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FIRE FOLLOWING THE M_W 7.05 HAYWIRED EARTHQUAKE SCENARIO

Charles Scawthorn[1]

ABSTRACT

Fire following earthquake is a significant problem in California. Potential losses arising from fires following the HayWired earthquake scenario, a hypothetical moment magnitude (*M*w) 7.05 earthquake occurring on April 18, 2018, at 4:18 p.m., on the Hayward Fault in the east bay part of the San Francisco Bay area, are analyzed herein. The earthquake causes Modified Mercalli Intensities of VI–X seismic intensities in the region, with very strong shaking along the fault in the densely built up east bay. Weather conditions are typical for the season, with strong onshore winds in the afternoon, subsiding to calm in the evening. 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. For the *M*w 7.05 scenario, it is estimated that approximately 668 ignitions will occur requiring the response of a fire engine. The first responding engine will not be able to adequately contain approximately 450 of these fires, such that in Alameda, Contra Costa and Santa Clara Counties dozens to hundreds of large fires are likely to merge into numerous conflagrations destroying tens of city blocks, with several of these potentially merging into one or several super conflagrations destroying hundreds of city blocks. Under the assumed scenario conditions, it is estimated that the about 450 large fires will result in an ultimate burned area of approximately 119 million square feet of residential and commercial building floor area, equivalent to more than 52,000 single family dwellings. Directly attributable to these fires following the earthquake will be the loss of hundreds of lives, and an economic loss approaching $30 billion. This loss is virtually fully insured and would be one of the largest historic single loss events in the history of the insurance industry. Other economic impacts include the loss of perhaps $1 billion in local tax revenues. A number of opportunities exist for mitigating this problem, including greatly enhancing post-earthquake supply of water for firefighting, and the mandatory use of automated gas shut-off valves, or seismic shut-off meters, in densely built areas.

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ABSTRACT

Fire following earthquake is a significant problem in California. Potential losses arising from fires following the HayWired earthquake scenario, a hypothetical moment magnitude (*M*w) 7.05 earthquake occurring on April 18, 2018, at 4:18 p.m., on the Hayward Fault in the east bay part of the San Francisco Bay area, are analyzed herein. The earthquake causes Modified Mercalli Intensities of VI–X seismic intensities in the region, with very strong shaking along the fault in the densely built up east bay. Weather conditions are typical for the season, with strong onshore winds in the afternoon, subsiding to calm in the evening. 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. For the *M*w 7.05 scenario, it is estimated that approximately 668 ignitions will occur requiring the response of a fire engine. The first responding engine will not be able to adequately contain approximately 450 of these fires, such that in Alameda, Contra Costa and Santa Clara Counties dozens to hundreds of large fires are likely to merge into numerous conflagrations destroying tens of city blocks, with several of these potentially merging into one or several super conflagrations destroying hundreds of city blocks. Under the assumed scenario conditions, it is estimated that the about 450 large fires will result in an ultimate burned area of approximately 119 million square feet of residential and commercial building floor area, equivalent to more than 52,000 single family dwellings. Directly attributable to these fires following the earthquake will be the loss of hundreds of lives, and an economic loss approaching $30 billion. This loss is virtually fully insured and would be one of the largest historic single loss events in the history of the insurance industry. Other economic impacts include the loss of perhaps $1 billion in local tax revenues. A number of opportunities exist for mitigating this problem, including greatly enhancing post-earthquake supply of water for firefighting, and the mandatory use of automated gas shut-off valves, or seismic shut-off meters, in densely built areas.

Introduction

This paper is part of a larger USGS project to assess the impacts *M*w 7.05 earthquake on the Hayward Fault [1], and specifically to quantitatively describe the fires following that event, with primary emphasis for assisting emergency planning. The charge for development of the scenario specified that the scenario occurs on Wednesday, April 18, 2018, at 4:18 p.m., with average April weather conditions; that it should be realistic and not a "worst-case" scenario; and it should address the following questions: (a) what is a realistic scenario of ignitions, fire growth, and spread? (b) How will ignitions be reported after an earthquake? How will fire departments respond? How long will it take for the fires to be extinguished? What mutual aid agreements are

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in place and how will they be activated? (c) How will damage to telecommunications, water supply, and roadway damage affect response? (d) What, if any, effective mitigation actions have been undertaken elsewhere that might be practical in the bay area? (e) What are the limitations of the fire-following-earthquake scenario and what research would provide a more realistic, perhaps more challenging or detailed, scenario?

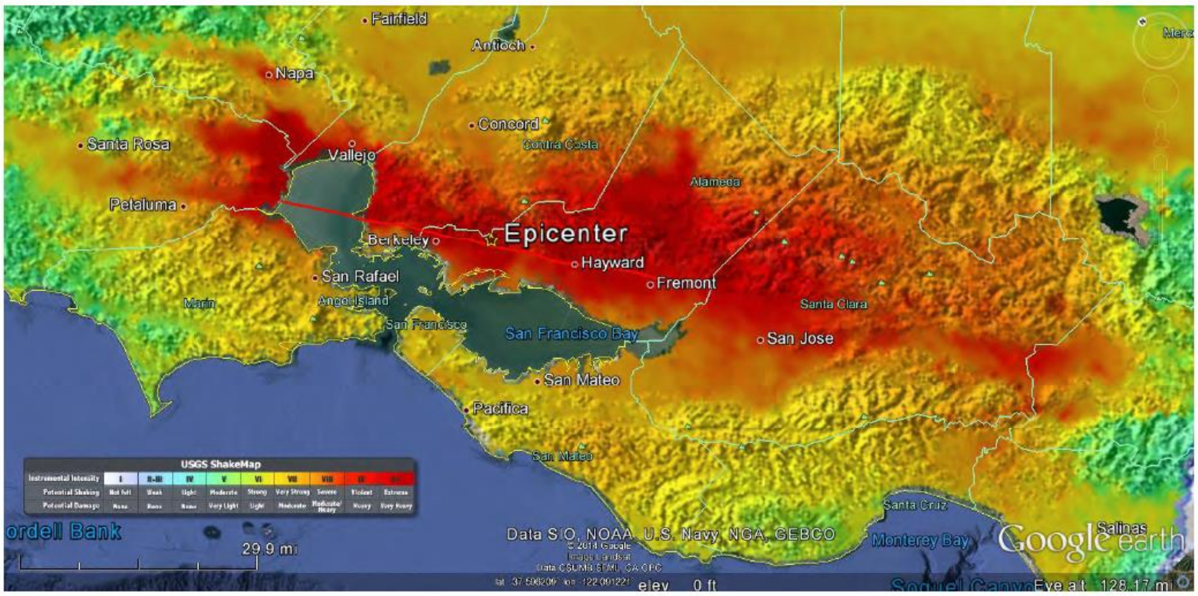

Figure 1. Map of San Francisco Bay area showing HayWired scenario M_w 7.05 earthquake fault trace and offset.

Haywired scenario and fire-related background

The scenario event is a *M*w 7.05 earthquake on the Hayward Fault which affects the San Francisco Bay area, Fig. 1. Ten San Francisco Bay area counties are affected by the event—the total affected population is approximately 7.7 million with a total building floor area of 5.77 billion square feet and estimated value (structure only) of approximately $1.15 trillion at risk. Regarding fire protection, over 500 fire stations were considered in the analysis with a total of 229 fire engines immediately available in the most heavily impacted area. While many jurisdictions have seismically retrofitted fire stations (and other critical infrastructure), the functionality of a significant number of fire stations is still questionable [2]. Each fire station in the affected region was allocated an immediate area using a Voronoi diagram as an approximation of the station's "first due" area, which was the fundamental basis for subsequent analysis.

Weather can affect fire growth and spread and the direction and distance at which communities are affected by hazardous material release. In April wind conditions are typically created by a trough of low pressure east of the bay area, which draws in strong, westerly, cooler and more humid air from the ocean in the afternoon, subsiding to more calm conditions in evening. Cumulative distribution functions for wind speed for 4 p.m., 5 p.m., and 9 p.m. for the years 2000–2012 indicate significant variability of the stronger afternoon winds, with consistently calmer conditions later in the evening. However, a reverse of the typical summertime weather pattern can occur, consisting of occasional intense katabatic winds, locally sometimes termed "Diablo winds." These are hot, dry, offshore winds from the northeast that sometimes occur in the San Francisco Bay area during the spring and fall. These winds differ from the more familiar Southern California Santa Ana winds, and are created by the combination of strong inland high pressure at the surface, strongly sinking air aloft, and lower pressure off the California coast. The air descending from aloft as well as from the Coast Ranges compresses at sea level where it warms as much as 20 °F (11 °C), and loses humidity. If the pressure gradient is large enough, the dry offshore wind can become quite strong with gusts reaching speeds of 40 miles per hour (64 km/h) or higher, particularly along and in the lee of the ridges of the Coast Ranges where warm, dry surface air from the windward eastern side is drawn up and over the ridgeline, Fig. 2. Such winds were major factors in the 1923 Berkeley, 1991 East Bay Hills Fires and 2017 Northern California fires. This effect is especially significant as it can enhance the updraft generated by large wild-land or urban fires. The pattern of wind speeds and direction used for the scenario was the more typical westerly wind subsiding in the evening, rather than the more dangerous Diablo-wind scenario.

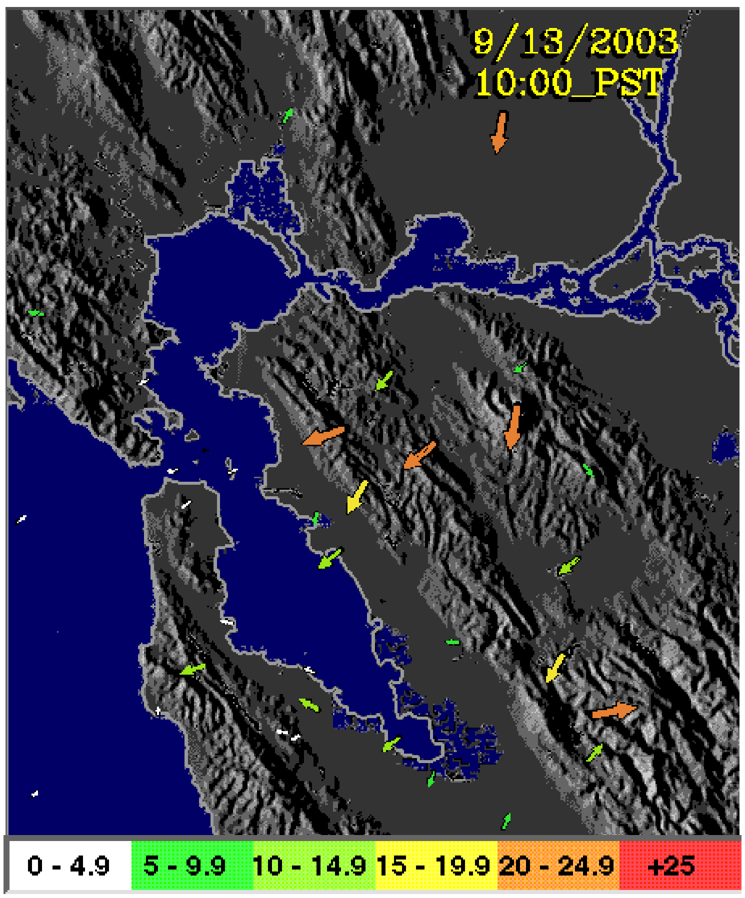

Figure 2. Map showing wind streak lines for September 13, 2003 at 10 a.m., typical of Diablo wind conditions in San Francisco Bay area. Wind speed in knots (see color bar), measured 10 m above surface elevation. Figure from San Jose State University's San Francisco Bay Wind Archives.

Modeling of Fire Following Earthquake

Methods detailed in [3] for modeling for fire following earthquake were employed for this study. Post-earthquake U.S. ignition rates have been studied by a number of investigators [4] with the most recent and relevant algorithms for estimating post-earthquake ignition rates being developed by [5] and [6], the latter of which after a comparative review was used for this study:

$$\text{(ignitions/million sq. ft. of building floor area)} = -0.029444\ PGA + 0.581895\ PGA^2 \qquad (1)$$

where PGA is peak ground acceleration (g). Ninety percent of the ignitions are confined to three counties—Alameda, Contra Costa and Santa Clara—with Alameda County alone having 53 percent of all ignitions. These are only ignitions that require fire department response; there may be other, typically minor, ignitions that are suppressed immediately by citizens, which are often not reported. Of the approximately 668 total ignitions, it is estimated 453 of these will grow to be large fires (defined as a fires exceeding the capacity of the first arriving engine).

Fire department response is initially dependent on reporting, which will be less effective following an earthquake. Emergency (9-1-1) dispatch centers will be overwhelmed, and doing as much as possible to triage events and dispatch resources. Reports of fires during the initial period will be haphazard. Most fire departments do not have their own helicopters, and reporting by TV news helicopters will be a valuable resource for a few major incidents, but not most. The initial response of fire companies and personnel in the region of the scenario will be to protect themselves during violent shaking, and as soon as possible open the doors and remove apparatus (such as 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 5 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. Local fire service resources will be completely committed, and in need of assistance from outside the region. The primary needs will be personnel, additional hose, hard suction hose (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 the Community Emergency Response Team (CERT) program, 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 join 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 physical limits. 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 668 ignitions will not all develop into large fires. Nevertheless, the normal 4 minute structural fire response time will hardly be met. This delayed response, owing primarily to delayed reporting and dispatch, will result in many of the fires on arrival having grown such that a multi-engine capacity is needed, termed “large fires.” The number of large fires for the scenario event is estimated based on several rules, including (a) availability of water for firefighting within each fire response area, and (b) ratio of ignitions to fire engines within each county (the latter to account for limited mutual aid), resulting in an estimate of 453 large fires. The large number of ignitions developing into large fires is due to the high shaking intensities in the east bay, which has high-density wood construction west of the hills.

The performance of lifelines, such as water supply, gas, electric power, communications, and transportation, is integral to the fire following earthquake process. Water supply will be severely impacted by the scenario event, with extensive portions of the distribution systems vulnerable and likely to sustain a number of breaks. The following was noted in a recent study by the Association of Bay Area Governments [7]: “…68.1 percent of critical water system facilities…are exposed to extremely high shaking level (peak ground accelerations, PGA…there could be, for example, 6,000~10,000 water pipeline breaks or major leaks in an earthquake on the Hayward fault (compared to 507 in the Loma Prieta earthquake)…” Owing to their proximity to the Hayward Fault, East Bay water distribution systems are particularly vulnerable [8]: “…earthquake hazard information…with more detailed information on materials and design of these facilities, and pipeline materials and connections associated with EBMUD, were used to estimate the problems associated with District facilities in a 1994 study. At that time, EBMUD estimated that, should an earthquake occur on the Hayward fault EBMUD customers could have expected: • Water cut off immediately to 63% of customers, including hospitals and disaster centers; ● Loss of water for fire hydrants and increased fire risk; ● Over 5,500 pipelines serving homes and businesses to break; ● A likelihood of untreated drinking water due to damage to four of six treatment plants; ● EBMUD’s most critical water conduit, the Claremont Tunnel, to be cut off west of the Oakland/Berkeley hills—affecting 70 percent of EBMUD customers; ● Major damage to 65 water reservoirs and about 87 pumping plants that would require months, or even years, to repair; ● An estimated impact of $1.2 billion (in 1994 dollars) to the regional economy due to fire damage; and ● lack of water after an earthquake, with some customers lacking service as long as six months.” Some of these issues, such as the Claremont Tunnel, have or are being addressed by EBMUD, but others (such as the more than 5,000 pipeline failures) remain to be addressed.

Data on pipe breaks and leaks from the Haywired project was employed and found the scenario event devastates the water supply infrastructure in the affected area, causing a total of about 9,400 buried water mains to require repairs, owing to a combination of fault rupture, shaking, and permanent ground displacement. The result is a lack of water supply to most hydrants in the East Bay. Without water infrastructure, firefighters will have to resort to alternative water sources, with limited effectiveness, see [9] for details.

Final Burned Area

The 453 large fires will be spread over a large area of varying building density and availability of water for firefighting. The number of large fires that will grow into conflagrations, and the ultimate extent of the final burnt area, will depend on the building density, weather conditions, initial unfought size of the fire prior to fire service response, number of responding fire engines and water supply available for firefighting associated with each large fire. Under the assumed scenario conditions, it is estimated that of the 453 large fires, about 321 will grow to a size such that they will spread beyond the city block of origin (i.e., become a 'conflagration'), with the final burnt area then largely dependent on fires crossing streets and other firebreaks. Based on the probability of fire crossings, the estimated final burnt area is approximately 119 million square feet of residential and commercial building floor area equivalent to about more than 52,000 single-family dwellings. This loss is equivalent to a total replacement value of almost $16 billion (2014 dollars), representing about 2% of the entire exposed value (Fig. 3, Table 1), with most of the loss large concentrated in Alameda county.

Impacts

Human: Estimating the fatalities associated with the fires following the scenario earthquake is very problematic. A very simple approach is taken here; in the 1991 East Bay Hills Fire, which destroyed approximately 3,500 dwellings, 25 people perished. The building losses projected here are approximately 20 times larger. In proportion, there would be hundreds of deaths caused by fire following this earthquake. Such an approach is admittedly very simplistic, and does not account for the potential overwhelming of the regional emergency medical capacity in a large earthquake, as opposed to the isolated nature of the 1991 East Bay Hills fire. Injuries would probably be an order of magnitude greater. Half to one million people are estimated to need shelter owing to fire following earthquake.

Economic: Regarding the $16 billion value of the burned structures, the value of contents and other improvements (for example, landscaping) will add to this loss. Residential contents for example are commonly insured to 70 percent of the replacement cost of the building, so content loss could realistically amount to an additional $11 billion. An additional loss is loss of use; that is, the people normally living in these destroyed buildings (or conducting business in them) must find other accommodations, which will most likely not be available in the San Francisco Bay area given the scenario event. This loss, termed "additional living expenses" by the insurance industry, can be consequential, equivalent to many tens of billions of dollars. Accounting for this can be difficult; if people who have lost their dwellings are housed in hotels at insurance company expense, the loss is simply the hotel bill. If people are forced to live in tents following the event, at public expense, there may be no bill. In such a situation, people haven't paid for their tents, and can't therefore claim against the insurance company for a financial loss. However, they have lost value in services (of their house) approximately equivalent to the rental value of their house (minus the rental value of the tent), but won't be compensated for those losses. Nevertheless, this is a loss that should be accounted for, overall. One approximation is to estimate the additional living expenses in proportion to the typical limit of liability for homeowner's insurance: 20 percent of the replacement cost of the building, or in this case $3 billion. Since virtually all buildings and contents in the United States are insured for fire, and U.S. insurance contracts include fire-following-earthquake losses under the fire policy, the direct fire-following-earthquake losses for the scenario event are likely to result in a loss approaching $30 billion of insurance claims. Because $30 billion amounts to nearly 6 percent of the gross domestic product of the San Francisco Bay area, and shaking-related damage (discussed elsewhere) adds to the demands for construction services, it is likely that demand surge will occur (the temporary increase in construction costs following major natural disasters). Losses of this magnitude are probably sustainable by the U.S. insurance industry (the $60 billion in insured claims arising from 9/11 were handled without great strain). The 1991 East Bay Hills Fire, in which 3,500 homes were lost, resulted in about $1 billion in insured losses—the total loss projected here is affected by 24 years of inflation, but is perhaps 30 times as large. In 2017 the Northern California fires destroyed approximately 8,800 homes, the cost of which has yet to be accounted. In summary, the fire following earthquake losses are likely to be the largest portion of the insured losses in the scenario event, and would be one of the largest single-loss events in the history of the insurance industry. Another aspect of the economic impacts is the loss of real estate tax revenues. A loss of tens of billions of dollars in value of improvements is likely to result in a decrease in regional real estate tax revenues of $1 billion, for several years, directly attributable to fire following earthquake.

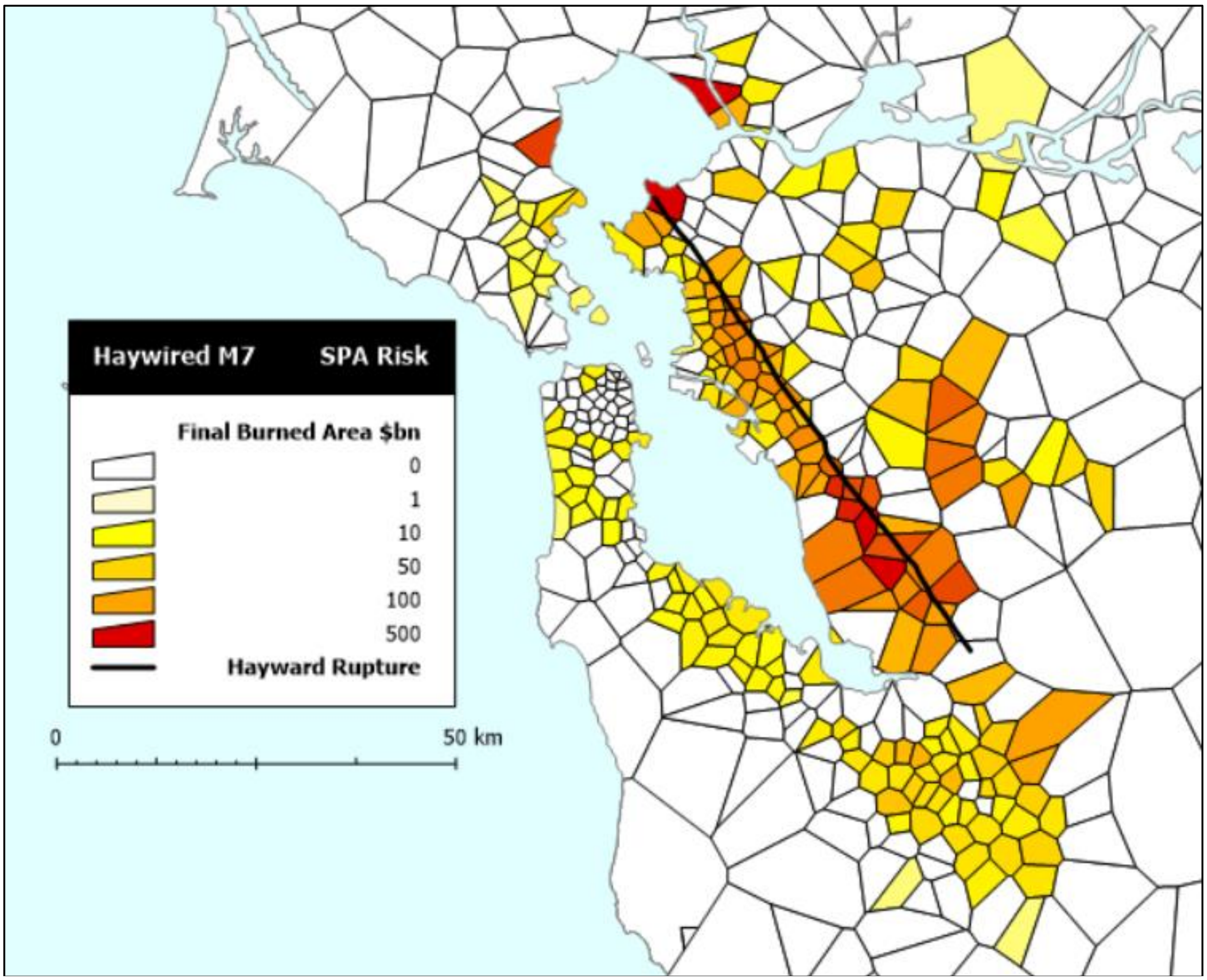

Figure 3. Map showing final burned area in the HayWired scenario.

Table 1. Estimated ignitions and damage from the HayWired scenario (M_w 7.05 earthquake on April 18, 2018, at 4:18 p.m.; breezy conditions and moderate humidity) [TFA, Total floor area]

County	Exposed building TFA[1]	Ignitions	Large fires	Conflagrations (multi-block fires)	Final burned TFA[1]	Final burned loss[2]	Percent burned	Percent of total losses
Alameda	1,853	352	279	198	49	$9,710	3%	53%
Contra Costa	1,480	123	60	43	11	$2,103	1%	18%
Marin	342	23	14	10	2	$500	0.7%	4%
Napa	90	27	19	13	3	$651	3.6%	4%
San Francisco	817	21	5	4	1	$177	0%	3%
San Mateo	576	19	15	11	3	$519	0%	3%
Santa Clara	1,610	83	56	40	10	$1,940	1%	12%
Santa Cruz	96	1	-	-	-	$-	0.00%	0%
Solano	338	12	4	3	1	$142	0.2%	2%
Sonoma	38	7	0	0	0	$13	0.2%	1%
10 county total	**7,241**	**668**	**453**	**321**	**79**	**$15,755**	**1.1%**	**100%**

[1] Total Floor Area (TFA), in millions of square feet. [2] Structure only, in millions of dollars

Mitigation of Fire Following Earthquake

Mitigation of fire following earthquake has been extensively discussed elsewhere [3] so that only some limited observations specific to the scenario are provided here. The fire services in California are perhaps the most experienced in the world in dealing with large conflagrations, due to the wild-land fires recurring annually in the region. The fire service has also been relatively diligent in preparing for a large earthquake—the CERT program is a model in that regard. However, the following opportunities for improvement are noted: (a) Improvements are needed in the ability to more quickly assess the incident, and facilitate incident reporting. Reconnaissance using unmanned aerial vehicles, and cellular text messaging incident reports directly to a 911 portal, should be developed and operationalized; (b) Alternative water sources need to be better identified, and access and water movement capabilities enhanced. Hard suction hoses should be carried on all engines. Large diameter hose (LDH) systems, comparable to San Francisco Fire Department's PWSS [10], should be developed on a regional basis. In this regard and as part of this project, a Workshop was held on 29 October 2014, at the University of California's Richmond Field Station, Fig. 4. The Workshop was attended by 76 personnel, representing 31 fire departments and emergency response agencies, including many of the major fire departments in the bay area. The four existing PWSSs, belonging to Berkeley, Oakland, San Francisco, and Vallejo Fire Departments were brought together and exercised; (c) A regional task force should be formed within the fire service, to examine urban conflagration potential in more detail. The task force should be multidisciplinary.

The water service in California has worked to prepare for a major earthquake, but more can still be done [11]. One overriding issue with regard to fire following earthquake is that water agencies typically aren't institutionally responsible for fire protection. That is, while they provide hydrants, if the hydrants fail to supply water, the water agency is not responsible. Therefore, water system upgrades are typically more oriented to maintenance of customer service, and minimizing direct damage to the system, than to maximizing water-supply reliability. A mandate needs to be developed to make water agencies more responsive to this need. Given the realities of the limited water supply in California, this may be unlikely to occur, but should at least be raised for discussion. A real way in which water agencies could be more responsive to the fire-following-earthquake problem is if each agency were to configure and upgrade their system so as to provide a "backbone" system of water mains of high seismic reliability, that provide water to major sections of the community and from which the fire service could draw water to suppress a conflagration using an LDH system. This entire aspect is discussed in more detail in [11].

Figure 4. Photograph of four portable water supply systems, belonging to Berkeley, Oakland, San Francisco, and Vallejo Fire Departments, taken at foot of Gilman Street, Berkeley, on October 29, 2014. This was the first time the four systems had been brought together and exercised.

Since 1906 significant progress has been made in making buildings more earthquake and fire resistant, yet there are still opportunities for improvement. For example, residential fire sprinklers are now required by a number of communities for new construction (at a cost less than the carpeting), but generally there are no requirements for existing homes (where the cost is significantly higher). Similarly, seismic retrofitting of existing buildings is increasingly being considered for older commercial buildings, but very few communities have requirements for existing single-family homes. Seismic retrofitting would reduce the number of post-earthquake ignitions. Both seismic retrofitting, and installation of fire sprinklers, should be more widely mandated for existing buildings.

The gas industry could contribute significantly to reducing the fire-following-earthquake problem by developing a program to either install automated gas shut-off valves or redesign meters with seismic shutoffs, particularly in densely built up areas. Los Angeles City Fire Department, for example, has shown leadership in seeking legislation to require gas shut-off valves. Note that the gas industry in Japan moved to do this proactively following the 1995 Kobe earthquake. The petroleum refineries and related facilities in the bay area are likely to sustain major fires in the scenario event. Their degree of earthquake preparedness is generally unclear, and should be reviewed.

Concluding Remarks

That fire following earthquake is a significant problem in California is confirmed historically, by recent events and by analysis. The M_w 7.05 HayWired earthquake scenario is estimated to result in approximately 668 ignitions such that in Alameda, Contra Costa and Santa Clara Counties dozens to hundreds of large fires are likely to merge into numerous conflagrations destroying tens of city blocks, with several of these potentially merging into one or several super conflagrations destroying hundreds of city blocks. The ultimate burned area is estimated to total 119 million square feet of residential and commercial building floor area, equivalent to more than 52,000 single-family dwellings, with an economic loss approaching $30 billion. This loss is virtually fully insured and would be one of the largest historic single loss events in the history of the insurance industry. Other economic impacts include the loss of perhaps $1 billion in local tax revenues. A number of opportunities exist for mitigating this problem, including greatly enhancing post-earthquake supply of water for firefighting, and the use of automated gas shut-off valves, or seismic shut-off meters, in densely built areas.

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