

# The HayWired Earthquake Scenario—Engineering Implications



Scientific Investigations Report 2017–5013–I–Q

**Cover.** This oblique aerial photograph captures a moment during which San Francisco, California, firefighters are extinguishing a fire that occurred shortly after an apartment building collapsed and burned to the ground as a result of the moment-magnitude-6.9 Loma Prieta earthquake of 1989. Another apartment building across the street has fallen into the intersection of Beach and Divisadero Streets, bursting out the walls of the weak first story as the structure buckled and collapsed. The damage (building collapses, damage to gas pipelines and other utilities, and fire) in the city's Marina District shown here was caused by amplified ground shaking and liquefaction (soils becoming liquid-like during shaking).

Since 1989, these and five other collapsed buildings in San Francisco's Marina District have been replaced or rebuilt, other buildings' soft first stories have been braced and strengthened, and flexible-conduit gas lines have replaced old, brittle rigid gas lines throughout the neighborhood. Such risk-reduction measures, intended to prevent building collapse and to curtail fire following earthquake, have not yet been taken in many other areas surrounding San Francisco Bay that have been identified as being susceptible to liquefaction. (Photograph copyright Deanne Fitzmaurice/San Francisco Chronicle/Polaris, used with permission.)

# **The HayWired Earthquake Scenario— Engineering Implications**

Edited by Shane T. Detweiler and Anne M. Wein

Scientific Investigations Report 2017–5013–I–Q

**U.S. Department of the Interior  
U.S. Geological Survey**

**U.S. Department of the Interior**

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exercising the authority of the Director

U.S. Geological Survey, Reston, Virginia: 2018

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## Foreword

The 1906 Great San Francisco earthquake (magnitude 7.8) and the 1989 Loma Prieta earthquake (magnitude 6.9) each motivated residents of the San Francisco Bay region to build countermeasures to earthquakes into the fabric of the region. Since Loma Prieta, bay-region communities, governments, and utilities have invested tens of billions of dollars in seismic upgrades and retrofits and replacements of older buildings and infrastructure. Innovation and state-of-the-art engineering, informed by science, including novel seismic-hazard assessments, have been applied to the challenge of increasing seismic resilience throughout the bay region. However, as long as people live and work in seismically vulnerable buildings or rely on seismically vulnerable transportation and utilities, more work remains to be done.

With that in mind, the U.S. Geological Survey (USGS) and its partners developed the HayWired scenario as a tool to enable further actions that can change the outcome when the next major earthquake strikes. By illuminating the likely impacts to the present-day built environment, well-constructed scenarios can and have spurred officials and citizens to take steps that change the outcomes the scenario describes, whether used to guide more realistic response and recovery exercises or to launch mitigation measures that will reduce future risk.

The HayWired scenario is the latest in a series of like-minded efforts to bring a special focus onto potential impacts when the Hayward Fault again ruptures through the east side of the San Francisco Bay region as it last did in 1868. Cities in the east bay along the Richmond, Oakland, and Fremont corridor would be hit hardest by earthquake ground shaking, surface fault rupture, aftershocks, and fault afterslip, but the impacts would reach throughout the bay region and far beyond. The HayWired scenario name reflects our increased reliance on the Internet and telecommunications and also alludes to the interconnectedness of infrastructure, society, and our economy. How would this earthquake scenario, striking close to Silicon Valley, impact our interconnected world in ways and at a scale we have not experienced in any previous domestic earthquake?

The area of present-day Contra Costa, Alameda, and Santa Clara Counties contended with a magnitude-6.8 earthquake in 1868 on the Hayward Fault. Although sparsely populated then, about 30 people were killed and extensive property damage resulted. The question of what an earthquake like that would do today has been examined before and is now revisited in the HayWired scenario. Scientists have documented a series of prehistoric earthquakes on the Hayward Fault and are confident that the threat of a future earthquake, like that modeled in the HayWired scenario, is real and could happen at any time. The team assembled to build this scenario has brought innovative new approaches to examining the natural hazards, impacts, and consequences of such an event. Such an earthquake would also be accompanied by widespread liquefaction and landslides, which are treated in greater detail than ever before. The team also considers how the now prototype ShakeAlert earthquake early warning system could provide useful public alerts and automatic actions.

Scientific Investigations Report 2017–5013 and accompanying data releases are the products of an effort led by the USGS, but this body of work was created through the combined efforts of a large team including partners who have come together to form the HayWired Coalition (see chapter A). Use of the HayWired scenario has already begun. More than a full year of intensive partner engagement, beginning in April 2017, is being directed toward producing the most in-depth look ever at the impacts and consequences of a large earthquake on the Hayward Fault. With the HayWired scenario, our hope is to encourage and support the active ongoing engagement of the entire community of the San Francisco Bay region by providing the scientific, engineering, and economic and social science inputs for use in exercises and planning well into the future.

### David Applegate

Associate Director for Natural Hazards,  
exercising the authority of the Deputy Director  
U.S. Geological Survey



## HayWired Review Panel

The HayWired Review Panel, a group whose expertise spans the scope of the HayWired scenario, assessed the overarching goals of the project along with the scientific approach and oversaw the reviews of each individual chapter in this volume. The panel consisted of Jack Boatwright (U.S. Geological Survey, USGS), Arrietta Chakos (Urban Resilience Strategies), Mary Comerio (University of California, Berkeley), Douglas Dreger (University of California, Berkeley), Erol Kalkan (USGS), Roberts McMullin (East Bay Municipal Utility District), Andrew Michael (chair, USGS), David Schwartz (USGS), and Mary Lou Zoback (Build Change, Stanford University).

## HayWired Coalition Partners

Alameda County Mayors' Conference  
 Alameda County Sheriff's Office, Office of Emergency Services  
 American Red Cross  
 Art Center College of Design  
 ARUP—Design and Engineering Consultants  
 Association of Bay Area Governments—Metropolitan  
 Transportation Commission  
 Aurecon  
 Bay Area Center for Regional Disaster Resilience  
 Bay Area Council  
 Bay Area Rapid Transit Authority  
 Bay Area Urban Area Security Initiative  
 Bay Planning Coalition  
 Boston University  
 Business Recovery Managers Association  
 California Business, Consumer Services, and Housing Agency  
 California Department of Public Health  
 California Department of Transportation  
 California Earthquake Authority  
 California Earthquake Clearinghouse  
 California Geological Survey  
 California Governor's Office of Business and  
 Economic Development  
 California Governor's Office of Emergency Services  
 California Independent Oil Marketers Association  
 California ISO  
 California Public Utilities Commission  
 California Resiliency Alliance  
 California Seismic Safety Commission  
 Carnegie Melon University Silicon Valley  
 City and County of San Francisco  
 City of Berkeley  
 City of Fremont  
 City of Hayward  
 City of Oakland

City of Oakland, Fire Department  
 City of San Francisco, Department of Emergency  
 Management  
 City of Walnut Creek  
 Contra Costa County Mayors' Conference  
 Earthquake Country Alliance  
 Earthquake Engineering Research Institute  
 East Bay Municipal Utility District  
 Federal Emergency Management Agency  
 Joint Venture Silicon Valley  
 Laurie Johnson Consulting|Research  
 March Studios  
 Marin Economic Consulting  
 MMI Engineering  
 Office of the Mayor, City and County of San Francisco  
 Pacific Earthquake Engineering Research Center  
 Pacific Gas and Electric  
 Palo Alto University  
 Price School of Public Policy and Center for Risk and  
 Economic Analysis of Terrorism Events, University of  
 Southern California  
 Rockefeller Foundation—100 Resilient Cities  
 San Jose Water Company  
 Southern California Earthquake Center  
 SPA Risk LLC  
 SPUR  
 Strategic Economics  
 Structural Engineers Association of Northern California  
 The Brashear Group LLC  
 University of California Berkeley Seismological Laboratory  
 University of Colorado Boulder  
 University of Southern California  
 U.S. Department of Homeland Security  
 U.S. Geological Survey  
 Wells Fargo



# Contents

Foreword .....	iii
By David Applegate .....	
HayWired Review Panel .....	v
HayWired Coalition Partners .....	v

## Chapters

I. Overview of the HayWired Scenario Engineering-Implications Volume .....	1
By Keith A. Porter .....	
Introduction.....	1
A Recap of Earthquake Hazards .....	2
Engineering Implications .....	2
Hazus-MH Analysis .....	2
Societal Consequences of Current Code Performance Objectives .....	3
A Survey of Public Preferences for the Seismic Performance of New Buildings .....	5
Earthquake Urban Search and Rescue .....	5
Water-Network Resilience .....	6
Repair Costs and Downtime of High-Rise Buildings .....	7
Fire Following Earthquake .....	8
Benefit of Combining Earthquake Early Warning with Drop, Cover, and Hold On .....	9
Future Research.....	10
Conclusion.....	10
References Cited.....	11
J. HayWired Scenario—Hazus Analyses of the Mainshock and Aftershocks .....	13
By Hope A. Seligson, Anne M. Wein, and Jamie L. Jones .....	
Abstract.....	13
Introduction.....	14
Building Inventory Data .....	14
Hazus Results—HayWired Mainshock.....	18
HayWired Liquefaction Implementation in Hazus .....	18
HayWired Landslide implementation in Hazus .....	19
HayWired Mainshock Hazus Results .....	22
Liquefaction Modeling in Selected HayWired Aftershocks .....	27
Ground Shaking Results for the HayWired Earthquake Sequence .....	27
Unreinforced Masonry Construction.....	30
Population Impacts—Casualties .....	38
Population Impacts—Displacement and Shelter Requirements.....	38
Combining Losses in the Mainshock and Aftershocks .....	41
Repeat Liquefaction .....	43
Model Limitations and Data Gaps .....	46
Conclusions.....	49

Mainshock Assessment .....	49
Aftershock Assessment.....	49
Acknowledgments .....	50
References Cited.....	51
Appendix. Calculation of Shelter Parameters for the 2008 Southern California ShakeOut Scenario.....	52
By Kimberley Shoaf .....	
Displacement.....	52
Shelter Needs.....	53
Other Parameters to Consider.....	53
References Cited .....	54
K. Societal Consequences of Current Building Code Performance Objectives for Earthquakes ....	57
By Keith A. Porter .....	
Abstract.....	57
Introduction.....	57
Background.....	58
Implications of Seismic Performance Objectives for the HayWired Scenario .....	60
Impairment Rate at $MCE_R$ Shaking.....	61
Validation Using Data from the August 2014 Napa Earthquake .....	63
Impairment Rate at Other Levels of Shaking.....	63
Fraction and Number of Impaired Buildings at the Societal Level.....	66
Options for Improving Building-Stock Performance.....	66
Building Impairment Resulting from Ground Failure.....	69
Public Expectations for the Seismic Performance of New Buildings .....	70
Limitations of this Study.....	72
Summary.....	72
Conclusion.....	73
References Cited.....	73
L. Not Safe Enough—A Survey of Public Preferences for the Seismic Performance of New Buildings in California and the New Madrid Seismic Zone .....	79
By Keith A. Porter .....	
Abstract.....	79
Introduction.....	80
Objectives.....	81
Survey Approach .....	82
Respondent Population and Sampling Procedure .....	83
Survey Questions and Responses .....	83
Response Rate .....	83
Role or Relation to Building Codes .....	84
Current and Preferred Code Objectives.....	84
Preferred Performance Measure .....	86
Acceptable Cost for Better Performance.....	87
How Important are These Issues?.....	88
Respondent Demographics.....	88
Are Respondents Representative of the Population?.....	91
Are Some Groups Willing to Pay More for Better Seismic Performance? .....	93

Conclusions.....	94
Study Implications .....	94
Limitations and Research Needs .....	95
Acknowledgments .....	95
References Cited.....	95
M. An Earthquake Urban Search and Rescue Model and its Application to the HayWired Scenario..	99
By Keith A. Porter	
Abstract.....	99
Introduction.....	99
Objective.....	100
Literature Review.....	100
Literature About People Trapped by Building Collapse.....	100
Literature About People Trapped in Elevators .....	103
Methodology.....	103
Methodology for Estimating the Number of People Trapped by Collapse .....	103
Methodology for Estimating the Number of People Trapped in Elevators .....	111
Application to HayWired Scenario .....	111
People Trapped in Collapsed Buildings, Based on the Building-Code Objectives .....	111
People Trapped in Collapsed Buildings, Based on Hazus-MH.....	112
Scenario Estimate of People Trapped in Collapsed Buildings .....	116
Number of People Trapped in Stalled Elevators.....	116
Conclusions.....	117
USAR Demands Under Current Conditions .....	117
USAR Demands Under Ideal-World Conditions.....	118
Limitations.....	118
Acknowledgments .....	118
References Cited.....	118
Appendixes 1 through 12—National Information Service for Earthquake Engineering	
e-Library Images of Building Collapse in California, 1965–2014.....	120
Appendix 1. Santa Rosa (1969) Collapse Images.....	120
Appendix 2. San Fernando (1971) Collapse Images .....	122
Appendix 3. Imperial Valley (1979) Collapse Images.....	141
Appendix 4. Westmorland (1981) Collapse Images .....	143
Appendix 5. Coalinga (1983) Collapse Images .....	144
Appendix 6. Morgan Hill (1984) Collapse Images .....	152
Appendix 7. Whittier Narrows (1987) Collapse Images .....	154
Appendix 8. Loma Prieta (1989) Collapse Images.....	159
Appendix 9. Northridge (1994) Collapse Images.....	173
Appendix 10. San Simeon (2003) Collapse Images.....	189
Appendix 11. South Napa (2014) Collapse Images .....	191
Appendix 12. Earthquakes With No Available Collapse Images.....	192
N. A New Model of Water-Network Resilience, with Application to the HayWired Scenario...	195
By Keith A. Porter	
Abstract.....	195
Introduction.....	195
How Water Supply is Important in an Earthquake .....	195

Study Objectives .....	196
Literature Review .....	197
A Panel Approach to Estimating Water-Supply Impacts .....	197
Analytical Approaches to Estimating Water Supply Impacts .....	197
Damageability of Buried Pipe .....	198
Tasks and Methods to Repair Leaks and Breaks .....	202
Time to Repair Pipe Leaks and Breaks .....	202
Serviceability of Water Supply .....	205
Lifeline Interaction .....	206
Pipeline Damage in Afterslip .....	210
Measuring Loss of Resilience .....	211
Methodology .....	211
Overview of the Methodology .....	211
Vulnerability Model .....	212
Damage Analysis (Number of Repairs Required) .....	214
Restoration Model .....	215
Measuring Water-Supply Resilience .....	223
Optional Stochastic Simulation Methodology .....	223
Accounting for Afterslip and Aftershocks .....	225
Adjusting Hazus-MH's Lifeline Restoration Model .....	226
Mitigation Options .....	227
Summary of the Methodology .....	228
Case Study 1—San Jose Water Company .....	228
San Jose Water Company Asset Definition .....	229
San Jose Water Company Hazard Analysis .....	229
San Jose Water Company Damage Analysis .....	230
San Jose Water Company Restoration Analysis .....	236
Validation of San Jose Water Company Restoration Analysis .....	240
Effect of Lifeline Interaction and Consumable Limits .....	242
Case Study 2—East Bay Municipal Utility District .....	242
East Bay Municipal Utility District Asset Definition .....	242
EBMUD Hazard Analysis .....	244
EBMUD Damage Analysis .....	245
EBMUD Restoration Analysis .....	251
Validation of EBMUD Damage and Recovery Estimates .....	254
Effect of Lifeline Interaction and Consumable Limits on EBMUD .....	255
Performance of Other Water Utilities Based on Hazus-MH .....	255
Conclusions .....	258
Summary .....	258
Innovations Introduced Here .....	258
Research Needs .....	260
Acknowledgments .....	260
References Cited .....	260



O. Case Studies of Tall-Building Structural Analyses and Downtime and Loss Assessment for the HayWired Earthquake Scenario Mainshock .....	267
By Ibrahim M. Almuti, Carlos Molina-Hutt, Michael W. Mieler, Nicole A. Paul, and Chad R. Fusco	
Abstract.....	267
Introduction.....	268
Objectives.....	268
Report Structure .....	268
HayWired Ground Motions .....	269
Description of Archetype Buildings, Design, and Analysis Assumptions .....	272
Steel Office Tower .....	272
Reinforced-Concrete Residential Tower.....	276
Loss-Assessment Methodology .....	278
REDi Downtime Methodology .....	278
Input Parameters .....	280
Replacement Value.....	280
Utility Disruption.....	281
Summary of Loss-Assessment Results .....	281
Conclusion.....	283
Acknowledgments .....	283
References Cited.....	284
Appendix 1. Building Structural and Nonstructural Components .....	285
Structural Components .....	286
Nonstructural Components.....	291
Appendix 2. S-SF-B-43—40-Story Steel-Frame Building in San Francisco (Baseline Orientation).....	312
S-SF-B-43 Description .....	312
Engineering-Demand Parameters .....	312
Loss-Assessment Results .....	312
Appendix 3. S-SF-R-43—40-Story Steel-Frame Building in San Francisco (Rotated Orientation).....	316
S-SF-R-43 Description.....	316
Engineering-Demand Parameters .....	316
Loss-Assessment Results .....	316
Appendix 4. S-SF-B-20—20-Story Steel-Frame Building in San Francisco (Baseline Orientation).....	320
S-SF-B-20 Description .....	320
Engineering-Demand Parameters .....	320
Loss-Assessment Results .....	320
Appendix 5. S-SF-R-20—20-Story Steel-Frame Building in San Francisco (Rotated Orientation).....	324
S-SF-R-20 Description.....	324
Engineering-Demand Parameters .....	324
Loss-Assessment Results .....	324

Appendix 6. S-OK-B-20—20-Story Steel-Frame Building in Oakland (Baseline Orientation).....	328
S-OK-B-20 Description.....	328
Engineering-Demand Parameters .....	328
Loss Assessment Results .....	328
Appendix 7. S-OK-R-20—20-Story Steel-Frame Building in Oakland (Rotated Orientation) .....	332
S-OK-R-20 Description .....	332
Engineering-Demand Parameters .....	332
Loss-Assessment Results .....	332
Appendix 8. C-SF-B-46—42-Story Reinforced-Concrete Building in San Francisco (Baseline Orientation).....	336
C-SF-B-46 Description .....	336
Engineering-Demand Parameters .....	336
Loss-Assessment Results .....	339
Appendix 9. C-SF-R-46—42-Story Reinforced-Concrete Building in San Francisco (Rotated Orientation).....	342
C-SF-R-46 Description.....	342
Engineering-Demand Parameters .....	342
Loss-Assessment Results .....	345
Appendix 10. C-OK-B-46—42-Story Reinforced-Concrete Building in Oakland (Baseline Orientation).....	348
C-OK-B-46 Description.....	348
Engineering-Demand Parameters .....	348
Loss-Assessment Results .....	351
Appendix 11. C-OK-R-46—42-Story Reinforced-Concrete Building in Oakland (Rotated Orientation).....	354
C-OK-R-46 Description.....	354
Engineering-Demand Parameters .....	354
Loss-Assessment Results .....	357
Appendix 12. Inventory of Existing Tall-Building Stock in San Francisco .....	360
<b>P. Fire Following the HayWired Scenario Mainshock .....</b>	<b>367</b>
By Charles Scawthorn .....	
Abstract.....	367
Introduction.....	367
Purpose.....	368
Background.....	368
Scenario Earthquake and Prevailing Conditions.....	368
Rupture Segment, Magnitude, and Intensity .....	369
Affected Region .....	369
Fire Following Earthquake Aspects of the Scenario.....	379
Modeling of Fire Following Earthquake .....	379
Ignitions.....	380
Initial Response.....	381
Fire Spread.....	384
Lifelines.....	384

Regional and State Response .....	390
Final Burned Area .....	391
Uncertainty, Verification, and Validation .....	393
Impacts of Fire Following Earthquake .....	394
Human Impacts .....	395
Economic and Insurance Impacts .....	395
Mitigation of Fire Following Earthquake .....	395
Fire-Service Opportunities .....	395
Water-Service Opportunities .....	396
Building-Standards Opportunities .....	396
Energy-Industry Opportunities .....	396
Conclusion.....	397
References Cited.....	397
Q. How Many Injuries Can Be Avoided in the HayWired Scenario Through Earthquake Early Warning and Drop, Cover, and Hold On? .....	401
By Keith A. Porter and Jamie L. Jones	
Abstract.....	401
Introduction.....	401
Background.....	401
Objectives.....	402
Literature Review.....	402
Methodology.....	403
Estimating Avoided Injuries.....	403
Estimating the Acceptable Cost to Avoid Injuries .....	404
Survey Design.....	404
Findings.....	404
Distribution of DCHO Reaction Time .....	404
Calculation of Benefits.....	406
Conclusions.....	406
Limitations and Research Needs .....	410
References Cited.....	410
Appendix 1. Survey of DCHO Reaction Times .....	412
Appendix 2. HayWired Mainshock Earthquake Early Warning Time Calculation.....	427
By Elizabeth S. Cochrane, Anne M. Wein, Erin R. Burkett, Douglas D. Given, and Keith Porter	
References Cited .....	428

## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
acre	4,047	square meter (m <sup>2</sup> )
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km <sup>2</sup> )
square foot (ft <sup>2</sup> )	0.09290	square meter (m <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
<b>Volume</b>		
gallon (gal)	3.785	liter (L)
<b>Pressure</b>		
pound per square inch (lb/in <sup>2</sup> )	6.895	kilopascal (kPa)
kilopounds per square inch (lb/in <sup>2</sup> )	6.895	megapascal (MPa)
<b>Cohesion</b>		
pound per square foot (lb/ft <sup>2</sup> )	0.04788	kilopascal (kPa)
<b>Velocity</b>		
mile per hr (mi/hr)	1.60934	kilometer per hour (km/hr)
<b>Angle</b>		
degree (°)	0.0174533	radian (rad)

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
<b>Area</b>		
square meter (m <sup>2</sup> )	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km <sup>2</sup> )	247.1	acre
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
<b>Volume</b>		
liter (L)	0.2642	gallon (gal)
<b>Pressure</b>		
kilopascal (kPa)	0.1450377	pound per square inch (lb/in <sup>2</sup> )
megapascal (MPa)	0.1450377	kilopounds per square inch (lb/in <sup>2</sup> )

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Velocity</b>		
centimeter per second (cm/s)	0.3937	inch per second (in./s)
centimeter per second (cm/s)	0.0223694	mile per hour (mi/hr)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per second (m/s)	2.23694	mile per hour (mi/hr)
kilometer per hour (km/hr)	0.621371	mile per hour (mi/hr)
<b>Angle</b>		
radian (rad)	57.2958	degree (°)

## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

## Abbreviations and Acronyms

1D	one dimensional
2D	two dimensional
3D	three dimensional
ABAG	Association of Bay Area Governments
AIS	abbreviated injury scale
ASCE	American Society of Civil Engineers
ATC	Applied Technology Council
BAREPP	Bay Area Regional Earthquake Preparedness Project
BART	Bay Area Rapid Transit
BORP	Building Occupancy Resumption Program
BSSC	Building Seismic Safety Council
Cal OES	California Governor's Office of Emergency Services
Caltrans	California Department of Transportation
CalWARN	California Water/Wastewater Agency Response Network
CAPSS	Citizens Advisory Panel on Seismic Safety or Community Action Plan for Seismic Safety
CDC	Centers for Disease Control and Prevention
CERT	community emergency response team
CGS	California Geological Survey
CPT	cone penetration test
CUREE	Consortium of Universities for Research in Earthquake Engineering

DBE	design-basis earthquake
DCHO	drop, cover, and hold on
DDR	demand-to-design ratio
$DDR_1$	1-second DDR
$DDR_s$	short-period DDR
DEM	digital elevation model
EBMUD	East Bay Municipal Utility District
EDP	engineering-demand parameter
EERI	Earthquake Engineering Research Institute
EEW	Earthquake early warning
EQE	EQE International
ESIP	Earthquake Safety Improvements Program
ETAS	epidemic type aftershock sequence
$F_A$	amplification factor
FEMA	Federal Emergency Management Agency
$F_v$	site coefficient
$g$	acceleration due to gravity
GMPE	ground-motion prediction equation
GMPGV	geometric mean of the peak ground velocity
hr	hour
IBC	International Building Code
ICC	International Code Council
IDR	interstory drift
$I_e$	seismic importance factor
IRB	institution review board
LA BOMA	Los Angeles Building Owners and Managers Association
LADWP	Los Angeles Department of Water and Power
LLEQE	Life Line Earthquake Engineering software
LPI	liquefaction potential index
LRFD	load- and resistance-factor design
M	magnitude
Ma	mega-annum or millions of years ago
MCE	maximum considered earthquake
$MCE_R$	risk-adjusted maximum considered earthquake
MEP	mechanical, electrical, and plumbing

MMI	Modified Mercalli Intensity
MRF	moment-resisting frame
MSA	metropolitan statistical area
$M_w$	moment magnitude
NAD83	North American Datum of 1983
NED	National Elevation Dataset
NEHRP	National Earthquake Hazards Reduction Program
NGA-West2	Next Generation Attenuation Relationships for Western United States
NIBS	National Institute of Building Sciences
NISEE	National Information Service for Earthquake Engineering
NIST	National Institute of Standards and Technology
NISTIR	National Institute of Standards and Technology Interagency Reports
NLRHA	nonlinear response-history analysis
NMSZ	New Madrid Seismic Zone
NRC	National Research Council
$P$	probability
PACT	Performance Assessment Calculation Tool
PBEE	performance-based earthquake engineering
PBEE-2	second generation Performance-based earthquake engineering
PDT	Pacific Daylight Time
PEER	Pacific Earthquake Engineering Research Center
PG&E	Pacific Gas and Electric Company
PGA	peak ground acceleration
PGD	permanent ground displacement
PGV	peak ground velocity
PHS	U.S. Public Health Service
PSA or pSa	pseudo-spectral acceleration
PSA03	short-period (0.3-second) pseudo-spectral-acceleration response
PSA10	long-period (1-second) pseudo-spectral-acceleration response
PST	Pacific Standard Time
PVC	polyvinyl chloride
PWSS	portable water-supply system
$R^2$	coefficient of determination
REDi™	Resilience-based Earthquake Design Initiative for the Next Generation of Buildings
RIDR	residual interstory drift

SA	spectral acceleration
$S_a$	spectral-acceleration response
SAFRR	USGS Science Application for Risk Reduction project
SCEC	Southern California Earthquake Center
SDC	seismic-design categories
SEAOC	Structural Engineers Association of California
SEAONC	Structural Engineers Association of Northern California
SEI	Structural Engineering Institute
SHZ	seismic hazard zone
SIP	seismic improvement programs
SJWC	San Jose Water Company
SLE	serviceability-level earthquakes
$S_{M1}$	1-second spectral response acceleration parameter
$S_{MS}$	short-period spectral acceleration response parameter
SPUR	San Francisco Bay Area Planning and Urban Research Association
$S_s$	short-period spectral acceleration response at MCER shaking
$T$	period
UCERF3	Uniform California Earthquake Rupture Forecast, version 3
UPS	uninterruptible power supply
URM	unreinforced masonry
USAR	urban search and rescue team
USD	U.S. Dollars
USGS	U.S. Geological Survey
$V_{S30}$	time-averaged shear-wave velocity to a depth of 30 meters
WGS84	World Geodetic Survey 1984
$\rho$	correlation coefficient
$\Phi$	standard normal cumulative distribution function



## Chapter P

# Fire Following the HayWired Scenario Mainshock

By Charles Scawthorn<sup>1</sup>

## Abstract

Fire following earthquake is a significant problem in California. This chapter discusses potential losses arising from fires following the HayWired earthquake scenario, a hypothetical moment magnitude ( $M_w$ ) 7.0 earthquake (mainshock) 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. The earthquake causes Modified Mercalli Intensities of VI–X in the greater San Francisco Bay region, with very strong shaking along the fault in the densely urbanized 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 nonlinear 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  $M_w$  7.0 scenario mainshock, 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 79 million square feet of residential and commercial building floor area, equivalent to more than 52,000 single

family dwellings. The fires following the scenario mainshock would be directly responsible for the loss of hundreds of lives, a total building replacement value of almost \$16 billion, and property losses approaching \$30 billion (2014 dollars). This loss is virtually fully insured and would be one of the largest 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 the postearthquake 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

The HayWired earthquake scenario examines a hypothetical moment magnitude ( $M_w$ ) 7.0 earthquake (mainshock) 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. This chapter discusses the potential for fire in the bay region after the mainshock. “Fire following earthquake” refers to a series of events or a stochastic process initiated by a large earthquake. Fires occur following all earthquakes that significantly shake a human settlement but are generally only a significant problem in large metropolitan areas predominantly composed of densely spaced wood buildings. In such circumstances, multiple simultaneous ignitions can lead to catastrophic conflagrations<sup>2</sup> that may be the dominant agent of damage. Example regions vulnerable to such conflagrations include Japan, New Zealand, parts of Southeast Asia, and western North America. A large earthquake, such as a  $M_w$  7.0 event on the Hayward Fault in the San Francisco Bay area (or comparable events in southern California, Washington’s Puget Sound region, or the lower mainland of British Columbia), combines all of the requisite factors for major conflagrations that, depending on circumstances, can be uniquely catastrophic, such as the fire following the  $M_w$  7.8 Great 1906 San Francisco, California, earthquake.

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<sup>1</sup>SPA Risk LLC.

<sup>2</sup>Usage of the term conflagration varies within the fire service (and interestingly, does not appear in the 1,449-page National Fire Protection Association’s Glossary of Terms, 2013 Edition; [http://www.nfpa.org/~media/files/codes-and-standards/glossary-of-terms/glossary\\_of\\_terms\\_2013.pdf](http://www.nfpa.org/~media/files/codes-and-standards/glossary-of-terms/glossary_of_terms_2013.pdf)). It has previously been defined by the author (Scawthorn and others, 2005) as “. . . in the urban context, a conflagration usually denotes a large fire that spreads across one or more city streets.”

## Purpose

The purpose of this chapter is to quantitatively describe fires following a hypothetical  $M_w$  7.0 earthquake on the Hayward Fault, with primary emphasis for assisting emergency planning. The HayWired scenario occurs on Wednesday, April 18, 2018, at 4:18 p.m., with average April weather conditions. This analysis is intended to be realistic and not a “worst-case” scenario, and addresses the following questions:

- What is a realistic scenario of ignitions, fire growth, and spread?
- How will ignitions be reported after an earthquake, how will fire departments respond, and what factors will influence the spread of fires? What mutual-aid agreements are in place and how will they be activated?
- How will damage to telecommunications, water supply, and roadways affect response?
- What, if any, effective mitigation actions have been undertaken elsewhere that might be practical in the San Francisco Bay region in addition to those already taken?
- What are the limitations of the fire-following-earthquake scenario and what research would provide a more realistic, perhaps more challenging or detailed, scenario?

## Background

Large fires, measured in terms of square miles of burned area, have not been unique to fires following earthquakes—indeed the great fires of London (1666) and Chicago (1871) are only the most noteworthy of a long succession of nonearthquake related urban conflagrations. Large urban conflagrations were common in 19th century America, which allowed the National Board of Fire Underwriters (1905) to state the following with some confidence:

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.

Although the 1906 San Francisco earthquake had major geological effects and damaged many buildings, it was the ensuing fire that resulted in 80 percent of the total damage—a fire foreseen and expected, irrespective of an earthquake. As the fire service was professionalized in the 20th century—with improvements in equipment, communications, training, and organization—large urban conflagrations tended to become much less common (National Commission on Fire

Prevention and Control, 1973). However, they were not entirely eliminated, as witnessed in the San Francisco Bay area in the 1991 East Bay Hills Fire, when 3,500 buildings were destroyed in a matter of hours.

The two largest peacetime, urban conflagrations in history have been fires following earthquakes—1906 San Francisco ( $M_w$  7.9) and 1923 Tokyo ( $M_w$  7.9) earthquakes. In Tokyo, the fires caused the great majority of the 140,000 fatalities.

Much larger wildland fires also occur and continue to be a major source of loss in places such as southern California almost every year. However, historical earthquakes have not caused major wildland fires.

Although the combination of professionalized fire services, improved water supply, and better building practices has largely eliminated nonearthquake-related large urban conflagrations in the United States, fire following earthquakes is still a concern. This is owing to the correlated effects of a large earthquake simultaneously causing numerous ignitions, degrading building fire-resistive features, dropping pressure in water-supply mains, and overwhelming communications and transportation routes, thus allowing some fires to quickly grow into conflagrations that outstrip local resources. It is not sufficiently appreciated that the key to modern fire protection is a well-drilled, rapid response by professional firefighters in the early stages of structural fires, arriving in time to suppress a fire while that is still relatively feasible. For example, a typical response goal for urban fire departments is 4 minutes (from time of report to arrival) for a single ignition. If suppression is delayed, owing to either delayed response or lack of water, a single structural fire can quickly spread to neighboring buildings and grow to the point where an entire municipality’s fire resources are required, and perhaps even assistance from neighboring communities. This is for a single ignition. Most fire departments are not sized or equipped to cope with the fires following a major earthquake. A major earthquake and its associated fires is a low probability event for which, although having very high potential consequences, it may not be feasible to adequately prepare. There are exceptions to this; the Cities of San Francisco, Los Angeles, and Vallejo Fire Departments (California) and Vancouver (British Columbia) Fire and Rescue Services have all undertaken special measures, which are discussed below.

## Scenario Earthquake and Prevailing Conditions

This section summarizes the seismological aspects and affected region for the HayWired scenario. The focus is primarily on the fire-related aspects of the scenario.

## Rupture Segment, Magnitude, and Intensity

The HayWired scenario  $M_w$  7.0 mainshock on the Hayward Fault affects the entire San Francisco Bay region (fig. 1). Seismological aspects of the scenario are discussed in Detweiler and Wein (2017). Peak ground acceleration (PGA) and Modified Mercalli Intensity (MMI) distributions were developed by Aagaard and others (2017) for this project and furnished for this report (fig. 2). Noteworthy are the high MMI (VIII–X) along the fault in the entire east bay.

## Affected Region

Ten San Francisco Bay region counties affected by the scenario mainshock were analyzed for fire following earthquake. The region is densely urbanized (fig. 3), and the total affected population is approximately 7.7 million people (table 1; California Department of Finance, 2014), with population density as shown in figure 4.

## Exposure

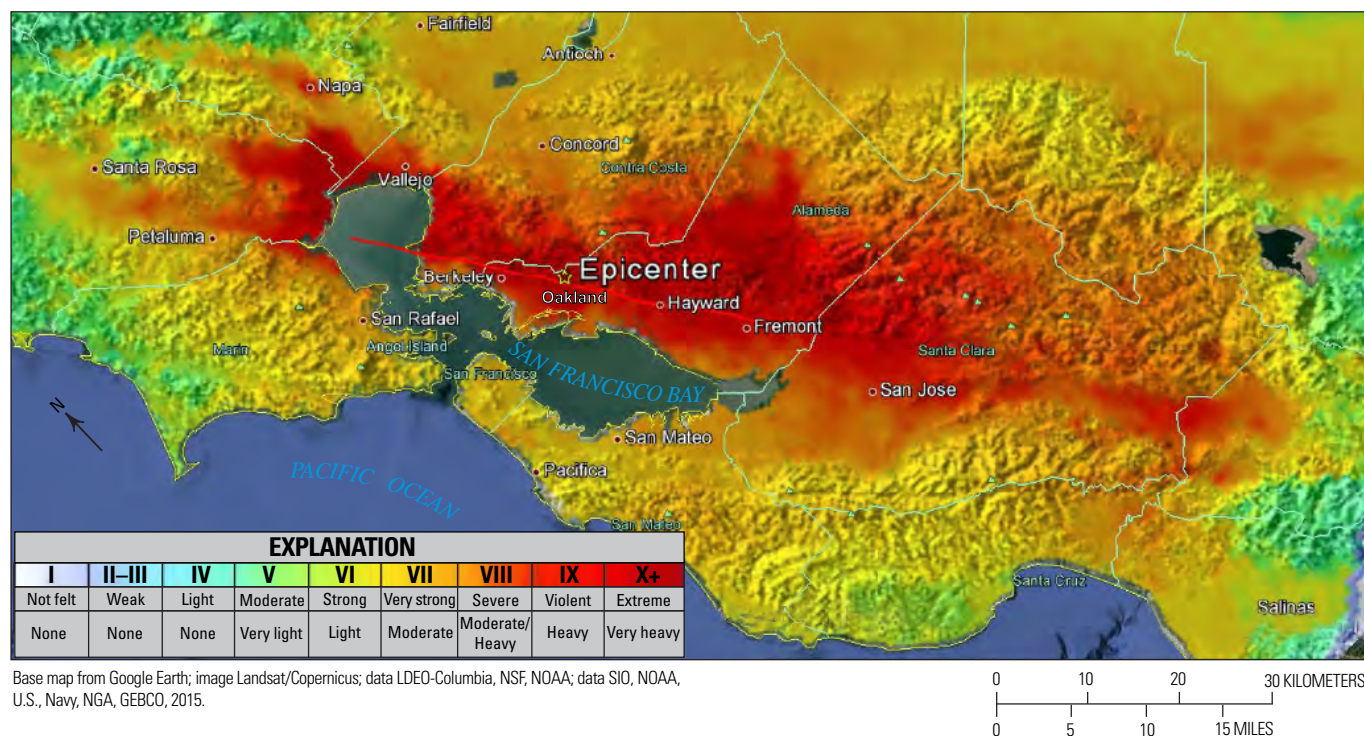
Building exposure data for the San Francisco Bay area was provided by the Federal Emergency Management Agency

**Table 1.** Counties and populations in the San Francisco Bay region, California, affected in the HayWired earthquake scenario.

County	Estimated population (2014) <sup>1</sup>
Alameda	1,573,254
Contra Costa	1,087,008
Marin	255,846
Napa	139,255
San Francisco	836,620
San Mateo	745,193
Santa Clara	1,868,558
Santa Cruz	271,595
Solano	424,233
Sonoma	490,486
Total	7,692,048

<sup>1</sup>From California Department of Finance (2014).

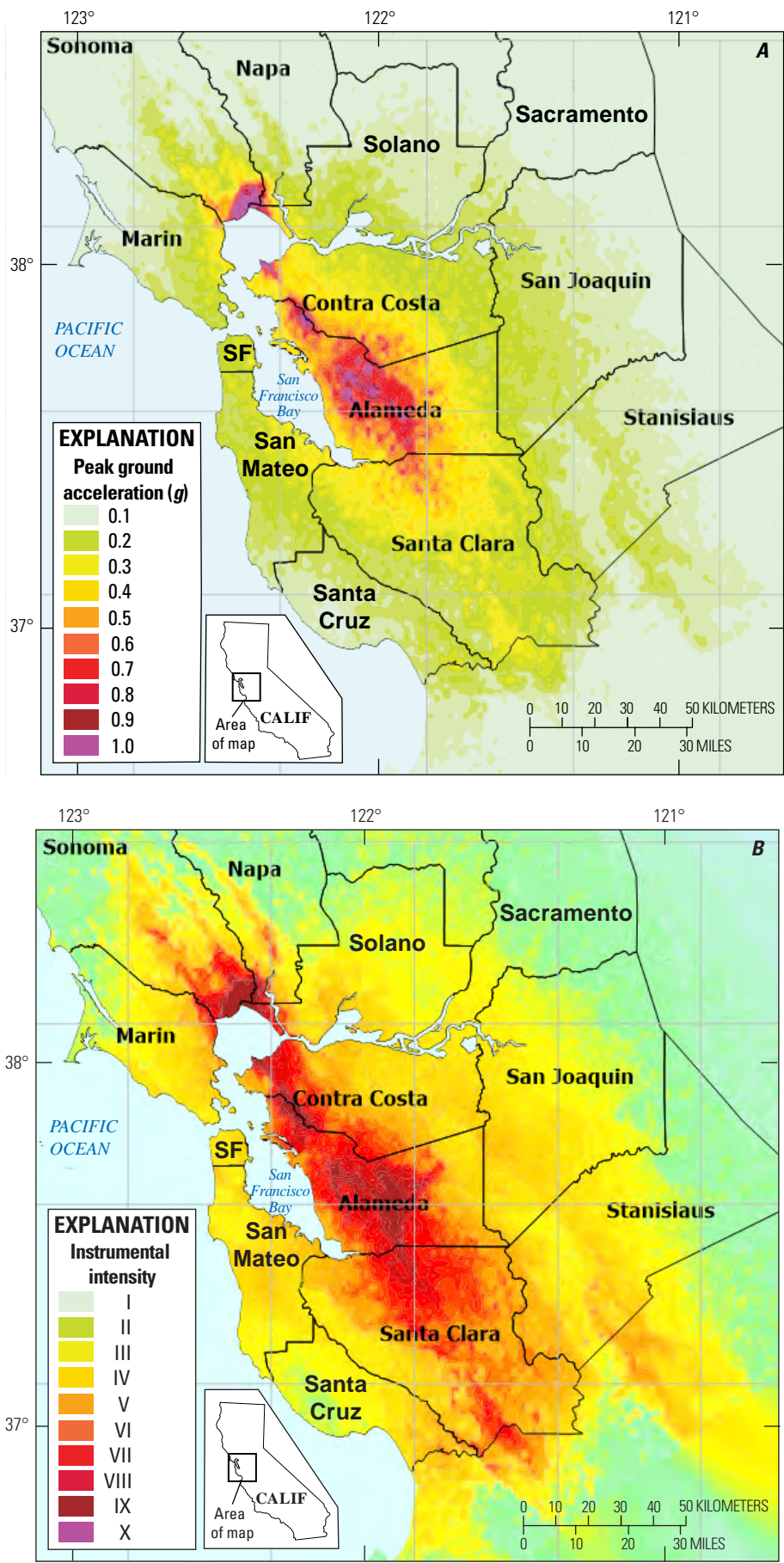
based on Hazus-MH (Federal Emergency Management Agency, 2012) building inventory. There is a total building floor area of 5.77 billion square feet, with an estimated value (structure only) of approximately \$1.15 trillion, distributed as shown in figure 5.



**Figure 1.** Satellite image of the San Francisco Bay region, California, overlaid with a U.S. Geological Survey ShakeMap for the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault (fault rupture shown by bright red line). (Mainshock data from Aagaard and others, 2017.)



**Figure 2.** Maps of the San Francisco Bay region, California, showing (A) peak ground acceleration (PGA) and (B) instrumental intensity (approximately Modified Mercalli Intensity) for the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. *g*, acceleration due to gravity. SF, San Francisco. (Mainshock data from Aagaard and others, 2017.)





**Figure 3.** Satellite image of San Francisco Bay region, California. The region is densely urbanized, with a population approximately 7.7 million people (California Department of Finance, 2014).

## Fire Protection

More than 500 fire stations were considered in the analysis of fire protection (fig. 6). In the most heavily impacted area there are a total of 229 fire engines potentially available immediately following the HayWired mainshock.

Although many jurisdictions have seismically retrofitted fire stations (and other critical infrastructure), the functionality of a significant number of fire stations is still questionable (fig. 7). According to Bello and others (2006), an Earthquake Engineering Research Institute survey of these fire stations in 2006:

... indicated that average peak ground acceleration are [sic] 0.5 g, and 52 percent of the stations are in areas mapped as moderate to very high liquefaction susceptibility with 102 stations being located within State designated Seismic Hazard Zone of Required Investigation for liquefaction or landsliding. More than 60 volunteers conducted walk-through field surveys of about 100 stations. In terms of life safety considerations, based on construction type, age and assessment of vulnerability, 42 percent of fire stations are in moderate to high-risk categories. In terms of functionality of the fire stations, based on a subset (293 stations) for which information was available, 67 percent were of moderate to high risk of not functioning after an earthquake. Based on these results, it is recommended that those fire stations at higher risk be evaluated and retrofitted such that life safety and vulnerability are improved before the next large earthquake occurs.

Each fire station in the affected region was allocated an immediate area using a Voronoi diagram<sup>3</sup> as an approximation

<sup>3</sup>For this analysis, the Voronoi diagram was a partition of the region into polygons, each side of which was a line equidistant from the nearest two fire stations. (For an explanation of Voronoi diagrams see [https://en.wikipedia.org/wiki/Voronoi\\_diagram](https://en.wikipedia.org/wiki/Voronoi_diagram).)

of the station's primary response area (fig. 8). The subsequent analysis is based on these primary response areas.

## Time of Day

Time of day is relevant in that more human activity occurs during waking hours, typically resulting in higher ignition rates at those times. The HayWired mainshock is specified as occurring Wednesday, April 18, 2018, at 4:18 p.m. However, the specific time of occurrence is not considered in this analysis.

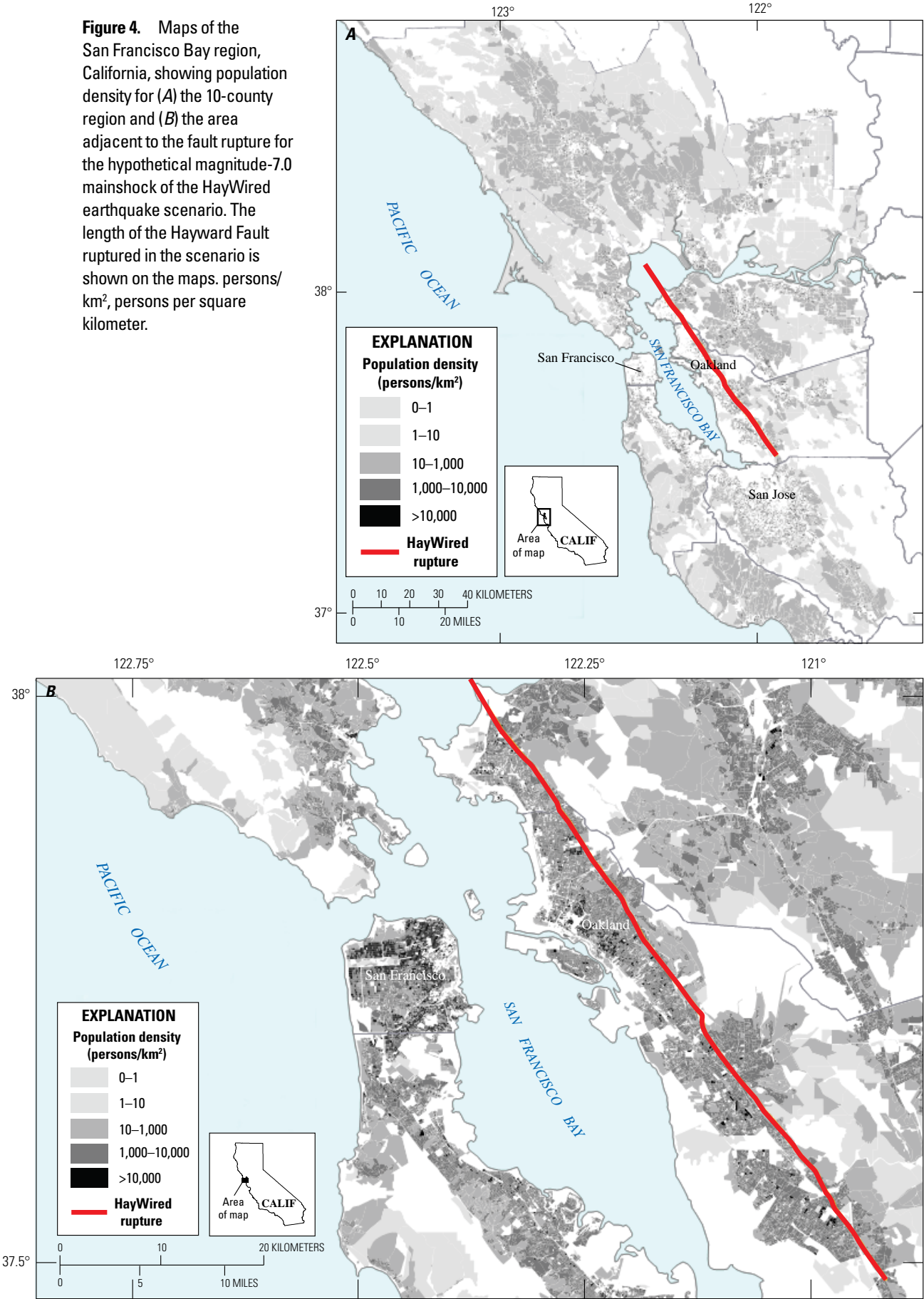
## Wind and Humidity

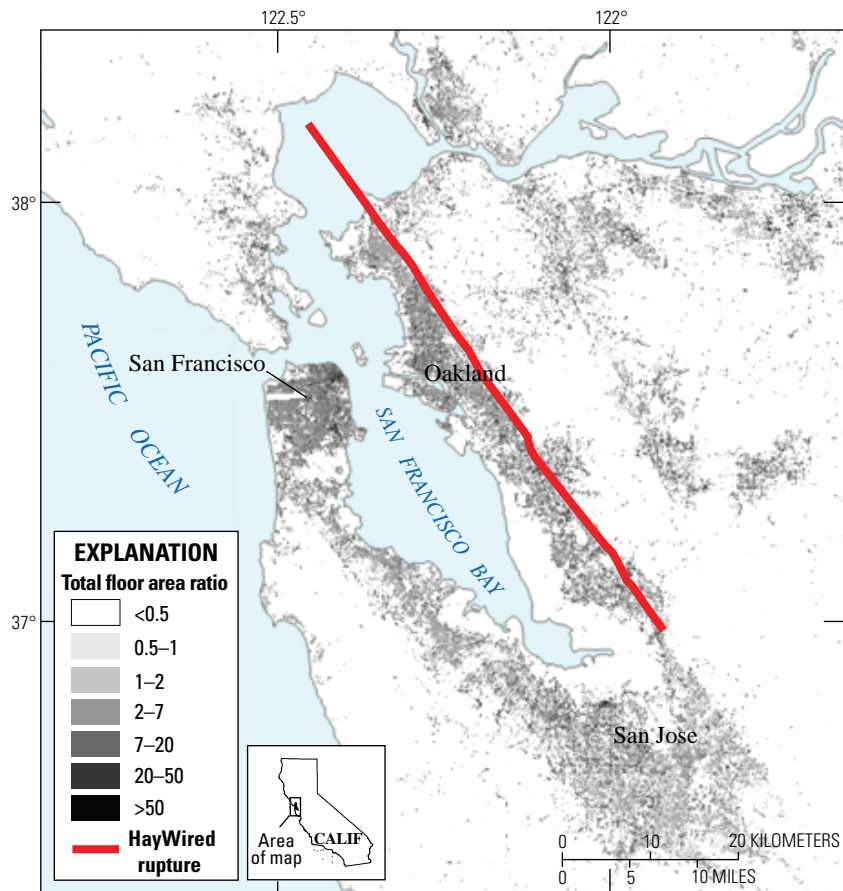
Weather can affect fire growth and spread, as well as the direction and distance at which communities are affected by hazardous material release. Important meteorological parameters include windspeed, wind direction, temperature, rain, and humidity. For purposes of estimating fire effects in the HayWired scenario, average April conditions were assumed to apply, based on data for the period 1974–2012 (WeatherSpark, 2014). Average conditions for the three San Francisco Bay area international airports are shown in table 2 and figure 9. In the case of precipitation, the most common condition is reported (for example, no rain), along with the probability of precipitation at some point in the day and the most common form of precipitation when it does rain. In the case of wind direction, the most common direction is tabulated. Humidity is reported as average daily low and high.

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. An example of this is shown in figure 10 for April 18, 2012, in which major streaklines are shown at 4 p.m. and 5 p.m., with much shorter streaklines at 9 p.m. Cumulative distribution functions for windspeeds for 4 p.m.,

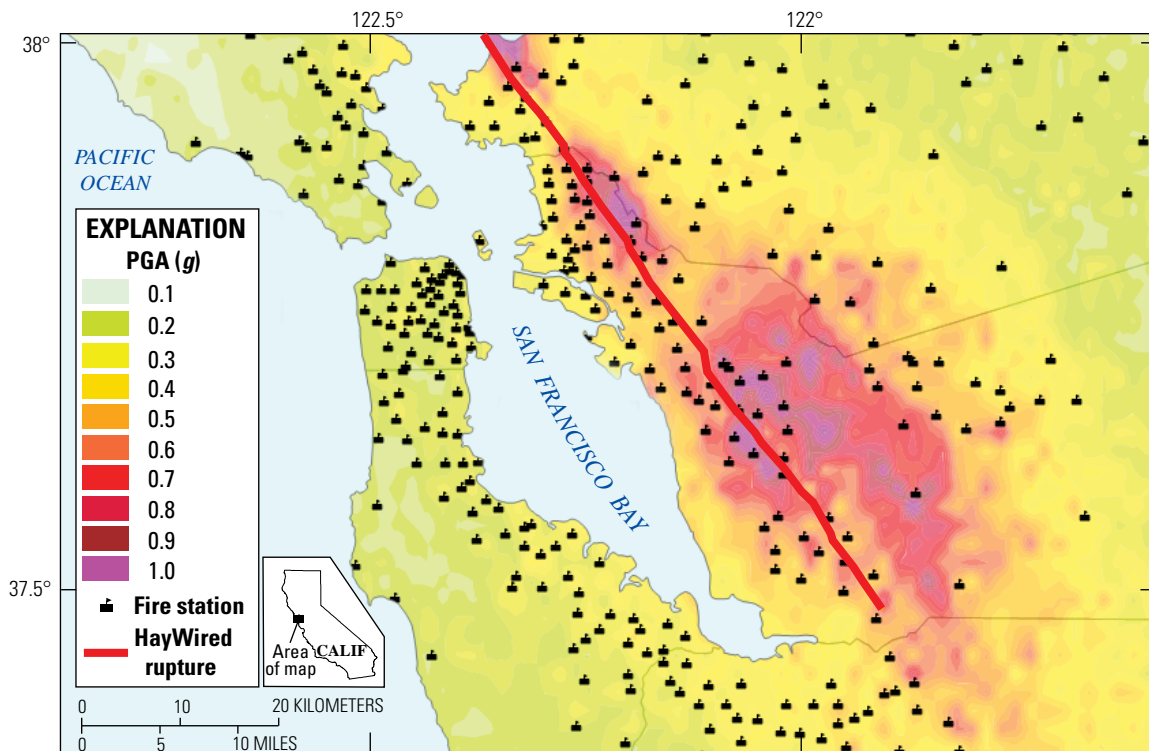


**Figure 4.** Maps of the San Francisco Bay region, California, showing population density for (A) the 10-county region and (B) the area adjacent to the fault rupture for the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario. The length of the Hayward Fault ruptured in the scenario is shown on the maps. persons/km<sup>2</sup>, persons per square kilometer.



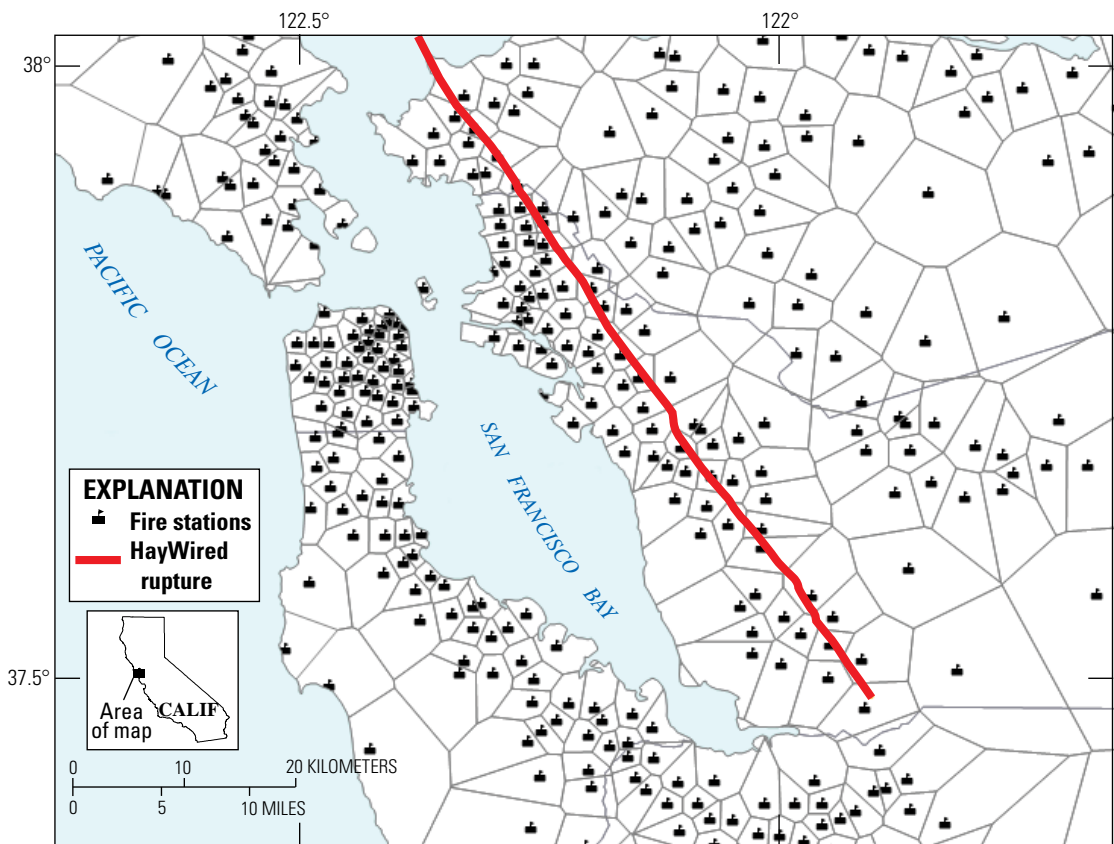
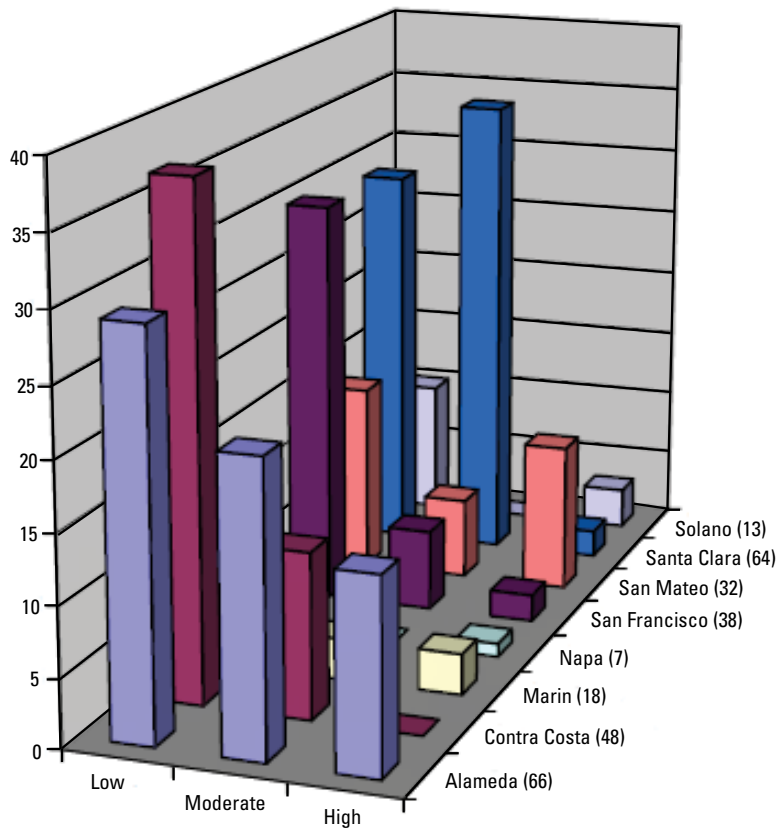


**Figure 5.** Map showing building density of San Francisco Bay region, California. The length of the Hayward Fault ruptured in the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario is shown on the map. Total floor area ratio, total building floor area in a census block divided by the area of the census block.



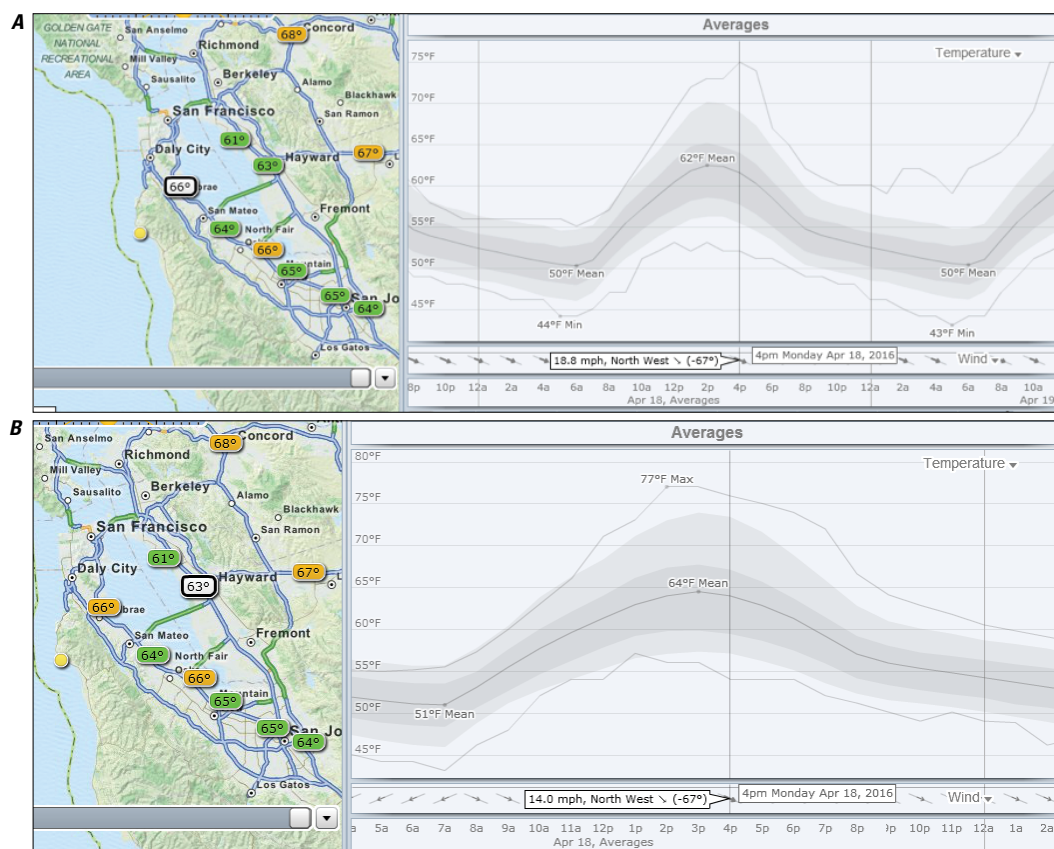
**Figure 6.** Map of San Francisco Bay area, California, fire stations overlaid on peak ground acceleration (PGA) for the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario. The length of the Hayward Fault ruptured in scenario is shown on the map. *g*, acceleration due to gravity. (Mainshock data from Aagaard and others, 2017.)

**Figure 7.** Three-dimensional graph showing the number of fire stations in San Francisco Bay area, California, counties that are at low, moderate, and high risk of earthquake damage in the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario (data from Bello and others, 2006).

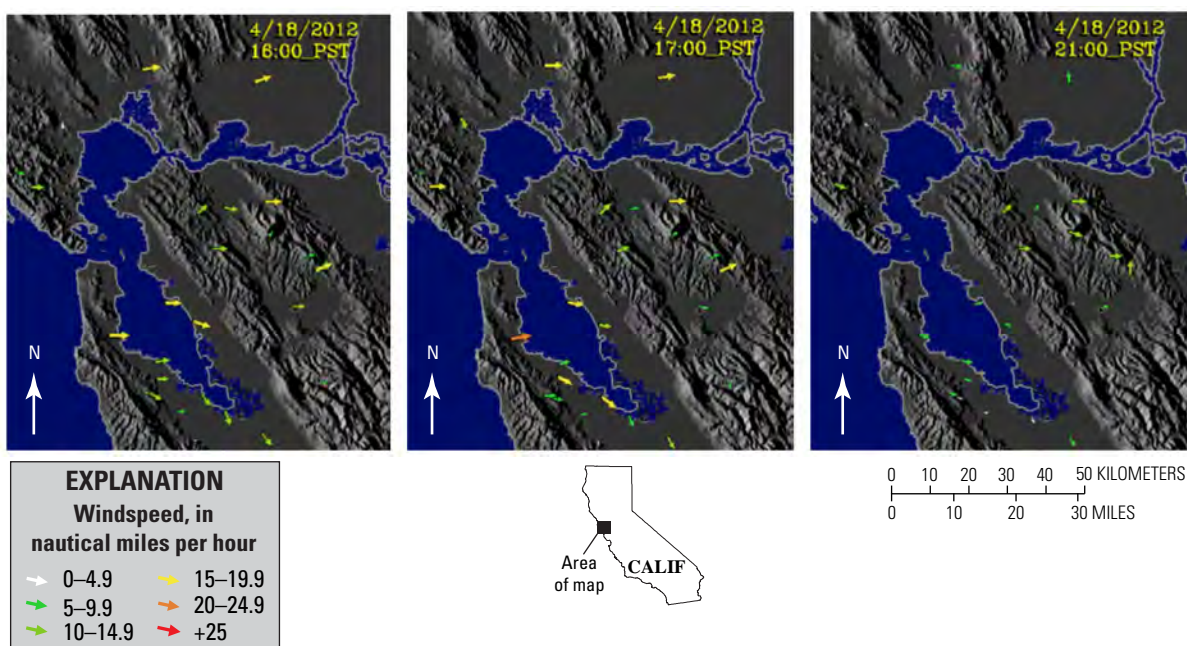


**Figure 8.** Map of San Francisco Bay area, California, fire stations with associated Voronoi areas. The primary response area for each fire station was approximated by a Voronoi diagram. The length of the Hayward Fault ruptured in the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario is shown on the map.





**Figure 9.** Maps and charts of average temperatures on April 18 at (A) San Francisco International Airport and (B) Hayward Executive Airport in the San Francisco Bay area, California. Average windspeeds are noted. (Images from WeatherSpark, 2014; <http://www.weatherspark.com>, used with permission.)



**Figure 10.** Maps showing wind streaklines (arrows) for April 18, 2012 (4/18/2012), at 4 p.m. (left), 5 p.m. (center), and 9 p.m. (right), typical of April wind conditions in the San Francisco Bay region, California. Strong westerly winds in late afternoon subside in evening. Windspeed was measured 10 meters above surface elevation. PST, Pacific Standard Time. (Images from San Jose State University, 2014.)

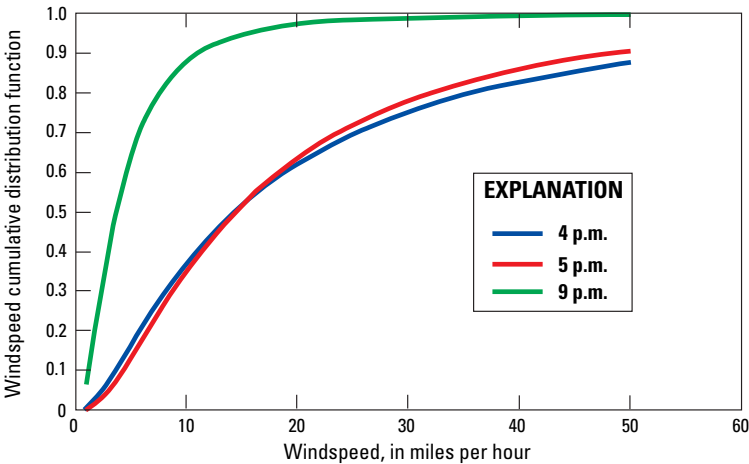
**Table 2.** Average wind conditions in April at San Francisco Bay area, California, major airports.

[Weather data from WeatherSpark (2014); mi/hr, miles per hour; °F, degrees Fahrenheit; NW, northwest; W, west]

Airport (city/identifier)	Windspeed (mi/hr)	Direction	Temperature (°F)	Light rain (percent chance)	Percent humidity
San Jose (SJC)	7	NW	50–65	19	42–93
San Francisco (SFO)	12	W	50–65	28	52–88
Oakland (OAK)	10	W	50–65	22	56–92

5 p.m., and 9 p.m. for the years 2000–2012 are shown in figure 11, and indicate significant variability of the stronger afternoon winds, with consistently calmer conditions later in the evening.

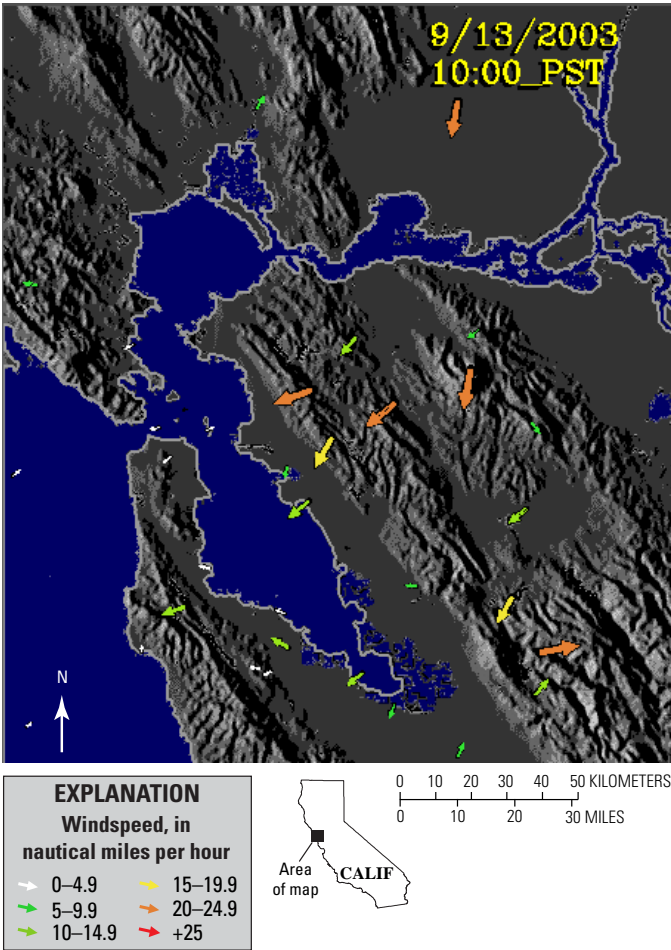
However, a reverse of the typical summertime weather pattern can occur, consisting of occasional intense katabatic winds, locally sometimes termed “Diablo winds.” These are hot, dry, offshore winds from the northeast that sometimes occur in the San Francisco Bay region during the spring and fall. These 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 degrees Fahrenheit (°F) (11 degrees Celsius, °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 kilometers per hour) 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 ridgelines (fig. 12). Such winds were major factors in the 1923 Berkeley and 1991 East Bay Hills Fires (discussed below). This effect is especially significant as it can enhance the updraft generated by large wildland or urban fires. The pattern of windspeeds 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 11.** Graph showing cumulative distribution function of windspeeds in the central San Francisco Bay region, California, for 4 p.m., 5 p.m., and 9 p.m. for the years 2000–2012. (Data from San Jose State University, 2014.)

### Experience with Large Fires in the San Francisco Bay Region

The Great 1906 San Francisco earthquake and fire is the archetypical fire following earthquake event. It is so familiar and well documented that we will not spend much time on it here. Simply put, it was the largest peacetime urban fire in history at the time, only exceeded since by the 1923 Tokyo earthquake and fire. The 1906 earthquake and resulting fires caused an estimated 3,000



**Figure 12.** Map showing wind streaklines (arrows) for September 13, 2003 (9/13/2003), at 10 a.m., typical of Diablo wind conditions in the San Francisco Bay region, California. Windspeed was measured at 10 meters above surface elevation. PST, Pacific Standard Time. (Images from San Jose State University, 2014.)



deaths and \$524 million (1906 dollars) in property loss. Fires that ignited in San Francisco soon after the onset of the earthquake burned for 3 days because of the lack of water to control them. The damage in San Francisco was devastating and 28,000 buildings were destroyed, although 80 percent of the damage was caused by the fire rather than the shaking (fig. 13). Fires also intensified the losses in 1906 at Fort Bragg and Santa Rosa (see Scawthorn and O'Rourke, 1989; Scawthorn and others, 2005; Scawthorn and others, 2006).

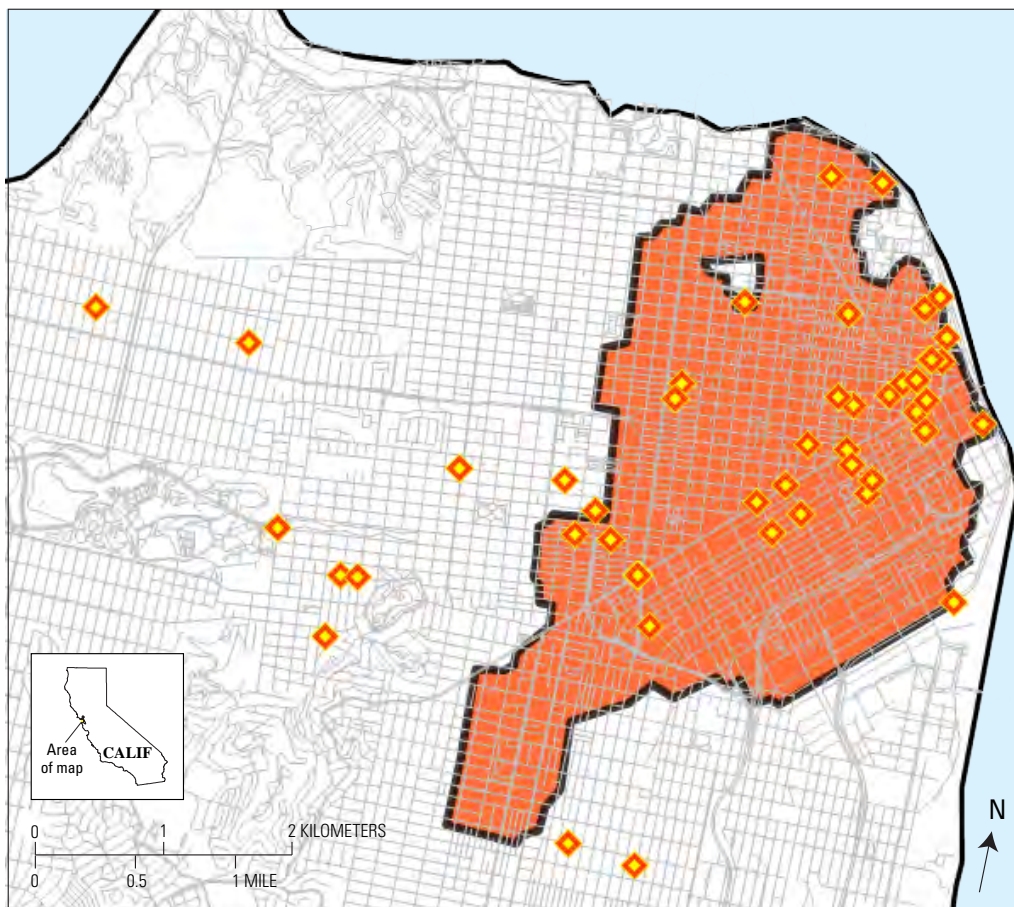
Beyond the 1906 San Francisco earthquake and fire, the San Francisco Bay region has a long history of conflagrations (fig. 14), owing in large part to the Diablo winds discussed above. According to the Hills Emergency Forum (2005), over the period from 1923 to 1991 the east bay has averaged a 585-acre fire every 5 years, destroying on average 266 homes (2005). However, most of these building losses occurred in only two of these fires—the 1923 and 1991 events (fig. 15, table 3). It should also be noted that almost all of these fires occurred in autumn (which is typically the region's greatest fire-risk season), in contrast to the scenario being considered here.

Three recent fires in the San Francisco Bay region are worthy of mention:

- On September 9, 2010, a buried, high-pressure, 30-inch steel natural-gas pipeline exploded in a residential neighborhood in San Bruno, California, near San Francisco. The explosion and ensuing fire killed 8 people

and injured 58. It destroyed 38 homes and damaged an additional 70. During the first 50 hours following the incident, more than 500 firefighters and 90 firefighting apparatus responded, involving 42 fire agencies. The total cost of the disaster was estimated to be approximately \$1.6 billion (Davidson and others, 2012).

- The Mission Bay fire was a five-alarm fire that occurred shortly before 5 p.m. on March 11, 2014, in the Mission Bay neighborhood of San Francisco, California. The conflagration appeared to completely destroy block 5, a 172-unit building, part of Mega Blocks 360, a \$227 million apartment complex being developed by San Francisco-based BRE Properties, Inc., at China Basin Street and Fourth Street (San Francisco Chronicle, 2014). The San Francisco Fire Department needed a large amount of resources to combat the fire, including the city's auxiliary water-supply system.
- On the night of October 8, 2017, Diablo winds started and drove widespread wildfires in the northern San Francisco Bay region counties of Napa, Sonoma, and Solano. The fires killed at least 43 people, destroyed 8,900 homes and other structures, and burned 164,000 acres. More than 10,000 firefighters responded to the fires (Wikipedia, 2017). (Note that because of its recency, this fire was not considered further in this chapter.)

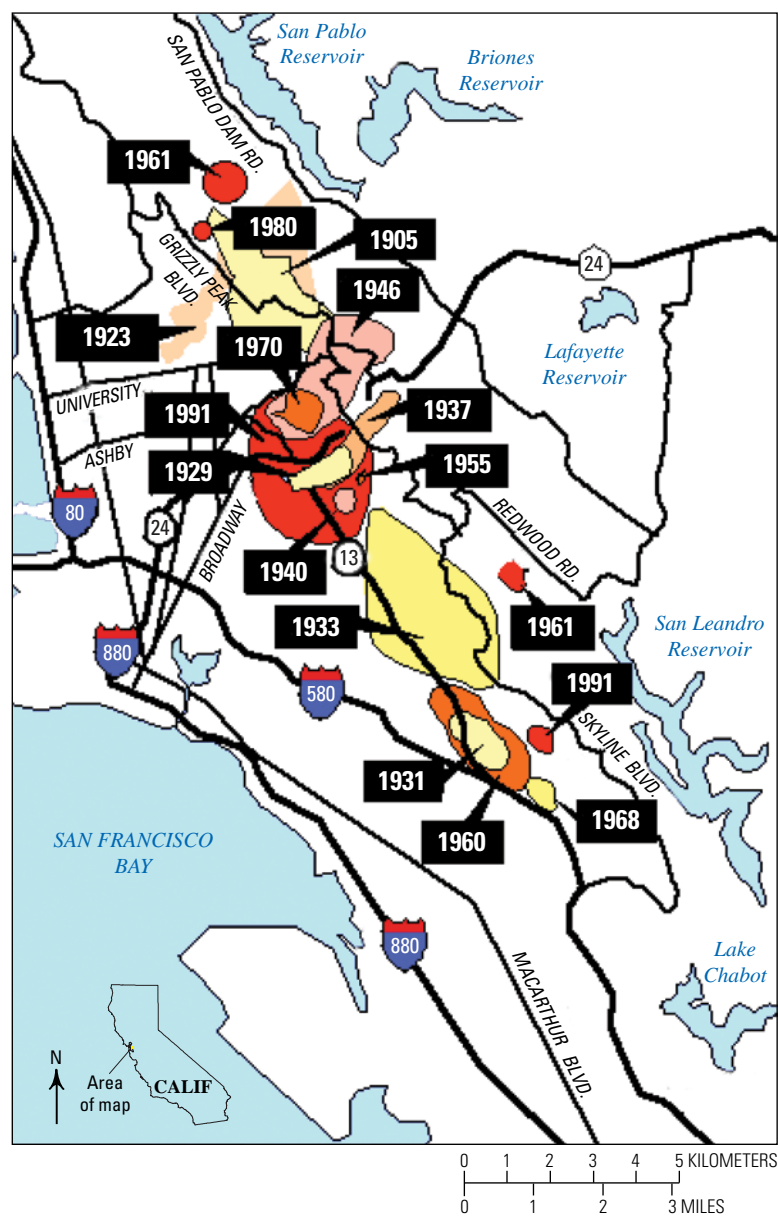


**Figure 13.** Map of fires (orange and yellow diamonds) caused by the moment-magnitude-7.8 1906 San Francisco, California, earthquake and area burned in the great conflagration that followed (orange). Ignition data from Scawthorn and O'Rourke (1989) and Scawthorn and others (2005).

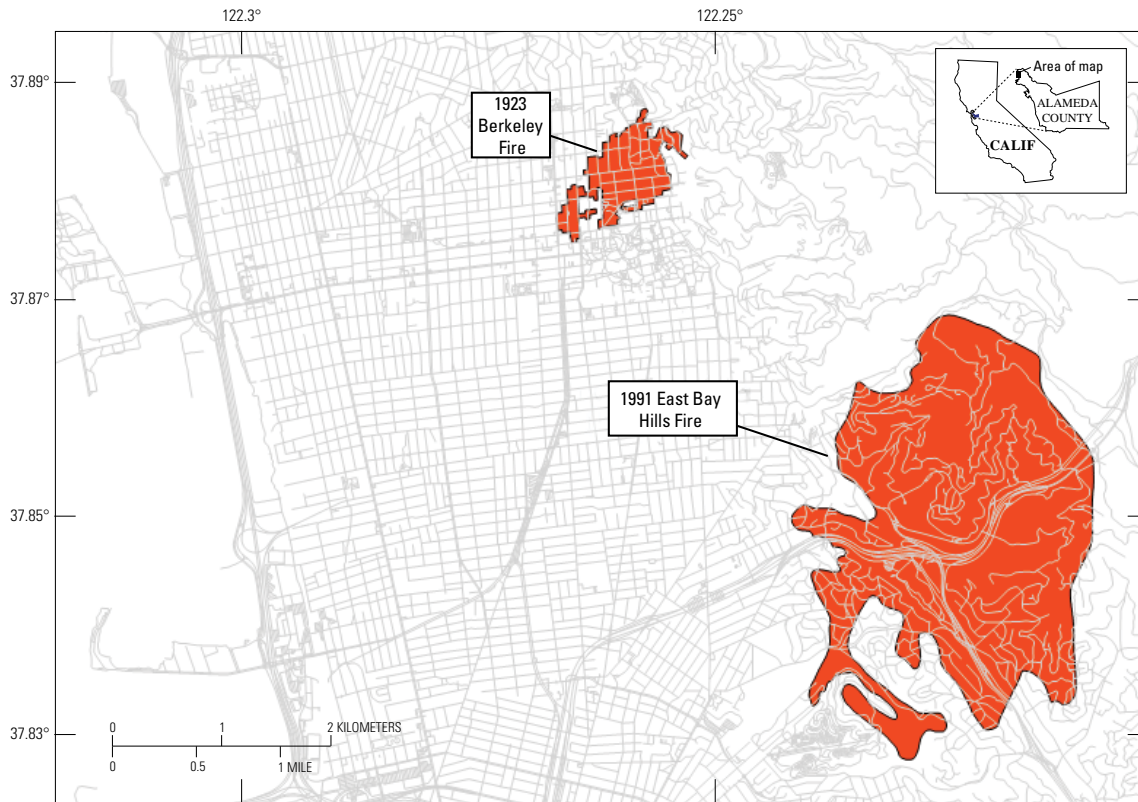
**Table 3.** List of some large, historical fires driven by Diablo winds in the east bay part of the San Francisco Bay area, California (data from Hills Emergency Forum, 2005; California Governor’s Office of Emergency Services, 2013; Routley, [n.d.]; National Board of Fire Underwriters, 1923.

[--, no data]

Month/year	Fire name/location	Deaths	Structures destroyed	Acres burned	Estimated damage, in billions of U.S. dollars	Ignition cause
September 1923	City of Berkeley	0	584	130	--	Smoker
November 1933	Joaquin Miller (Redwood Road)	1	20 homes	1,000	--	Smoker
September 1946	Buckingham Boulevard/Norfolk Road	0	0	1,000	--	Arson and rekindle
October 1960	Leona Hillside	0	2 homes	1,200	--	Unknown
September 1970	Oakland Hills	0	37 homes and 21 damaged	204	--	Arson
October 1991	East Bay Hills	25	3,354 homes and 456 apartments	1,600	1.5	Rekindle



**Figure 14.** Map of fires in the east bay part of the San Francisco Bay area, California, from 1923 to 1991. Note that colors are only used to differentiate among areas burned by fires. (Modified from Hills Emergency Forum, 2005.)



**Figure 15.** Map of final burned areas (dark orange) for 1923 Berkeley and 1991 East Bay Hills Fires in the east bay part of the San Francisco Bay area, California.

## Fire Following Earthquake Aspects of the Scenario

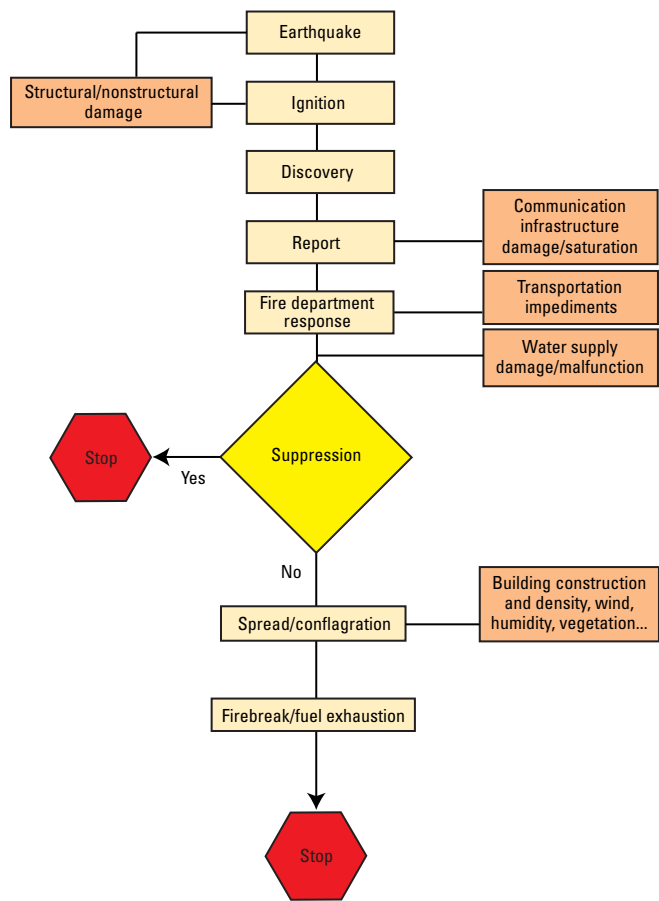
This section presents the analysis underlying the estimation of fires and losses likely to result from the HayWired scenario mainshock. The section discusses modeling of fire following earthquake, ignitions, initial response, fire spread, and performance of lifelines (for example, utilities and transportation).

### Modeling of Fire Following Earthquake

A full probabilistic methodology for analysis of fire following earthquake was developed in the late 1970s (Scawthorn and others, 1981) and has been applied to major cities in western North America (Scawthorn and Khater, 1992). Scawthorn and others (2005) summarizes modeling for fire following earthquake, so only a brief review is presented here. In summary, the steps in the process of fire following earthquake are shown in figure 16:

- Occurrence of the earthquake—causing damage to buildings and contents, even if the damage is as simple as objects (such as candles or lamps) falling over.
- Ignition—whether a structure has been damaged or not, ignitions can occur as a result of earthquakes. The sources of ignitions are numerous, including overturned heat sources, abraded and shorted electrical wiring, spilled chemicals having exothermic reactions, and friction from objects 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 in more detail below). In the confusion following an earthquake, the discovery may take longer than it might otherwise.
- Report—if it is not possible for people discovering a fire to immediately extinguish it, fire department response will be required. For a fire department to respond, a report has to be made to the fire department. Communications-system malfunction and congestion may delay many reports.
- Response—a fire department then has to respond but may be delayed by responding to nonfire emergencies (for example, building collapse) and by transportation disruptions.
- Suppression—a fire department then has to suppress the fire. If the fire department is successful, they move on to the next incident. If not successful, they continue to attempt to control the fire, but it can spread and become a conflagration. Success or failure hinges on numerous factors, including the functionality of the water-supply system, building construction and density, and weather conditions such as wind and





**Figure 16.** Flow chart of the fire-following-earthquake process (from Scawthorn and others, 2005).

humidity. If the fire department is unable to contain the fire, the process ends when the fuel is exhausted or when the fire reaches a firebreak.

This fire-following-earthquake process is also shown in figure 17, which is a fire department operations time line. A rapid response is essential to reduce losses from fire following earthquake. Fire following earthquake is not a linear process, and modeling it is not very precise—in many cases, only a few small fires versus a major conflagration can be distinguished.

**Ignitions**

Postearthquake ignition rates in the United States have been studied by a number of investigators (Lee and others, 2008) with the most recent and relevant algorithms for estimating postearthquake ignition rates being developed by Davidson (2009a,b) and SPA Risk LLC (2009), both of which are considered here.

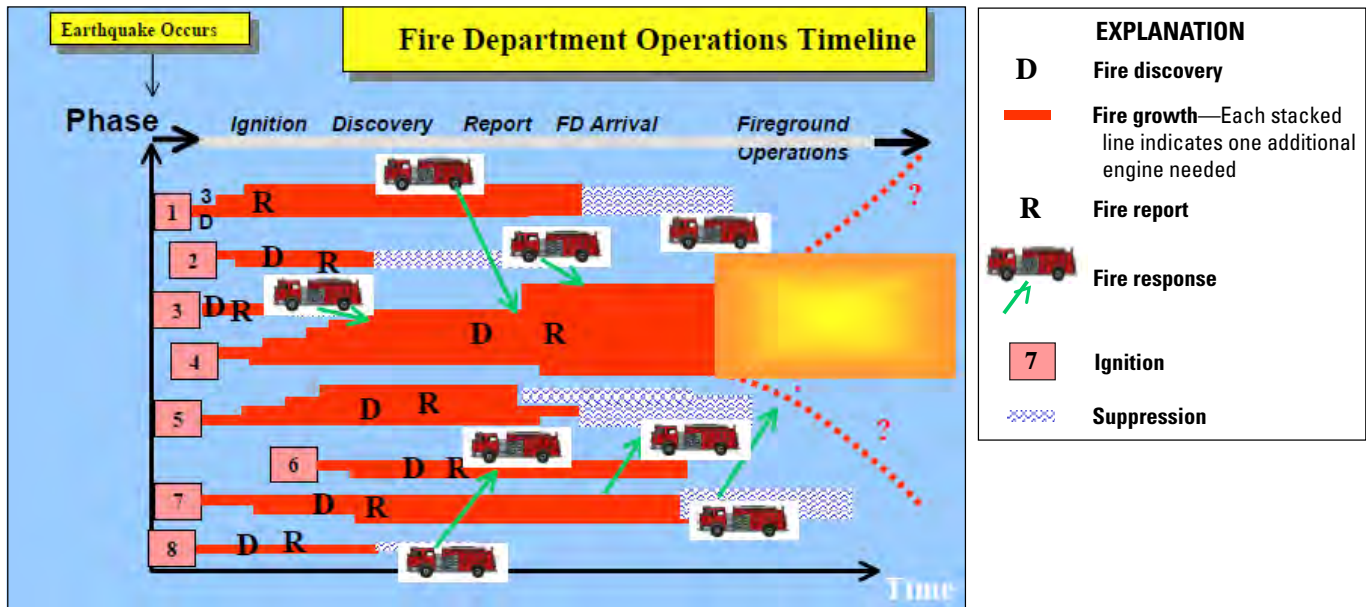
Davidson (2009b) conducted an exhaustive selection to evaluate 48 potential covariates, of which model A.NB2 is:

$$\ln(\mu) = \beta_0 + \beta_{II}II + \beta_{tbl dg} \ln(tbl dg) + \beta_{\%CTT}x_{\%CTT} + \beta_{dens}x_{dens}, \quad (1)$$

where

- $\mu$  is ignitions per census tract,
- $II$  is the instrumental intensity of the earthquake,<sup>4</sup>

<sup>4</sup>Modified Mercalli Intensity (MMI) and Instrumental Intensity (II) are used synonymously here.



**Figure 17.** Chart of fire department (FD) operations timeline when responding to fires following an earthquake. 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). (From Scawthorn and others, 2005.)

$x_{\%CIT}$	is the percent of land area that is commercial, industrial, or transportation,
$tbldg$	is the total building area in thousands of square meters,
$x_{\%URM}$	is the percent of building area that is unreinforced masonry (URM),
$x_{dens}$	is the population density (persons per square kilometer), and

parameter ( $\beta$ ) estimates are  $\beta_0 = -15.42$ ,  $\beta_{ii} = 1.13$ ,  $\beta_{\%CIT} = -32.48$ ,  $\beta_{tbldg} = 0.85$ ,  $\beta_{\%URM} = 27.72$ , and  $\beta_{dens} = 0.0000453$ .

The SPA Risk LLC (2009) relation used the Davidson (2009b) dataset restricted to census tracts that (1) fell within jurisdictions for which ignition data was available, (2) experienced  $MMI \geq VI$ , and (3) had population densities greater than 3,000 per square kilometer. Using this approach, relatively simple regressions to model postearthquake ignitions were developed:

$$\text{Ignitions per million square feet of building floor area} = -0.029444PGA + 0.581895PGA^2, \quad (2)$$

$$\text{Ignitions per million square feet of building floor area} = 1.0449 - 0.338MMI + 0.0277MMI^2, \quad (3)$$

where  $PGA$  is the peak ground acceleration of the earthquake, relative to the acceleration due to gravity at the Earth's surface ( $g$ ).

Of the two ignition regressions, the one in equation 1 requires more data, some of which may not be readily available (for example, percentage of URM building).<sup>5</sup> A comparison of the two ignition models is shown in figure 18A, where equation 1 is plotted using median values (standard deviations in parentheses) for  $tbldg = 244.7$  (164),  $x_{\%CIT} = 0.027$  (0.016),  $x_{\%URM} = 0.013$  (0.01), and  $x_{dens} = 3,445$  (4,048) as provided in Davidson (2009b), and equation 3 (SPA Risk LLC, 2009) is plotted in black using 2.6 million square feet of building floor area per census tract. Dotted lines in the figure are equation 1 plus and minus one standard deviation (determined by way of numerical simulation).

Figure 18B and C are similar, except that the variable  $x_{\%CIT}$  in Davidson's (2009b) equation, representing the percentage of land area employed for commercial, industrial, and transportation (CIT) purposes, is varied by plus and minus one sigma (sigma of  $x_{\%CIT}$ ), with equation 3 remaining the same in all plots. In figure 18A, it can be seen that the median SPA Risk LLC (2009) model is higher than the Davidson (2009b) model, by a factor of 2.8 at MMI VI and 2.3 at MMI VIII, while actually being lower (0.93) at MMI X. In figure 18B,

corresponding to lower CIT land use (more representative of residential areas), the two models are in closer agreement, whereas C (representative of higher CIT uses) shows a somewhat greater difference of the two models.

Equation 2 was used to estimate the total number of ignitions for the HayWired mainshock, resulting in a mean estimate of 668 ignitions, as shown in figure 19 and table 4. 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 fires exceeding the capacity of the first arriving engine).

The cause of these ignitions will likely be similar to causes following the 1994  $M_w$  6.7 Northridge, California, earthquake, which is the best U.S. dataset for fire following a recent earthquake; about half of all ignitions would be electrical, a quarter gas related, and the remainder owing to a variety of causes, including chemical reactions (table 5). Also, on the basis of the Northridge experience, nearly half of all ignitions would typically occur in single-family residential dwellings, with another 26 percent in multifamily residential dwellings—that is, about 70 percent of all ignitions occur in residential dwellings (Scawthorn and others, 1998). Ignitions in educational facilities would be a small percentage of the total (3 percent in Northridge), and most of these would be a result of the exothermic reactions of spilled chemicals in chemistry laboratories.

A particular concern is the large number of oil refineries, tank farms, and related facilities in the northern bay area. These facilities refine one-third of the gasoline used west of the Rocky Mountains. When strongly shaken, oil refineries and tank farms have typically had large fires, which have burned for days. Examples include the Showa Refinery fire following the  $M_w$  7.6 1964 Niigata, Japan, earthquake (Kawasumi, 1968), the Tüpraş Refinery fire following the  $M_w$  7.6 1999 İzmit, Turkey, earthquake (Scawthorn, 2000), and the Idemitsukosan Hokkaido Refinery fire following the  $M_w$  8.3 2003 Tokachi-Oki, Japan, earthquake (Scawthorn and others, 2005).

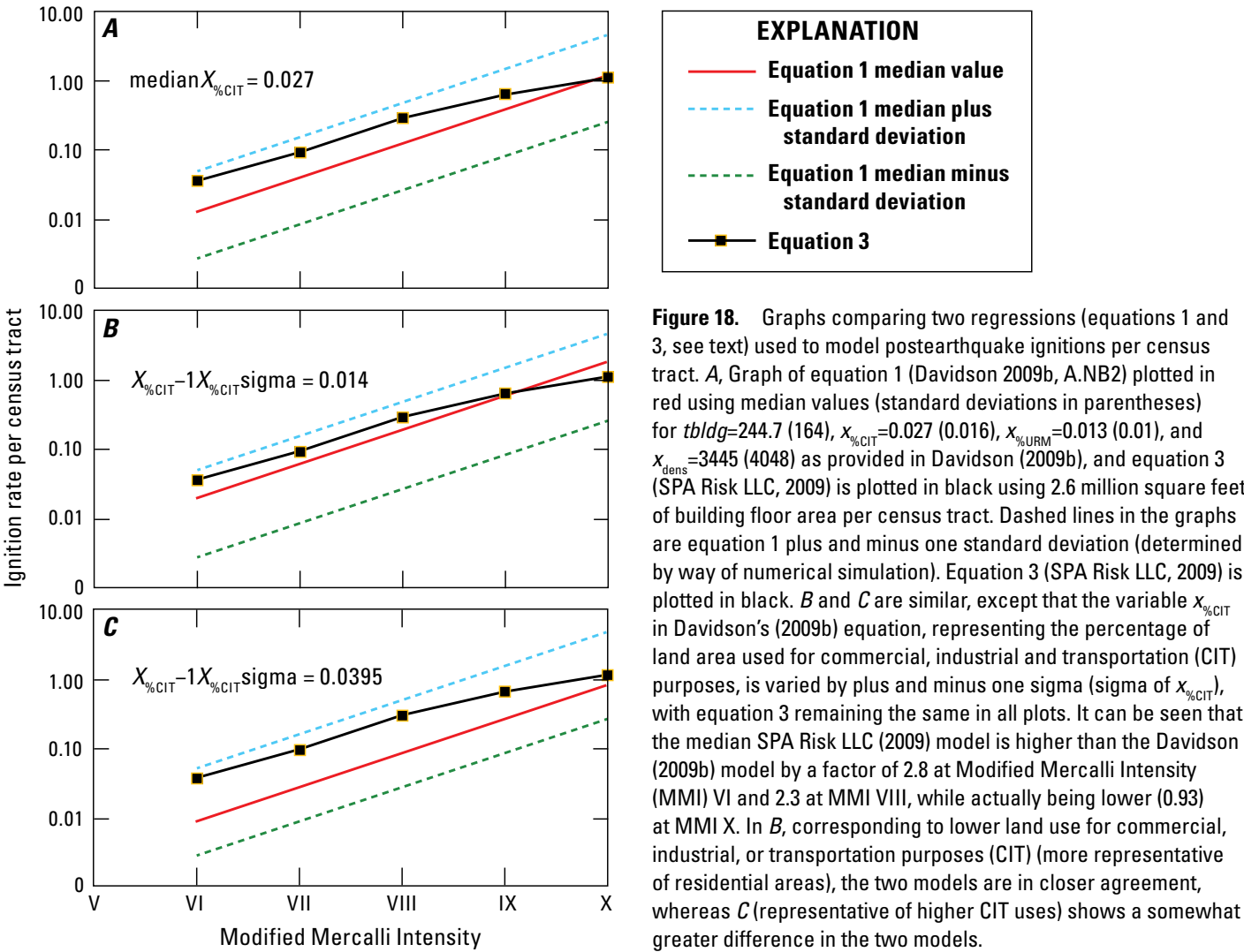
## Initial Response

This section discusses the initial response to ignitions following an earthquake. Reporting of fires is particularly crucial, yet problematic, following an earthquake.

## Citizen Response

Initially, citizens will respond to the approximately 668 ignitions requiring fire-department response in the HayWired scenario. When they realize suppressing the fires is beyond their capabilities, they will attempt to contact emergency

<sup>5</sup>Davidson (2009b) used default data from Hazus-MH MR2 (Federal Emergency Management Agency, 2003) for building floor area and unreinforced masonry (URM) estimates. An issue exists with the use of "URM" default data since most URM buildings in California have been retrofitted, so whether such buildings are now unreinforced is unclear. Ding and others (2008) have examined the Hazus-MH MR2 building inventory data (in general, in the context of flood) and found it to have significant inaccuracies. That being said, at the regional level the database can be useful, and Davidson's use of it was innovative.



**Table 4.** Estimated ignitions and damage from the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario on April 18, 2018, at 4:18 p.m. (breezy conditions and moderate humidity).

[--, no data; TFA, total floor area]

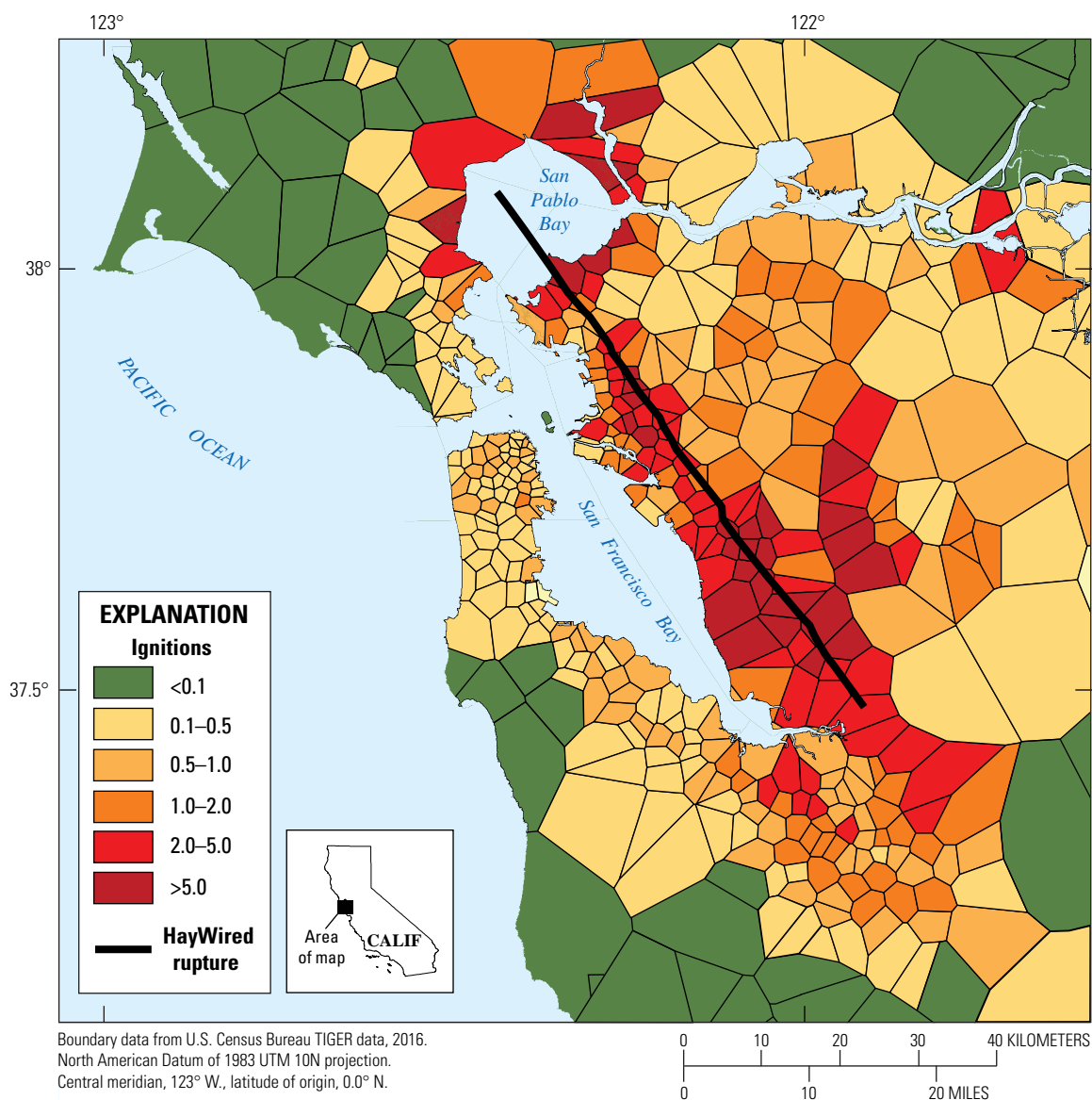
County	Exposed building TFA	Ignitions	Large fires	Conflagrations (multiblock fires)	Final burned TFA, in millions of square feet	Final burned loss, in millions of 2014 U.S. dollars (\$)	Percent burned	Percent of total losses
Alameda	1,853	352	279	198	49	\$9,710	4	53
Contra Costa	1,480	123	60	43	10	\$2,103	1	18
Marin	342	23	14	10	2	\$500	1.1	4
Napa	90	27	19	13	3	\$651	5.3	4
San Francisco	817	21	5	4	1	\$177	0	3
San Mateo	576	19	15	11	3	\$519	1	3
Santa Clara	1,610	83	56	40	10	\$1,940	1	12
Santa Cruz	96	1	--	--	--	--	0.01	0
Solano	338	12	4	3	1	\$142	0.4	2
Sonoma	38	7	0	0	0	\$13	0.3	1
Total	7,241	668	453	321	79	\$15,755	2	100



**Table 5.** General sources of ignition after the moment-magnitude-6.7 1994 Northridge, California, earthquake. (ignition data from Scawthorn and others, 1998).

Source of ignition	Percentage of ignitions
Electrical	56
Gas-related	26
Other	18

services by telephone, because street fire-alarm pull boxes have largely disappeared from the U.S. urban landscape. Attempts to report fires by calling 9-1-1 will likely be unsuccessful, owing to congestion of the system and overwhelmed 9-1-1 dispatch centers. Citizens may then go in person to the nearest fire station, but such “still alarms” will largely be futile because the fire companies will have already responded (self-dispatched) to the nearest fire, if not dispatched by 9-1-1. Experience shows that citizens on scene will respond rationally (Van Anne and Scawthorn, 1994), rescuing as many people as possible and protecting neighboring buildings (exposures). Water supply from mains (discussed below) will often be unavailable.



**Figure 19.** Map of San Francisco Bay region, California, showing estimated number of ignitions within fire station primary response areas (see fig. 8) following the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario. Green indicates a small likelihood of ignition and dark red indicates five or more ignitions per area. The length of the Hayward Fault ruptured in the scenario is shown on the map.

## Reporting

As noted above, 9-1-1 dispatch centers will be overwhelmed and doing as much as possible to triage events and dispatch resources after the HayWired mainshock. Reports of fires during the initial period will be haphazard. Most fire departments do not have their own helicopters, and reporting by television news helicopters will be a valuable resource for a few major incidents, but not most. The first knowledge the San Francisco Emergency Operations Center had of the Marina fire following the 1989  $M_w$  6.9 Loma Prieta earthquake was from television news reports (despite several fire companies having responded). Quickly gaining an accurate and complete awareness of fires following an earthquake remains a challenge.

## Fire Department Initial Response

The initial response of fire companies and personnel in the region of the HayWired scenario will be to protect themselves during violent shaking, and as soon as possible, open fire-station doors and remove firefighting apparatus (such as pumpers and ladder trucks). Different fire departments have somewhat varying earthquake procedures, but in general companies will remove firefighting apparatus to a predesignated 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 fire companies into a strike team.

Local fire department resources will be completely committed, and in need of assistance from outside of the San Francisco Bay 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), firefighting 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, but will still prove useful as extraregional 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 after the HayWired mainshock, and tripled it within 12–24 hours. How these personnel join their fire companies will be an issue, and there will be some inefficiencies as personnel join first available companies. Nevertheless, arrival of off-duty personnel will be very important to relieve on-duty personnel nearing physical limits.

## Fire Spread

This analysis assumes that after the HayWired mainshock 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 most likely be delayed. This delayed response, owing primarily to delayed reporting and dispatch, will result in many fires having grown such that a multiengine capacity is needed on arrival. Especially in low humidity conditions, an ignition that has not been suppressed can become a room-sized fire within several minutes and grow into a fully involved, single-family structural fire within several more minutes. To protect neighboring buildings, typically two or more companies are needed. If only one fire company is available, it is possible but unlikely that it might be able to protect two exposures using a monitor (water cannon) and hand line (fire hose) with civilian assistance. In fire following earthquake modeling, fires that have grown to exceed one engine company's capabilities are termed large fires. The number of large fires for the HayWired mainshock is estimated based on several rules, including (1) availability of water for firefighting within each fire-response area and (2) 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 (table 3). The large number of ignitions developing into large fires is a result of the high earthquake shaking intensities in the east bay combined with fuel provided by the high-density of wood construction between San Francisco Bay and hills to the east (East Bay Hills).

## Lifelines

The performance of lifelines, such as water supply, gas, electric power, communications, and transportation, is integral to the firefighting process during fire following earthquake. A detailed discussion of lifeline performance for this scenario is beyond the scope of this report, which only briefly discusses selected lifelines with regard to fire following earthquake.

## Water Supply

Water supply would be severely impacted by an earthquake like the HayWired scenario mainshock (see Porter, Water Supply, this volume). A significant part of the San Francisco Bay area's water derives from the Sierra Nevada and is conveyed by several major canals and aqueducts, particularly the Mokelumne and Hetch Hetchy Aqueducts (fig. 20). In the last few decades, earthquake hazards mitigation has been largely focused on assuring delivery of water from these distant sources to the bay area. Major seismic retrofit programs have been completed by the East Bay Municipal Utilities District (EBMUD), Contra Costa Water District, and Marin Municipal Water District and are ongoing for the Santa Clara Valley Water District and the Hetch Hetchy system, which is owned by the City of San Francisco and serves that city as well as much of the west and south bay area (fig. 21).

These retrofit programs have focused on the dams, tanks, and major transmission lines; however, most of these

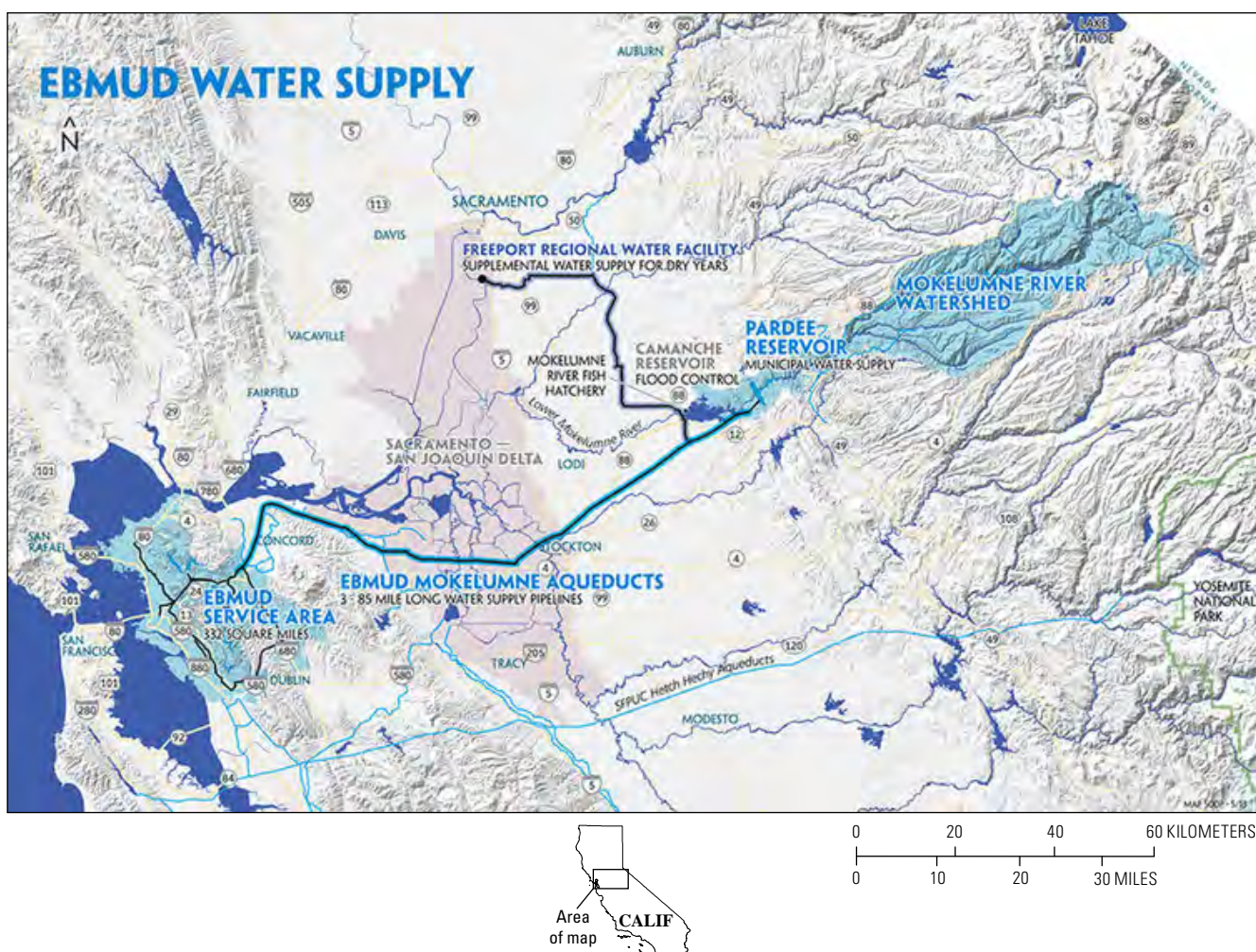
water operators have found that significant upgrading of their extensive water distribution systems is beyond available resources. As a result, extensive portions of the water distribution systems are very vulnerable and likely to sustain a number of breaks in a large earthquake. The following was noted in a recent study by the Association of Bay Area Governments (2010):

... 68.1% of critical water system facilities ... are exposed to extremely high shaking levels (peak ground accelerations, PGA, of greater than 60%  $g$  with a 10% chance of being exceeded in the next 50 years) ... 95.2% of pipelines are estimated to be exposed to high shaking levels (PGA >40%  $g$ ), and 62.8% are exposed to extremely high shaking levels (PGA >60%  $g$ ) ... [the Association of Bay Area Governments] has estimated that 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) ...

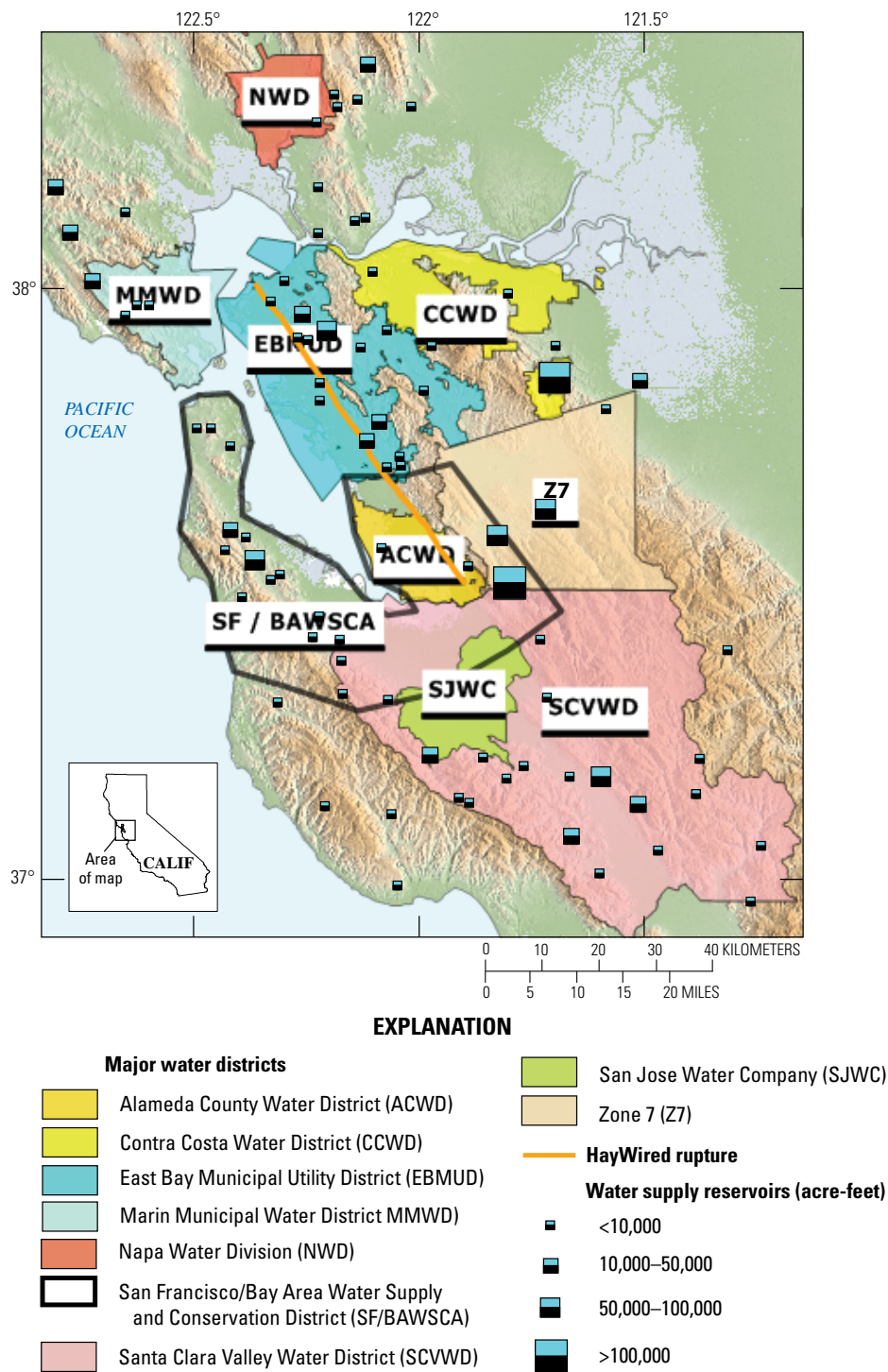
Pipe breaks in the 1989 Loma Prieta earthquake are shown in figure 22. Owing to their proximity to the Hayward Fault, east bay water distributions are particularly vulnerable (East Bay Municipal Utility District, 2011):

... 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:

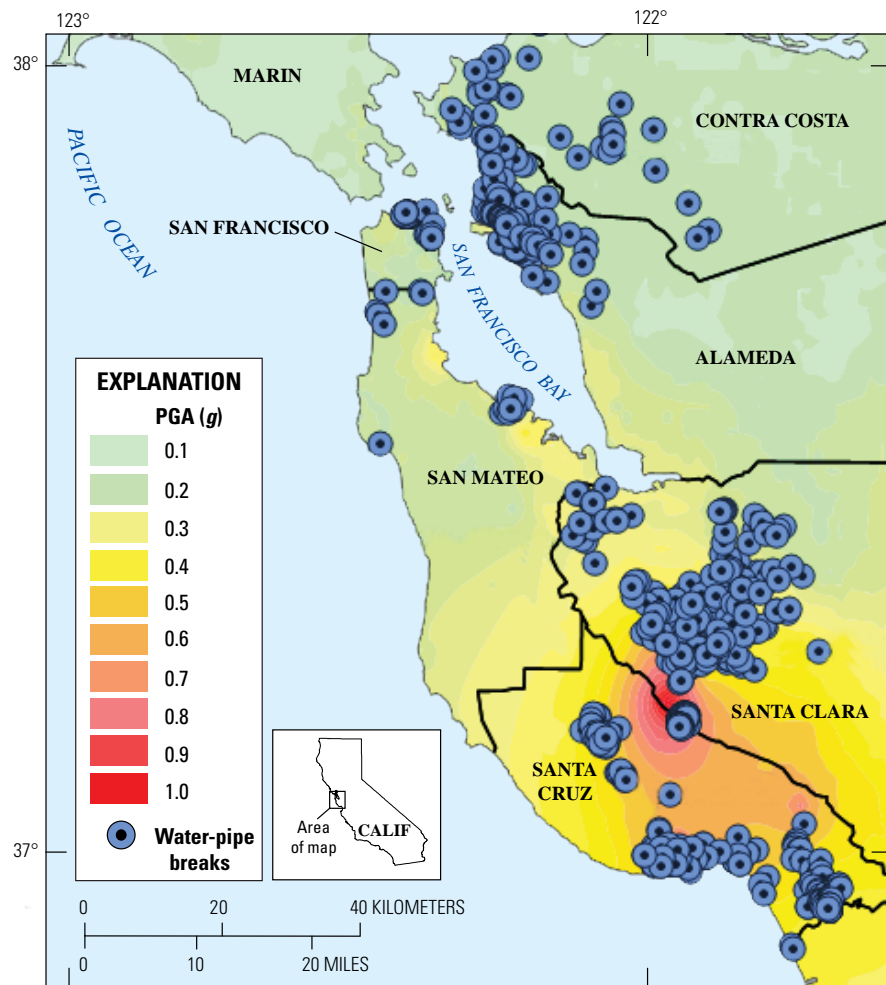


**Figure 20.** East Bay Municipal Utility District (EBMUD) map showing major water-supply systems of the San Francisco Bay area, California. A significant part of the bay area's water comes from reservoirs in the Sierra Nevada. The Mokelumne Aqueduct supplies much of the water to the EBMUD service area, and the San Francisco Public Utilities Commission's (SFPUC) Hetch Hetchy system primarily conveys water to San Francisco and the west and south bay. (From East Bay Municipal Utility District, 2017).





**Figure 21.** Map of major water districts and water-supply reservoirs in the San Francisco Bay region, California. The length of the Hayward Fault ruptured in the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario is shown on the map. (Water district and reservoir data from Bay Area Water Supply and Conservation Agency, [n.d.]; California Department of Water Resources, [n.d.]; and Datahub, [n.d.] )



**Figure 22.** Map of the San Francisco Bay region, California, showing breaks in water-distribution pipes from the moment-magnitude-6.9 1989 Loma Prieta earthquake overlaid on peak ground acceleration (PGA) for the event. *g*, acceleration due to gravity. (Data from Lund and Schiff, 1992.)

- Water cut off immediately to 63 percent of customers, including hospitals and disaster centers;
  - Loss of water for fire hydrants and increased fire risk;
  - More than 5,500 pipelines serving homes and businesses to break;
  - A likelihood of untreated drinking water resulting from 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 owing to fire damage and lack of water; and
  - Lack of water weeks after an earthquake, with some customers lacking service for as long as six months afterwards.
- ... As a result of the 1994 water system study, EBMUD developed a \$189 million Capital Improvement program that, between 1995 and 2007, resulted in a system-wide mitigation of these impacts with the goal of providing an improved post-earthquake

functional water system with no redundancies. . . . In addition, portable equipment, such as pumps, hoses and generators, required to maintain operations following a disaster, has been procured. A number of other facilities still require seismic upgrades. . . . Finally, roadway and building damage in EBMUD's service area may result in delays in recovery that may necessitate on-going communication with service vehicles to ensure that repairs to pipelines and critical facilities are completed in a timely manner.

Although dating from 2011, these estimates (for distribution piping damage) actually rely on analyses developed in 1994. However, although key facilities such as the Claremont Water Tunnel, which crosses the Hayward Fault in Alameda County, have been improved, little has changed since 1994 regarding distribution piping, and the situation remains largely the same today (EBMUD, oral commun., October 30, 2014).

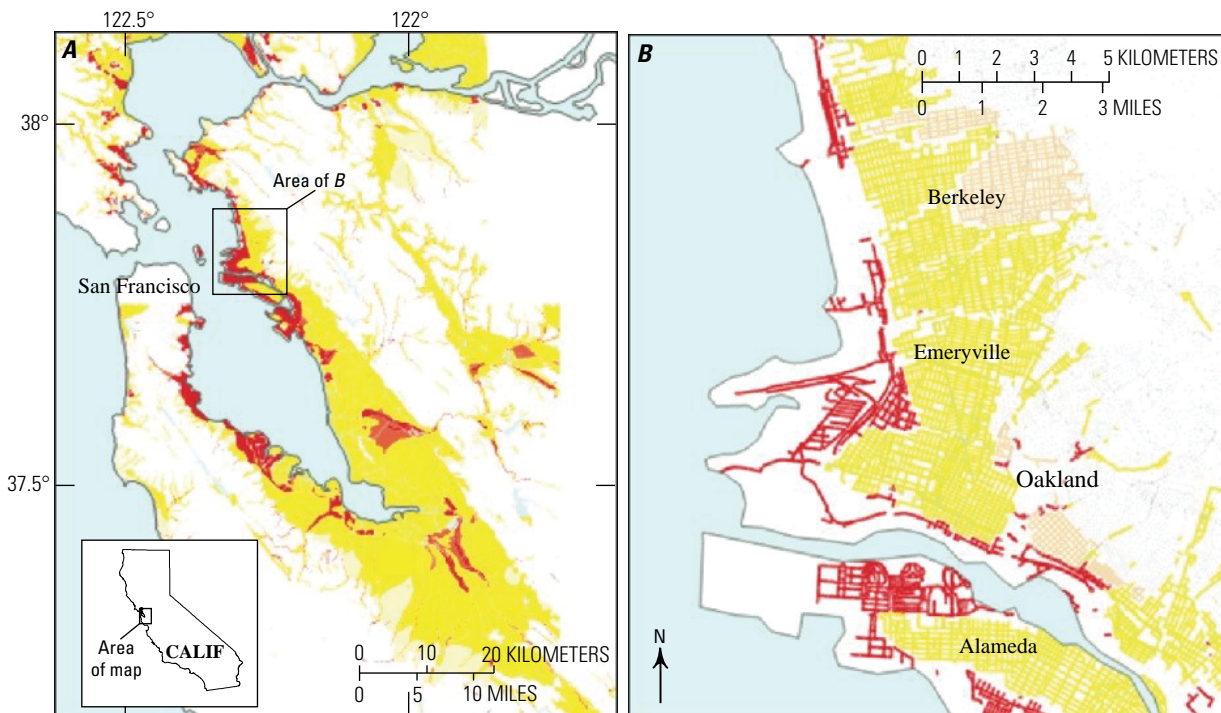
To examine the impacts of this situation following the HayWired mainshock, two sources of information were used to estimate the number and pattern of distribution pipe breaks and leaks. Data on pipe breaks and leaks from Porter (Water Supply, this volume) was used for one of the main water-distribution service areas affected by this earthquake, that of EBMUD. Outside of the EBMUD service area, a more approximate method was used to estimate water-main breaks and leaks, which consisted of assuming an "average" water main was under each street, and basing damage to water-distribution

networks on that assumption. Sections of pipe in zones of high liquefaction susceptibility are shown in figure 23.

Based on this data, the HayWired mainshock devastates the water-supply infrastructure in the affected region, causing a total of about 9,400 buried water mains to require repairs,<sup>6</sup> 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 (fig. 24).

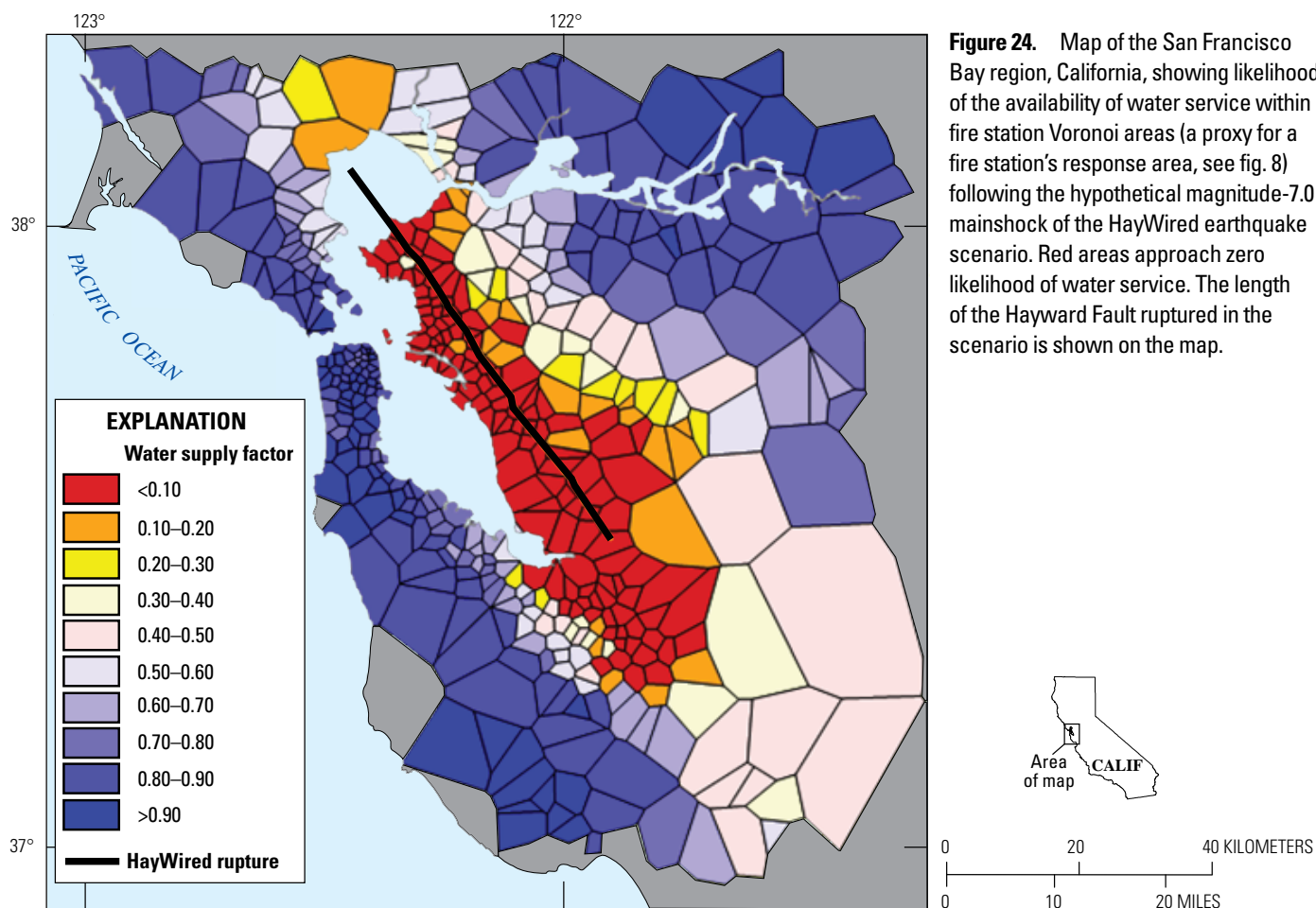
Without water infrastructure, firefighters will have to resort to alternative water sources, which in many cases require hard suction hose. Hard suction hose is a specific type of fire hose that allows a fire engine to create a vacuum in order to draft water from a source that is not pressurized (such as a swimming pool, river, or bay; fig. 25). The hose is reinforced with embedded metal rings to be circumferentially rigid so as to withstand an external pressure (such as internal vacuum). In the United States, the National Fire Protection Association specifies hard suction hose as standard equipment for class-A fire engines. However, in recent years some fire departments have adopted a practice of keeping hard suction hose in fire stations rather than carried on their engines. A limited survey of San Francisco Bay region fire departments conducted as part of this study found only about one-third of the departments could be confirmed as carrying hard suction hose on their engines.

<sup>6</sup>The estimate of 9,400 buried water mains requiring repairs is the total from Porter (Water Supply, this volume) combined with the estimate in this paper based on street lengths.



**Figure 23.** Maps of the San Francisco Bay region, California, showing water mains in areas of high liquefaction susceptibility in an earthquake (water mains were presumed to be under each road). *A*, Overview map of the San Francisco Bay region; *B*, detail map of parts of the Cities of Berkeley, Emeryville, Oakland, and Alameda. Water-main susceptibility to liquefaction—red, very high; light red, high; yellow, moderate; pink, low. (Roads from U.S. Census Bureau, 2015; liquefaction data for most of the region from Witter and others, 2006, which omits San Francisco County.)





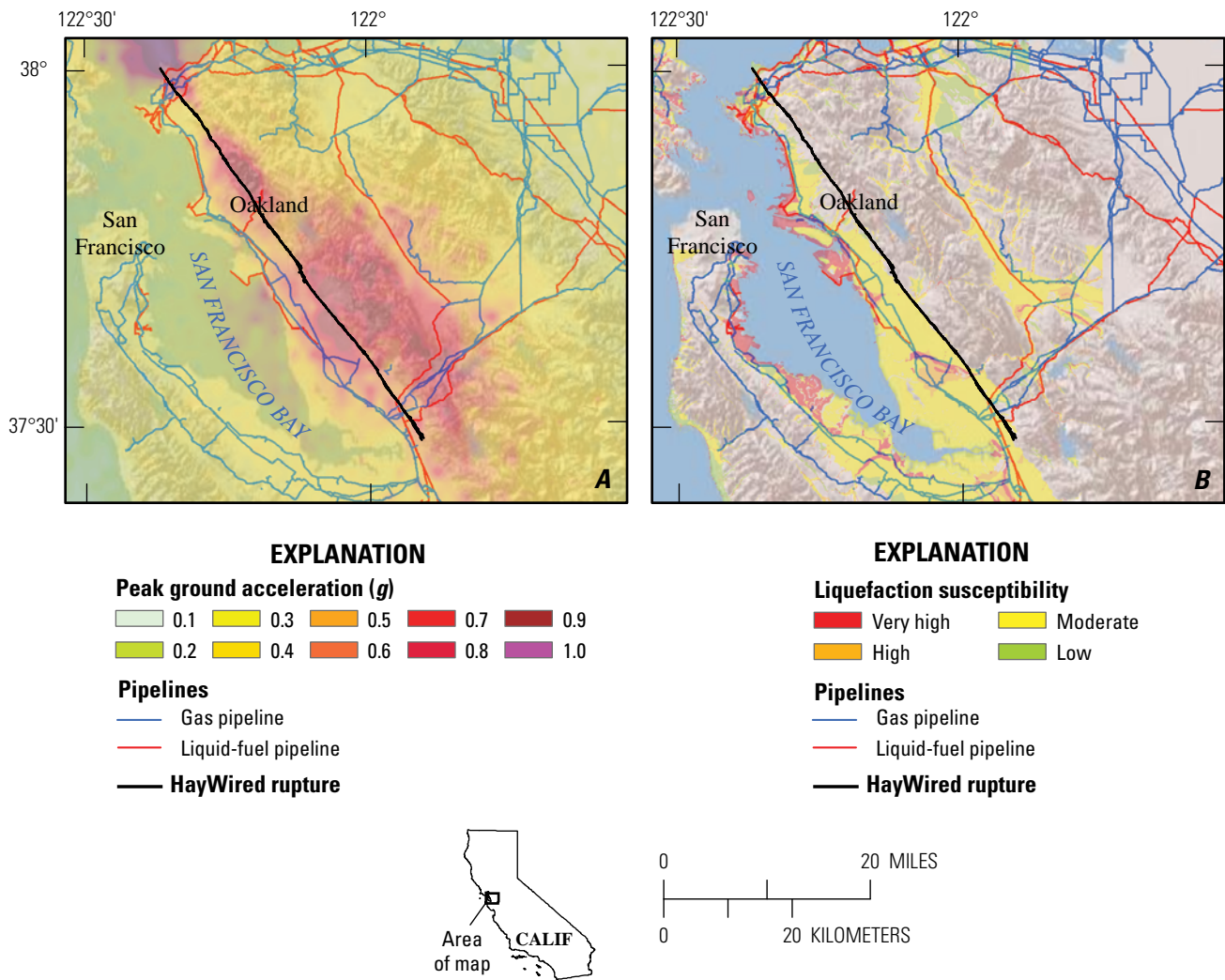
**Figure 24.** Map of the San Francisco Bay region, California, showing likelihood of the availability of water service within fire station Voronoi areas (a proxy for a fire station's response area, see fig. 8) following the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario. Red areas approach zero likelihood of water service. The length of the Hayward Fault ruptured in the scenario is shown on the map.

## Gas and Liquid Fuels

Gas and liquid fuel are used throughout many modern cities; there are buried major transmission lines (fig. 26) with associated terminals, refineries, and tank farms. A rupture of one large gas or liquid-fuel transmission line can be catastrophic and require the resources of a major fire department to respond. Similarly, a major petroleum refinery fire requires a major response, which may not be possible in the immediate aftermath of an earthquake. The San Francisco Bay area has five major petroleum refineries, which constitute 40 percent of California's refining capacity. These refineries are concentrated at the north end of the HayWired scenario fault rupture. In the  $M_w$  7.0 scenario mainshock, these crucial refineries will experience severe shaking such that at least one (and possibly several) refineries will have major fires that may burn for several days, as has occurred in the past few decades in large earthquakes near refineries, such as the  $M_w$  8.3 2003 Tokachi-Oki, Japan, and  $M_w$  7.6 1999 İzmit, Turkey, earthquakes. In the bay area, and very significantly, gas distribution pipes underlie nearly every street, with connections to nearly every building. Ignitions from these sources typically account for about 25 percent of the total number of fire-following-earthquake ignitions.



**Figure 25.** Photograph of a San Francisco Fire Department, California, engine and firefighters using a hard-suction hose to draft water from a cistern (photograph by Charles Scawthorn).



**Figure 26.** Maps showing gas and liquid-fuel transmission pipelines in the San Francisco Bay region, California. *A*, Pipelines overlaid on scenario peak ground acceleration distribution for the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. *B*, Pipelines overlaid on zones of high liquefaction susceptibility. Length of fault rupture in the HayWired scenario shown by black lines. *g*, acceleration due to gravity. (Pipeline data from U.S. Department of Transportation, 2015; mainshock data from Aagaard and others, 2017; liquefaction data for most of the region from Witter and others, 2006, which omits San Francisco County.)

## Communications

Communications systems, particularly telephone networks, will sustain some damage but perhaps not enough to reduce functionality following the HayWired mainshock. However, congestion will reduce functionality to a great degree, for several hours or more. This lack of telephone service will result in delayed reporting of fires, with consequences as discussed above.

## Transportation

The transportation system most relevant to fire following earthquake is the road network, which is most vulnerable at

bridge crossings. The California Department of Transportation (Caltrans) has nearly completed a major seismic review and retrofit of all bridges under its purview (California Department of Transportation, 2014). Although the local road and highway networks are sufficiently dense in most places that redundant pathways exist within the San Francisco Bay region, heavy traffic following a major earthquake could significantly impede emergency responders. Emergency strike teams arriving from outside of the bay region may also be delayed owing to traffic disruptions at several chokepoints at the boundaries of the region, including U.S. Route 101 north of the Golden Gate Bridge and south of San Jose and westbound Interstates 80 and 580.



## Regional and State Response

The HayWired scenario mainshock primarily affects California Governor's Office of Emergency Services (Cal OES) region II (fig. 27). The most likely sources of regional resources will be a number of strike teams assembled by Cal OES from the Central Valley, arriving in the affected region within 6–24 hours. Some of these will be brush rigs (wildland fire engines specifically designed to assist in fighting wildfires), which are more suited to wildland than urban-structural fires. By the time of their arrival in the region affected by the HayWired mainshock, the issue will be large fires that have grown into conflagrations, constituting a much larger challenge.

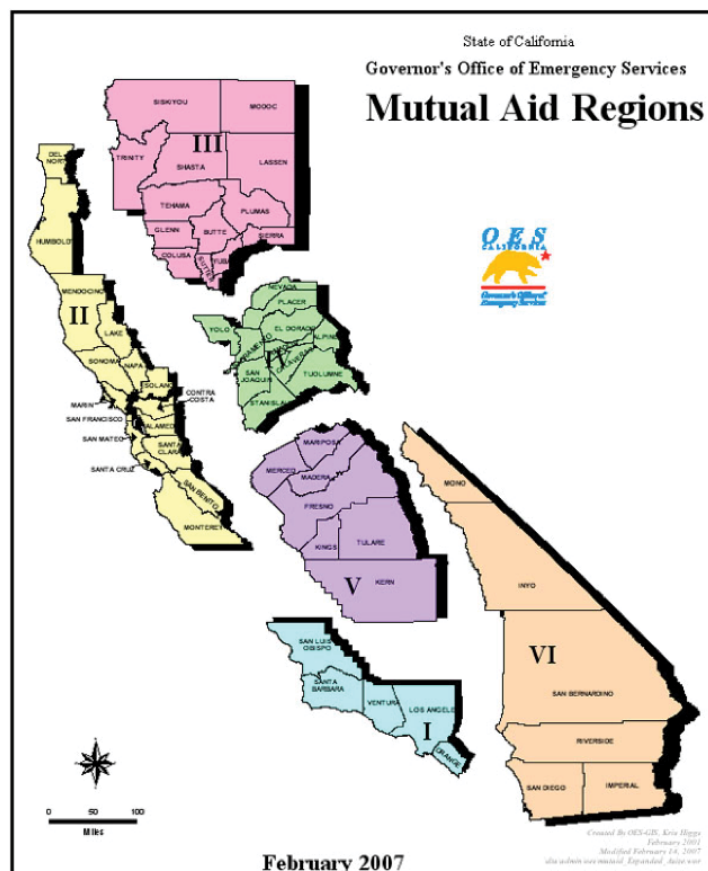
Outside of region II, Cal OES is likely to stage a number of strike teams, drawn generally from southern California and the Central Valley. Assembling 100 strike teams, consisting of approximately 500 pumpers and other firefighting apparatus, as well as firefighters, is easily within Cal OES capability, and several times this number of people and equipment can be managed if necessary. Within about 12 hours of notification, 100 strike teams can arrive at staging areas, with probably another 100 teams arriving during the next week. In our analysis, however, mutual aid will be largely ineffective in the immediate period following the HayWired mainshock, owing to the following factors:

- Delayed response time to fire scene:
  - Fire departments in the San Francisco Bay area (for example, peninsular and Walnut Creek-Concord area) will conserve resources and not be able to respond quickly to the east bay.
  - Mutual aid will have to come from farther afield (northern California, southern California, and the Central Valley), requiring at least several hours, and will be arriving at night in blackout conditions (owing to wide-scale failure of electric power).
- Water shortages:
  - Water-tanker truck refills will be at some distance from fires, resulting in delays. Although a few fire departments (Berkeley, Oakland, Vallejo, and San Francisco) have portable water-supply systems (PWSS), these are currently inadequate for the demands that will be placed on them.
  - Aerial firefighting effectiveness in urban areas is currently unknown.
  - Firefighting foam is a “force-multiplier,” greatly increasing the effectiveness of a hose stream. However, current local fire-department supplies of foam are limited.

- Access:
  - The east bay hills are quite steep, with relatively narrow and winding roads that hinder access.
  - The hills are also heavily vegetated which, combined with prevailing winds and topography, will greatly enhance fire spread and impede firefighting.
  - Supplying water to higher elevations in the hills will be very difficult.
- Limited access to the San Francisco Bay area.

## Final Burned Area

The 453 large fires estimated to follow the HayWired scenario mainshock 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 burned area, will depend on the building density, weather conditions, initial unfought size of the fire before fire department response, number of responding fire



**Figure 27.** Map showing California Governor's Office of Emergency Services mutual-aid regions (from California Governor's Office of Emergency Services, 2017).

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 (in other words, become a conflagration), with the final burned 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 79 million square feet of residential and commercial building floor area equivalent to more than 52,000 single-family dwellings.<sup>7</sup> This loss is equivalent to a total building replacement value of almost

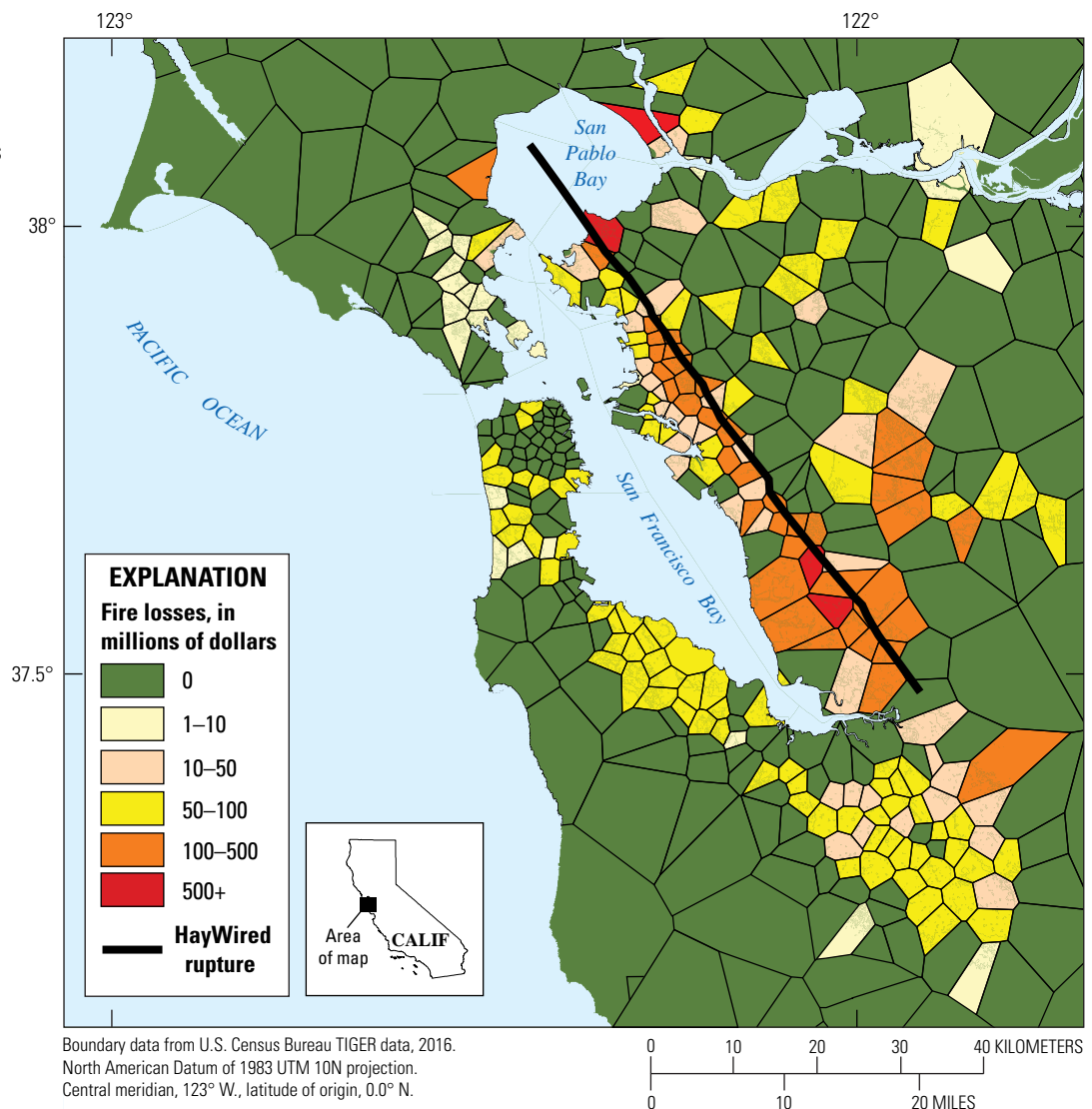
<sup>7</sup>An average single-family equivalent dwelling is 1,500 square feet of residential or commercial occupancy floor area, and this measure is used to normalize and communicate overall building losses in a readily comprehensible way. A loss of 1.5 million square feet of residential and commercial building for example is equivalent to 1,000 single-family dwellings. Most people can more readily interpret the loss of 1,000 houses than 1.5 million square feet of floor area.

<sup>8</sup>Based on a replacement cost of \$200 per square foot. Note this is a conservative estimate of replacement cost. Hogan (2014) estimates that construction in San Francisco can cost \$300 per square foot, not counting subsidies, permits, and selling expenses.

\$16 billion<sup>8</sup> (2014 dollars), representing about 2 percent of the entire exposed value (fig. 28, table 4), with most of the loss concentrated in Alameda County.

Under the assumed wind and humidity conditions during the HayWired mainshock, the areas of most concern for fire following earthquake are parts of Alameda and Santa Clara Counties, where large areas of relatively uniform, dense, low-rise buildings provide a fuel bed such that dozens to hundreds of large fires are likely to merge into many dozens of conflagrations, destroying tens of city blocks. Two particular concerns exist in this regard—(1) if Diablo winds are present (which is not assumed in this scenario), losses could be much larger; and (2) if extremely calm conditions exist (which is also not assumed in this scenario), a symmetric wind pattern could develop where uprising air from conflagrations draws air inward (an example of the stack effect) to create a self-sustaining feedback situation (commonly termed a firestorm), which can be very destructive. Although relatively unlikely, this potential should not be ignored. The first concern is a larger mass conflagration, fed by higher winds; the second is potentially much worse. Both would be catastrophic.

**Figure 28.** Map of the San Francisco Bay region, California, showing final burned-area losses (in millions of 2014 U.S. dollars) from fire following earthquake after the hypothetical magnitude-7.0 mainshock of the HayWired earthquake scenario. Areas shown are fire station Voronoi areas (a proxy for a fire station's response area, see fig. 8). The length of the Hayward Fault ruptured in the scenario is shown on the map.



Another major concern is the very large concentration of high-rise buildings in the financial district of San Francisco. Firefighting under postearthquake conditions in more than one of these buildings could be beyond the resources of the San Francisco Fire Department, so the loss of several high-rises is quite possible.

## Uncertainty, Verification, and Validation

There is considerable uncertainty in the estimates of ignitions and final burned area presented above. The United States has been very fortunate in having few large earthquakes within urban areas in the past 50 or more years, so the experience database for ignitions following earthquakes is relatively sparse and has significant uncertainty, as can be seen in the confidence bands shown in figure 18, which span an order of magnitude. Moreover, the majority of data for ignitions (178 of 244 or 73 percent) are drawn from very early morning earthquakes, a time of day associated with low normal fire occurrence (U.S. Fire Administration, 2008). A full exploration of uncertainty is beyond the scope of the present study, but the number of ignitions estimated to follow the HayWired mainshock (668) could vary by hundreds, depending on many factors.

Regarding verification (accuracy of the estimate) and validation (meeting the intended need) of estimates of ignitions and final burned area in the HayWired scenario, a large earthquake like the  $M_w$  7.0 mainshock is a rare event, and the postearthquake fire situation even rarer, so that verification and validation is very challenging.

Verification is particularly difficult, owing to the sparsity of data and experience. Qualitatively, the following experiences tend to support the scenario losses presented above:

- Precedent—several events support the potential for large postearthquake losses, including in the HayWired study region:
- Catastrophic fires following the 1906 San Francisco ( $M_w$  7.8) and 1923 Tokyo ( $M_w$  7.9) earthquakes.

- More than 100 ignitions (each) following the 1971 San Fernando, California ( $M_w$  6.6); 1994 Northridge, California ( $M_w$  6.7); and 1995 Kobe, Japan ( $M_w$  6.9), earthquakes.
- At least 348 ignitions, more than any other earthquake in history, occurring in the 2011 Tohoku, Japan ( $M_w$  9.0), earthquake and tsunami (Anderson and others, 2016)
- The 1991 East Bay Hills Fire (East Bay Hills Fire Operations Review Group, 1992), a massive conflagration centered in the study region that overwhelmed fire and water agencies.
- Quantitatively, the methods in this study were used to hindcast (estimate):
  - Ignitions in previous California earthquakes (tables 6–8 and fig. 29) with reasonable agreement. The base data is dataset A in Davidson (2009a).
  - Large fires for the 1989 Loma Prieta ( $M_w$  6.9) and 2014 South Napa ( $M_w$  6.0), California, earthquakes, the only events for which sufficient data on all aspects (fire resources, firefighting water availability, and so forth) was available.

Although this quantitative verification is quite limited, it tends to confirm the reasonableness of the estimates and also illustrate the uncertainty. Both the SPA Risk LLC (2009) and Davidson (2009b) ignition models produce enough fires following the HayWired mainshock to overwhelm currently available firefighting resources in the San Francisco Bay region, so the conclusions of this chapter would be the same regardless of which model was used.

Validation (meeting the intended need) for fire following earthquake in the HayWired scenario is also a challenge but toward this end the above methodology and findings were presented to a workshop on fire following earthquake, held at the University of California, Berkeley, Richmond Field Station on October 29, 2014. The workshop was attended by 76 personnel, representing 31 fire departments

**Table 6.** Summary count of ignition data from California earthquakes since 1971 (SPA Risk LLC, 2009, 2014).

Earthquake	Number of ignitions	Date source <sup>1</sup>
1971 San Fernando	91	Unpublished data
1983 Coalinga	3	Scawthorn (1984)
1984 Morgan Hill	6	Scawthorn (1985)
1986 North Palm Springs	1	Earthquake Engineering Research Institute (1986)
1987 Whittier Narrows	20	Wiggins (1988)
1989 Loma Prieta	36	Mohammadi and others (1992); Scawthorn (1991)
1994 Northridge	81	Scawthorn and others (1997)
2014 Napa	6	SPA Risk LLC (2014)
Total number of ignitions	244	

<sup>1</sup>See SPA Risk LLC (2009, 2014) for detailed references.

**Table 7.** Hindcast (estimated) ignitions for selected California earthquakes (1984–2014), using equations from Davidson (2009b) and SPA Risk LLC (2009) (see discussion in text and equations 1 and 3, respectively).

[NA, not applicable]

Earthquake	Observed ignitions	Davidson (2009b; model A.NB2) estimated ignitions	SPA Risk LLC (2009) estimated ignitions
1984 Morgan Hill	4 <sup>1</sup>	1.2	4.0
1986 North Palm Springs	1	2.1	4.1
1987 Whittier	13	22.2	72.1
1989 Loma Prieta	36	29.5	15.9
1994 Northridge	81	99.0	166.4
2014 Napa	6	NA	6.24

<sup>1</sup>There were four structural ignitions in Morgan Hill and two in San Jose in the 1984 earthquake. The total of six is indicated in table 6. For validation, only Morgan Hill was modeled, so table 7 shows only four observed ignitions.

**Table 8.** Observed and hindcast (estimated) large fires for selected northern California earthquakes.

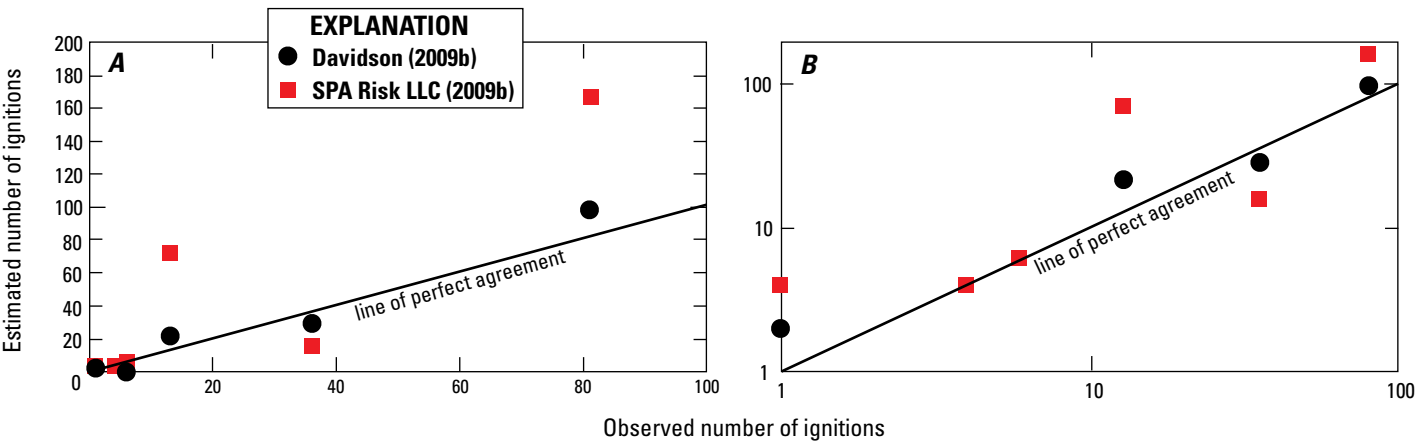
Fire type	Observed	Estimated
1989 Loma Prieta earthquake <sup>1</sup>		
Total ignitions	31	24
Large Fires	12	Negligible
Conflagrations	1?	Negligible
2014 Napa earthquake		
Total ignitions	6	6.24
Large Fires	1	Negligible
Conflagrations	?	Negligible

<sup>1</sup>Based on 1990 census population (dataset A in Davidson, 2009a).

and emergency response agencies. The workshop was subsequently independently evaluated by Allison Madera and others (Natural Hazards Center, University of Colorado Boulder, written commun., 2016), who found “almost all of the survey respondents (95.8 percent) indicated that they believed the HayWired scenario accurately represented what a fire following earthquake incident might look like in the San Francisco Bay Area.”

### Impacts of Fire Following Earthquake

This section discusses the human and economic impacts of fire following earthquake. Not well understood, but discussed here, is the major impact such events can have on the insurance industry.



**Figure 29.** Observed and hindcast (estimated) ignitions for selected California earthquakes (1984–2014), using equations from Davidson (2009b) and SPA Risk LLC (2009) (see discussion in text and equations 1 and 3, respectively; see table 7 for data). A, Number of ignitions plotted on arithmetic axes. B, Number of ignitions plotted on log-log axes.

## Human Impacts

Estimating the fatalities associated with the fires following the HayWired mainshock 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 the scenario mainshock. 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 fire. Injuries would probably be an order of magnitude greater. For the HayWired scenario, an estimated 500,000 to 1 million people will need shelter as a result of fire following earthquake.

## Economic and Insurance Impacts

Regarding the estimated \$16 billion value of the structures burned by fire following earthquake in the HayWired scenario, the value of contents and other improvements (for example, landscaping) will add to this loss. For example, the contents of residences 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 most likely would not be available in the San Francisco Bay region given the impact of the scenario mainshock. 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 mainshock, at public expense, there may be no bill.<sup>9</sup> In such a situation, people have not paid for their tents, and cannot 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 would not 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 buildings, which for the HayWired scenario is about \$3 billion.

Because virtually all buildings and contents in the United States are insured for fire, and U.S. insurance contracts include losses from fire following earthquake under the fire policy, the direct fire-following-earthquake losses for the HayWired mainshock 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 region—and shaking, liquefaction, and landslide-related

damage 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 the September 11, 2001, attacks were handled without great strain). The 1991 East Bay Hills Fire, in which 3,500 homes were lost, at the time resulted in about \$1 billion in insured losses—the event projected here is 23 years of inflation later and about 60 times as large. In summary, losses from fire following earthquake are likely to be the largest part 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 the value of property improvements is likely to result in perhaps a decrease of a billion dollars in regional real-estate tax revenues for several years, directly attributable to fire following earthquake.

## Mitigation of Fire Following Earthquake

Mitigation of fire following earthquake has been extensively discussed elsewhere (Scawthorn and others, 2005). Only some limited observations specific to the HayWired scenario are provided here.

### Fire-Service Opportunities

The fire service in California is perhaps the most experienced in the world in dealing with large conflagrations, owing to the wildland fires recurring annually in the region. Fire departments have 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:

- Improvements are needed in the ability to more quickly assess the event and facilitate fire incident reporting. Reconnaissance using unmanned aerial vehicles, as well as cellular text-messaging incident reports directly to a 9-1-1 portal, could be developed and operationalized.
- Alternative water sources need to be better identified and access and water movement capabilities enhanced. Hard suction hoses could be carried on all engines. Large diameter hose (LDH) systems, comparable to San Francisco Fire Department’s PWSS (Scawthorn and others, 2006), could be developed on a regional basis. In this regard and as part of the HayWired scenario project, the earlier mentioned October 29, 2014, workshop was held at the University of California’s Richmond Field Station. The four existing PWSSs, belonging to Berkeley, Oakland, San Francisco, and Vallejo Fire Departments

<sup>9</sup>Note that public authorities may attempt to recoup their expenses, if the sheltered people are insured.



(fig. 30) were brought together and used in a joint exercise for the first time.

- A regional multidisciplinary task force could be formed within the fire service, to examine urban conflagration potential in more detail.

## Water-Service Opportunities

Water-service providers in California have worked to prepare for a major earthquake, but more can still be done (Scawthorn, 2011a,b). One overriding issue with regard to fire following earthquake is that water agencies typically are not institutionally responsible for fire protection. That is, although 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 could 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 problem of fire following earthquake 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, which would both help ensure the reliability of water services to communities and provide fire departments with sources to draw water from to suppress a conflagration using an LDH system. This entire aspect is discussed in more detail in Scawthorn (2011a,b).

## Building-Standards Opportunities

Since the 1906 San Francisco earthquake, 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 many 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 could be more widely mandated for existing buildings.

## Energy-Industry Opportunities

The gas industry could contribute significantly to reducing the fire following earthquake by developing a program to either install automated gas shut-off valves (fig. 31) or redesign gas meters to have seismic shutoffs, particularly in densely built up areas. If the number of ignitions could be reduced by 25 percent, the number of large fires would be decreased in greater proportion and the total losses further reduced. For example, the City of Los Angeles Fire Department 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.



**Figure 30.** Photograph of four portable water-supply systems, belonging to the Berkeley, Oakland, San Francisco, and Vallejo Fire Departments, at the edge of San Francisco Bay in Berkeley, California, on October 29, 2014. This was the first time the four systems were brought together and used in a joint exercise. (Photograph by Charles Scawthorn.)



**Figure 31.** Photograph of an automatic gas shut-off valve installed after the meter on a gas-service line (photograph by Charles Scawthorn).

In regard to electricity, opportunities to reduce fire following earthquake are problematic. Electric power often fails in large earthquakes, owing to automatic system trips, as well as damage to the system. However, the power failure usually takes several seconds, during which power is a source of many ignitions. Certain electric appliances (such as those with heating elements) can still cause fires even after power is cut. Large-scale intentional curtailment of electric power would be problematic, because some communications systems and other essential equipment would not be useable.

Petroleum refineries and related facilities in the San Francisco Bay area are likely to sustain major fires in the HayWired scenario. The degree of earthquake preparedness of these facilities is generally unclear and may need to be reviewed.

## Conclusion

That fire following earthquake is a significant problem in California is confirmed historically, by recent events, and by analysis. The  $M_w$  7.0 mainshock of the 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 more super conflagrations, destroying hundreds of city blocks. The ultimate burned area is estimated to total 79 million square feet of residential and commercial building floor area, equivalent to more than 52,000 single-family dwellings, with property losses approaching \$30 billion. This loss is virtually fully insured and would be one of the largest 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 fire following earthquake, including greatly enhancing the potential postearthquake 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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