delayed response, due primarily to failure of the 911 system, will result in many of the fires on arrival having grown such that a multi-engine capacity is needed. That is, an unfought ignition can grow into a room-sized fire within several minutes, and a fully involved single family structural fire within several more. To protect neighboring buildings ("exposures") typically two or more engine companies are needed. If only one company is available, it is possible that it might be able to protect two exposures (using monitor and a hand line, with civilian assistance), but sometimes unlikely. In fire following earthquake modeling, such fires, where the fire has grown exceeding one engine company's capabilities, are termed 'large fires'. The spread of these fires is a function of building materials and density, windspeed and firefighting efforts. Within city blocks, unfought fires can spread rapidly – experience of urban fire spread in the absence of firefighting in modern urban regions is limited although some data is available from wildland urban interface (WUI) fires and other events. Spread from block-to-block – that is, across streets and other fuel breaks, can easily occur in the absence of firefighting, Figure 87.

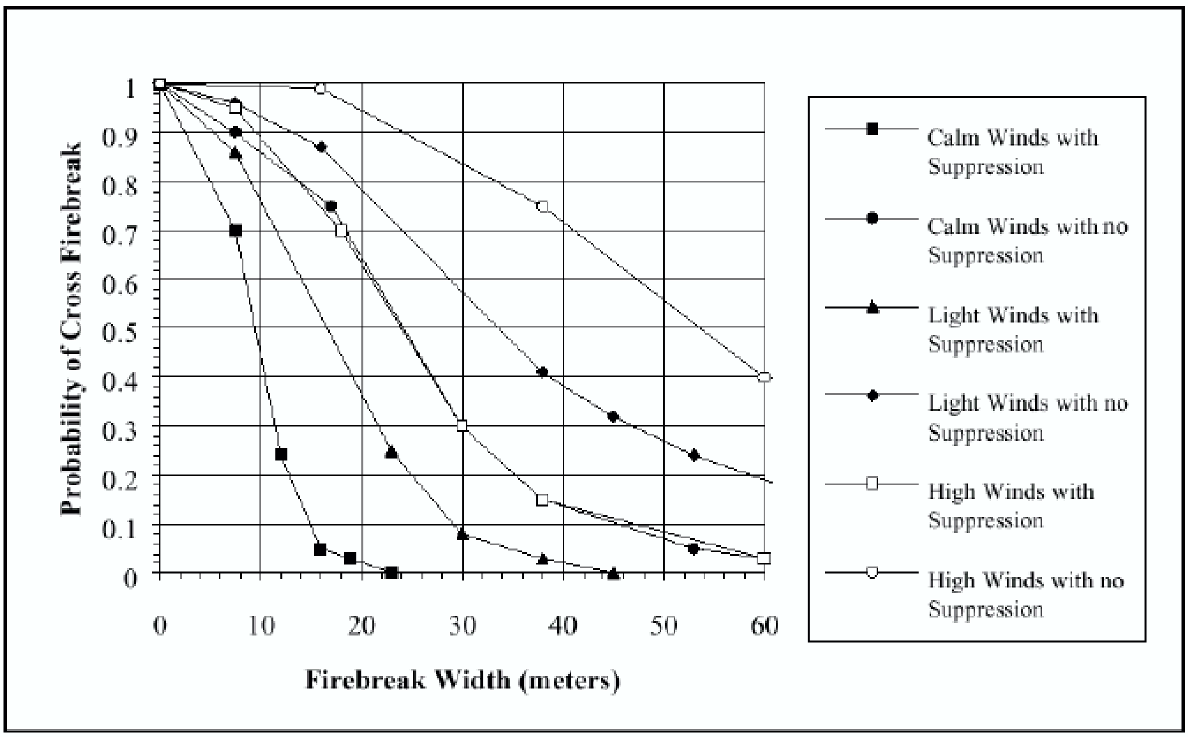


Figure 87 Probability of crossing firebreak (Scawthorn 1987; TCLEE 2005)

4.2.6 Firefighting and suppression

Modeling of post-earthquake firefighting and suppression differs somewhat from ordinary firefighting in that minimization of property damage via aggressive interior attack, the firefighting tactic for ordinary small to medium fires, is no longer the preferred tactic. Rather, while this remains the tactic for small fires (i.e., within one moderately sized room), the post-earthquake tactic is more defensive, seeking to contain and suppress the fire with as little commitment of resources as possible. Thus, the model uses algorithms from ordinary firefighting for small to medium sized fires (e.g., within one building (Benfer and Scheffey. 2015; Davis 2000; Grimwood and Barnett. 2005; Hadjisophocleous and Richardson 2005; Särdqvist 1998). For larger fires, perimeter defense becomes necessary and is employed to the capacity of available fire engines at the fireground. If this capacity is less than required for full containment, the fire grows, albeit at a slower rate. As and if more engines arrive, capacity becomes sufficient for full containment, and fire growth ceases. Water use continues, with no effort to conserve water but rather to contain and suppress the fire. When the fire has been fully contained and the fuel largely exhausted, some number of fire engines are required to remain for mop-up, to minimize the possibility of a rekindle. All during this period, water is still required. Water flow is tracked and is the primary measure of water usage for this report. Integration of water flow over the duration of the fire provides an estimate of total water required.

4.2.7 Required Water

Measurement of firefighting water for purposes of this study is more complex than for more ordinary fires, since the goal of this study is to estimate the water flow rate <u>required</u> at any point of time, rather than the flow rate actually applied. Thus is a subtle but elusive point that is best illustrated by example:

a) Consider a single family dwelling in a relatively densely built city block of similar dwellings. Think of the Richmond, Western Addition, Mission and similar districts in San Francisco.

b) Consider the earthquake occurs, and a lamp tips over and the hot bulb lands on and ignites the fabric covering a sofa. At this point, the amount of water required to suppress the ignition is miniscule – one might suppress the ignition by beating it with a magazine or use a cookpot of water.

c) However, the ignition hasn't yet been discovered, and grows. As can be seen in many demonstrations, the flames will rapidly spread, first across the fabric, then to the upholstery. Within 30 seconds, the fire cannot be beat out, but a gallon or two of water might suffice.

d) By 60 seconds, the fire has doubled in size and several gallons are required (think – where and how would you get several gallons of water to the living room, within a few tens of seconds? Without a garden hose, you probably couldn't).

e) By two minutes, the fire has again doubled in size and several tens of gallons of water are probably required.

f) By minute three, the fire has flashed over. Anyone in the room would now be badly if not fatally burned. Before this point, the amount of water and skill has passed beyond the capacity anyone but trained firefighters. With adequate water, trained firefighters contain the fire within another 45 seconds.

The above process is illustrated in Figure 88. The point is, at the 30th second, only a gallon or two of water is required. Because it hasn't been applied, within another 90 seconds, tens of gallons of water are required, and so on. Thus, **the amount of water required at any point in time is a function of the amount of water previously applied**. That is, the amount of water required at any point in time is a function of the fire department response, and the performance of the water network (or other sources) to supply the firefighters.

Figure 88 Flashover demonstration
Source: Oakridge TN FD, https://www.youtube.com/watch?v=BtMmymOxdjc)

Thus, the amount of water at any point in time can be measured according to four categories:

- ***Actual***, being the water flow actually applied by firefighters, according to actual practice in other fires. In the above example, at minute 2, this was zero – no water had been applied.

- ***Available***, being the maximum water flow that could be applied by all fire engines on-scene. In the above example, at minute 2, this was zero – firefighters hadn't yet arrived. At minute 3:45, with a fire engine on scene, this flow is 1500 gpm, the maximum capacity of the fire engine (which is far greater than what is needed to suppress this fire).
- ***Required***, being the water flow that is required to suppress the fire at that moment, considering previous suppression activities. At minute 2, this was several tens of gallons of water. At minute 3:35, this is one handline, or a flow of 250 gpm.
- ***Theoretical***, being the water flow required for full suppression and assuming there has been no prior suppression. At minute 3:45, this is the same as previously – that is, 250 gpm. At minute 5, if the firefighters hadn't arrived, this would now probably be 500 or more gpm.

Typically, Actual water flow will be less than or equal to Required, which may be more or less than Available, which will be less than Theoretical. That is Actual ≤ Required and/or Available < Theoretical. See Figure 89 and Figure 90 for illustration of these categories. Of these four categories, Actual and Required Water are the most realistic measures of the water the EFWS needs to provide, and Required Water has been selected as the most relevant for this project's purposes. All results will be in terms of Required Water.

Figure 89 Example fire for purposes of defining the four categories of water usage – example here is for a typical block in the Richmond, where one engine is available, and five buildings are fully involved (this size fire would normally be 3rd or 4th alarm fire, requiring the response of at least four to six engines, two trucks and other apparatus and senior officers).

Figure 90 Four categories of water usage: (top left) Actual water, being the water used by available firefighters; (top right) Available water, being the maximum flow by available engines (typ. a master stream); (lower left) Required water, being the total flow required to control the fire, and (lower right) "Theoretical" water, being the total flow at a point in time required to control the fire, if no firefighting has previously occurred (in this last case, the fire will have grown larger than the previous cases).

4.3 Monte Carlo simulation

The beginning of this chapter explained that the modeling of ignition, growth and spread of fires, and firefighting to suppress those fires, is performed within a Monte Carlo simulation framework. Therefore, for one trial, the simulation parameters or "case" are established. These consisted of deciding:

1. What scenario to consider (Mw 7.9 on the San Andreas fault, or Mw 7 on the Hayward).
2. What Phase was the EFWS in – Phase (0) meaning the current stage of buildout, or a later stage? Determining the Phase also determined future growth – Phase 0 corresponded to the year 2020, Phase 1 to 2030, Phase 2 to 2040 and Phase 3 to 2050, solely to determine future growth – there was no intention to imply that this was the schedule for EFWS buildout. Hopefully, the EFWS expansion will occur sooner than these dates.
3. Was the analysis to consider damage to the EFWS, or hypothetically to assume no damage at all?

4. Were the sysEff and sysImpr variables discussed above Low, Moderate or High?
5. Was SFFD its current size – that is, 44 engines on duty – or by say 2050 had SFFD added more engines commensurate with the City's growth?
6. Was the City's growth factored into the analysis? (in all Phase 1-3 cases, it was).

Not all possible combinations of the above parameters were considered – some of them were unrealistic and were eliminated by inspection. In total, there were 91 Cases that might be considered, which are listed in Table 1 above.

Having determined the simulation parameters, each trial of the Monte Carlo consisted of the following process:

1. Select an arbitrary day, hour and minute of the year. Based on this, select temperature, windspeed and direction, precipitation and relative humidity from the weather database.
2. Determine the scenario ground motion – there were 100 simulations of these to choose from, each calculated considering spatial correlation.
3. At time step 1, for the TFA of each block for the Phase under consideration and taking time of day into account, estimate the frequency of ignition considering randomness in the ignition equation. Comparing a random number to the frequency, determine if one or more ignitions have occurred in that block
4. Continue stepping time (10 minute time steps were employed) until that fire is discovered and reported. At the time of report, find the closest available engine.
5. Determine the time of arrival of that engine at the fireground, and the size of the fire at that time.
6. Taking into account WSFs for the EFWS, cisterns and Alternative Water Supplies, determine the probability of water being available. Compare this with a random number to determine if water is actually available.
7. If water is not available, on that engine remains on scene, for a standard amount of time, to assure life safety (that is, evacuate occupants from the burning and nearby buildings and attend to other needs as required).
8. If water is available, start application. If the capacity of the engine is sufficient to contain the fire, the engine remains on scene for a standard amount of time. Size of the fire at each time step is calculated taking into account building materials of construction, occupancy, building spacing, number of floors and other features, and weather conditions.
9. If the fire exceeds the capacity of the initial engine, the crew partially contains the fire, which grows at a slower rate. More engines are called for. As and if they arrive, the fire is contained, or not. In the latter case, the fire continues to grow.
10. As the fire grows, track its growth considering on-scene engines and water availability. Determine if and when the fire spreads to neighboring blocks, considering windspeed and direction.
11. Continue this process to the end of the simulation (hour 25), tracking each fire as to if and when contained, burnt out due to lack of fuel (i.e., didn't cross to a neighboring

block, or that block was vacant of fuel) or was still burning at the end. During the entire process, track Required Water at each fire for each time step.

The above is one trial of the Monte Carlo simulation and is illustrated in Figure 91, which should be read from the top (ie, Ground Shaking) and then counter clockwise following the arrows, until the process arrives at the top again, which has been one time step. Repeat for each of 150 ten minute time steps.

For each case, 100 trials were run, with each trial selecting a day and time (and weather) in Step 1, a different scenario ground motion in Step 2, and so on.

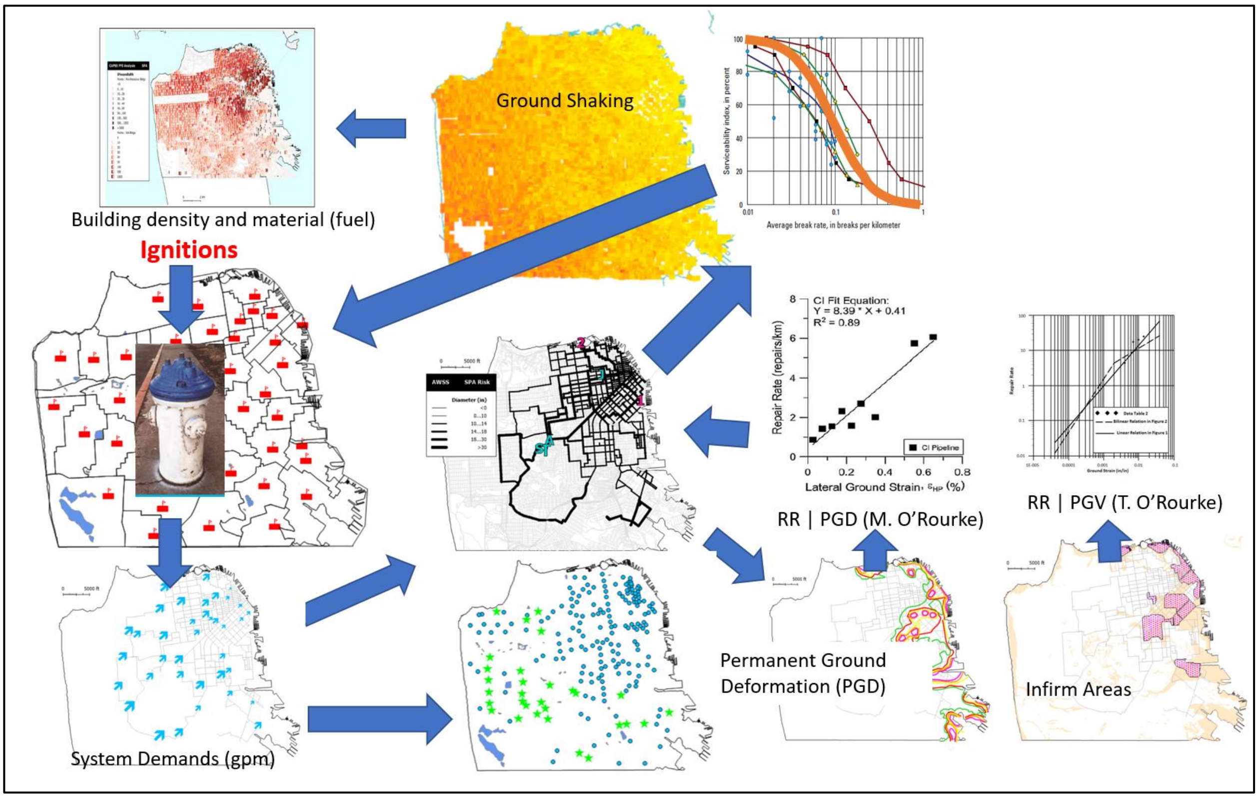


Figure 91 Process for one trial of the Monte Carlo simulation employed in this study. Process begins at the top (ie, Ground Shaking) and then proceeds counter clockwise following the arrows, until the process arrives at the top again, which has been one time step.

5 DETAILED RESULTS

Detailed numerical and graphical results have been transmitted to SFPUC in the form of 46,930 electronic files totaling 122 mb. Results of the analysis of 21 Cases for current and future variations in EFWS and SFFD improvements shows that effective firefighting under current conditions is estimated to require flows of about 140,000 gpm (median, 75th percentile is 200,000+ gpm) after the first few hours, equivalent to a total volume of about 200+ million gallons in the first 24 hours after an earthquake. Results for various Cases show that future water requirements can remain about the same, or be much larger, depending on the improvements made to the EFWS and SFFD.

5.1 Introduction

This section reviews results in three aspects:

- Analysis cases
- File structure for results
- Examination of Case 1 results
- Summary results for selected cases

5.2 Analysis Cases

The Monte Carlo Simulation was applied to a number of cases eacj denoted

Phx v1v2v3v4v5

where

Phx refers to Phases 0 (the existing EFWS high-pressure network) and Phases 1, 2 and 3 refer to succeeding stages of EFWS buildout.

v1 denotes whether and how **system damage** is considered – that is, v1 = D denotes pipe breaks and leaks are included in the analysis, v1 = N considers the system to be undamaged, and v1 = P triggers a probabilistic weighting of damage occurrence.

v2 denotes whether and how **system operational efficiency** is considered – that is, v2 = L denotes a slow operational response to system damage, with some time required to assess damage and respond with valve closures and other measures, v1 = M denotes a moderate operational response, v3 = H denotes good situational awareness (e.g., via a high-resolution SCADA) and rapid response (e.g., via a dense network of automatic or remotely operable motor operated valves, MOVs), and v3=E denotes efficient system operations, significantly exceeding v3=H such that the system is fully functional almost without interruption.

v3 denotes whether **system improvements** have been implemented – that is, v3 = Y denotes system improvements for that Phase have been implemented, while v31 = N denotes no improvements.

v4 denotes whether **SFFD resources have been increased** – that is, v4 = C denotes the current number of SFFD fire engines (initially 43, as described above) are what is available for that Phase, while v4 = A considers SFFD has been increased in size with additional engines and hose tenders commensurate with the population growth for that Phase.

v5 denotes whether **City growth** is considered – that is, v5 = B the current population and building inventory, while v5 = F denotes population and growth projections for 2030 (Phase 1), 2040 (Phase 2) and 2050 (Phase 3) were employed. Use of these specific years is not meant to imply that EFWS expansion will occur by that year.

Thus, for example, Ph0 DLNCB denotes an analysis for Ph0 (i.e., the current EFWS high-pressure network) considering damage to the system, Low system operational response to that damage, No system improvements, Current SFFD resources and current (i.e., 2020) City growth, the latter three variables being consistent with Ph0. Another example: Ph3 PHNAF denotes Ph3 buildout of the EFWS, High system operational response to that damage, No system improvements, a larger SFFD with more resources and Future (i.e., 2050) City growth. In all, there are 91 feasible combinations of Phases and v1 to v5, as shown in Table 10.

Table 10 Case List

Case	Ph	sysDmg	sysEff	sysImpr	SFFD	Growth
1	0	D	L	N	C	B
2	0	D	M	N	C	B
3	0	D	H	N	C	B
4	0	N	E	N	C	B
5	0	P	L	N	C	B
6	0	P	M	N	C	B
7	0	P	H	N	C	B
8	1	D	L	Y	C	F
9	1	D	L	Y	A	F
10	1	D	L	N	C	F
11	1	D	L	N	A	F
12	1	D	M	Y	C	F
13	1	D	M	Y	A	F
14	1	D	M	N	C	F
15	1	D	M	N	A	F
16	1	D	H	Y	C	F
17	1	D	H	Y	A	F
18	1	D	H	N	C	F
19	1	D	H	N	A	F
20	1	N	E	Y	C	F
21	1	N	E	Y	A	F
22	1	N	E	N	C	F
23	1	N	E	N	A	F
24	1	P	L	Y	C	F
25	1	P	L	Y	A	F
26	1	P	L	N	C	F
27	1	P	L	N	A	F
28	1	P	M	Y	C	F
29	1	P	M	Y	A	F
30	1	P	M	N	C	F
31	1	P	M	N	A	F
32	1	P	H	Y	C	F
33	1	P	H	Y	A	F
34	1	P	H	N	C	F
35	1	P	H	N	A	F
36	2	D	L	Y	C	F
37	2	D	L	Y	A	F
38	2	D	L	N	C	F
39	2	D	L	N	A	F
40	2	D	M	Y	C	F
41	2	D	M	Y	A	F
42	2	D	M	N	C	F
43	2	D	M	N	A	F
44	2	D	H	Y	C	F
45	2	D	H	Y	A	F
46	2	D	H	N	C	F
47	2	D	H	N	A	F
48	2	N	E	Y	C	F
49	2	N	E	Y	A	F
50	2	N	E	N	C	F
51	2	N	E	N	A	F
52	2	P	L	Y	C	F
53	2	P	L	Y	A	F
54	2	P	L	N	C	F
55	2	P	L	N	A	F
56	2	P	M	Y	C	F
57	2	P	M	Y	A	F
58	2	P	M	N	C	F
59	2	P	M	N	A	F
60	2	P	H	Y	C	F
61	2	P	H	Y	A	F
62	2	P	H	N	C	F
63	2	P	H	N	A	F
64	3	D	L	Y	C	F
65	3	D	L	Y	A	F
66	3	D	L	N	C	F
67	3	D	L	N	A	F
68	3	D	M	Y	C	F
69	3	D	M	Y	A	F
70	3	D	M	N	C	F
71	3	D	M	N	A	F
72	3	D	H	Y	C	F
73	3	D	H	Y	A	F
74	3	D	H	N	C	F
75	3	D	H	N	A	F
76	3	N	E	Y	C	F
77	3	N	E	Y	A	F
78	3	N	E	N	C	F

Case	Ph	sysDmg	sysEff	sysImpr	SFFD	Growth
79	3	N	E	N	A	F
80	3	P	L	Y	C	F
81	3	P	L	Y	A	F
82	3	P	L	N	C	F
83	3	P	L	N	A	F
84	3	P	M	Y	C	F
85	3	P	M	Y	A	F
86	3	P	M	N	C	F
87	3	P	M	N	A	F
88	3	P	H	Y	C	F
89	3	P	H	Y	A	F
90	3	P	H	N	C	F
91	3	P	H	N	A	F

In consultation with SFPUC and AECOM it was determined that not all 91 possible cases need be analyzed, so that 21 cases were analyzed, consisting of Cases:

1) 1 Ph0 DLNCB
2) 2 Ph0 DMNCB
3) 3 Ph0 DHNCB
4) 4 Ph0 NENCB
5) 20 Ph1 NEYCF
6) 22 Ph1 NENCF
7) 48 Ph2 NEYCF
8) 50 Ph2 NENCF
9) 64 Ph3 DLYCF
10) 65 Ph3 DLYAF
11) 66 Ph3 DLNCF
12) 67 Ph3 DLNAF
13) 68 Ph3 DMYCF
14) 69 Ph3 DMYAF
15) 72 Ph3 DHYCF
16) 73 Ph3 DHYAF
17) 74 Ph3 DHNCF
18) 75 Ph3 DHNAF
19) 76 Ph3 NEYCF
20) 77 Ph3 NEYAF
21) 78 Ph3 NENCF

It is anticipated a number of additional cases will be analyzed as the EFWS design proceeds.

These 21 cases were run for both the San Andreas Mw 7.9 and Hayward Mw 7 scenario events, so in total 42 cases were run.

5.3 File structure

Data files transmitting complete results for all analyzed cases have been posted to the SFPUC project SharePoint archive folder "FFEWRS RESULTS" in a zip file containing 46,930 electronic files totaling 122 mb. The zip file is named

"FFEWRS output 28 May 2021.zip"

and is highlighted in Figure 92.

Figure 92 Image of zip file uploaded to Sharepoint archive

The zip file contains 42 folders named:

H7.05 Case 1 Ph0 DLNCB totSim 100 ts=10 2021-05-26 18-02
H7.05 Case 2 Ph0 DMNCB totSim 100 ts=10 2021-05-26 18-13
H7.05 Case 3 Ph0 DHNCB totSim 100 ts=10 2021-05-26 18-23
H7.05 Case 4 Ph0 NENCB totSim 100 ts=10 2021-05-26 18-34
H7.05 Case 20 Ph1 NEYCF totSim 100 ts=10 2021-05-26 18-45
H7.05 Case 22 Ph1 NENCF totSim 100 ts=10 2021-05-26 18-58
H7.05 Case 48 Ph2 NEYCF totSim 100 ts=10 2021-05-26 19-11
H7.05 Case 50 Ph2 NENCF totSim 100 ts=10 2021-05-26 19-26
H7.05 Case 64 Ph3 DLYCF totSim 100 ts=10 2021-05-26 19-45
H7.05 Case 65 Ph3 DLYAF totSim 100 ts=10 2021-05-26 20-12
H7.05 Case 66 Ph3 DLNCF totSim 100 ts=10 2021-05-26 20-42
H7.05 Case 67 Ph3 DLNAF totSim 100 ts=10 2021-05-26 21-02
H7.05 Case 68 Ph3 DMYCF totSim 100 ts=10 2021-05-26 21-18
H7.05 Case 69 Ph3 DMYAF totSim 100 ts=10 2021-05-26 21-33
H7.05 Case 72 Ph3 DHYCF totSim 100 ts=10 2021-05-26 21-47
H7.05 Case 73 Ph3 DHYAF totSim 100 ts=10 2021-05-26 22-03
H7.05 Case 74 Ph3 DHNCF totSim 100 ts=10 2021-05-26 22-20
H7.05 Case 75 Ph3 DHNAF totSim 100 ts=10 2021-05-26 22-35
H7.05 Case 76 Ph3 NEYCF totSim 100 ts=10 2021-05-26 22-51
H7.05 Case 77 Ph3 NEYAF totSim 100 ts=10 2021-05-26 23-06
H7.05 Case 78 Ph3 NENCF totSim 100 ts=10 2021-05-26 23-21
SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-05-14 22-23
SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-05-15 13-45
SA7.9 Case 1 Ph0 DLNCB totSim 100 ts=10 2021-05-17 17-06
SA7.9 Case 1 Ph0 DLNCB totSim 100 ts=10 2021-05-17 20-36
SA7.9 Case 2 Ph0 DMNCB totSim 100 ts=10 2021-05-17 21-15
SA7.9 Case 3 Ph0 DHNCB totSim 100 ts=10 2021-05-17 21-50
SA7.9 Case 4 Ph0 NENCB totSim 100 ts=10 2021-05-17 22-23
SA7.9 Case 20 Ph1 NEYCF totSim 100 ts=10 2021-05-17 22-54
SA7.9 Case 22 Ph1 NENCF totSim 100 ts=10 2021-05-17 23-28
SA7.9 Case 48 Ph2 NEYCF totSim 100 ts=10 2021-05-18 00-03
SA7.9 Case 50 Ph2 NENCF totSim 100 ts=10 2021-05-18 00-41
SA7.9 Case 64 Ph3 DLYCF totSim 100 ts=10 2021-05-18 01-20
SA7.9 Case 65 Ph3 DLYAF totSim 50 ts=10 2021-05-17 16-38
SA7.9 Case 65 Ph3 DLYAF totSim 100 ts=10 2021-05-18 02-05
SA7.9 Case 66 Ph3 DLNCF totSim 100 ts=10 2021-05-18 02-47
SA7.9 Case 67 Ph3 DLNAF totSim 100 ts=10 2021-05-18 03-33
SA7.9 Case 68 Ph3 DMYCF totSim 100 ts=10 2021-05-18 04-15
SA7.9 Case 69 Ph3 DMYAF totSim 100 ts=10 2021-05-18 04-59
SA7.9 Case 72 Ph3 DHYCF totSim 100 ts=10 2021-05-18 05-41
SA7.9 Case 73 Ph3 DHYAF totSim 100 ts=10 2021-05-18 06-23
SA7.9 Case 74 Ph3 DHNCF totSim 100 ts=10 2021-05-18 07-05
SA7.9 Case 75 Ph3 DHNAF totSim 100 ts=10 2021-05-18 07-47
SA7.9 Case 76 Ph3 NEYCF totSim 100 ts=10 2021-05-18 08-28
SA7.9 Case 77 Ph3 NEYAF totSim 100 ts=10 2021-05-18 09-10
SA7.9 Case 78 Ph3 NENCF totSim 100 ts=10 2021-05-18 09-54

For example, a folder name denotes the analysis is for

- the San Andreas Mw 7.9 event

- is Case 1 with
- identifier code "Ph0 DLNCB" as explained previously
- has a total of 100 simulations for the Case
- uses a time step "ts" of 10 minutes and
- is timestamped with date and time shown. The date and time are important as the unique identifier of a specific analysis.

Each folder contains 100 subfolders, one for each simulation, and also contains selected summary data files as shown in Figure 93 (the grayed out subfolder can be ignored for now – it is created in all cases but only optionally contains additional data, that option not exercised at this time).

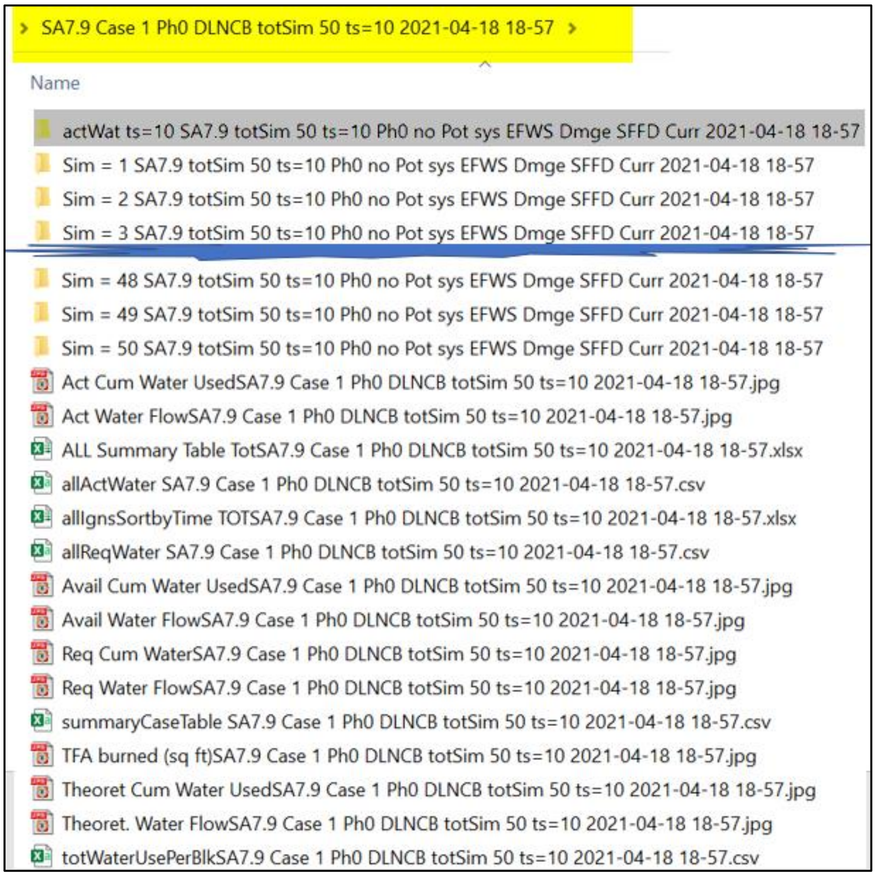


Figure 93 Example image of Case output folder structure

Case summary files

Summary files for the 100[17] simulations are contained in the main folder and are shown in Figure 94. File "ALL Summary Table TotSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv" is a comma separated variable ("csv") file that summarizes all simulations for this Case, a portion of which is shown in Figure 95 (and explained further in Figure 96 for Simulation (or

[17] The example figures are for an earlier run of 50 simulations, rather than 100 as delivered.

"trial") 1 of Case 1). Other files detail the actual, available, required and "theoretical" water used for each timestep, the timeline of area burned, the blocks that had fire, the timeline of burnt total floor area (TFA), the timeline of engine deployment (i.e., at each time step, which fire each engine is assigned to), the fire timeline (i.e., growth of each fire), a summary of ignitions (time, block), and which fires are due to firespread from another block ("XedTable").

Act Cum Water UsedSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Act Water FlowSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
ALL Summary Table TotSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.xlsx
allActWater SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv
allIgnsSortbyTime TOTSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.xlsx
allReqWater SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv
Avail Cum Water UsedSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Avail Water FlowSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Req Cum WaterSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Req Water FlowSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
summaryCaseTable SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv
TFA burned (sq ft)SA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Theoret Cum Water UsedSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
Theoret. Water FlowSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.jpg
totWaterUsePerBlkSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv

Figure 94 Example summary files for one Case

	A	B	C	D	E	F	G	H	I	J	K	L
1	No	gmNo	wIndx	month	day	hour	tempF	windspeed_mph	winddir	precip_in	totNoIgns	availWater
2	1	33	20390	1	29	2	56	2.2	270	0	85	900
3	2	4	36079	11	12	19	67	4.5	80	0	90	910
4	3	43	27395	11	16	23	62	13.4	290	0	111	1550
5	4	1	4252	3	27	16	49.3	4.5	300	0	96	1080
6	5	97	39029	3	15	17	57.8	4.5	330	0	91	980
7	6	95	8290	9	11	22	74.4	4.5	241	0	70	720
8	7	19	41641	7	2	13	59	2.2	244	0	93	960
9	8	98	4952	4	25	20	60.5	13.4	330	0	90	1200
10	9	25	28176	12	19	12	48.5	2.2	60	0.1	77	780
11	10	22	11726	2	2	2	50.3	2.2	179	0	96	1050
12	11	42	24810	8	1	6	63.4	6.7	260	0	66	750
13	12	27	21062	2	26	2	57.1	4.5	280	0	85	1020
47	46	2	10813	12	26	1	59.3	2.2	303	0	86	860
48	47	17	28363	12	27	7	36.3	2.2	102	0	94	980
49	48	2	3030	2	4	18	52.4	11.2	290	0	90	1400
50	49	50	39764	4	15	8	50.3	4.5	100	0	85	970
51	50	70	44451	10	27	15	54.1	2.2	175	0	81	820
52												

M	N	O	P	Q	R	S	T
initialSFED	initialAreaFireSQFT	initialEngsReqd	totNoBlksInvolved	totBurntAreaSF	totActualWaterGals	totAvailWaterGals	totTheoretWaterGals
425.1	637036	42	91	13185858.67	15339900	155280000	72464780
765.8	1147941	70.1	98	17207166.91	29922860	157410000	153582300
3571.8	5357043	231.9	161	21690148.3	81681100	244830000	398040580
398.5	596983	65.7	109	15327377.24	20240670	183075000	95343400
338.3	505950	51.3	99	13608369.61	22189600	171705000	107508040
71.6	107574	29.4	74	11085721	11384280	123750000	53682180
180.1	269104	38.5	98	14779862.33	7463890	157065000	33994670
738.2	1105646	158.5	127	15600252.28	54527590	191775000	263243320
186.8	279382	32.8	80	11524189.33	13143410	136140000	63898300
228.5	341765	50.6	112	17116675.22	24493340	181920000	133170980
53.7	80217	33.2	79	16449539	1265460	118965000	4073970
544.1	815892	80	104	14759599.82	18331810	176550000	87265990
433.6	650628	54	90	12952281.64	26116960	153075000	128379030
521.6	781882	58.2	99	13827273.67	23637460	168135000	115070810
1649.1	2472803	181.1	144	19052293.85	58871910	222435000	282845200
672	1007343	74.5	102	14948589.53	41420270	174180000	202123580
261.7	392355	39.4	86	15139457.96	23810570	153495000	117598130

Figure 95 Example "ALL Summary Table TotSA7.9 Case 1 Ph0 DLNCB totSim 50 ts=10 2021-04-18 18-57.csv" file, Case 1 Trial 1

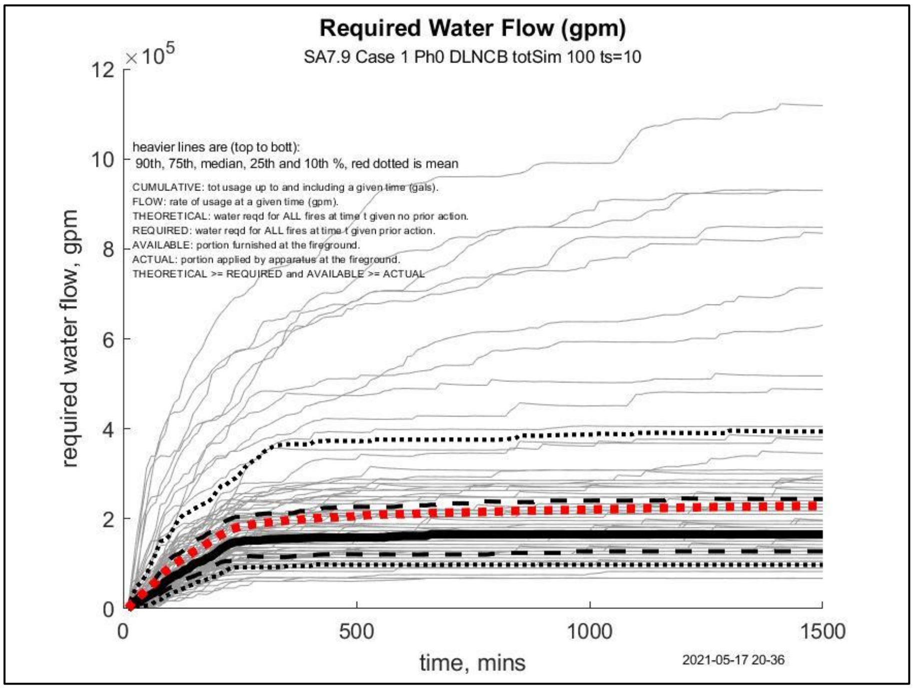
Col Name	explanation	value
No	Simulation no. 1 of 50 (i.e., 50 trials)	1
gmNo	ground motion ID used for this trial	33
wIndx	weather index (i.e., number of day)	20390
month	month for day corresp. to windx (January)	1
day	day of month	29
hour	hour of day (2 am)	2
tempF	temperature (F) at that time	56
windspeed_mph	windspeed (mph) at that time	2.2
winddir	direction of wind at that time (due West)	270
precip_in	precipitation at that time (inches)	0
totNoIgns	total no. original ignitions this trial	85
availWater	no. fires in this trial that had water available * time step	900
initialSFED	sum of single family equiv. dwellings (SFED) on fire at first arrival, all igns.	425.1
initialAreaFireSQFT	sum of floor area (sq. ft.) burning at first arrival, all igns.	637036
initialEngsReqd	initial no. of engines required	42
totNoBlksInvolved	total no. of blocks involved, including fire spread	91
totBurntAreaSF	tot. burnt area at 25th hour (sq. ft)	13185858.67
totActualWaterGals	total actual water used (gals) by 25th hour (gallons)	15339900
totAvailWaterGals	total available water (i.e., pumping capacity if full used) by 25th hours (gallons)	155280000
totTheoretWaterGals	tot "theoretical" water needed at hour 25 (gallons)	72464780

Figure 96 Explanation of line 1 of data in Figure 95 Case 1 Trial 1

There are a number of summary plots in jpg files.

File "Req Water FlowSA7.9 Case 1 Ph0 DLNCB totSim 100 ts=10 2021-05-17 20-36.jpg" is a jpg file of a plot of the Required water used for all 100 simulations for this Case, vs. time. This is shown as the upper plot in Figure 97: Required water flows (gpm), with the lower plot being cumulative Required water (gallons). As noted in the legend, individual simulations are shown as thin gray lines, with the median of the 50 simulations shown as a heavy black line, the 25th and 75th percentiles as heavy dashed lines, and the 10th and 90th percentiles shown as heavy dotted lines. The mean of the 50 simulations is shown as heavy red dashed line. The legend also provides a summary description of Actual vs. Available vs. Required vs. Theoretical water usage, as was described above. As can be seen in the figure, at 1500 minutes (ie, 25th hour) the median (i.e., 50th %) Required flow for the 100 simulations of this Case is 75,000 gpm, the mean (i.e., arithmetic average) Required flow is 88,000 gpm, the 75th % Required flow is 105,000 gpm and the 90th % Required from is 172,500 gpm.

The cumulative Required Water is also shown in Figure 97, where the median total amount of water required by the 25th hour is seen to be about 95 million gallons, the mean Required water about 125 million galls and the 75th percentile about 148 million gallons. The equivalent number of fire engines required to flow 148 million gallons of water is about 67 engines – that is, about 25% more engines than SFFD can currently deploy in a timely manner (this includes reserves). If as currently planned, a dozen or so more hose tenders are added to the roster, and with some mutual aid, the Required Water could be effectively applied. This is for current conditions and assets at risk (i.e., Phase 0). Table 2 summarizes Required Water (total usage in gallons, and flows in gpm) for selected time periods for the 9 analyzed cases. It can be seen that 24th hour Required water 75th percentile demands range from 140 to 220 million gallons, depending on the Case.



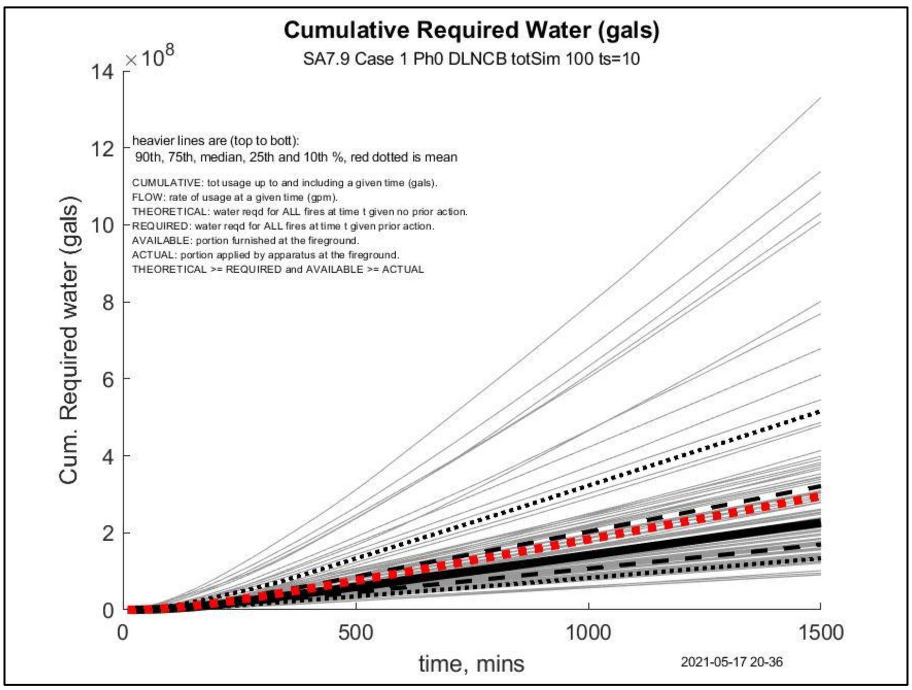


Figure 97 Plot of Required water usage for this Case (Case identification information shown at top with unique timestamp in lower left corner): (top) flows, gpm; (bottom) cumulative usage, gallons.

Example simulation results

Each subfolder (e.g., “Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57”) contains the csv files shown Figure 98, each of which provide actual water, area burned etc for each time step

actualWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
areaBurnedTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
availWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
blksInvolved Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
burntTFAtimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
engTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
fireTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
igns Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
reqWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
thWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv
XedTable Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57.csv

Figure 98 One simulation example subfolder content

For example, the Required Water (“reqWater”) timeline is shown in Figure 14 (note the view is split in four quadrants) and shows for each of 91 ignitions (the number of ignitions for this simulation – the number varies with each simulation; note that each row represents an ignition) the required water flow (gpm) at minute 0 (col A), minute 10 (col B) and so on to minute 1500 (col ET), each column being a 10 minute timestep. Total required water per fire in gallons is simply the summation of a row (times 10) and total water flow (gpm) at any 10 minute time step is simply the summation of that column.

	A	B	C	D	E	F	G	H	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET
1	0	181	147	125	107	92	79	67	0	0	0	0	0	0	0	0	0	0	0
2	0	269	215	181	155	133	114	98	0	0	0	0	0	0	0	0	0	0	0
3	66	50	42	36	31	26	23	19	0	0	0	0	0	0	0	0	0	0	0
4	82	61	51	43	37	32	27	23	0	0	0	0	0	0	0	0	0	0	0
5	87	67	56	48	41	35	30	26	0	0	0	0	0	0	0	0	0	0	0
6	0	102	83	70	60	51	44	38	0	0	0	0	0	0	0	0	0	0	0
7	39	31	26	22	19	16	14	12	0	0	0	0	0	0	0	0	0	0	0
8	0	343	246	203	173	148	128	110	0	0	0	0	0	0	0	0	0	0	0
9	53	371	309	264	227	195	167	142	0	0	0	0	0	0	0	0	0	0	0
10	120	86	71	60	52	45	38	33	0	0	0	0	0	0	0	0	0	0	0
11	86	62	51	43	37	32	27	23	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	13	10	8	5	3	1	0	0	0	0	0
84	0	0	0	0	0	0	0	0	12	10	8	6	4	2	1	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	132	106	90	77	66	57	48
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500
91	0	0	0	0	0	0	0	0	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500	7500

Figure 99 Example contents of file “reqWaterTimeline Sim = 1 SA7.9 totSim 50 ts=10 Ph0 no Pot sys EFWS Dmge SFFD Curr 2021-04-18 18-57” (note the view is split in four quadrants)

5.4 Required Water

The above sections have described in some detail the details of the electronic file deliverables of this project. This section presents summary tables of some of the results.

Table 11 presents summary results for the San Andreas scenario event, at hours 1, 2, 4, 8, 12 and 24 for the 21 Cases discussed above. The summary results are Required Water flow (gpm), total Required Water flow (gallons) and Burnt TFA (sq. ft). Three measures of these quantities are provided: median, mean and 75th percentile.

Table 12 presents comparable data, for the Hayward scenario event.

In each table, for each Case, headers identify the Case number, the scenario event (SA 7.9 or H7), the Phase, the Case code previously explained (e.g., DLNCB), the number of simulations (sim = 100), and the timestamp of the run.

This same data is presented in much greater detail in the electronic files, and also in graphical form such as Figure 97.

San Andreas Mw 7.9 scenario

Table 11 Selected Case results, Mw 7.9 San Andreas scenario

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	1	SA7.9	Ph0	DLNCB	sim = 100	2021-05-17 20-36			
1	1,391,215	2,200,707	2,398,095	37,925	60,101	68,534	6,073,395	6,558,901	7,746,627
2	5,450,310	7,838,924	9,104,115	85,073	112,493	129,626	10,013,565	9,816,052	11,322,081
4	20,567,835	26,226,905	30,591,395	148,343	181,792	203,760	13,722,122	14,042,751	15,013,476
8	57,747,605	73,483,358	83,810,745	158,355	205,114	226,475	16,188,562	16,771,795	17,941,779
12	97,126,680	124,073,438	140,085,875	165,258	214,280	234,132	17,721,483	18,218,647	19,345,646
24	217,945,215	284,066,060	309,417,000	165,059	228,439	243,896	18,805,777	19,494,772	20,138,189

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	2	SA7.9	Ph0	DMNCB	sim = 100	2021-05-17 21-15			
1	1,255,945	1,896,652	2,647,275	30,841	53,215	74,767	6,384,838	6,929,902	8,560,807
2	4,675,270	6,469,846	8,969,385	70,876	87,156	114,439	10,254,386	10,162,923	11,484,436
4	16,345,395	20,463,367	25,698,970	116,126	141,992	164,095	13,104,007	13,326,021	14,224,280
8	45,946,150	57,607,466	69,170,045	128,088	162,931	197,338	15,638,418	15,883,424	17,023,214
12	77,580,355	97,880,740	116,374,045	127,862	170,872	203,276	16,660,032	17,198,452	18,643,632
24	176,196,300	225,078,261	265,745,535	131,445	180,384	218,535	17,603,472	18,462,807	19,734,070

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	3	SA7.9	Ph0	DHNCB	sim = 100	2021-05-17 21-50			
1	1,137,315	1,866,674	2,305,065	35,644	53,877	63,928	6,180,604	6,873,323	8,784,098
2	4,736,810	6,348,172	7,098,815	70,604	84,456	101,050	10,215,474	9,883,545	11,015,106
4	16,017,340	19,048,431	22,532,790	113,099	127,981	153,976	12,919,952	12,834,924	13,737,418
8	44,944,890	52,508,526	62,958,075	118,837	148,174	184,056	14,746,539	15,362,821	16,713,232
12	73,886,420	89,192,294	108,299,705	120,467	155,730	188,025	16,223,247	16,779,169	17,985,514
24	161,506,565	205,388,588	245,721,935	120,072	166,243	195,212	17,014,129	17,952,085	18,886,069

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	4	SA7.9	Ph0	NENCB	sim = 100	2021-05-17 22-23			
1	989,065	1,726,091	1,751,555	29,964	47,639	52,221	6,125,272	6,832,634	8,552,232
2	4,110,440	5,737,384	6,456,865	60,978	76,128	89,719	10,133,817	9,991,565	11,256,234
4	12,927,880	17,249,632	20,050,455	98,274	116,963	133,421	12,647,680	12,636,931	13,673,695
8	37,488,420	48,410,831	55,955,625	105,660	139,427	158,226	14,354,011	15,177,212	16,237,165
12	62,652,855	83,122,634	94,711,645	105,338	149,046	159,105	16,161,046	16,588,637	17,411,674
24	140,612,055	194,052,835	222,871,470	112,510	159,258	184,002	16,857,818	17,850,175	18,150,123

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	20	SA7.9	Ph1	NEYCF	sim = 100	2021-05-17 22-54			
1	1,171,530	1,907,879	2,362,740	32,462	52,335	62,402	11,709,084	12,075,294	14,752,361
2	4,292,980	6,179,754	7,857,980	61,784	78,539	104,329	16,463,246	16,458,245	18,111,069
4	13,089,660	18,313,281	24,591,340	96,182	127,097	165,003	19,148,948	19,675,971	20,385,586
8	36,058,210	51,481,342	66,167,340	104,064	146,538	181,841	22,764,208	23,263,769	25,419,354
12	62,893,430	88,145,003	110,916,710	112,981	155,876	194,006	24,250,158	25,140,653	26,356,993
24	143,242,345	205,044,579	256,042,890	112,621	167,254	202,586	25,421,403	26,431,649	27,276,484

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	22	SA7.9	Ph1	NENCF	sim = 100	2021-05-17 23-28			
1	1,253,950	1,969,794	2,636,330	38,011	55,524	80,568	12,114,885	12,088,829	15,135,430
2	4,820,015	6,472,230	8,759,305	68,944	82,589	107,720	16,613,484	16,428,332	18,599,383
4	15,288,925	18,913,839	23,945,920	112,025	126,870	151,409	19,269,085	19,777,223	21,270,366
8	42,212,680	52,582,349	63,877,145	121,435	149,952	173,300	23,302,719	23,561,334	25,737,301
12	71,445,530	89,982,109	106,042,265	124,166	159,291	184,009	24,141,068	25,107,416	26,807,268
24	161,177,410	209,452,193	241,440,065	128,048	169,887	202,599	25,425,756	26,244,288	27,741,025

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	48	SA7.9	Ph2	NEYCF	sim = 100	2021-05-18 00-03			
1	1,322,300	2,005,477	2,387,100	37,644	54,558	63,437	20,034,920	18,957,171	21,956,161
2	4,354,210	6,179,094	7,698,940	56,920	75,341	91,629	23,888,789	23,878,774	25,148,952
4	12,936,320	18,007,641	21,178,490	98,441	123,216	139,056	26,124,559	26,917,463	27,866,586
8	36,647,015	51,198,363	57,036,810	105,594	150,302	159,368	31,611,899	31,948,674	33,254,545
12	63,205,560	88,863,457	98,012,975	105,715	163,142	166,046	32,371,524	33,417,080	33,888,012
24	142,715,990	212,507,420	220,579,450	113,026	178,722	176,621	33,513,741	34,964,177	35,581,884

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	50	SA7.9	Ph2	NENCF	sim = 100	2021-05-18 00-41			
1	1,264,460	1,787,696	2,262,075	36,709	48,845	65,669	19,972,419	18,721,699	21,922,542
2	4,710,555	5,721,779	7,503,965	58,503	71,038	92,055	24,003,139	23,627,291	25,132,058
4	14,020,085	16,677,650	20,856,705	95,153	115,250	127,472	25,751,286	26,668,721	27,102,774
8	37,953,715	47,899,020	55,395,170	102,692	141,156	159,371	31,274,181	31,694,002	32,849,286
12	61,890,810	82,874,820	96,629,565	102,033	148,963	166,927	32,388,153	33,060,874	34,060,371
24	141,648,060	194,134,862	216,036,940	112,719	159,024	173,056	33,417,956	34,548,456	35,207,102

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	64	SA7.9	Ph3	DLYCF	sim = 100	2021-05-18 01-20			
1	1,444,630	1,940,000	2,426,650	42,307	52,643	65,473	26,134,667	25,137,644	28,381,101
2	5,339,630	6,382,641	7,910,195	75,664	86,853	110,411	31,090,092	30,846,035	32,808,692
4	19,911,930	22,590,929	28,512,995	144,078	168,342	212,679	36,515,373	38,401,857	41,364,355
8	56,184,900	67,717,751	86,412,360	158,347	202,774	240,559	44,662,435	45,950,865	48,655,820
12	97,039,725	118,189,252	145,122,385	157,914	216,239	260,779	45,522,318	47,201,582	49,671,641
24	215,677,380	281,774,612	339,679,750	165,368	233,123	274,085	47,541,740	49,370,748	51,689,313

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	65	SA7.9	Ph3	DLYAF	sim = 100	2021-05-18 02-05			
1	1,887,730	2,775,484	2,857,530	57,888	81,987	92,935	22,331,538	21,528,318	25,421,238
2	8,334,565	10,874,997	12,656,115	131,461	163,737	188,676	30,771,900	30,603,452	32,227,143
4	26,881,870	34,047,366	38,270,915	173,829	209,886	238,059	37,295,853	38,084,152	41,385,291
8	70,886,815	88,443,231	98,700,775	188,195	238,354	262,213	42,943,725	44,785,920	47,745,313
12	117,518,785	146,949,736	161,287,050	188,023	248,913	270,612	43,908,960	46,004,852	49,456,660
24	254,369,330	332,188,918	366,472,575	191,502	262,908	285,350	45,526,423	47,899,987	50,225,050

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	66	SA7.9	Ph3	DLNCF	sim = 100	2021-05-18 02-47			
1	1,324,155	2,096,662	2,482,885	35,238	55,661	69,585	26,226,133	24,989,903	28,277,395
2	4,440,160	6,727,163	8,334,885	68,653	90,348	112,134	30,544,973	30,642,074	32,345,040
4	16,101,590	22,912,373	28,399,965	128,001	165,660	198,091	37,317,552	37,569,606	39,727,013
8	49,953,150	67,436,022	80,364,555	143,799	199,323	228,323	43,658,483	45,250,234	49,363,123
12	86,696,060	117,003,313	136,760,230	150,385	211,889	240,217	44,230,999	46,763,887	50,281,589
24	198,393,515	275,931,376	316,901,175	154,152	226,830	255,097	46,265,867	48,631,515	51,349,587

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	67	SA7.9	Ph3	DLNAF	sim = 100	2021-05-18 03-33			
1	1,844,460	2,733,856	3,264,000	59,980	81,972	101,785	22,235,018	20,990,237	25,384,898
2	8,841,305	11,096,348	12,689,770	146,610	170,377	186,337	30,386,020	30,207,320	32,161,653
4	29,517,820	34,954,412	37,960,025	188,387	213,950	226,490	35,885,548	37,465,365	40,383,416
8	77,418,295	89,626,825	95,929,530	196,787	237,728	256,616	42,932,334	44,418,371	47,427,834
12	125,763,335	148,574,395	159,528,305	203,330	250,790	267,297	43,326,441	45,687,432	48,609,625
24	275,022,805	334,291,091	359,693,880	210,124	262,226	281,481	45,247,229	47,241,914	49,907,466

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	68	SA7.9	Ph3	DMYCF	sim = 100	2021-05-18 04-15			
1	1,258,000	1,887,985	2,501,050	36,873	51,846	71,035	27,630,712	27,044,658	28,993,945
2	4,470,760	6,012,056	7,883,000	61,316	76,577	97,521	30,806,791	31,153,465	31,923,300
4	14,109,625	18,754,560	25,331,120	98,724	131,549	173,134	34,264,992	35,569,295	38,166,821
8	39,702,040	55,395,912	70,453,065	112,649	167,948	200,501	40,843,470	42,463,560	44,117,290
12	68,350,715	97,284,348	120,008,120	122,241	179,804	206,894	41,437,239	43,574,168	44,874,177
24	154,936,155	232,937,950	268,869,550	124,100	194,487	210,338	43,090,191	45,434,158	47,542,718

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	69	SA7.9	Ph3	DMYAF	sim = 100	2021-05-18 04-59			
1	1,811,825	2,966,725	3,683,400	58,184	89,892	115,741	23,216,896	21,820,975	25,494,264
2	8,220,875	11,461,571	14,859,940	128,883	165,350	191,161	30,425,914	30,192,228	31,720,085
4	24,926,825	33,241,398	40,271,180	153,565	191,284	211,353	33,518,854	35,179,165	37,421,458
8	62,848,705	83,227,689	98,346,735	160,505	222,282	258,941	40,071,239	41,602,928	43,223,975
12	102,853,620	138,332,788	162,844,585	164,156	234,344	278,266	41,058,977	42,751,818	44,444,160
24	218,806,855	313,275,818	365,440,150	165,176	249,334	288,888	42,052,328	44,590,338	46,390,267

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	72	SA7.9	Ph3	DHYCF	sim = 100	2021-05-18 05-41			
1	1,020,750	1,707,098	2,073,030	31,576	47,385	65,287	26,599,412	25,491,585	28,707,020
2	3,807,210	5,485,676	7,191,215	53,830	68,631	91,189	30,164,951	30,164,953	31,246,074
4	12,308,715	16,093,263	20,108,760	91,246	111,032	129,882	32,834,211	34,189,654	37,180,660
8	36,300,485	46,354,454	56,205,205	103,963	137,500	159,673	39,315,033	40,448,241	42,867,636
12	61,340,995	80,789,618	98,597,545	105,383	148,449	177,237	40,386,552	41,683,468	43,885,229
24	140,036,560	191,947,453	232,489,380	108,835	160,093	188,237	42,102,382	43,646,562	45,750,551

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	73	SA7.9	Ph3	DHYAF	sim = 100	2021-05-18 06-23			
1	1,656,365	2,790,488	3,776,135	58,677	86,432	122,204	22,407,339	21,258,743	24,630,586
2	8,078,245	11,007,234	14,963,450	125,535	160,518	212,947	30,174,749	30,015,749	31,397,131
4	24,091,810	31,668,517	42,338,300	143,342	181,468	228,712	33,324,250	34,622,192	37,095,877
8	60,640,280	79,804,324	102,202,500	158,261	215,479	262,696	39,640,534	40,874,694	42,373,026
12	98,388,935	133,479,592	165,788,245	158,721	228,880	270,751	40,830,547	42,298,609	43,398,729
24	215,895,235	305,903,349	370,911,045	165,255	245,180	289,105	42,312,534	44,143,987	45,125,477

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	74	SA7.9	Ph3	DHNCF	sim = 100	2021-05-18 07-05			
1	972,990	1,733,132	1,723,250	30,488	48,025	58,456	27,541,796	26,356,872	29,283,847
2	3,993,135	5,550,528	6,060,690	53,945	69,567	86,920	30,513,248	30,689,782	31,616,609
4	12,366,520	16,700,264	20,901,990	91,828	117,100	145,242	34,234,282	34,882,831	37,504,252
8	35,623,175	48,529,142	60,074,560	99,224	146,639	181,802	39,753,537	41,253,839	43,054,971
12	59,305,260	85,235,983	106,155,000	105,209	156,454	188,792	40,501,804	42,382,995	43,989,453
24	136,253,500	204,019,783	245,274,715	105,150	170,313	191,507	42,366,322	44,483,550	46,353,820

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	75	SA7.9	Ph3	DHNAF	sim = 100	2021-05-18 07-47			
1	1,482,460	2,265,014	2,903,760	50,424	70,237	85,113	22,133,058	20,510,587	25,008,624
2	8,015,140	9,449,568	11,851,615	123,053	142,190	177,241	29,870,685	29,631,605	31,127,415
4	24,030,000	27,911,258	34,225,815	136,386	161,106	200,240	32,526,748	33,869,735	36,579,038
8	58,731,975	69,386,743	84,174,805	148,866	181,114	212,499	39,476,769	40,495,731	41,486,449
12	94,871,000	114,069,995	135,608,075	152,115	189,451	222,621	40,515,732	41,752,274	42,397,723
24	207,643,295	253,952,573	304,619,840	157,598	198,034	237,922	41,836,620	43,385,841	44,409,022

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	76	SA7.9	Ph3	NEYCF	sim = 100	2021-05-18 08-28			
1	1,153,150	1,809,347	2,037,930	36,091	50,511	59,400	27,488,383	25,421,715	28,392,240
2	4,451,250	5,744,802	6,446,520	61,097	71,336	84,196	30,308,133	30,343,472	31,385,204
4	13,966,730	16,918,040	19,391,385	101,844	118,524	137,548	33,177,587	34,092,594	37,030,796
8	38,990,665	50,083,048	56,799,145	107,907	153,067	162,454	39,812,471	40,986,993	42,309,906
12	65,162,860	88,638,482	99,109,155	112,929	167,007	179,886	40,825,297	42,151,608	43,499,557
24	149,986,800	214,671,118	241,329,575	120,181	180,760	198,990	42,218,742	43,978,148	45,076,853

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	77	SA7.9	Ph3	NEYAF	sim = 100	2021-05-18 09-10			
1	1,656,925	2,820,946	3,201,220	56,290	84,595	103,258	23,356,445	22,120,557	25,387,460
2	7,946,095	10,789,051	13,055,520	127,422	154,795	191,079	30,363,046	30,362,796	31,864,904
4	24,243,585	30,661,593	37,301,640	136,490	174,713	212,121	32,882,908	34,494,884	37,197,182
8	58,327,955	76,628,548	92,569,425	150,787	205,257	230,189	39,406,591	41,079,327	43,200,343
12	94,106,290	127,978,326	150,583,180	151,699	219,718	255,594	40,569,034	42,542,502	44,200,844
24	207,899,730	294,392,218	333,982,525	161,549	237,548	262,762	42,249,874	44,719,426	46,217,949

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
	median	mean	75%	median	mean	75%	median	mean	75%
Hr	78	SA7.9	Ph3	NENCF	sim = 100	2021-05-18 09-54			
1	1,190,910	1,690,846	1,942,615	35,703	46,128	51,267	27,423,079	25,326,204	29,320,479
2	4,284,425	5,375,529	6,245,720	55,057	66,967	81,767	30,383,338	30,249,904	31,553,729
4	13,102,390	15,839,865	19,018,560	91,354	110,447	134,133	32,799,956	34,375,770	36,898,866
8	37,115,560	46,063,975	57,301,035	105,914	138,115	160,558	39,966,089	40,458,181	41,832,080
12	63,460,260	80,691,143	99,404,210	112,878	148,842	177,904	40,630,775	41,753,412	42,559,194
24	143,789,375	193,469,825	236,128,120	112,664	162,089	195,184	42,240,257	43,508,911	44,614,077

Hayward Mw 7 scenario

Table 12 Selected Case results, Mw 7 Hayward scenario

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
Hr	median	mean	75%	median	mean	75%	median	mean	75%
Case	1	H7.05	Ph0	DLNCB	sim=100	2021-05-2618-02			
1	191,185	430,878	559,015	4,740	10,613	12,731	1,050,465	1,246,650	1,695,975
2	808,630	1,317,102	1,557,580	9,319	17,467	17,907	1,726,694	2,217,920	2,508,458
4	2,139,275	3,931,589	4,798,465	15,213	24,676	31,495	2,901,938	3,583,297	4,612,064
8	6,377,975	10,248,295	12,578,615	15,078	27,196	34,203	4,427,694	5,079,198	6,442,807
12	10,110,510	16,879,134	20,264,915	15,057	28,232	37,548	5,154,145	5,897,988	7,673,398
24	20,943,785	38,239,651	48,314,585	15,013	31,255	41,897	5,997,287	7,178,319	9,191,731

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	2	H7.05	Ph0	DMNCB	sim=100	2021-05-2618-13			
1	107,215	284,007	345,240	1,972	6,738	9,581	604,378	887,972	1,068,478
2	287,665	778,348	1,146,520	2,718	8,870	11,666	1,206,247	1,384,048	1,812,811
4	1,489,005	2,125,817	3,290,545	7,993	12,733	15,951	2,148,007	2,179,358	2,924,069
8	3,629,125	5,443,796	7,990,880	7,709	14,409	22,512	3,360,280	3,590,850	4,661,081
12	5,599,435	8,937,867	12,946,180	7,675	15,011	22,544	4,203,418	4,374,635	5,215,448
24	11,439,255	20,162,827	29,191,110	7,707	16,058	22,529	5,231,256	5,593,801	6,154,114

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	3	H7.05	Ph0	DHNCB	sim=100	2021-05-2618-23			
1	104,645	382,023	496,695	1,943	9,312	11,629	593,704	852,726	1,002,862
2	230,120	1,109,515	1,248,015	1,776	14,001	10,616	875,498	1,302,491	1,509,488
4	960,685	3,286,110	3,563,045	7,734	20,461	22,920	1,694,122	2,406,333	2,358,006
8	3,046,625	8,607,295	8,304,355	7,591	22,892	23,078	2,984,540	3,760,679	4,157,414
12	4,919,505	14,252,054	14,677,890	7,655	23,897	22,593	4,091,021	4,613,273	5,072,926
24	10,401,555	32,162,287	30,934,940	7,518	25,387	22,662	5,214,594	5,792,980	5,849,590

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	4	H7.05	Ph0	NENCB	sim=100	2021-05-2618-34			
1	104,280	370,464	582,880	1,878	8,158	11,853	574,688	855,287	887,333
2	292,535	992,860	1,405,435	2,840	12,270	19,615	968,569	1,244,780	1,615,939
4	1,129,545	2,885,808	4,837,060	7,746	17,522	23,824	1,734,713	2,137,277	2,349,856
8	3,101,750	7,299,819	10,925,520	7,593	19,097	30,033	3,175,004	3,647,248	4,409,472
12	4,914,530	11,999,578	17,702,095	7,577	19,898	30,125	4,088,388	4,309,411	5,062,618
24	10,480,605	27,382,510	40,021,125	7,540	22,335	30,065	5,214,594	5,641,846	5,809,874

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	20	H7.05	Ph1	NEYCF	sim=100	2021-05-2618-45			
1	141,065	472,685	542,930	2,718	10,742	11,726	960,725	1,670,718	1,961,036
2	358,095	1,398,020	1,327,795	8,418	18,830	17,369	2,133,531	2,664,849	3,369,968
4	2,054,915	4,553,101	4,452,330	8,437	29,653	34,207	3,614,482	4,503,562	5,714,520
8	4,076,180	12,004,458	13,610,290	11,769	32,271	37,678	5,869,149	6,914,649	8,208,731
12	6,846,705	20,011,288	22,839,410	15,005	34,245	37,551	6,961,398	8,162,106	9,193,640
24	19,335,495	45,469,760	49,890,745	15,011	36,615	37,500	8,932,463	10,453,074	12,391,457

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	22	H7.05	Ph1	NENCF	sim=100	2021-05-2618-58			
1	132,705	449,545	597,045	2,699	10,507	12,410	1,145,303	1,619,763	2,054,756
2	478,530	1,356,816	1,676,545	8,840	18,454	23,225	2,229,350	2,791,466	3,553,324
4	2,125,940	4,306,359	4,823,040	15,266	27,772	30,462	3,659,067	4,673,455	5,563,031
8	5,821,605	11,315,781	12,085,525	15,153	30,574	30,989	5,768,984	7,068,519	7,688,090
12	9,443,985	18,724,853	19,324,805	15,069	31,333	31,219	7,095,575	8,180,121	9,015,959
24	20,620,410	42,347,896	40,986,770	15,022	34,248	37,692	8,677,924	10,244,310	13,107,476

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	48	H7.05	Ph2	NEYCF	sim=100	2021-05-2619-11			
1	187,610	460,925	542,825	4,932	10,915	12,095	2,252,324	2,709,137	3,562,301
2	884,975	1,474,623	1,592,720	11,028	22,320	26,751	4,561,807	4,626,904	5,797,034
4	3,212,345	5,620,686	6,392,620	23,385	40,408	49,923	7,491,361	8,427,066	10,004,611
8	9,034,185	15,692,218	17,656,820	23,050	43,524	53,058	10,983,942	11,935,177	14,424,660
12	14,491,465	26,219,327	30,656,600	22,797	44,166	52,740	12,915,319	14,000,764	16,782,187
24	31,890,935	58,439,761	70,869,850	30,000	45,248	52,762	18,306,130	18,229,248	21,968,712

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	50	H7.05	Ph2	NENCF	sim=100	2021-05-2619-26			
1	168,595	605,898	651,245	4,435	14,692	13,118	2,776,793	2,842,529	3,451,382
2	862,100	1,940,837	1,823,330	12,255	28,222	29,323	3,771,139	4,588,848	5,587,925
4	3,309,360	6,683,669	6,876,815	22,835	44,812	46,488	7,374,345	8,239,910	10,293,743
8	9,180,940	17,979,768	19,924,060	22,988	49,067	57,051	10,423,575	11,582,708	14,507,221
12	15,213,475	29,959,902	33,569,835	27,903	50,744	60,091	12,589,860	13,604,201	16,338,263
24	37,608,335	68,381,517	77,630,835	30,005	55,465	60,009	17,758,149	17,437,214	22,226,906

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	64	H7.05	Ph3	DLYCF	sim=100	2021-05-2619-45			
1	559,600	709,486	970,345	13,031	18,320	23,594	4,144,787	4,531,528	6,142,329
2	1,796,790	2,620,145	3,149,750	24,306	42,807	48,839	8,609,189	8,556,246	10,745,111
4	6,496,615	10,185,151	12,388,440	45,595	71,671	90,922	13,812,019	14,903,204	17,821,527
8	17,970,680	28,086,952	36,163,970	45,449	76,442	98,224	18,971,014	20,152,935	24,162,895
12	29,079,315	46,702,611	58,765,200	45,312	78,478	97,567	21,588,378	23,484,334	28,119,428
24	62,692,750	103,827,028	126,939,270	48,873	79,984	97,637	29,502,757	30,066,646	35,166,447

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	65	H7.05	Ph3	DLYAF	sim=100	2021-05-2620-12			
1	571,760	781,562	1,092,725	12,831	20,251	27,594	4,642,210	4,957,541	6,765,229
2	1,888,710	2,617,734	3,011,400	26,678	36,435	43,027	9,548,270	9,184,416	11,414,026
4	6,298,600	8,442,885	9,039,080	38,410	54,695	66,164	14,036,139	14,470,377	17,000,499
8	15,967,560	22,804,773	26,544,390	41,499	63,482	68,463	18,675,272	20,073,486	24,309,192
12	25,204,535	38,508,955	44,603,480	42,283	66,593	80,237	21,633,375	23,288,759	26,948,540
24	56,532,665	88,373,647	107,050,025	41,442	71,182	83,318	30,287,967	30,244,480	33,052,377

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	66	H7.05	Ph3	DLNCF	sim=100	2021-05-2620-42			
1	556,035	767,401	1,028,285	11,620	20,681	27,793	4,343,959	4,771,878	6,499,583
2	1,920,990	2,902,415	3,541,780	32,938	46,642	58,652	8,530,160	9,036,025	11,205,687
4	7,356,980	10,672,391	13,586,155	53,676	72,707	94,734	14,818,061	15,150,422	18,781,889
8	20,359,370	29,031,643	37,464,840	53,322	79,173	97,692	20,320,177	20,716,439	24,917,636
12	33,016,215	48,399,046	61,207,305	52,789	81,814	98,083	22,712,574	23,884,707	29,441,356
24	72,592,400	109,038,496	131,743,180	60,007	85,505	108,963	30,838,481	30,821,315	35,024,599

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	67	H7.05	Ph3	DLNAF	sim=100	2021-05-2621-02			
1	426,555	625,983	734,090	10,324	17,476	22,151	4,048,789	4,567,609	6,328,912
2	1,395,015	2,248,397	2,687,180	18,657	33,600	39,813	8,631,576	8,450,850	10,545,382
4	5,054,945	7,780,889	9,373,805	31,482	52,093	66,404	13,932,691	14,033,028	17,120,836
8	13,175,420	20,890,514	25,050,915	37,652	56,528	67,689	18,494,707	18,954,444	22,757,801
12	21,628,170	34,799,767	41,505,595	37,586	59,111	67,725	21,894,116	22,178,748	26,024,958
24	50,166,505	79,081,740	90,557,100	37,696	63,664	67,585	29,592,336	28,965,656	33,013,490

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	68	H7.05	Ph3	DMYCF	sim=100	2021-05-2621-18			
1	379,045	691,933	755,935	9,760	19,340	24,838	3,836,925	4,224,331	5,736,370
2	1,318,825	2,634,041	3,264,975	20,689	41,108	55,262	7,352,945	7,618,113	9,259,035
4	5,912,195	9,888,983	12,777,955	39,710	69,441	91,342	12,185,740	13,182,132	16,116,775
8	16,202,050	27,307,605	36,350,215	45,248	74,553	102,588	17,239,573	18,346,219	22,362,512
12	26,617,575	45,399,334	61,556,850	45,309	76,332	109,014	19,791,687	21,127,438	26,358,964
24	59,064,640	101,802,206	140,256,160	45,190	80,284	113,948	28,297,966	27,816,156	32,521,134

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	69	H7.05	Ph3	DMYAF	sim=100	2021-05-2621-33			
1	293,745	702,490	871,330	9,117	18,671	23,074	3,678,304	3,990,624	5,776,859
2	1,277,740	2,484,022	2,729,425	17,770	37,544	39,728	6,838,697	7,414,998	9,602,620
4	4,664,660	8,837,247	9,425,765	38,059	61,029	76,335	10,929,038	11,963,282	14,759,033
8	13,725,145	24,315,319	29,213,250	37,746	66,216	82,787	15,798,105	16,943,484	20,688,115
12	22,774,700	40,360,936	49,878,465	37,629	67,332	82,584	19,552,652	20,512,945	25,165,098
24	49,831,405	89,764,187	111,239,425	37,604	69,738	86,269	27,578,535	27,149,587	31,216,844

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	72	H7.05	Ph3	DHYCF	sim=100	2021-05-2621-47			
1	267,470	704,368	750,670	7,687	18,924	19,169	3,723,417	3,704,624	5,177,279
2	1,195,495	2,566,391	2,579,680	19,892	39,140	41,040	6,541,170	7,061,772	9,285,848
4	5,417,500	9,782,377	11,475,675	42,152	70,122	86,603	10,610,997	12,961,325	15,651,502
8	15,299,510	27,356,839	35,022,875	45,234	75,231	93,964	16,372,390	18,202,785	21,542,232
12	26,033,760	45,572,140	59,468,570	45,146	76,544	101,285	19,503,211	21,421,142	25,221,837
24	59,592,750	102,122,768	132,845,480	45,167	80,181	101,264	27,697,146	28,088,325	31,357,173

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	73	H7.05	Ph3	DHYAF	sim=100	2021-05-2622-03			
1	204,255	604,009	705,935	5,105	15,251	17,143	2,885,581	3,585,805	4,280,494
2	956,405	2,023,246	2,558,965	13,327	30,901	35,274	6,191,823	6,344,240	8,461,027
4	3,680,020	7,648,073	8,668,165	30,726	53,846	68,216	10,135,466	11,243,180	14,138,613
8	10,991,680	21,466,160	29,210,110	30,147	59,778	78,960	14,419,586	15,877,196	18,686,207
12	18,248,135	36,058,628	49,091,670	30,178	61,518	79,166	17,378,064	19,147,093	24,145,432
24	40,358,380	81,576,344	107,820,545	30,072	64,857	82,530	25,406,828	25,936,889	30,244,400

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	74	H7.05	Ph3	DHNCF	sim=100	2021-05-2622-20			
1	232,245	740,310	823,185	7,536	19,471	20,888	3,720,038	3,877,523	5,194,834
2	1,052,115	2,528,556	2,577,955	15,731	37,132	41,450	6,407,699	6,792,082	8,908,468
4	4,369,210	9,249,293	10,392,140	38,049	64,826	79,708	11,174,925	11,880,962	14,240,688
8	13,270,230	25,650,701	29,924,935	37,869	70,966	81,736	15,354,215	17,067,895	20,440,253
12	22,396,100	42,896,318	49,053,230	37,856	72,696	82,793	18,841,771	20,227,169	24,490,015
24	51,346,385	97,030,302	109,474,180	41,375	76,808	90,151	27,548,438	27,038,902	30,637,056

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	75	H7.05	Ph3	DHNAF	sim=100	2021-05-2622-35			
1	258,410	560,767	751,400	7,083	13,919	14,767	3,466,092	3,601,753	4,566,511
2	1,235,835	1,908,872	1,979,215	16,373	29,359	31,474	6,421,117	6,729,795	8,792,360
4	4,115,605	7,081,394	7,549,090	30,570	49,482	53,732	9,884,659	11,260,458	13,091,398
8	11,888,315	19,448,811	21,679,185	30,307	52,911	64,732	14,190,176	15,670,913	17,531,188
12	19,388,695	32,355,389	37,032,150	30,199	54,343	63,859	16,996,798	18,724,283	22,586,017
24	41,078,115	72,262,249	83,071,690	30,133	56,278	63,988	25,670,607	25,658,380	28,816,824

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	76	H7.05	Ph3	NEYCF	sim=100	2021-05-2622-51			
1	265,840	581,875	742,270	8,690	14,459	18,024	3,123,844	3,584,571	4,658,739
2	1,293,800	2,060,257	2,360,755	18,176	32,763	41,378	6,489,374	6,672,228	8,582,495
4	5,169,470	8,570,023	11,155,450	45,800	64,464	83,974	11,047,341	11,845,342	13,649,334
8	16,318,100	24,657,300	30,134,485	45,391	67,996	86,823	15,797,747	16,774,207	19,455,238
12	27,142,560	41,133,436	51,280,530	45,132	69,112	91,607	18,799,026	19,740,624	22,252,969
24	59,592,065	92,216,102	116,160,090	45,068	72,299	90,715	27,381,040	26,845,468	30,513,870

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	77	H7.05	Ph3	NEYAF	sim=100	2021-05-2623-06			
1	227,600	546,532	764,415	5,428	12,489	13,537	3,373,423	3,535,187	4,136,442
2	1,038,305	1,732,100	2,052,685	13,447	25,804	30,449	6,157,260	6,413,462	8,219,391
4	4,274,460	6,684,645	8,460,500	37,716	48,793	60,803	10,906,833	11,174,141	13,016,360
8	13,443,520	19,342,941	23,672,870	37,728	55,113	69,157	15,676,931	16,070,391	18,917,902
12	22,620,490	32,735,319	39,936,365	37,606	56,534	77,844	19,866,049	19,421,209	23,631,715
24	50,156,305	74,954,143	96,532,445	37,686	61,132	82,501	27,607,146	26,025,028	30,104,673

	Total Required Water Flow (gallons)			Required Water Flow (gpm)			Burnt TFA (sq ft)		
hour	median	mean	75%	median	mean	75%	median	mean	75%
Case	78	H7.05	Ph3	NENCF	sim=100	2021-05-2623-21			
1	245,855	717,125	875,760	6,253	17,871	19,994	3,430,958	3,749,359	4,651,919
2	1,090,175	2,375,770	2,639,960	22,435	35,680	41,590	6,688,487	6,939,868	8,549,734
4	5,595,790	9,080,773	10,545,120	46,009	65,701	87,032	10,284,331	12,013,369	14,378,689
8	17,867,050	25,549,647	32,337,395	52,551	71,097	90,135	15,479,030	17,098,618	19,103,571
12	30,598,420	42,872,058	54,938,670	52,603	73,074	93,880	19,268,788	20,698,135	24,513,460
24	69,247,375	96,748,442	124,885,215	52,871	76,020	97,500	27,379,774	27,148,098	30,578,687

6 REFERENCES

ABAG. 2021. "ABAG Draft RHNA Methodology Report 2023-2031." Pp. 111. San Francisco: Assn. Bay Area Governments.

Abrahamson, Norman A, Walter J Silva, and Ronnie Kamai. 2014. "Summary of the ASK14 ground motion relation for active crustal regions." *Earthquake Spectra* 30(3):1025-55.

Anderson, D., R.A. Davidson, K. Himoto, and C. Scawthorn. 2016. "Statistical Modeling Of Fire Occurrence Using Data From The Tōhoku, Japan Earthquake And Tsunami." *Risk Analysis* 36(2):378-95.

ATC-52-1. 2010. "Here Today—Here Tomorrow: The Road To Earthquake Resilience In San Francisco, Potential Earthquake Impacts." San Francisco: Prepared for the Department of Building Inspection, City and County of San Francisco, under the Community Action Plan for Seismic Safety (CAPSS) Project by the Applied Technology Council.

ATC-52-1A. 2010. "Here Today—Here Tomorrow: The Road To Earthquake Resilience In San Francisco, Potential Earthquake Impacts: Technical Documentation." Pp. 178. San Francisco: Prepared for the Department of Building Inspection, City and County of San Francisco, under the Community Action Plan for Seismic Safety (CAPSS) Project by the Applied Technology Council.

Benfer, Matthew E., and Joseph L. Scheffey. 2015. *Evaluation of Fire Flow Methodologies*. New York, NY: Springer New York.

Boore, David M, Jonathan P Stewart, Emel Seyhan, and Gail M Atkinson. 2014. "NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes." *Earthquake Spectra* 30(3):1057-85.

Campbell, Kenneth W, and Yousef Bozorgnia. 2014. "NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra." *Earthquake Spectra* 30(3):1087-115.

Chiou, Brian S-J, and Robert R Youngs. 2014. "Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra." *Earthquake Spectra* 30(3):1117-53.

CS-199. 2014. "Planning Support Services For Auxiliary Water Supply System (Awss), Final Report." Pp. 288. San Francisco: CS-199 Project Report Prepared for San Francisco Public Utilities Commission by AECOM/AGS JV.

Davidson, Rachel A., James Kendra, Sizheng Li, Laurie C. Long, David A. McEntire, and Charles Scawthorn. 2012. "San Bruno California, September 9, 2010 Gas Pipeline Explosion And Fire." Pp. 210. Newark: Disaster Research Center, University of Delaware.

Davis, S.K. 2000. "Fire Fighting Water: A Review Of Fire Fighting Water Requirements, A New Zealand Perspective." in *School of Engineering*. Christchurch, New Zealand: University of Canterbury.

Detweiler, S.T., and A.M. Wein (Eds.). 2017. *The HayWired earthquake scenario—Earthquake hazards (ver. 1.1, March 2018):*. Washington: U.S. Geological Survey Scientific Investigations Report 2017–5013–A–H, available at https://pubs.er.usgs.gov/publication/sir20175013v1.

DHS. 2003. "Multi-Hazard Loss Estimation Methodology, Earthquake Model, Hazus-Mh Mr3 Technical Manual." Pp. 699pp. Washington, DC.: Developed by: Department of Homeland

Security, Emergency Preparedness and Response Directorate, FEMA Mitigation Division Washington, D.C. Under a contract with: National Institute of Building Sciences.

Eqe/ags. 1989. "San Francisco Fire Department Facilities Seismic Evaluation Study - Summary Report." Pp. 250pp. San Francisco: Prepared By EQE/AGS Under Contract to Department of Public Works, City and County of San Francisco, for San Francisco Fire Commission; C. Scawthorn, Principal in Charge; R. Hamburger, Project Manager.

FEMA. 2003. "Multi-Hazard Loss Estimation Methodology, Earthquake Model, Hazus-Mh Mr4 Technical Manual." Pp. 712. Washington, D.C.: Developed by: Department of Homeland Security, Federal Emergency Management Agency, Mitigation Division, Under a contract with: National Institute of Building Sciences.

Freeman, John Ripley. 1932. *Earthquake Damage And Earthquake Insurance; Studies Of A Rational Basis For Earthquake Insurance, Also Studies Of Engineering Data For Earthquake-Resisting Construction*. New York: McGraw-Hill.

Gregor, Nick, Norman A Abrahamson, Gail M Atkinson, David M Boore, Yousef Bozorgnia, Kenneth W Campbell, Brian S-J Chiou, IM Idriss, Ronnie Kamai, and Emel Seyhan. 2014. "Comparison of NGA-West2 GMPEs." *Earthquake Spectra* 30(3):1179-97.

Grimwood, Paul, and Cliff Barnett. 2005. "'Fire-Fighting Flow-Rate.' London Fire Brigade (Retired)." ". www. firetactics. com.

Hadjisophocleous, G. V., and J. K. Richardson. 2005. "Water Flow Demands For Firefighting." *Fire Technology* 41(3):173-91.

Jayaram, Nirmal, and Jack W Baker. 2009. "Correlation model for spatially distributed ground-motion intensities." *Earthquake Engineering & Structural Dynamics* 38(15):1687-708.

Johnson, Kenneth A., and Greg W. Bartow (Eds.). 2018. *Geology of San Francisco, California, United States of America*. Issued to registrants at the 61st Annual Meeting of the Association of Environmental & Engineering Geologists and 13th International Association of Environmental & Engineering Geologists Congress in San Francisco, CA: Association Engineering Geologists.

Kiran, KC, and Jonathan Corcoran. 2017. "Modelling residential fire incident response times: A spatial analytic approach." *Applied Geography* 84:64-74.

Knudsen, Keith L., Janet M. Sowers, Robert C. Witter, Carl M. Wentworth, and Edward J. Helley. 2000. "Description Of Mapping Of Quaternary Deposits And Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California, Open-File Report 00-444, Part 3." Pp. 60. Washington: U.S. Geological Survey.

Lee, Selina, Rachel Davidson, Norihito Ohnishi, and Charles Scawthorn. 2008. "Fire Following Earthquake - Reviewing The State-Of-The-Art Of Modeling." *Earthquake Spectra* 24(4):933-67pp.

LMA. 2010. "California Earthquake Risk - Report from the LMA Lloyd's Market Academy Earthquake Seminar in San Francisco " Pp. 44. London: Lloyd's Market Academy

Manson, M., H. D. H. Connick, T. W. Ransom, and W. C. Robinson. 1908. "Reports On An Auxilary Water Supply System For Fire Protection For San Francisco, California." Pp. 173 p. San Francisco, Calif.,: San Francisco Board of Public Works.,.

NBFU. 1905. "Report Of National Board Of Fire Underwriters By Its Committee Of Twenty On The City Of San Francisco, Cal., Henry Evans, Chmn." Pp. 64pp.

O'Rourke, T. D., Scawthorn C. R., Blackburn E. T., Dickerman, T. S. 1990. "Response Of The San Francisco Water Supply System During The 1989 Loma Prieta Earthquake." Conference organized by California Governor's Office of Emergency Services and the Earthquake Engineering Research Institute, San Francisco, CA, Oct. 1990, 10 p.

O'Rourke, T.D., P. A. Beaujon, and C. R. Scawthorn. 1992. "Large Ground Deformations And Their Effects On Lifeline Facilities: The 1906 San Francisco Earthquake." in *in O'Rourke T D. Hamada M editors. Case Studies Of Liquefaction And Lifeline Performance During Past Earthquakes: Volume 2 United States Case Studies*: National Center for Earthquake Engineering Research, State University of New York, Buffalo, NY, February 1992., REPORT: NCEER-92-0002, ISSN: 1088-3800.

Odell, Kerry A., and Marc D. Weidenmier. 2004. "Real Shock, Monetary Aftershock: The 1906 San Francisco Earthquake And The Panic Of 1907." *Journal of Economic History* 64(4):1002-27.

Planning Department. 2020. "2019 San Francisco Housing Inventory." Pp. 84. San Francisco: San Francisco Planning Department.

Porter, K.A. 2018. "A new model of water-network resilience, with application to the HayWired scenario." in *The HayWired earthquake scenario—Engineering Implications: chap. N* edited by S.T. Detweiler, and Wein, A.M.: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q.

Porter, K.A., C.R. Scawthorn, and D. Sandink. 2021. "An Impact Analysis for the National Guide for Wildland-Urban Interface Fires - Overview." Pp. 5. Toronto, ON, : Prepared for the National Research Council of Canada, Institute for Catastrophic Loss Reduction.

Porter, keith, lucile jones, dale cox, james goltz, ken hudnut, dennis mileti, sue perry, daniel ponti, michael reichle, adam z. rose, Charles r. Scawthorn, hope a. Seligson, kimberley i. Shoaf, jerry Treiman, and anne wein. 2011. "The Shakeout Scenario: A Hypothetical Mw7.8 Earthquake On The Southern San Andreas Fault." *Earthquake Spectra* 27(2):239-61.

Reed, s. Albert. 1906. *The San Francisco Conflagration Of April, 1906 : Special Report To The National Board Of Fire Underwriters, Committee Of Twenty*. New York: National Board of Fire Underwriters.

Särdqvist, Stefan. . 1998. ""Real fire data: Fires in non-residential premises in London 1994-1997." ". Lund: Department of Fire Safety Engineering, Lund Institute of Technology, Lund University.

Scawthorn, C. 2018a. "Fire following the Mw 7.05 HayWired earthquake scenario." Pp. 367-400 in *The HayWired Earthquake Scenario—Engineering Implications*, edited by Shane T. Detweiler and Anne M. Wein. Washington: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q.

Scawthorn, c. . 2008. "Enhancements In Hazus-Mh Fire Following Earthquake." Pp. 45pp: SPA Risk LLC Prepared for PBS&J and the National Institute of Building Sciences.

Scawthorn, C., J. M. Eidinger, and A.J. Schiff (Eds.). 2005. *Fire Following Earthquake*. Reston: American Society of Civil Engineers.

Scawthorn, C., Frank T. Blackburn. 1990a. "Performance Of The San Francisco Auxiliary And Portable Water Supply Systems In The 17 October 1989 Loma Prieta Earthquake." in *4th U.S. National Conference on Earthquake Engineering*. Palm Springs, CA.

Scawthorn, C., Khater M. 1992. "Fire Following Earthquake - Conflagration Potential In The Greater Los Angeles San Francisco Seattle And Memphis Areas." in *prepared for the Natural Disaster Coalition by EQE International*: San Francisco, CA. [EQE's study for the Natural Disaster Coalition, Fire Following Earthquake in the Greater Los Angeles, San Francisco, Seattle and Memphis Areas, is available from the National Committee on Property Insurance, 75 Tremont Street, Suite 510, Boston, MA 02108-3910, (617. 722-0200.].

Scawthorn, c., and T. D. O'rourke. 1989. "Effects Of Ground Failure On Water Supply And Fire Following Earthquake: The 1906 San Francisco Earthquake." in *Proceedings 2nd U.S. - Japan Workshop on Large Ground Deformation*. Buffalo.

Scawthorn, C. R., O'Rourke T. D., Khater M. M., Blackburn, F. 1990b. "Loma Prieta Earthquake And San Francisco Awss: Analysis And Observed Performance." San Francisco, CA: National Center for Earthquake Engineering Research, Buffalo, NY, pp. 527-540.

Scawthorn, C., Y. Yamada, and H. Iemura. 1981. "A Model For Urban Postearthquake Fire Hazard." *Disasters* 5(2):pp. 125-32.

Scawthorn, C., Y. Yamada, H. Iemura, and M. Kobayashi. 1982. "A Model For Urban Post-Earthquake Fire Hazard." *Transactions Arch. Institute of Japan*.

Scawthorn, Charles. 1987. *Fire Following Earthquake: Estimates Of The Conflagration Risk To Insured Property In Greater Los Angeles And San Francisco*. Oak Brook, Ill.: All-Industry Research Advisory Council.

—. 2012. "Memorandum to D. Myerson re Water Demand results." Pp. 3 pgs with attached data files.

—. 2018b. "Fire Following the Mw 7.05 Haywired Earthquake Scenario." Pp. 12 in *Eleventh U.S. National Conference on Earthquake Engineering - Integrating Science, Engineering & Policy*. Los Angeles, California.

—. 2020. "Fire following earthquake in the Vancouver region." Ontario: Institute for Catastrophic Loss Reduction, available at https://www.iclr.org/wp-content/uploads/2020/11/Vancouver-fire-following-earthquake-E.pdf and video recording presentation available at https://youtu.be/y7lKTU58x5I.

Scawthorn, Charles, Andrew D. Cowell, and Frank Borden. 1998. "Fire-Related Aspects Of The Northridge Earthquake." Pp. 165pp. Gaithersburg, MD: NIST GCR 98-743; National Institute of Standards and Technology Building and Fire Research Laboratory.

Scawthorn, Charles, and et al. 2018. "Fire Following the Mw 7.0 HayWired Earthquake." in *11th National Conference on Earthquake Engineering*. Los Angeles: Earthquake Engineering Research Institute.

Seed, H.B. , and I.M. Idriss. 1982. "Ground Motions and Soil L iquefaction during Earthquakes, Monogr. 5, ." Berkeley.: Earthquake Engineering Research Institute and the University of California, .

SFFD. 2009. "Apparatus Inventory." Pp. 112: San Francisco Fire Department.

SPA Risk. 2009. "Enhancements In Hazus-Mh Fire Following Earthquake, Task 3: Updated Ignition Equation " Pp. 74pp. San Francisco: SPA Risk LLC, Berkeley CA. Principal Investigator C. Scawthorn. Prepared for PBS&J and the National Institute of Building Sciences.

Steinbrugge, Karl, V. 1968. "Earthquake Hazard In The San Francisco Bay Area: A Continuing Problem In Public Policy " Pp. x, 80pp: Institute of Governmental Studies, University of California, Berkeley.

Steinbrugge, Karl v., eugene e. Schader, harry c. Bigglestone, and carl a. Weers. 1971. *San Fernando Earthquake, February 9, 1971*. San Francisco, Calif.: Pacific Fire Rating Bureau.

TCLEE (Ed.). 2005. *Fire Following Earthquake*. Reston: American Society of Civil Engineers, Technical Council for Lifeline Earthquake Engineering, Scawthorn et al (eds).

Van Anne, Craig, Charles Scawthorn, and Dennis S. Mileti. 1994. *The Loma Prieta, California, Earthquake Of October 17, 1989 : Fire, Police, Transportation, And Hazardous Materials*. Washington: U.S. Geological Survey.

Whitney, Albert W. 1906. *On Insurance Settlements Incident To The 1906 San Francisco Fire*. Pasadena, Calif.: reprint by the Center for Research on the Prevention of Natural Disasters Division of Engineering and Applied Science California Institute of Technology, 1972.

Wills, CJ, CI Gutierrez, FG Perez, and DM Branum. 2015. "A Next Generation VS30 Map for California Based on Geology and TopographyA Next Generation VS30 Map for California Based on Geology and Topography." *Bulletin of the Seismological Society of America* 105(6):3083-91.

Zio, Enrico. 2013. *The Monte Carlo Simulation Method for System Reliability and Risk Analysis.* London ; New York: : Springer.