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The HayWired Earthquake Scenario—Societal Consequences



Scientific Investigations Report 2017–5013–R–W
Version 1.1, October 2021

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

Cover. U.S. Geological Survey photograph of damage to the Collins Brothers Druggist building and adjacent building in Oakland, California, from the 1906 San Francisco earthquake. The magnitude 7.8 earthquake occurred on the San Andreas Fault that runs along the San Francisco Peninsula. One hundred and fifteen years later, the HayWired scenario vol. 3 examines the societal consequences of an earthquake on the Hayward Fault in the east part of the San Francisco Bay region with an epicenter in Oakland. The photograph portends the people and businesses that will be affected by a rupture of the Hayward Fault and the evolution of telecommunications and earthquake early warning systems. Following the 1989 Loma Prieta earthquake, as much as $80 billion have been invested in strengthening critical infrastructure and facilities. Despite this, the HayWired scenario vol. 3 shines a light on cascading effects through interdependencies of utility, telecommunications, and transportation systems, the vulnerable populations living in heavily damaged areas, and economic ripple effects.

The HayWired Earthquake Scenario—Societal Consequences

Edited by Shane T. Detweiler and Anne M. Wein

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Jones, J.L., Johnson, L.A., Wein, A.M., and Peters, J., 2020, Estimated geospatial and tabular damages and vulnerable population distributions resulting from exposure to multiple hazards by the M7.0 HayWired scenario on April 18,2018, for 17 counties in the San Francisco Bay region, California: U.S. Geological Survey data release, https://doi.org/10.5066/P94Z8BOZ.

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Foreword

The 1906 Great San Francisco, California, earthquake (magnitude 7.8) and the 1989 Loma Prieta earthquake (magnitude 6.9) each motivated residents of the San Francisco Bay region to build back stronger. Since the Loma Prieta earthquake, bay-region communities, governments, and utilities have invested about $80 billion in seismic upgrades as well as 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 for the purpose of increasing seismic resilience throughout the region. However, as long as people live and work in seismically vulnerable buildings or rely on seismically vulnerable transportation, utility, and telecommunications services, 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 collaborative tool to raise awareness and enable further actions that can change the outcome before the next major earthquake strikes.

The area of present-day Contra Costa, Alameda, and Santa Clara Counties experienced 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. Scientists have documented a series of prehistoric earthquakes on the Hayward Fault and are confident that a large earthquake is likely to rupture along the fault through the east side of the San Francisco Bay region in the future. An earthquake, such as that portrayed in the HayWired scenario, could happen at any time—so preparation is due.

The question of what a large earthquake on the Hayward Fault would do has been examined before and is now revisited in detail in the HayWired scenario. Cities in the east bay along the Richmond, Oakland, and Fremont corridor would be hit hardest by the magnitude-7 HayWired scenario earthquake ground shaking, surface fault rupture, and fault afterslip. The earthquake shaking would trigger other hazards of widespread liquefaction, landslides, and aftershocks. The evolving nature of ongoing hazards of afterslip and aftershocks are demonstrated in examples of forecasts. Furthermore, as the ShakeAlert earthquake early-warning system was implemented during the development of the HayWired scenario, it illustrates potential warning times and benefits of protective actions

The name HayWired reflects our increased reliance on the internet and telecommunications and alludes to the interconnectedness of built infrastructure, society, and the economy. The third HayWired volume and data releases associated with Scientific Investigations Report 2017–5013 presents the most in-depth look yet at the societal consequences of a major earthquake in the San Francisco Bay region. It was led by the USGS with partners, including urban planners, economists, insurers, academics, telecommunications experts, utilities, and transportation agencies.

HayWired vol. 3 was completed during the Coronavirus Disease 2019 (COVID-19) pandemic that has, in turn, emphasized the important aspects of risk communication, planning and preparedness for disasters, and recovering from one disaster stronger and better prepared for another. Use of the HayWired scenario began in April 2017 and our hope is to encourage and support the active ongoing engagement of the entire community of the San Francisco Bay region by providing scientific and engineering inputs for use in exercises and planning well into the future. The scenario can be used to guide more realistic response and recovery exercises or to launch mitigation and preparedness measures that will save lives and preserve well-being by keeping people in their homes and businesses open when the next earthquake occurs. HayWired is about connecting with others to take steps to change the outcomes that the scenario describes.

David Applegate

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

HayWired Review Panel

The HayWired Review Panel, a group who provided additional review of chapters within volume 3, consisted of Jeff Bellisario (Bay Area Council Economic Institute), Mary Comerio (University of California Berkeley), Harvey Cutler (Colorado State University), Andrew Michael (U.S. Geological Survey), Alexis Kwasinski (University of Pittsburgh), Robert Olshansky (University of Illinois at Urbana-Champaign), Alex Tang (L&T consultant), and Mary Lou Zoback (Build Change, Stanford University).

HayWired Coalition Partners

Abhineet Gupta
Alameda County Sheriff's Office, Office of Emergency Services
Alameda County Water District
American Red Cross
ARUP—Design and Engineering Consultants
Association of Bay Area Governments—Metropolitan Transportation Commission
Bank of America
Bay Area Council
Bay Area Rapid Transit Authority
Bay Area Regional Collaborative
Bay Area Regional Interoperable Communications System
Bay Area Urban Area Security Initiative
Bay Planning Coalition
Berkeley Seismology Lab
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 Fuels and Convenience Alliance
California Geological Survey
California Governor's Office of Business and Economic Development
California Governor's Office of Emergency Services
California Independent Service Operator
California Public Utilities Commission
California Resilience Alliance
California Seismic Safety Commission
California Water/Wastewater Agency Response Network
Carnegie Mellon University Silicon Valley
City and County of San Francisco
City of Berkeley
City of Fremont
City of Hayward
City of San Francisco
City of Walnut Creek
CoreLogic Inc.
Cynthia Kroll
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Earthquake Country Alliance
Earthquake Engineering Research Institute
East Bay Municipal Utilities District
Federal Emergency Management Agency
Joint Venture Silicon Valley
Laurie Johnson Consulting|Research
March Studios
Marin Economic Consulting
Pacific Earthquake Engineering Research Center
Pacific Gas and Electric Company
Palo Alto University
Price School of Public Policy and Center for Risk and Economic Analysis of Terrorism Events, University of Southern California
San Francisco Bay Area Planning and Urban Research Association
San Jose State University, Department of Anthropology
San Jose Water Company
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SPA Risk LLC
Stanford University
Strategic Economics
Structural Engineers Association of Northern California
University of California Berkeley
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University of Southern California
U.S. Department of Homeland Security
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Contents

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

Chapters

R. Overview of the HayWired Scenario Societal-Consequences Volume
By Anne M. Wein
Introduction 1
Earthquake Hazards 2
Engineering Implications 3
Societal Consequences 3
Telecommunications Vulnerabilities and Service Restorations 3
Lifeline Infrastructure Systems and Multi-hazards 5
Communities at Risk 6
Economic Impacts 8
Earthquake Early Warning 13
Future Research 13
Conclusion 15
Acknowledgments 16
References Cited 16
S. The HayWired Scenario—Telecommunications and Information Communication Technology
By Anne M. Wein, David T. Witkowski, Jamie L. Jones, Keith A. Porter, Laurel R. Ballanti, and Sara K. McBride
Abstract 19
Introduction 20
Today's World of Telecommunications 20
Telecommunications and Earthquakes 21
Disruption of Telecommunications Services 21
Study Approach 22
Chapter Overview 23
Telecommunications Systems, Subscriber Connectivity, and Infrastructure Failure Modes 23
Telecommunications Systems 23
Subscriber Connectivity 30
Physical Failure Modes 31
Telecommunications Infrastructure Exposure and Damage from HayWired Earthquake Hazards 32
HayWired Scenario Hazards 33
Observations of Earthquake Damage 33
Methods 35
HayWired Hazard Exposure and Damage Results 40

Voice and Data Service Restoration....58
Voice and Data Service Restoration After Disasters....60
Simple Model of Voice and Data Demand Served....61
Voice and Data Demand Served....70
Knowledge Gaps and Study Limitations....74
Earthquake Hazard Uncertainties....74
Limitations of Study Scope....74
Data Limitations of Evolving Telecommunications Infrastructure Data....75
Scant Telecommunications Infrastructure Design and Fragility Data....75
Simple Model of Network Capacity and Service Restoration Times....75
Summary and Conclusion....76
Telecommunications Infrastructure Hazard Exposure and Damage....76
Network Functionality and Demand for Services....78
Societal Consequences....80
Opportunities for Increasing Resilience....82
Resilience Opportunities for Voice and Data Service Providers....82
Resilience Opportunities for Users of Voice and Data Services....87
Acknowledgments....89
References Cited....90
Glossary....98
Appendix 1. Program of the U.S. Geological Survey's Telecommunications Phase 2 Workshop....101
Appendix 2. Demand Served Restoration Curves by County....103
Appendix 3. Home Uninterruptible Power Supply Set Up....111

T. Lifeline Infrastructure and Collocation Exposure to the HayWired Earthquake Scenario—A Summary of Hazards and Potential Service Disruptions
By Jamie L. Jones, Anne M. Wein, Amy E. Schweikert, and Laurel R. Ballanti
Abstract....113
Introduction....114
Lifeline Infrastructure Exposure to HayWired Earthquake Scenario Hazards....116
HayWired Hazard Descriptions and Classifications....116
Individual Lifeline Exposure to Individual Hazards....127
Combinations of Hazards....133
Methods....133
Results for Hazard Combinations....135
Results for Lifeline Infrastructure Exposure to Three or More Hazards....135
Exposure of Individual Lifeline Infrastructure to Multi-hazard Intensities....135
Multi-hazard Intensity Classification....139
Results for Individual Lifeline Infrastructure Exposure to Multi-hazard Intensities....140
Collocated Lifeline Infrastructure....140
Method for Identifying Collocated Infrastructure....142
Density of Collocated Infrastructure....143
Exposure of Collocated Infrastructure to Multiple Hazards....147
Relative Importance of Lifeline Infrastructure....148
Lifeline Infrastructure Interactions....154
Interaction and Interdependencies Among Lifeline Infrastructure Systems....154

Illustration of Interactions Among Lifeline Infrastructure Systems in the HayWired Scenario....156
Lifeline Infrastructure System Damage and Downtime Assessments....160
Damage Impact Assessments....160
HayWired Lifeline Infrastructure Restoration Times....161
Knowledge Gaps and Modeling Limitations....165
Summary and Conclusion....166
Acknowledgments....169
References Cited....169
Appendix 1. HayWired Scenario Liquefaction Modeling Expansion Methodology....175
Appendix 2. Individual Lifeline Exposure to Individual HayWired Scenario Hazards....180
Appendix 3. Electric Power Assessment using Hazus-MH....195
Appendix 4. Bay Area Rapid Transit Damage Assessment to HayWired Scenario Ground Shaking....202
Appendix 5. California Department of Transportation Bridge Damage Assessment to HayWired Scenario Ground Shaking....211

U. Analysis of Communities at Risk in the HayWired Scenario
By Laurie A. Johnson, Jamie L. Jones, Anne M. Wein, and Jeff A. Peters
Abstract....219
Introduction....220
Integrated Building Damage, Property Losses, and Areas of Concentrated Damages....222
Integration of Building Damage Caused by Ground Shaking, Liquefaction, Landslide, and Fire....222
Areas of Concentrated Damage....224
Population Movements and Vulnerabilities....226
Population at Risk of Displacement from Building Damage and Lifeline Outages....226
Specific Population Groups Vulnerable to Displacement....228
Emergency Sheltering and Interim Housing Influences on Population Movements....233
Anticipating Population Return....234
Long-Term Community Recovery Challenges....234
Assembling the Financing Resources for Recovery....235
Repairing and Replacing Damaged Housing....236
Areas Requiring Substantial Governmental Intervention and Replanning....237
Policy Implications for Improving Community Resilience....240
1. Accelerate the Seismic Mitigation of Homes....246
2. Strengthen or Replace Infrastructure....248
3. Build More Housing for All Income Groups....248
4. Promote Seismic Resilience in Land Use and Development Policies....248
5. Address Population Movements and Long-Term Displacement in Local, Regional, and State Preparedness, Response, and Recovery Plans....249
6. Plan for the Management of Long-Term Recovery at All Levels of Government....249
7. Develop a Recovery Financing Strategy....249
Conclusion....250
Acknowledgments....250

References Cited....251
Section A. Integrated Building Damages and Areas of Concentrated Damage....259
Section B. Population Movements and Vulnerabilities....289
Section C. Long-Term Community Recovery Challenges....329
V1. Summary of Economic Impact Analyses and Policy Implications of the HayWired Scenario
By Stephen Levy, Anne M. Wein, and Cynthia Kroll
Introduction....359
Overview of the HayWired Economic Analysis....359
High-Level Findings from the HayWired Scenario....360
Macroeconomic Impacts and Economic Resilience Analysis—The First 6 Months....362
Longer Term Macroeconomic Analysis—Effects of a Major Earthquake on the Region's Future....363
How Business Characteristics and Location affect Vulnerability and Outcomes....367
Geographic Concentrations of Impacts and their Interactions—A Spatial Analysis....368
Policy Implications Related to the Economic Analyses....373
Planning Ahead....373
The Role of Employers....374
Policies Effective After the Earthquake....375
The Relation with Housing....375
The Role of Insurance....375
Closing Statement....376
References Cited....376
Reflections on the COVID-19 Pandemic, June 2020....377
V2. Economic Consequences of the HayWired Scenario—Digital and Utility Network Linkages and Resilience
By Ian Sue Wing, Dan Wei, Adam Z. Rose, and Anne M. Wein
Abstract....381
Introduction....381
Literature Review of Economic Impact Analysis of Earthquake Events or Scenarios....383
San Francisco Bay Region Economy....384
Economic Impact Estimation Model—Computable General Equilibrium Modeling....388
Economic Resilience....389
Defining Economic Resilience....389
An Operational Economic Resilience Metric....390
Inputs into the Economic Impact Model....390
Property Damage....390
Digital and Utility-Service Disruptions....392
Resilience Adjustments....393
Resilience Adjustments on the Output Side of CGE Modeling....397
Total Economic Impacts....398
Base Case Without Resilience Tactics....398
Total Economic Impacts with Resilience Tactics....404
Dynamic Economic Recovery....408

Study Limitations....410
CGE Model Limitations....410
Simple Dynamic Recovery Model Limitations....413
Conclusion....414
Acknowledgments....415
References Cited....415
Appendix 1. Sectoring Scheme....422
Appendix 2. Techinical Description of the CGE Model....424
Appendix 3. Sector Property Damages....428
Appendix 4. Inconvenience Cost for Loss of Water....444
Appendix 5. REsource Isolation Resilience Factors....447
Appendix 6. Data- and Voice-Services for the Base Case and Three Resilience Cases....450
Appendix 7. Adjustments on the Economic Impacts for Electricity and Water Service Disruptions Adjust....456
Appendix 8. Technical Description of the Dynamic Economic Model....460
V3. The Economic Effects of the HayWired Scenario Using the Association of Bay Area Governments Regional Growth Forecast
By Cynthia Kroll, Shijia Bobby Lu, Aksel Olsen, and Anne Wein
Abstract....463
Introduction....463
What Past Experience Tells Us about Long-Term Effects of Natural Disasters....464
The HayWired Scenario....466
The ABAG Regional Control Forecast and the REMI Model....468
Hypothetical Sequence of Effects and Their Incorporation into REMI....470
Assumptions and Simulated Effects within the REMI Model—Part 1....471
Direct Output Loss from Building Damage....471
Transportation Network and Commuting Flows....474
Recovery Time Adjustment for Trade and Manufacturing Sectors....482
Effects on Population Beyond Employment....483
Assumptions and Simulated Effects within the REMI Model—Part 2: Rebuilding the Region....485
Government Response and Recovery Investment....485
HayWired Scenario Combined Effects on Employment and Population....488
Employment Effects....490
Population Effects....491
Gross Regional Production Effects....491
Summary of REMI Simulation of HayWired Scenario Effects....492
Sensitivity Tests....495
Construction Costs....495
Displaced Population....495
Commuter Resilience....496
Insurance....497
Government Spending....498
Technology Sector Exodus....498
Policy Implications....500
Future Research with REMI Modeling....502
Acknowledgments....502

References Cited....502
Appendix 1....506
Appendix 2....512
Appendix 3....514
Appendix 4....516
Appendix 5....518
Appendix 6....520
V4. Characteristics of Businesses Disrupted by Building Damages from the HayWired Scenario Mainshock
By Anne M. Wein, Jon Haveman, Cynthia Kroll, and Jeff Peters
Abstract....521
Introduction....522
Literature on Business and Owner Characteristics....523
Business Owner Characteristics....523
Business Characteristics....524
Methods....526
Data Sources....527
Algorithm....528
Results....528
Business Characteristics in the San Francisco Bay Region....528
Distribution of Employment at Risk across Counties....529
Disruptive Building Damage Risk by Business Characteristics....530
Study Limitations....533
Policy Discussion and Conclusion....534
Risk from Business Location....534
Sector Risk and Vulnerability....534
Small Business Vulnerability....535
Business Owner Vulnerability....536
Other Vulnerable Business Characteristics....536
Turning Risk into Opportunity....536
Acknowledgments....537
References Cited....537
Appendix 1. Crosswalk between Hazus Occupancy Classes and NAICS Categories....542
Appendix 2. Building Damage Risk Results for the HayWired Scenario, San Francisco Bay Region....544
Appendix 3. Building Damage Risk Results for the HayWired Scenario by Business Owner Demographics and San Francisco Bay County....581
Appendix 4. Building Damage Risk Results for the HayWired Scenario by San Francisco Bay Subarea....583
V5. Spatial Analysis of Industries, Employment, and Commute Flows in Areas of Concentrated Damage from the HayWired Earthquake Scenario
By Anne M. Wein, Dena Belzer, Cynthia Kroll, Carline Au, Jamie L. Jones, Laurie Johnson, Aksel Olsen, and Jeff Peters
Abstract....589
Introduction....590
Disaster Literature on Spatial Aspects....591

Analytical Framework 592
The Spatial Building Blocks in Hazus: Census Tracts 592
Building Damage States 592
Areas of Concentrated Damage 594
Subareas 594
Building Occupancy Groups 594
Industry Employment Groups 594
Household and Workplace Relation 598
Limitations and Knowledge Gaps of the Analytical Framework 598
Building Occupancy Damages 598
Regional 598
Concentrated-Damage Areas 600
Subareas 600
Employment by Industry Group 604
Regional Employment 604
Subarea Employment 605
Employee Residence and Workplace Relation 607
Regional 607
Industry Segment 608
Subarea and Industry Segment 610
Employee Well-Being 616
Summary and Discussion 616
Summary of Study Findings 616
Drawing Insights from other Regional Research and Experience 618
Policy Implications 619
Acknowledgments 622
References Cited 622
Appendix 1. Correspondence Tables 626
Appendix 2. Building Damages 627
Appendix 3. Employed Residents and Workers 638

W. The HayWired Scenario—Earthquake Early Warning Forecast and Potential Hazard Mitigation Actions

By Jennifer A. Strauss, Anne M. Wein, Jamie L. Jones, and Douglas D. Given

Abstract 647
Introduction 647
ShakeAlert Time Estimation for the HayWired Scenario 648
ShakeAlert Can Prompt Automated Controls 651
Elevator Systems 653
Transportation Systems 654
ShakeAlert Can Prompt Protective Actions 656
Hospitals and Injuries 656
Drop, Cover, and Hold On 658
ShakeAlert and Aftershocks 658
Actions Discussed Elsewhere in the Literature 663
Conclusion 664
Acknowledgments 664
References 664

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Rate	
inch per second (in/s)	2.54	centimeter per second (cm/s)
mile per second (mi/s)	1.609	kilometer per second (km/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Rate	
centimeter per second (cm/s)	0.3937	inch per second (in/s)
kilometer per second (km/s)	0.6214	mile per second (mi/s)

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

3G	third generation cellular
3GPP	Third Generation Partnership Project, a standards body
4G	fourth generation cellular
5G	fifth generation cellular; an ITU recommendation governed by the IMT-2020 standard
ABAG	Association of Bay Area Governments
ACS	American Community Survey
ADSL	asynchronous digital subscriber line
AM	amplitude modulation
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ATC	Applied Technology Council
BACRDR	Bay Area Center for Regional Disaster Resiliency
BART	Bay Area Rapid Transit
BayRICS	Bay Area Regional Interoperable Communications System
Bay Area UASI	Bay Area Urban Area Security Initiative
BCDC	San Francisco Bay Conservation and Development Commission
BEA	Bureau of Economic Analysis
BI	business interruption
BLS	Bureau of Labor Statistics
Cal EMA	California Emergency Management Agency (now the California Governor's Office of Emergency Services)
Cal OES	California Governor's Office of Emergency Services
Caltrans	California Department of Transportation
CBD	central business district
CDBG	Community Development Block Grant
CDBG-DR	Community Development Block Grant Disaster Recovery program
CDI	California Department of Insurance
CEA	California Earthquake Authority
CEC	California Energy Commission
CES	constant elasticity of substitution
CGE	computable general equilibrium

COLT	cell on light truck
COVID-19	Coronavirus Disease 2019
COW	cell on wheels
CSCC	Communications Sector Coordinating Council
CVI	community vulnerability indicator
DAS	distributed antenna system
DCHO	drop, cover, and hold on
DHS	U.S. Department of Homeland Security
DLC	digital loop carrier
DOCSIS	Data Over Cable Service Interface Specification
DRI	displacement risk index
DSL/xDSL	digital subscriber line; xDSL is a generic term for a family of digital subscriber lines, including ADSL, ADSL2+, and VDSL
DSLAM	digital subscriber line access multiplexer
DSn	digital signal line, where n is an ordinal number (DS1, DS2, and so on)
EBB	Earthquake Brace + Bolt program
EBMUD	East Bay Municipal Utility District
EERI	Earthquake Engineering Research Institute
EEW	earthquake early warning
EPA	U.S. Environmental Protection Agency
EQC	New Zealand Earthquake Commission
FEMA	Federal Emergency Management Agency
FIRE	finance, insurance, and real estate
FM	frequency modulation
FOA	Fiber Optic Association
FRS	Facility Registry Service
g	acceleration due to gravity
GAMS	General Algebraic Modeling System
GAO	U.S. Government Accountability Office
GDP	Gross Domestic Product
GETS	Government Emergency Telecommunications Service
GIS	geographic information system
GRP	gross regional product
GSP	gross state product
GT	guyed tower

HCV	Housing Choice Voucher
HetNet	heterogeneous network
HIFLD	Homeland Infrastructure Foundation-Level Data
HMGP	Hazard Mitigation Grant Program
HRC	New Zealand Human Rights Commission
HRP	HayWired review panel
HSIP	Homeland Security Infrastructure Program
HUD	U.S. Department of Housing and Urban Development
IBC	International Building Code
ICT	information and communications technology
IEEE	Institute of Electrical and Electronics Engineers
IMPLAN	impact analysis for planning
I-O	input-output
IoT	Internet of Things
IP	internet protocol
ISP	internet service provider
IXP	internet exchange point
LAHD	City of Los Angeles Housing Department
LEHD	Longitudinal Employer-Household Dynamics
LODES	LEHD Origin-Destination Employment Statistics
LTE	Long-Term Evolution
M	magnitude
M_w	moment magnitude
microwave	electromagnetic frequencies above 3 gigahertz
MMI	Modified Mercalli Intensity
MMS	multimedia service messages
MOP	methods of procedures
MP	monopole
MPSGE	Mathematical Programming System for General Equilibrium analysis
MRI	magnetic resonance imaging
MSC	mobile switching center
MTC	San Francisco Bay Area Metropolitan Transportation Commission
MTSO	Mobile Telephone Switching Office
MTX	mobile telephone exchange
NAICS	North American Industry Classification System
NAS	Network Attached Storage

NCC	National Coordinating Center for Communications
NECA	National Electrical Contractors Association
NETS	National Establishment Time-Series Database
NFPA	National Fire Protection Association
NOAA	National Oceanic and Atmospheric Administration
NTSC	National Television System Committee
OLC	optical loop carrier
ONT	optical network terminal
OSH	optical short hop
PBX	private branch exchange
PDA	priority development area
PDR	production, distribution, and repair
PERE	University of Southern California Program for Environmental and Regional Equity
PG&E	Pacific Gas and Electric Company
PGA	peak ground acceleration
PGV	peak ground velocity
POL	petroleum, oil, and lubricants
POTS	plain old telephone service
PSA	peak spectral acceleration
PSAP	public safety answering point
PSPS	Public Safety Power Shutoff
PSTN	public switched telephone network
RED	Routing on Empirical Data project
REMI	Regional Economic Modeling Inc.
RF	radio frequencies
s	second
SA	spectral acceleration
SAFFR	Science Application for Risk Reduction
SBA	Small Business Administration
SCADA	Supervisory Control and Data Acquisition
SCIRT	Stronger Christchurch Infrastructure Repair Team
SCVWD	Santa Clara Valley Water District
SDA	structural-decomposition analysis
SFPUC	San Francisco Public Utilities Commission
SIM	subscriber identity module

SIR	Scientific Investigations Report
SJWC	San Jose Water Company
SMS	short message service
SOW	switch on wheels
SPUR	San Francisco Bay Area Planning and Urban Research Association
SST	self-supporting tower
S-wave	secondary wave
TCP	Transmission Control Protocol
TIA	Telecommunications Industry Association, a standards body
Tn	transmission system, where n is a version number (T1, T2, and so on)
TSP	Telecommunications System Priority
UPS	uninterruptible power supply
USB	Universal Serial Bus
USC	University of Southern California
USGS	U.S. Geological Survey
VA	voltampere
VDSL	very high bitrate digital subscriber line
VoIP	Voice over Internet Protocol
WEA	Wireless Emergency Alert
Wi-Fi	wireless internet, the IEEE 802.11 family of standards
WPS	Wireless Priority Service

The HayWired Earthquake Scenario—Societal Consequences
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Chapter R

Overview of the HayWired Scenario Societal-Consequences Volume

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Introduction

The HayWired scenario is a hypothetical yet scientifically realistic depiction of a 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 region, California. The earthquake scenario epicenter is in Oakland, and strong ground shaking from the scenario causes a wide range of severe effects throughout the greater bay region. In the scenario, the Hayward Fault is ruptured along its length for 83 kilometers (about 52 miles), an event significant enough to affect the lives of everyone who lives or works in the region. The Hayward Fault is arguably the most urbanized active fault in the United States.

The HayWired scenario is only one of many potential major earthquakes that could occur on the Hayward Fault or other major fault systems in the San Francisco Bay region. For every scenario, the damage distributions and service disruptions, and the most affected communities, populations groups, and business sectors will be different. The HayWired scenario therefore offers an informative case study of the effects of a large urban earthquake on a modern U.S. metropolitan region.

The HayWired Earthquake Scenario—Societal Consequences is the third and final volume of U.S. Geological Survey (USGS) Scientific Investigations Report (SIR) 2017–5013 developed with partners. The first volume of this work (SIR 2017–5013–A–H; Detweiler and Wein, 2017) described a M_w 7.0 mainshock on the Hayward Fault that triggers geologic hazards of shaking, fault rupture, liquefaction, and landslides, followed by an aftershock sequence occurring over a 2-year span. The second volume (SIR 2017–5013–I–Q; Detweiler and Wein, 2018) presents engineering implications for buildings, water distribution systems, fire following earthquake, urban search and rescue, and earthquake early warning.

The third volume (SIR 2017–5013–R–W) presents the societal consequences of damages and disruptions from the M_w 7.0 HayWired scenario mainshock and aftershocks for the San Francisco Bay region as follows.

1. *Telecommunications*.—A formative analysis of telecommunications infrastructure exposure to or damage from earthquake shaking, ground failure (landslides and liquefaction), and fire hazards is used to identify vulnerabilities and inform estimates of residual network capacity (see Wein, Witkowski, and others, this volume). Network functionality is further degraded by electric power outages and surges in demand for voice and data services that overwhelm the network. The ameliorating effects of permanent backup power (lasting hours to a few days) and user demand management are critical for health and safety during the initial response. Once labor and trucks arrive at failed sites to deliver fuel and deploy portable equipment, service restoration is bolstered and sustained. The analyses inform policy implications for the telecommunications industry, government, and subscribers.

2. *Lifeline infrastructure systems*.—An extensive geographical analysis of energy (electric power; oil and gas), water, telecommunications, and transportation systems show variable exposure to each of the HayWired scenario hazards and collocated infrastructure in areas exposed to multiple hazards (see Jones and others, this volume). Compiled utility and transportation service restoration times are days to weeks for telecommunications and electric power services, weeks to months for gas and water services, and months to years for transportation systems in the San Francisco Bay region. Considerations of interactions between systems inform planning and coordination of earthquake responses and service restorations.

3. *Communities at risk*.—A progressive examination of communities at risk of population displacement is conducted through the lens of neighborhood impairment caused by concentrated building damage (see Johnson and others, this volume). Areas of concentrated damage are defined as 20 percent or higher extensive or complete building damage from earthquake hazards and (or) fire. Estimates of populations in the San Francisco Bay region at risk of displacement over time are approximately 720,000 to 1.45 million people. Long-term community recovery issues are highlighted for areas affected by ground failure, concentrated building damage, and (or) protracted lifeline service restoration that contain socially vulnerable and (or) mobile populations. Seven topics to consider when developing mitigation and preparedness policy are: the quality and quantity of housing for all income levels,

strength of lifeline infrastructure, land use planning, evacuation and temporary housing planning, and recovery management and financing strategies.

4. *Economic consequences*.—A broad collection of macro- and micro-economic studies estimate effects of property damages and utility and transportation service disruptions on regional economies and businesses.

   A. A summary of the economic studies assembles the economic policy implications for planning ahead and recovering from an earthquake, roles of employers and insurers, and the importance of housing (see Levy and others, this volume). Although the economic losses are substantial, the toll on humans would be more devastating. A reflection on the Coronavirus Disease 2019 (COVID-19) pandemic compares economic effects and reinforces the benefits of advanced preparations and seizing opportunities to recover from one disaster in a way that makes society more resilient to other disasters.

   B. An estimate of California's gross state product (GSP) loss during the first 6 months after the M_w 7.0 HayWired earthquake scenario amounts to $44.2 billion, or 4.2 percent of the State's projected baseline GSP for that period (see Sue Wing and others, this volume). The business interruption losses are primarily caused by property damages, which are amplified by the losses from water, power, and telecommunication service disruptions. The losses could be reduced by 42 percent to $25.3 billion with the implementation of business continuity and recovery practices of filling backorders, holding inventories, conserving and substituting inputs, and relocating economic activity.

   C. In the first year after the M_w 7.0 earthquake, output losses from property damages and transportation disruptions cause an employment drop of almost half a million jobs, an 8 percent decrease in gross regional product (GRP), and a population decline of 150,000 residents (2 percent) compared to the San Francisco Bay region's projected economic growth (see Kroll and others, this volume). The two counties nearest the epicenter of the earthquake, Alameda and Contra Costa, suffer a 15 percent job loss and 13 percent loss in GRP. Economic recovery of counties in the San Francisco Bay region takes 5 to 10 years but would be prolonged by labor shortages and increased costs of construction or expansions by major employers outside of the region.

   D. Extensive and complete building damage from the M_w 7.0 earthquake disrupts 7 to 8 percent of business establishments and employment, affecting at least 40,000 establishments and 240,000 employees (see Wein, Haveman, and others, this volume). The risk is larger in heavily damaged areas where 35 to 40 percent of businesses may be disrupted by extensive or complete building damage in central Alameda County and western Contra Costa County. The risk is more extreme for industries concentrated in these areas such as construction, manufacturing, transportation and wholesale, and public administration. Combined with other known business vulnerabilities (for example, small-sized businesses) the analyses inform opportunities to improve business preparedness and recovery through programs and interorganizational arrangements.

   E. About 595,000 employees (or 14 percent of bay region employment) live and (or) work in areas of concentrated damage from HayWired earthquake hazards and (or) fire following earthquake (see Wein, Belzer, and others, this volume). The spatial perspective of concentrated building damages highlights considerations of neighborhood- and business-district-level planning, safety cordon management, spread of impacts between business districts and neighborhoods, sector resilience planning, protection of middle-income jobs, and potential industrial and geographical shifts in economic activity.

5. *Earthquake early warning*.—Applications and benefits of ShakeAlert, an earthquake early warning system for the West Coast of the United States, are envisioned for automated systems and self-protection. Benefits include providing seconds of estimated warning of strong shaking to slow trains, execute hospital patient safety procedures, hold elevators at floors, and for individuals to drop, cover, and hold on. Three HayWired scenario aftershocks in the earthquake sequence are examined for various situations that may arise when warnings are activated throughout an earthquake sequence.

Earthquake Hazards

The HayWired Earthquake Scenario—Earthquake Hazards volume (Detweiler and Wein, 2017) is the foundation of the scenario. It describes the ground shaking and fault rupture of the hypothetical M_w 7.0 HayWired scenario mainshock, with additional descriptions of induced landslides and liquefaction (soils becoming liquid-like during shaking), afterslip (subsequent movement on a fault), and aftershocks (subsequent earthquakes).

Ground-motion modeling for the HayWired mainshock shows that damaging shaking (Modified Mercalli Intensity VI or higher) occurs over a region of approximately 50,000 square kilometers (about 19,000 square miles from the Pacific Coast to the Sierra Nevada and from north of Clear Lake to south of Coalinga), including almost all the urbanized area of the nine counties bordering San Francisco Bay, as well as Santa Cruz County to the south.

The modeled scenario mainshock causes as much as 2 meters (about 6.5 feet) of fault offset either in the form of coseismic slip

(fault slip during the mainshock) or afterslip. Liquefaction and landslides threaten people, property, and lifeline infrastructure in every county in the San Francisco Bay region. The aftershock sequence includes 16 aftershocks of M_w 5.0 or larger that occur over 2 years and as far as 50 km (about 30 miles) from the Hayward Fault, several of which cause local damaging ground shaking that is stronger than the mainshock.

Engineering Implications

The HayWired Earthquake Scenario—Engineering Implications volume (Detweiler and Wein, 2018) estimates the earthquake damages to the general building stock, three archetypical tall buildings, and water supply systems. A simulation of fire following earthquake exacerbates building damages. Entrapment in elevators and collapsed buildings form the basis for an estimation of needs for urban search and rescue. Risk reduction opportunities are illustrated for stronger building codes, water supply pipe replacement and utility emergency fuel plan, and the use of earthquake early warning with drop, cover, and hold on actions.

Property (building and content) damages cause direct business interruption losses of more than $82 billion (from shaking, liquefaction, and landslide hazards) and 800 fatalities. The current International Building Code helps to protect lives but does not ensure buildings are safe to occupy after the earthquake. When people understand the building code objective of life safety, most express a preference and a willingness to pay more for a stronger building. An additional 1-percent construction cost could increase the percentage of occupiable homes and workplaces from 75 to 95 percent following a large earthquake in the San Francisco Bay region.

A state-of-the-art, performance-based, earthquake-engineering study of older (20 and 40 story) regular steel-frame high-rise office buildings and a new regular (42 story) reinforced-concrete residential building in downtown Oakland and San Francisco finds that the HayWired scenario mainshock could cause non-structural damage that renders them unusable for as long as 10 months. The strongest shaking in the HayWired scenario does not occur where tall building types are analyzed, and older or irregular buildings are not immune to collapse.

Urban search and rescue could be required to rescue 2,400 people from collapsed buildings and more than 22,000 people from stalled elevators. Nonfatal injuries from shaking and building damage could amount to 18,000 from shaking and liquefaction hazards; as many as 1,500 nonfatal injuries could be prevented when drop, cover, and hold on actions are practiced with earthquake early warning.

Estimates of water distribution pipeline damages from shaking and ground failure throughout the earthquake sequence amount to about 1,800 breaks and 3,900 leaks in the 4,162 miles (6,698 km) of East Bay Municipal Utility Department service area and about 1,000 pipe repairs in the San Jose Water Company service area. On average, an east bay resident could lose water service for 6 weeks (some for as long as 6 months). Service losses could be reduced by half if current efforts to replace old, brittle pipe are completed before the next large regional earthquake occurs. Dependence on electric power restoration is greater for lesser impacted utilities that restore faster; implementing a fuel plan could reduce San Jose Water Company's service losses by about 25 percent.

Water supply outages impede the fighting of fires. A simulation of fire following earthquake shows that the HayWired mainshock could cause about 400 large fires in counties nearest the fault rupture. Fires may then spread to burn a building-floor area equivalent to that of about 52,000 single-family dwellings. Such fires could kill hundreds of people and cause property losses approaching $30 billion. Following review of these results by fire agencies in the San Francisco Bay region, a first-ever joint exercise of portable firefighting water-supply systems was conducted.

Societal Consequences

The HayWired Earthquake Scenario—Societal Consequences volume (this volume) examines how the HayWired scenario earthquake sequence could affect recovery of communities, businesses, and regional economies. This includes effects of property damages and water-supply service disruptions estimated in volume 2, and telecommunications, electric power, highway, and Bay Area Rapid Transit (BART) system disruptions described in this volume. Aside from insurance analyses (for example, Grossi and Zoback, 2013), community-at-risk and economic impact analyses had not been conducted for a Hayward Fault earthquake in the San Francisco Bay region before. Volume 3 closes with envisioning plausible future implementations of earthquake early warning automated actions and how they could improve resiliency.

Telecommunications Vulnerabilities and Service Restorations

The HayWired scenario is named, in part, to recognize society's dependence on wired and wireless information and communication technologies (especially telecommunications). In chapter S (Wein, Witkowski, and others, this volume), analyses of telecommunications infrastructure and services complement the Applied Technology Council (ATC; 2016) effort that broadly considers telecommunications standards, guidelines, and performance criteria; lifeline infrastructure interdependencies and societal impacts; and research and operational recommendations for disaster recovery. Whereas ATC's effort considers several types of hazard events and draws from recent hurricane events in the United States, the HayWired scenario telecommunications analysis comprehensively examines effects of multiple earthquake hazards in the San Francisco Bay region and service restoration pathways.

Addressing the question of how voice and data services may be disrupted and restored after a large earthquake in the region

is more complex than that for static single-operator systems (such as electric power, transportation, or water supply) which have more advanced capabilities to model earthquake damage and system performance. The approach taken was to engage with industry experts, learn from recent global earthquakes and U.S. disasters, and employ geographic information systems to analyze central offices, data centers, cellular sites, and fiber optic lines for exposures to or damages from the HayWired scenario hazards. Figure 1 illustrates the results of a simple model of voice and data service restoration. The worst case uses an estimate of residual network capacity after earthquake damages, assumes full dependence of telecommunications equipment on commercial electric power, and increases the demand for services after a disaster. Alameda County voice and data service is reduced to serving 7 percent of demand after the earthquake when residual network capacity is halved, power outages affect more than 75 percent of customers, and demand for services increases tenfold. The figure also shows improvements in the demand served with (1) permanent backup power on telecommunications equipment that is 90 percent available with batteries lasting less than a day and generators running for as long as 3 days, (2) delivery of fuel and (or) deployment of portable equipment to failed sites that takes 2 to 7 days in Alameda County, (3) and management of user behavior that reduces demand for services by 10 percent.

Industry, users, and governments have roles in improving telecommunications services after an earthquake. Mitigation opportunities include reducing infrastructure damage from ground failure hazards, collateral damage from collocated infrastructure, and vulnerable buildings hosting telecommunications equipment. Large numbers of cellular sites are on buildings in the San Francisco Bay region. Power dependencies could be decoupled with permanent backup power including solutions for the increasing numbers of small cell sites used to infill populated areas. Restoration opportunities involve coordination with other lifeline infrastructure operators about repair and restoration processes (especially with electric power and transportation systems), and the industry's preparedness for restoration contingencies (especially the potential fuel and skilled labor shortages in the San Francisco Bay region). Readiness to use scientific earthquake hazard information such as earthquake early warning (for example, ShakeAlert) and forecasts of fault afterslip and aftershocks could further inform response and recovery decisions. On the consumer side, individuals and businesses could be knowledgeable about ways to conserve bandwidth and could benefit from having sufficient power and data backups and alternatives for operations requiring communication or information. Local governments could address or prepare for telecommunications infrastructure vulnerabilities and restoration in their communities, limitations of regulatory constraints, loss of 9-1-1 system functionality, and communications with evacuated and (or) socially vulnerable populations and people with access and functional needs.

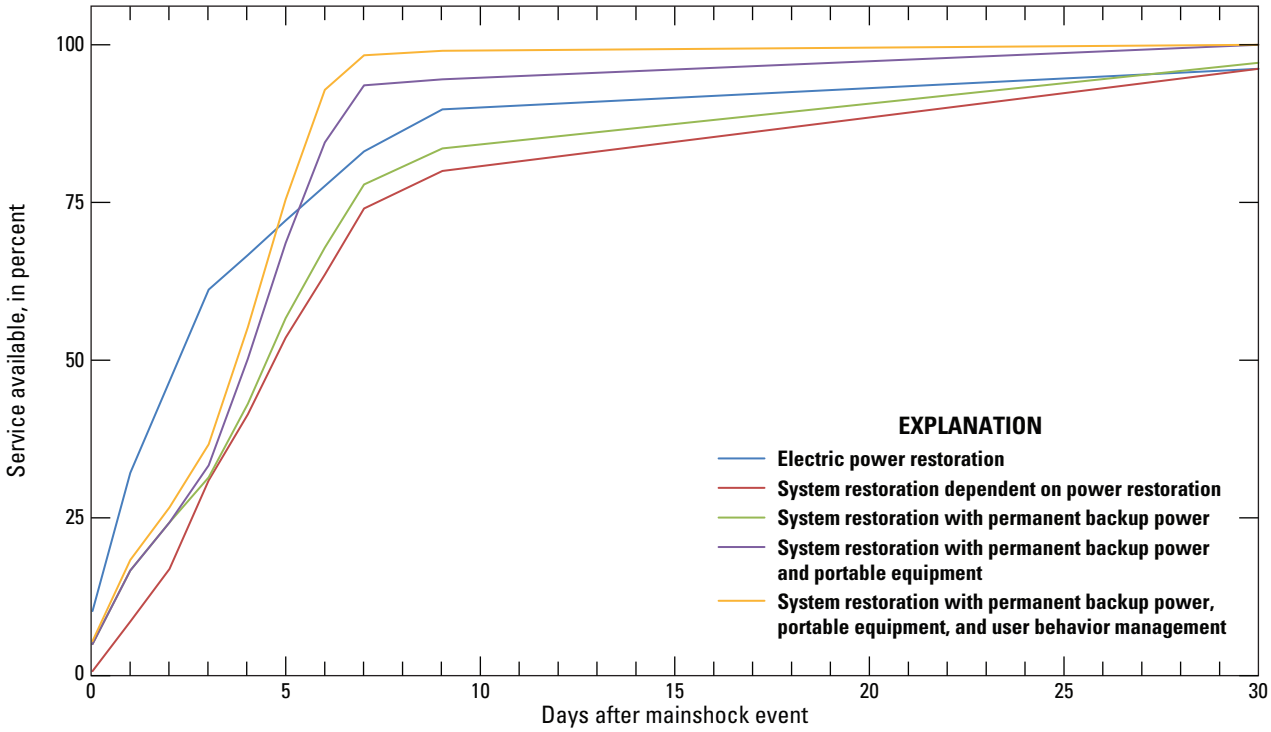


Figure 1. Line graph showing the percentage of demand for voice and data services served and electric power restoration curves for Alameda County after the HayWired scenario earthquake mainshock in the San Francisco Bay region, California. The base case (red line) assumes that telecommunications are fully dependent on electric power restoration and there is a surge in demand for voice and data services following a large earthquake. Implementation of fixed power backup, portable equipment, and user behavior management achieves the most optimistic outcome (orange line). Figure from Wein, Witkowski, and others (this volume).

Lifeline Infrastructure Systems and Multi-hazards

For the HayWired scenario, chapter T (Jones and others, this volume) presents a comprehensive and standardized hazard exposure analysis of facilities and conveyances in five lifeline infrastructure systems: transportation, water supply and wastewater, oil and gas, electric power, and telecommunications. New geographic information system methods were developed to (1) create a more detailed liquefaction probability map for the San Francisco Bay region than the existing one at the census-tract scale; (2) map relative levels of earthquake hazard intensities into a single multi-hazard intensity map; and (3) overlap the collocation and density of infrastructure systems onto the multi-hazard intensity map (fig. 2). Using these new methods, the interaction between lifeline infrastructure systems and hazards is examined in several ways: the exposure of each lifeline infrastructure system to each hazard; the exposure of each lifeline infrastructure system to combinations of multiple hazards; and potential interactions between systems collocated in multi-hazard areas

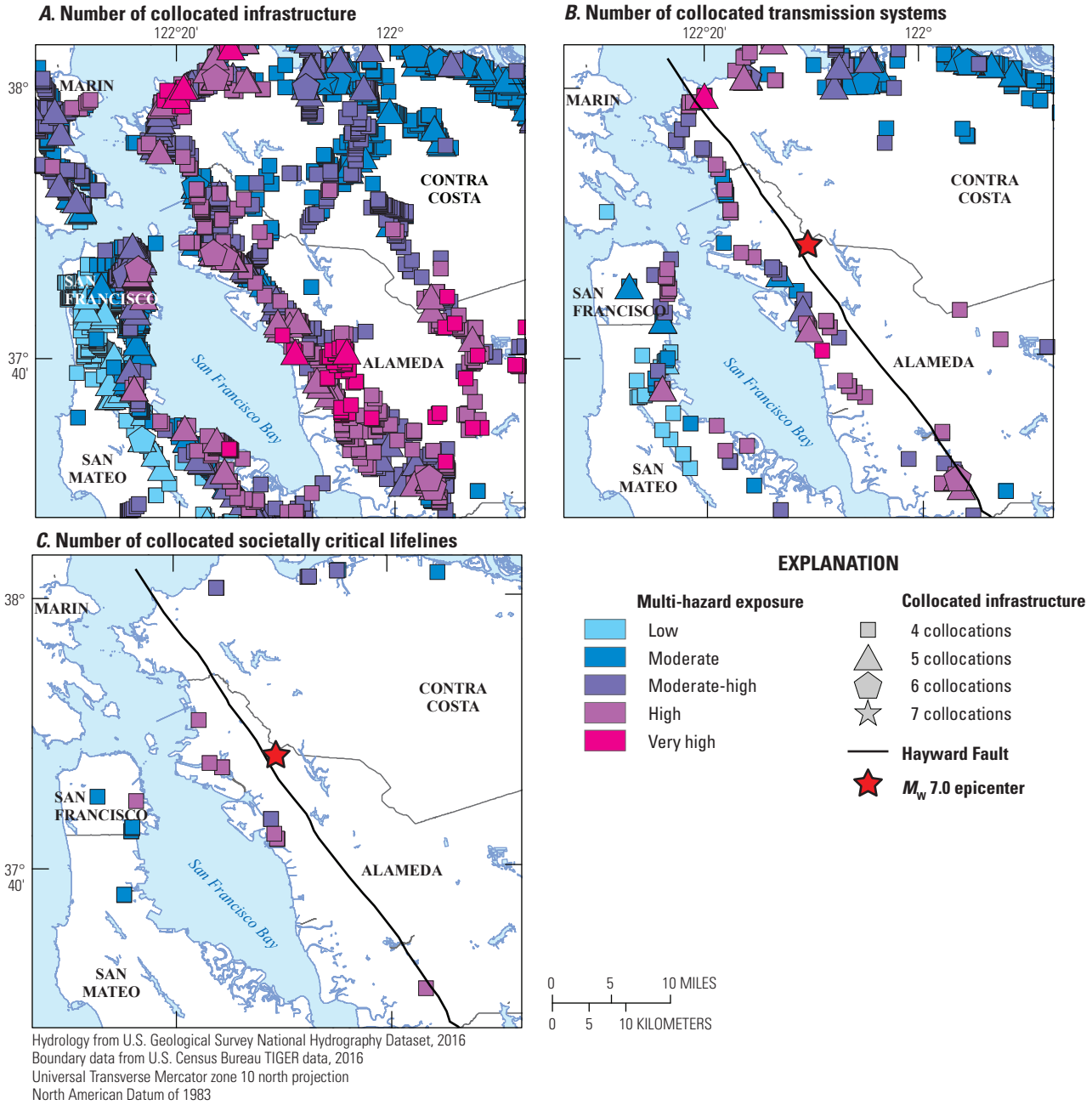


Figure 2. Maps of the San Francisco Bay region, California, showing exposure of lifeline infrastructure collocations to multi-hazards. Three examples are: *A*, Collocations for all lifeline infrastructure systems, showing points with four or more collocated lifelines. *B*, Collocations for transmission systems, showing points with four or more collocated lifelines. *C*, Collocations for societally critical lifelines, showing points with four or more collocated lifelines. M_w, moment magnitude. Figure modified from Jones and others (this volume).

after an earthquake. Finally, lifeline infrastructure system restoration times acquired from various collaborations with service providers are compiled noting their capabilities to consider multiple hazards and interactions between systems.

Eleven (27 percent of) internet exchange points and five (20 percent of) oil refineries are relatively the most exposed to high shaking intensity (defined as above 50 percent of the ground motion in the low-rise building design maps of the International Building Code). Liquefaction is the primary hazard at the three international airports, several seaports, several water treatment plants, and one refinery. Only 22 facilities are located in the fault zone, but hundreds of roadways and fiber optic cables cross the surface rupture and (or) could be affected by fault afterslip. The urban nature of fire following the HayWired scenario M_w 7.0 earthquake exposes relatively more BART facilities to this hazard. Contrary to the outcome of the 1989 Loma Prieta earthquake in California, safe egress from the east bay (especially away from ensuing fires) might well be west across the trans-bay bridges rather than to the east owing to fault rupture and landslide hazards.

Long-haul fiber optic cables are relatively more prevalent in multi-hazard areas than other types of lifeline infrastructure. The combination of shaking, liquefaction, and fire affect 5 percent or more of petroleum, oil, or lubricant terminals, storage facilities, or tank farms; internet exchange points; fiber-lit buildings[1]; cellular sites; natural gas compressor stations; microwave towers; and AM radio antennas. Infrastructure that is potentially exposed to all five hazards at one location include a few bridges and cellular sites, and kilometers of roadways, fiber optic cables, and oil and gas pipelines.

Most commonly, collocated infrastructure in multi-hazard areas involves distribution infrastructure of surface streets or interoffice fiber, although collocated transmission infrastructure of highways, railways, natural gas and petroleum pipelines, and high-voltage electric infrastructure may be a higher priority to repair following an earthquake. Oil and gas pipelines run parallel to and across roads, rails, and fiber optic cables in areas with high liquefaction probability. Societally critical infrastructure[2] are collocated around freight transport hubs (specifically, the Port of Oakland and San Francisco International Airport) and in densely developed areas.

Repairs to BART stations and train yards between Oakland and Fremont could take a few years to complete, likely longer than highway bridge repairs. In Alameda County, water supply services take 6 weeks to restore on average and as long as 6 months. Gas service restoration times are also on the order of months, exceeding electric power service restorations of weeks to a month. Voice and data services are most affected by damage, power outages, and congestion at first but are restored more quickly in days to weeks compared to utilities and transportation systems. All restoration times could be elongated by additional damage from fires following the earthquake, aftershocks, and collateral damage or other unaccounted restoration interactions.

Chapter T offers an analytical approach to support planning and coordination among organizations of lifeline infrastructure providers, communities, government officials, businesses, and public safety. Such plans could be undertaken by forming a regional lifeline council (for example, City and County of San Francisco, 2020). The multiple hazards and infrastructure collocation results could be used to inform and facilitate dialogue among organizations about increased societal risks from cascading failures and complex restoration interactions, and to highlight areas with potential interactions that could arise following a major earthquake for emergency management exercises among organizations.

Communities at Risk

Chapter U (Johnson and others, this volume) adds a social dimension and long-term perspective to the rich details of the hazard and immediate impacts of the HayWired scenario for the nearly 7.7 million residents of the San Francisco Bay region, California, and their many communities. “Communities at risk” are places where normal community functions will be severely impaired or cease to exist for months, even years, after a disaster and where residents may be forcibly displaced because of direct damage to their homes and neighborhoods, or voluntarily relocate because they cannot obtain services or otherwise recover. The topic of communities at risk for the HayWired scenario is developed in three analyses: (1) integrated building damage and areas of concentrated damage (fig. 3); (2) population movements and vulnerabilities; and (3) long-term community recovery challenges. These analyses inform the development of seven policy opportunities for improving community resilience in the San Francisco Bay region before such a potentially unprecedented and catastrophic earthquake disaster occurs.

For the HayWired M_w 7.0 earthquake scenario, integration of property damage caused by ground shaking, liquefaction, and landslides (Seligson and others, 2018) and by fires (Scawthorn, 2018) results in an estimated $74 billion in cumulative property damage, with damage to 1 million residential buildings (containing 1.37 million housing units) and nearly 39,000 nonresidential buildings. Concentrated-damage areas are foundational to understanding where people and places are most vulnerable to long-term community recovery challenges. In the HayWired scenario, the areas are defined by census tracts with extensive and complete building damages affecting 20 percent or more of the building square footage. Concentrations of older, seismically vulnerable residential and nonresidential buildings and post-earthquake fire spread are major determinants of concentrated-damage patterns in the urbanized parts of Alameda County and western Contra Costa County, the Novato area of Marin County, and the Vallejo area of Solano County.

[1]Fiber-lit buildings provide bandwidth capacity for end-user applications and display-service providers who have a fiber presence or optical switches connected to a fiber loop inside a building (see https://www.geo-tel.com/fiber-lit-buildings for more information).

[2]Societally critical infrastructure as a subset of transmission infrastructure were identified in terms of capacity (for example, large power generation facilities or number of licenses for microwave towers), service area (for example, broadcasting range), and safety (for example, seismic condition of dams or closeness of pipelines to buildings).

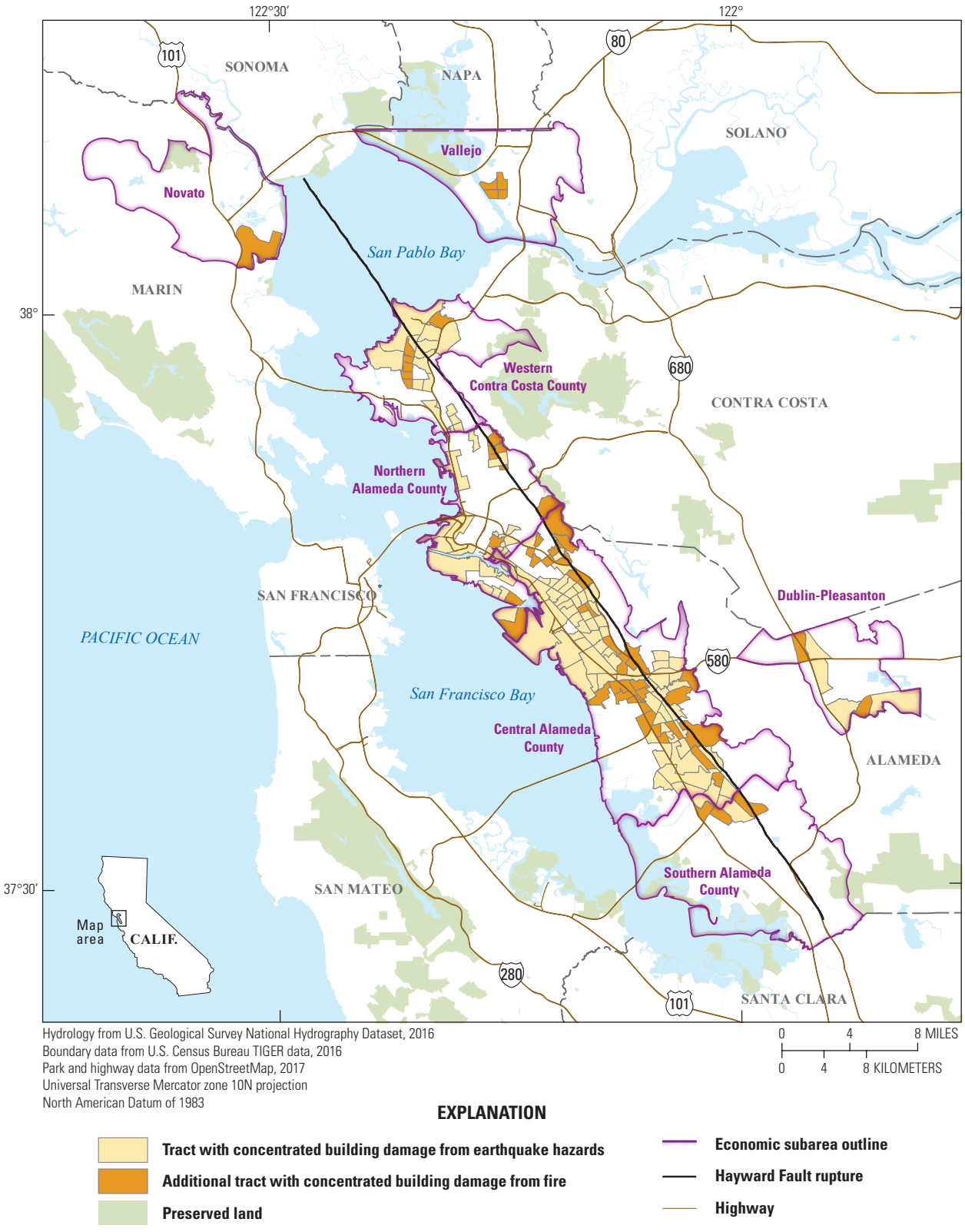


Figure 3. Map of the San Francisco Bay region, California, showing census tracts with concentrated damage in subareas as a result of hazards caused by the HayWired scenario mainshock on the Hayward Fault. Census tracts with concentrated damage are defined as tracts with 20 percent or more of their total building square footage in extensive or complete damage. Light orange areas are those affected only by earthquake hazards (ground shaking, liquefaction, and landslide) and dark orange areas are added if fire damages are included. Figure from Wein, Belzer, and others (this volume).

Figure 4 highlights the major estimates of population displacement and themes emerging from the analysis of communities at risk and how they are likely to unfold over time. Population displacement results from damaged housing and concentrated-damage neighborhoods in the short term, and is further aggravated by prolonged transportation, utility and other service outages, vulnerable populations, insufficient shelter capacity, and aftershocks affecting the ability of people to stay in the region in the intermediate term. Long-term recovery issues constrain population return, replanning, and rebuilding.

Seven policy opportunities for improving community resilience in the San Francisco Bay region address the major themes (fig. 4) of the analysis of communities at risk: (1) accelerate the seismic mitigation of homes; (2) strengthen or replace infrastructure; (3) build more new housing for all income groups; (4) promote seismic resilience in land-use and development policies across the region; (5) address population movements and long-term displacement in local, regional, and State preparedness, response, and recovery plans; (6) plan for the management of long-term recovery at all levels of government; and (7) develop a recovery financing strategy.

Economic Impacts

The effects of the HayWired scenario on regional economies and businesses are investigated in a set of four technical analyses (chapters V2–V5) that are summarized in chapter V1. Two studies focus on macroeconomic impacts of reduced output and employment, and associated population movements in the San Francisco Bay region after the earthquake. Two studies show effects of building damage in small geographic areas by considering business characteristics (for example, sector or industry group, age, size, structure, and ownership), concentrated damage in business districts, and relations between employee workplace and home locations.

Summary of Economic Impact Analyses and Policy Implications

Chapter V1 (Levy and others, this volume) summarizes the economic effects that could be expected from the HayWired earthquake scenario, how those effects would be distributed among geographic areas and types of businesses in the region, and

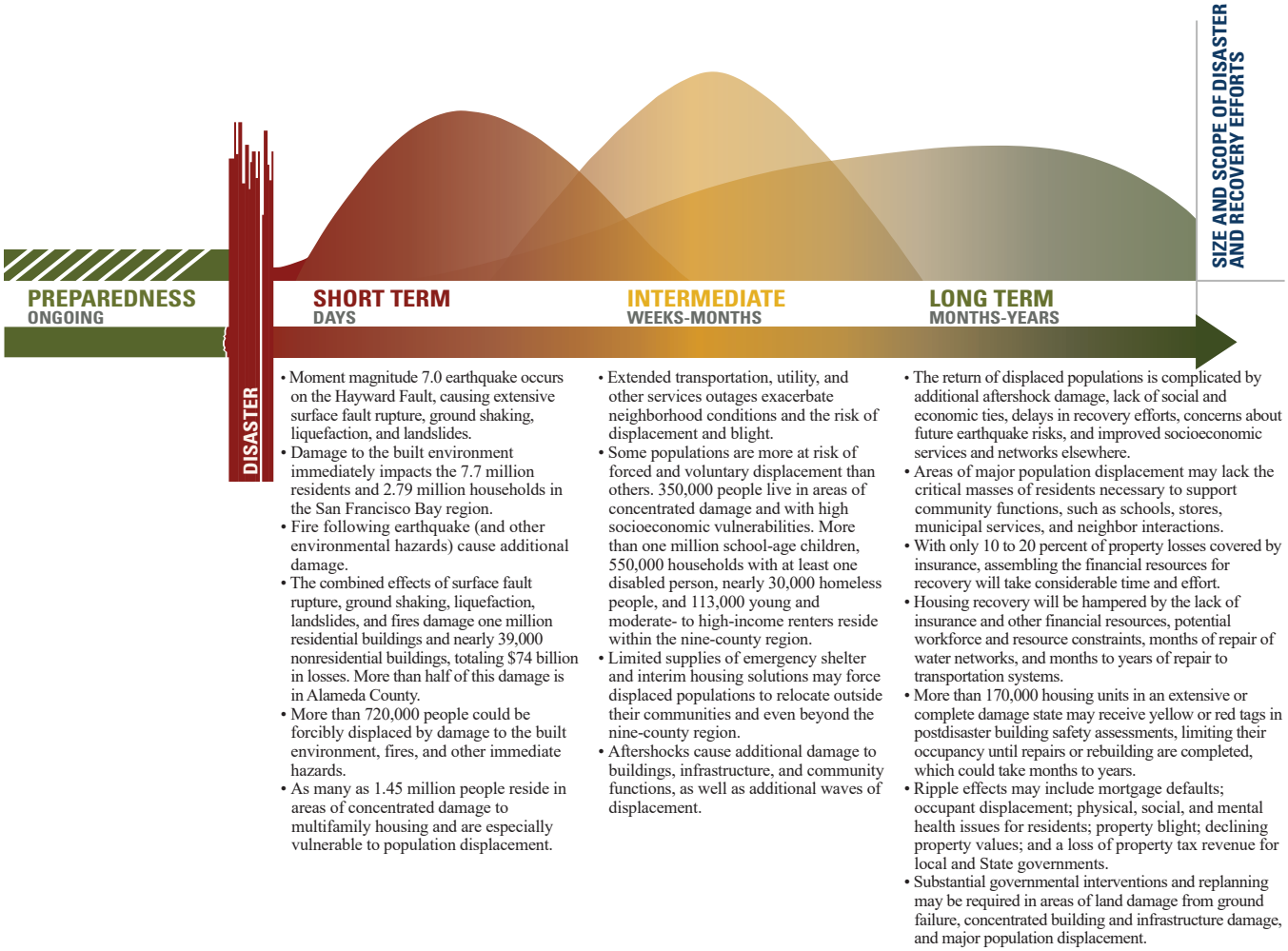


Figure 4. Schematic diagram showing major themes and estimates emerging from the analysis of communities at risk in the HayWired scenario in the San Francisco Bay region, California, with respect to the "disaster recovery continuum" timeline developed by the Federal Emergency Management Agency (2016). Figure from Johnson and others (this volume).

how individual and policy decisions made before or applied after the event can change the overall effect in the moment and over time. At the time of writing, a reflection on the economic effects of the COVID-19 pandemic was inserted.

Because macroeconomic losses can be overcome at a large regional scale, policy interventions can be most important for addressing human challenges and location-specific challenges. There are roles for government, major employers, and insurers to develop policies, mitigation approaches, and programs that could be helpful in the San Francisco Bay region before and after a large earthquake similar to the HayWired scenario. Mitigation actions taken in preparation for an earthquake to reduce economic and human toll include:

- Strengthening new and existing structures and infrastructure.
- Planning for temporary housing and relocating vital businesses and services.
- Planning for handling access in and out of damaged and unsafe areas.
- Building networks for cooperative responses among private and public sector entities, between businesses in similar industries, between businesses and neighborhoods, and inclusive of organizations representing vulnerable population groups with few resources.

Business resilience actions taken after an earthquake to reduce the magnitude and duration of economic and business losses include:

- Plans for relocating or rescheduling production and backups for data, water, and power outages.
- Plans to coordinate and share resources, including production and retail space, and provide flexibility in accessing supplies.
- Critical-infrastructure-provider plans to coordinate the restoration of telecommunications, electric power, and transportation services.
- Capability for quick response with emergency supplies to save lives, as with the COVID-19 pandemic.
- Postponements of private payment obligations (for example, rents) could reduce financial harm.

Low earthquake insurance (see Corelogic Inc., 2018) penetration and large city revenue losses are funding gaps that may be hard to fill.

Similar to the COVID-19 pandemic experience, the effects of the HayWired earthquake scenario are sudden, there will be issues with supply chains, and employers' use of the physical environment will change dramatically. Yet in the HayWired scenario, only the San Francisco Bay region is directly affected by the earthquake. However, some resilience measures that have worked well during the pandemic may be much more difficult to implement when faced with extensive physical damage. Lessons learned from the pandemic show that planning ahead for a large earthquake could help reduce suffering and improve recovery outcomes. How we recover from the pandemic could also help to prepare for an earthquake; stimulus funds could include support for infrastructure investments that also increase earthquake or fire resistance.

Digital and Utility Network Linkages and Resilience

Chapter V2 (Sue Wing and others, this volume) estimates macroeconomic effects of the HayWired earthquake scenario on the greater San Francisco Bay region's economy using two models: (1) a detailed multiregional static computable general equilibrium model for 6 months following the event and (2) a simpler, multiregional intertemporal partial equilibrium simulation model for the dynamic recovery in the 17 years following the earthquake. In the 6 months following the earthquake, total gross state product (GSP) losses are estimated to be $44.2 billion, or 4.2 percent of California's projected baseline GSP over the period. Capital stock losses from property damages accrued during the earthquake sequence are the primary causes of the GSP losses. Water and electric utility and telecommunications service disruptions cause about $1.4 billion of the GSP losses. The most vulnerable industry sectors are heavy manufacturing and service industries, such as education and healthcare. The hardest hit county (in absolute and relative terms of gross regional product losses) is Alameda County, followed by Santa Clara County.

However, the GSP losses could be reduced by 42 percent to $25.3 billion if microeconomic resilience measures are implemented after the damage and service disruptions have occurred (fig. 5). Economic resilience measures speed the restoration of services (for example, a portable cellular site), work around supply disruptions (for example, a change in supplier), and use remaining resources efficiently or beyond normal use (for example, conserve water or implement overtime to catch up on lost production).

The analysis examines effects on information and communications technology (ICT) sectors at the core of the digital economy, including internet publishing and broadcasting; telecommunications; data processing, hosting, and related services; and other information services. The internet publishing and broadcasting sector show losses in counties less directly affected by the earthquake (San Mateo and San Francisco Counties) and counties that produce and export 80 percent of these services (Marin, Solano, and Santa Cruz Counties).

Analysis Using the Association of Bay Area Governments Regional Growth Forecast

Chapter V3 (Kroll and others, this volume) uses the Association of Bay Area of Governments (ABAG) model that underlies the 2015 regional economic forecast through 2040 of the San Francisco Bay region, California (Association of Bay Area Governments Planning and Research Department, 2016) to estimate how a major earthquake along the Hayward Fault would change the trajectory of that forecast. The results for gross regional product (GRP), employment, and population

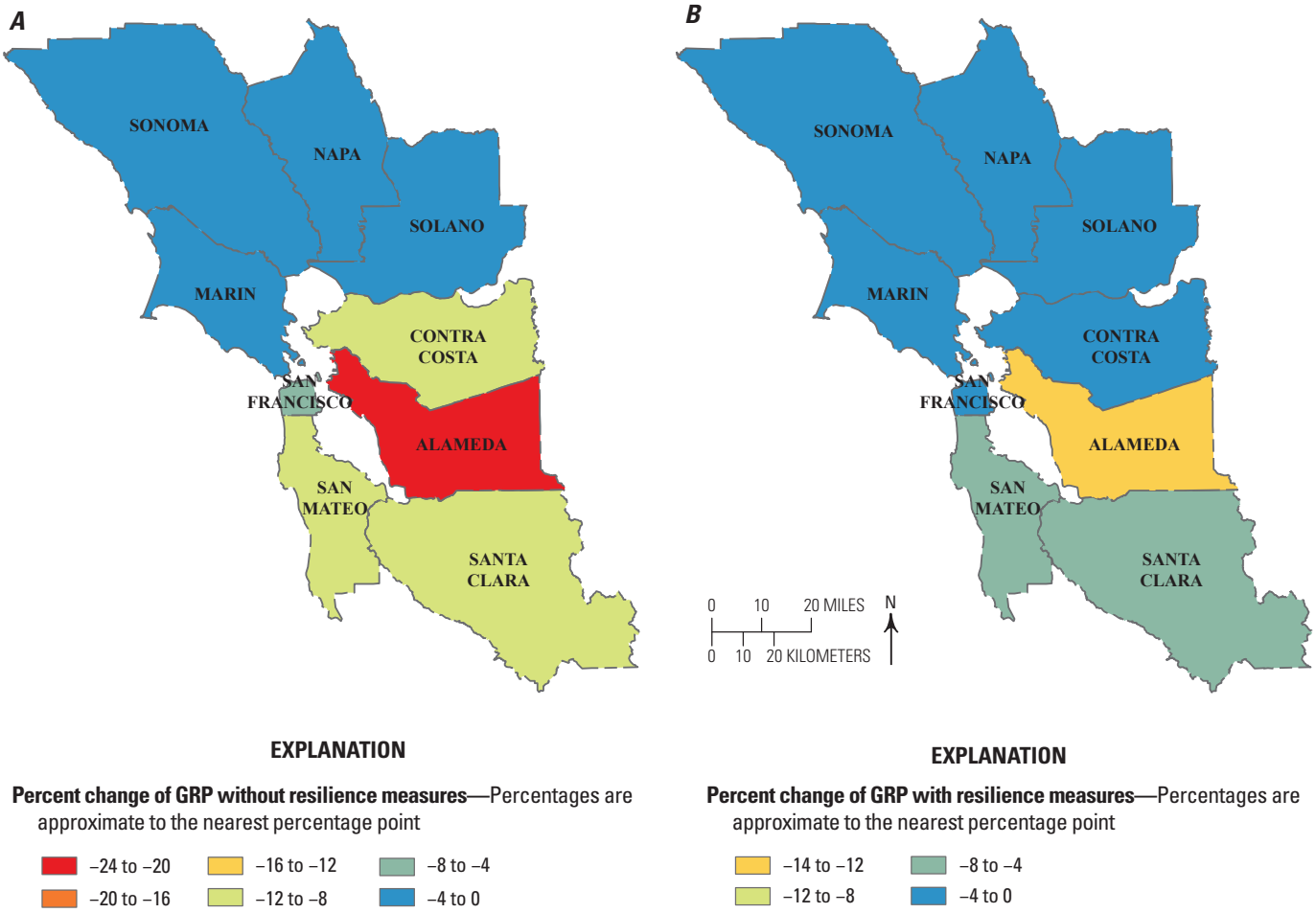


Figure 5. Maps showing the percentage of gross regional product (GRP) change in the first 6 months after the HayWired earthquake from property damages and water, electricity, and telecommunications service disruptions by county in the San Francisco Bay region. *A*, Base case without microeconomic resilience measures. *B*, Case with microeconomic resilience measures. The rest of California experiences a 1 percent loss in GRP in both cases. Data from table 23 of Sue Wing and others (this volume).

losses show an economy that would experience a recession. In the first year, employment could drop by almost half a million jobs (fig. 6), whereas GRP would decrease by 8 percent. The two east bay counties nearest the epicenter of the earthquake (Alameda and Contra Costa Counties) could suffer a 15 percent loss in jobs and 13 percent loss in GRP. Population losses from the economic migrations and accelerated retirements could be smaller—on the order of 150,000 (or 2 percent) in the first year, although the communities at risk analysis suggests that displacement within the region could be much higher, and social effects could lead to a larger outmigration than is indicated by the economic model.

The economic effects are primarily caused by output losses from building damage and commute flow interruptions from BART and highway disruptions that may last months to a few years. The decline in output from commute flow interruption more than doubles the employment and population losses from building damage alone. Although building damage is the major contributor to employment loss in the east bay, commute flow interruptions in the west and south bay affect employment to a much greater degree than employment loss from building damages. However, the analysis assumes teleworking levels below those seen during the COVID-19 pandemic.

Much of the economy could recover to the pre-earthquake level within a few years, but a full return to the previous forecast trajectory could take more than 5 years for the region and closer to a decade for the most severely affected counties. Recovery and rebuilding investments (for example, relief spending and insurance) are crucial to repairing the economic base of the region and returning it to its projected growth trajectory. A shortage of construction workers that postpones rebuilding would lead to a deeper and longer recession. Major technology employers relocating substantial portions of their operations (for example, middle income and back-office jobs) and expanding outside of the region, could stretch the earthquake-induced recession to 6 or 7 years and permanently damp the region's trajectory relative to the ABAG 2015 forecast for 2040. State and local policies, as well as business and personal preparedness, could reduce the length and severity of effects.

Characteristics of Businesses Disrupted by Building Damages

Chapter V4 (Wein, Haveman, and others, this volume) reviews business characteristics and associated vulnerability after a disaster (for example, type of business, location, sector, size, age, and owner demographics). A spatial analysis estimates percentages of business characteristics exposed to disruptive extensive or complete building damages in the HayWired scenario (for example, fig. 7). Disruptive building damage is estimated to affect 7–8 percent of business establishments and employment in the San Francisco Bay region, corresponding to more than 40,000 establishments and 240,000 employees. The risks vary by sector and range from 5–6 percent for business establishments in utility, finance and insurance, and management of companies sectors to 10–11 percent for establishments in the construction, education, and warehouse and transportation sectors and employment in the manufacturing sector. Business location strongly differentiates disruptive building damage such that about 25 percent of Alameda County businesses and employees could be affected by limited or restricted use of their buildings, and the risk increases to 40 and 35 percent in central Alameda County and western Contra Costa County, respectively. Overall, the profiles of business characteristics in Alameda County largely drives the result for the region. Although the building disruption risk to small businesses (measured by number of employees or revenue) is not notably elevated, the disaster research literature identifies their vulnerability because they have fewer resources for disaster mitigation, preparedness, and recovery than larger businesses.

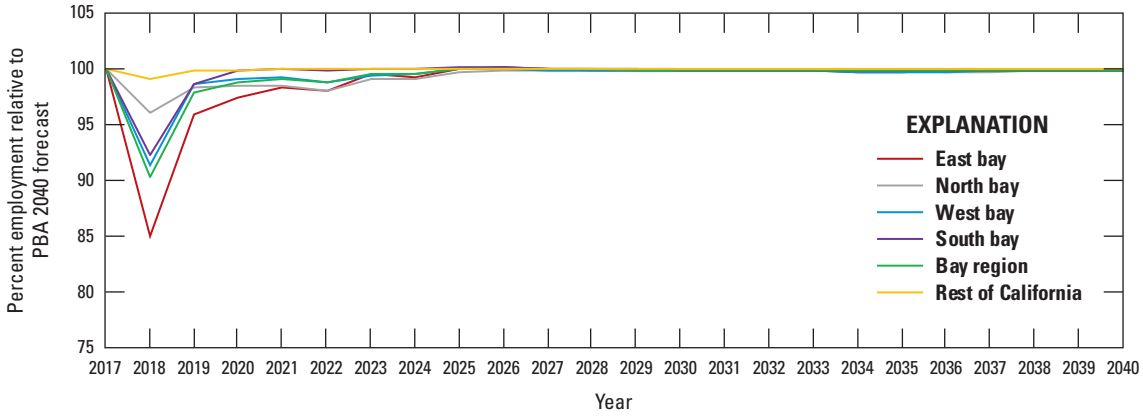


Figure 6. Line graph showing the employment difference resulting from the HayWired earthquake scenario in the San Francisco Bay region, California, by subregion compared to Association of Bay Area Governments (ABAG) regional and statewide projections. PBA 2040 is the ABAG Plan Bay Area 2040 forecast (ABAG Planning and Research Department, 2016). Figure modified from Kroll and others (this volume).

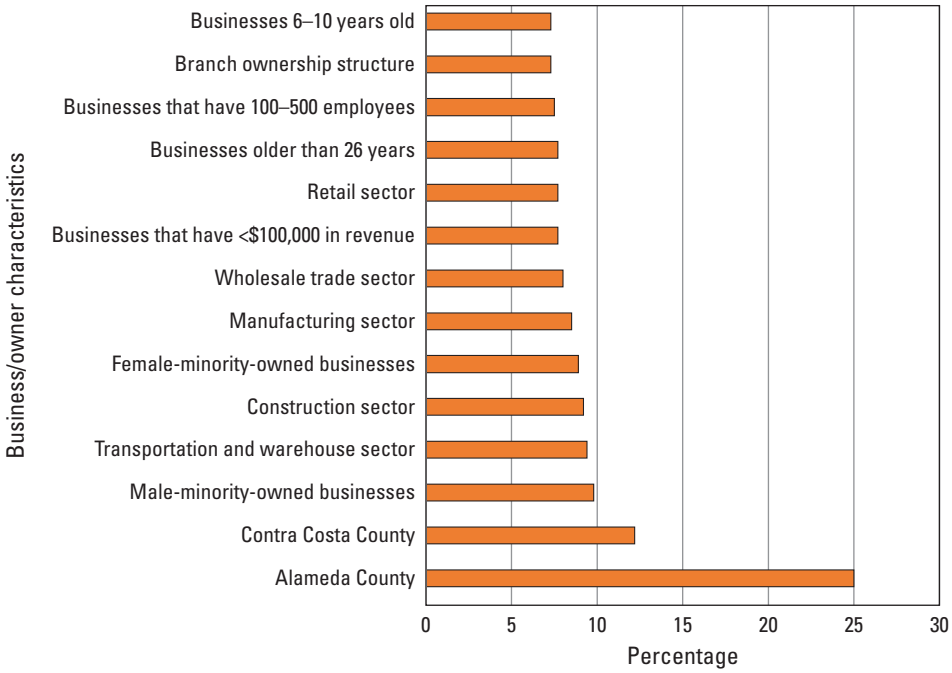


Figure 7. Plot showing business characteristics with average and larger risk of disruptive building damage from earthquake hazards in the HayWired scenario in the San Francisco Bay region, California. Figure from Levy and others (this volume).

The analysis and literature review are informative for policies, mitigation approaches, programs, and implementations that could be helpful in the San Francisco Bay region after a large earthquake. Programs for the retail and construction sector will be important as they have an above-average disruptive building damage risk from the HayWired scenario and a larger composition of small businesses. Manufacturing businesses also face above-average disruptive building damage risk, and combined with the difficulty of relocating fixed assets, may result in changes to the job base in Alameda County, requiring coordinated economic development. Transportation and warehouse establishments are disproportionately located in Alameda County, which could create a need for public and private coordination around emergency and production supply networks. The risk to education establishments and employees is potentially exacerbated by fire following the HayWired scenario mainshock and reinforces the importance of fire prevention and safety management in schools with laboratories. Slightly larger disruptive building damage risk for minority-owned businesses draws attention to programs for minority business owners.

Industries, Employment, and Commute Flows in Areas of Concentrated Damage

After a large earthquake, businesses and employees can be more affected by their work and home surroundings than direct damage to the buildings they occupy. Chapter V5 (Wein, Belzer, and others, this volume) explores how California's San Francisco Bay region industries, jobs, and the spatial relations between residences and workplaces could be disrupted by concentrations of damage in their neighborhoods and business districts. The authors use the definition of concentrated damage as determined in chapter U—areas where 20 percent or more of building square footage in census tracts would be extensively or completely damaged. Analyses show (1) areas of concentrated damage are largely determined by presence and vulnerability of industrial/warehouse, retail/commercial, and multifamily or group-living buildings; (2) the central Alameda County subarea is a focal point for concentrated damage that contains a large share of the region's industrial/warehouse employment and residents working in these jobs; (3) effects of concentrated damage are spread between business districts and neighborhoods by commute patterns and around 595,000 employees live and (or) work in areas of concentrated damage from earthquake hazards and fire following earthquake hazards (fig. 8).

Referencing recent disaster literature and regional studies, analyses of concentrated-damage areas and the home-workplace relation raise several considerations for emergency managers, businesses, communities, cities, and regional entities to mitigate, prepare, respond, and recover from a large earthquake in the San Francisco Bay region. Considerations include serving customers deterred by damaged areas; lack of business-interruption insurance for the contingency of restricted access; planning for business relocation, telework, and employee well-being support; business-district and neighborhood-level planning; implementation of safety cordon management; coordination within industrial and warehouse sectors; and realizing economic demand shifts in the region.

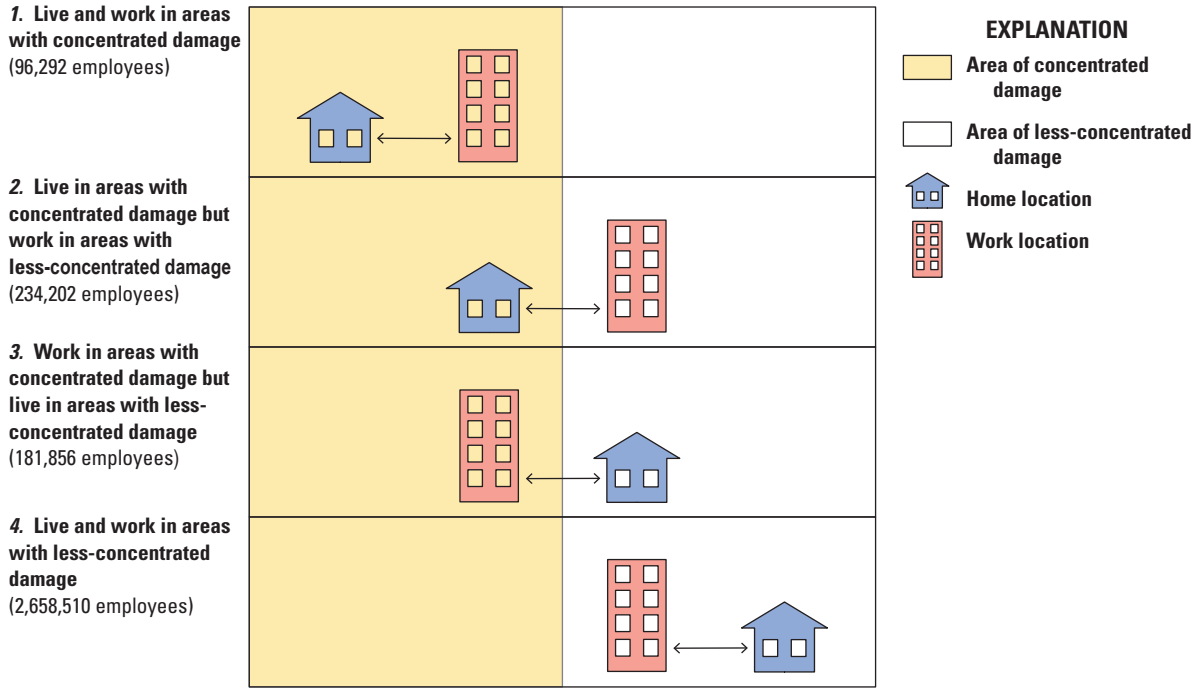


Figure 8. Cartoon showing possible home-workplace relations associated with areas of concentrated and less-concentrated damage resulting from the HayWired scenario mainshock in the San Francisco Bay region, California. Figure from Wein, Belzer, and others (this volume).

Earthquake Early Warning

Earthquake early warning (EEW) is the rapid detection of earthquakes, real-time assessment of the shaking hazard, and notification of people before seismic waves that cause the strongest shaking arrive at their location. Chapter W (Strauss and others, this volume) explores potential uses of EEW information and triggered automated controls for the HayWired scenario. To assess the utility and efficacy of EEW for a large earthquake in the San Francisco Bay region, alert times were calculated for the mainshock of the HayWired scenario and mapped against shaking intensities, population density (fig. 9), and healthcare facilities. Less than 15 km from the epicenter (for example, in the cities of Oakland and Berkeley), strong shaking was estimated to arrive before the alert. The calculation used the seismic-station density and ShakeAlert system capability during 2018, before the public rollout of the system throughout the West Coast.

Outside of this late warning zone, alerts could have widespread benefits in densely built urban environments, including possible reduction in injuries resulting from more time for people to take self-protective drop, cover, and hold on actions. In the San Francisco Bay region, BART is piloting the use of EEW to slow and berth trains. Consideration of hospital procedures are based on EEW observations in Japan, including securing patients during surgery to prevent errors, protecting equipment so it may be useable after shaking, and protecting staff so that they may be physically able to carry on their duties once shaking stops. Holding elevators at floors to reduce entrapment is limited by buildings that are not modern enough to permit retrofits with ShakeAlert EEW technology and California regulations that restrict internet services from initiating an elevator stop.

The use of ShakeAlert during an earthquake sequence is also illustrated for selected aftershocks chosen for earthquake magnitude, area of impact, and time of day, as well as elapsed time after an earthquake to assess a broad range of situations where EEW may be implemented. The analyses illustrate that late warning zones are different for each earthquake. It reinforces benefits of contingency planning, such as restricting entry to heavily damaged and dangerous areas that are potentially in late warning zones of nearby aftershocks. It proposes using timely alerts to protect response and recovery workers from hazards and to make early response decisions. An updated analysis using the current station density, algorithmic updates, and available licensed operators could change the estimated warning times, but the central themes of increased resiliency should still stand.

Future Research

The HayWired Societal Consequences volume explores new topics of telecommunications, collocated lifeline infrastructure, and earthquake early warning as well as deeper insights on population displacement, community recovery, and economic impacts and resilience. Each chapter identifies knowledge gaps and limitations. Taken together, the following overarching future research directions are identified.

1. *Modeling of data and voice network performance.*—More detailed simulations of network functionality and operability could help to identify the sources and locations of network vulnerabilities during earthquakes. Factors include fragilities of telecommunications infrastructure to shaking, ground failure, and fire hazards; effects of equipment failure on residual network capacity (similar to serviceability of water supply systems); dependency on commercial power and availability of backup power supplies for service providers and subscribers; logistical constraints of emergency fuel supplies, sufficient labor to deliver fuel and deploy equipment, and site accessibility in the San Francisco Bay region; and congestion caused by surges in demand for voice and data services with distance from the epicenter and time since the earthquake.

2. *Standardized modeling of lifeline infrastructure damage from multi-hazards and service restoration interactions.*—Capabilities to model lifeline water, energy, telecommunications, and transportation infrastructure damages from the multi-hazards of shaking, surface rupture, liquefaction, landslides, and fire could be standardized. Collocation analysis of multiple lifeline infrastructure systems in earthquake-prone areas could be developed into better understanding of potential collateral damages and restoration interactions. Analyses of fuel systems and distribution of available fuel would improve understanding of the competition for fuel among lifeline-infrastructure-system operators during response. Collaborations on air- and seaport operability could help to complete the picture of supply chain issues (for example, see ShakeOut [Jones and others, 2008] and Science Application for Risk Reduction [SAFRR] tsunami [Porter and others, 2013] scenarios).

3. *Systematic neighborhood-level post-disaster data collection and longitudinal study of housing repair and recovery times, population movements, and recovery plans, policies, and resources.*—The modeling of population movements could be refined at the community scale and over time in terms of uninhabitable homes from earthquake and fire damage and environmental health effects, tolerance for utility service disruptions, inconvenience of accessing community services, and job loss (through linkages with economic impact and recovery modeling). Housing inventories that are more tightly coupled with demographic data would better describe socioeconomic characteristics of populations, including people with access and functional needs, school-aged children, and young and mobile households (for example, Vargas and others, 2019). Notably, recent research has factored in effects of social ties and household preparedness on population displacement (Costa and others, 2020).

4. *Modeling linkages between macroeconomic and microeconomic scales and economic resilience.*—Finer resolution data on building occupants would improve algorithms to associate businesses' characteristics with

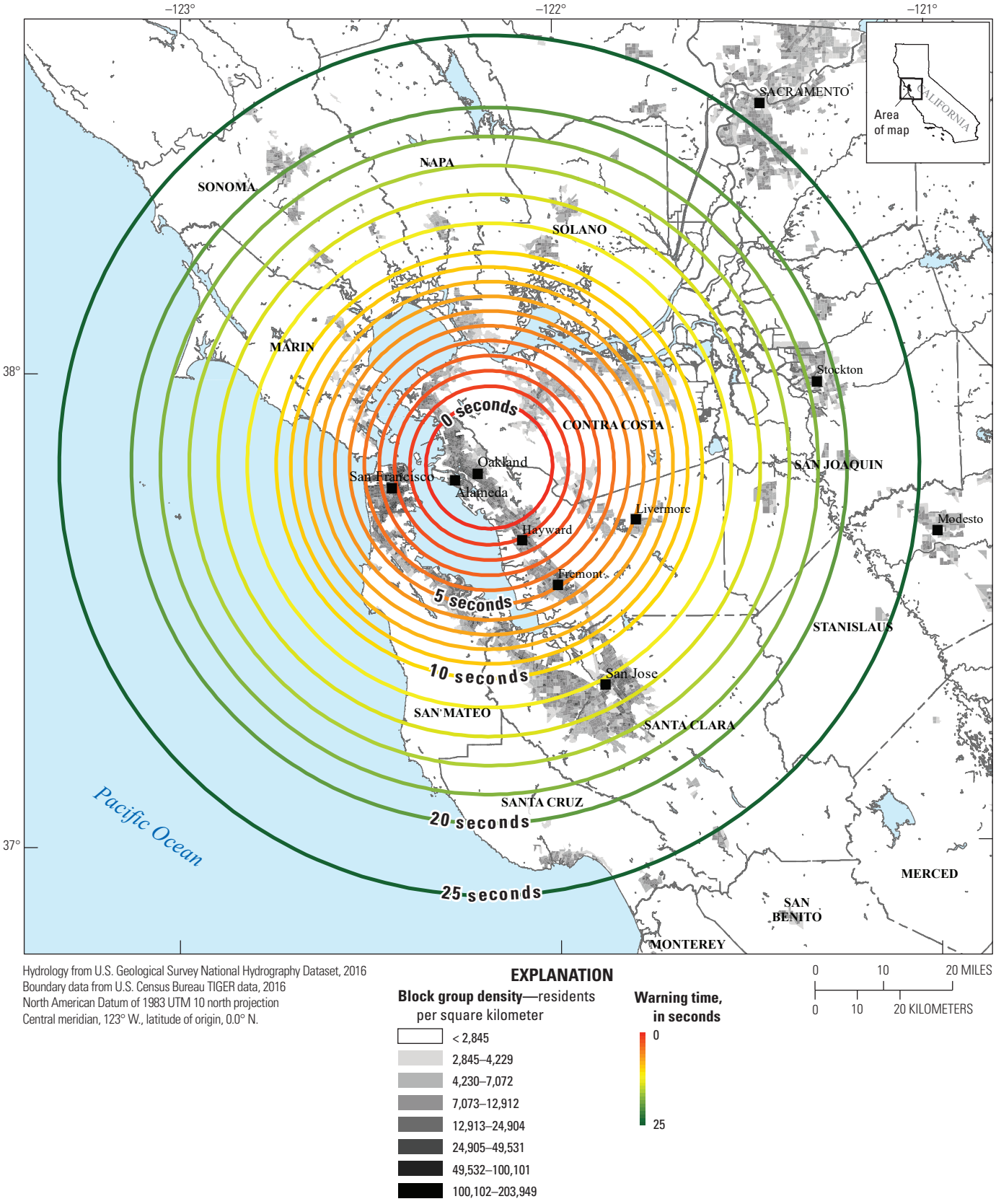


Figure 9. Map of the San Francisco Bay region, California, showing ShakeAlert (https://www.shakealert.org) earthquake early warning time estimates overlain with population density information for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. The geographically dispersed population experiences many different warning times in this scenario event. Figure from Strauss and others (this volume) and Porter and Jones (2018).

building-level damage simulations (for example, Gupta and others, 2020). Updated age and building-type data would account for the businesses in newer buildings that will perform better. Macroeconomic analyses could incorporate spatial analyses to estimate effects of concentrated damage in business districts and neighborhoods on business interruption. Data on telework and business productivity during the COVID-19 pandemic could be used to revise assumptions around telework after an earthquake.

5. *A deeper analysis of the effects of transportation disruptions on economic functions.*—Further exploration of transportation disruptions could include the economic resilience of alternative transportation modes, alternative temporary housing plans, and telecommunications capabilities at alternative workplaces.

6. *Understanding beneficial and detrimental implementations of earthquake early warning.*—During the course of the HayWired project, the implementation of ShakeAlert for EEW has gone from a demonstration system to an operational public alert system. There is continued need for study of implementable and beneficial uses of EEW both as the system matures and following actual use throughout an earthquake sequence. Deeper understanding of behavioral and emotional responses to an earthquake warning in various situations (for example, sleeping, at home, in the office, or driving) would improve estimation of potential injury and stress reductions. Examination of ShakeAlert throughout an earthquake sequence would demonstrate variable benefits depending on earthquake epicenter locations and magnitudes, phases of disaster response or recovery, damages to the built environment, and affected population attributes of density, earthquake awareness, and psychological distress. In addition, identifying potential issues from using earthquake early warning (for example, the distraction of an alert while performing dangerous actions) would counterbalance a focus on benefits.

7. *Understanding environmental health impacts.*—An analysis of environmental impacts remains to be done (for example, Plumlee and others, 2016). Environmental contamination could occur from hazardous chemicals released by damaged and (or) burning industrial facilities; from smoke, gases, and other combustion products of earthquake-generated urban firestorms; from toxicants in dusts and debris resulting from building collapse; and from releases of raw sewage caused by damaged sewer lines and wastewater treatment plants. Environmental health impacts could affect abilities to shelter-in-place, spur evacuations and population displacement, exacerbate business interruption, and interfere with utility, telecommunications, and transportation service restorations.

8. *Identifying best practices for engaging underrepresented groups in planning and recovery processes.*—A recurrent theme in the chapters that focus on communities at risk and economic impacts is the heightened risk to vulnerable populations and businesses not only from damage but also to displacement and relocation during the recovery process. Starting with past research on disaster recovery and analyses of types of vulnerability, additional work could focus on how communities today are working with under-resourced populations and neighborhoods to improve their resilience in business-as-usual planning processes as well as to sudden disruptive changes.

Conclusion

This chapter summarizes the societal consequences of a large earthquake on one of the most urbanized active faults in the United States—the Hayward Fault. It is not intended to represent a best case, a worst case, or an average case, rather one that is worth planning for. It shows a mid-range estimate of 750,000 people that may be displaced from their homes, the potential for 240,000 workers to be relocated from workplaces, and (or) almost half a million jobs lost. Business interruption losses may amount to $44 billion (4 percent of the State economy) in the first 6 months. However, about 40 percent of the losses could be avoided with implementation of business continuity and recovery practices. Recovery from the economic recession takes 5 to 10 years and the longest time in the most heavily damaged county of Alameda.

A cross-cutting theme of the HayWired scenario is interconnectedness to tell an integrated story. Earthquake effects are compounded within and between geologic, engineered, societal, and economic systems. Ground shaking causes ground failures and the mainshock energizes an aftershock sequence. Fire hazards are ignited by physical damages and spread during fire engine response delays caused by telecommunications, transportation, and water service disruptions. Lifeline infrastructure systems interact geographically in multi-hazard landscapes and operationally through restoration interdependencies. Concentrated damage in neighborhoods and business districts spread effects beyond direct building damage and through home-workplace relations. And business interruptions from damages and disruptions ripple through supply chains of industrial sectors.

On the other hand, the synergy of interconnectedness means that each entity's mitigation and resilience effort benefits the larger built environment, social network, and economy. Coordination among individuals and organizational entities, community and industry groups, and local, regional, and State governments across all phases of an earthquake disaster are inherent in many of the policy opportunities in the HayWired scenario volume 3 chapters.

San Francisco Bay regional economists and urban planners raise the need for integrated planning that recognizes the risks of multiple perils and interactions with climate change. For example, the HayWired scenario urban fire simulation did not consider fire taking off in wildland areas where fire risks are increasing with more extreme droughts and storms caused by climate change. The Association of Bay Area Governments and Metropolitan Transportation Commission

(2020) report titled "Resilient and Equitable Strategies for the Bay Area's Future" provides an example of future planning with flooding from sea-level rise and the HayWired earthquake scenario. Subsequently, the USGS instigated a study of the sensitivity of the liquefaction hazard to groundwater tables affected by sea-level rise using the HayWired scenario (Grant and others, 2021).

Furthermore, during the completion of the HayWired scenario analyses there has been an awakening and stronger commitment to equitable recovery from disasters. The disproportionate effects on socially and economically vulnerable populations are evident in the analysis of communities at risk (chapter U; Johnson and others, this volume). In parallel to the HayWired scenario, Markhvida and others' (2020) study of Hayward Fault earthquakes and damages showed larger well-being losses for lower income populations. Such studies highlight opportunities for earthquake policies and programs to be designed for equitable outcomes. The opportunity to increase the quality and quantity of affordable housing for earthquake resilience aligns with the urgency for building housing to alleviate overcrowding and homelessness during the COVID-19 pandemic in the San Francisco Bay region.

The HayWired scenario volume 3 authors hope that the information here and in other HayWired scenario volumes will inform readers' decisions about how to prepare for a large earthquake, whether by strengthening infrastructure to better resist earthquakes or through improved planning to recover more quickly despite damage. Ideally, the HayWired scenario volumes will help the organizations in the HayWired Coalition (see chapter A; Hudnut and others, 2017) and others to continue to develop relationships before a large earthquake occurs and collectively conduct planning and preparedness activities to improve their own and their community's resilience in future disasters. As an aid, the HayWired exercise toolkit distills findings of the HayWired scenario into exercises for earthquake preparedness, mitigation, response, and recovery. The launch of the toolkit is planned to coincide with the rollout of volume 3.

Acknowledgments

The coproduction of societal consequences of the HayWired scenario relied on the dedication of all chapter authors for volume 3. I thank each and every one for the relationships we built, their technical contributions, and their commitment to communicating about earthquake risk reduction. I thank Jamie Jones, Laurie Johnson, Cynthia Kroll, and Jennifer Strauss for their suggestions for this overview of volume 3. This chapter was improved by the attentive review of Danielle Mieler and Andrew Michael. Further thanks to Andrew for setting up the HayWired review panel. USGS's editors have maintained consistency in our technical chapters and improved the documentation of the HayWired scenario from chapters A to W.

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Chapter S

The HayWired Scenario—Telecommunications and Information Communication Technology

By Anne M. Wein, David T. Witkowski, Jamie L. Jones, Keith A. Porter, Laurel R. Ballanti, and Sara K. McBride

Abstract

The HayWired scenario—a moment magnitude (M_w) 7.0 rupture of the Hayward Fault and an aftershock sequence—is initiated in the east bay part of the San Francisco Bay region of California and is within 25 miles of Silicon Valley, a global center of internet commerce and communications technology. The scenario is named, in part, to recognize society's dependence on wired and wireless communication technologies (telecommunications) and the networked information, computing, data storage, and processing technologies known collectively as information and communications technology. Following the Applied Technology Council, we refer to these technologies collectively as telecommunications.

This chapter considers how voice and data services may be disrupted and restored after a large earthquake in the region. The problem is complex, pertaining to multiple competitive service providers in a largely unregulated industry, the convergence of analog and digital systems on to the internet protocol platform, layers of hardware and software functionality, dependence of equipment on electric power, and the dynamic evolution of technology. It is challenging to stay abreast of changes in infrastructure and design standards, let alone assess network functionality and resilience. Telecommunications systems contrast with the more static single operator systems (electric power, transportation, and water supply) for which capabilities to model earthquake damage and system performance are more developed.

Our approach is to build upon previous earthquake studies of telecommunications and engage with industry experts about potential earthquake damage to telecommunications infrastructure and restoration of phone and internet services. We also consider restoration of phone and internet services after non-seismic incidents (hurricanes, wildfires, floods, and wide-scale power shutdowns). By using locations of central offices, data centers, wireless switches, cellular sites, and fiber optic lines from GeoTel Communications, LLC, we employ a geographic information system (GIS) to illustrate potential infrastructure damage from ground shaking and exposure to ground failure (surface fault rupture, liquefaction, and landslides), fire following earthquake, and aftershocks. We develop a simple restoration model that incorporates residual network capacity (informed by the GIS analyses and expert opinion), further capacity losses from dependence on electric power (using the HayWired analysis of electric power restoration), and increased demand for these services after a disaster (indicated by expert input and reports on prior seismic and non-seismic disasters). This model incorporates resilience assumptions about the prevalence of permanent backup power on equipment, delivery of fuel and deployment of portable equipment to failed sites, and management of user behavior to illustrate the effects of these measures on demand served—a percentage of the demand for telecommunications services delivered.

For the HayWired scenario, we find potential fragilities of central offices and unanchored equipment to extreme shaking in the east bay, which is compounded by fires following the earthquake, and that data centers are more prone to liquefaction and cumulative effects of large aftershocks in Silicon Valley. Cellular towers built to Telecommunications Industry Alliance standards for wind loads appear to resist seismic loads of the HayWired scenario and are mostly located away from other earthquake hazards, but are vulnerable to power outages. Cellular equipment on poles and buildings are vulnerable to extreme shaking, liquefaction, and fire hazards. Long-haul and interoffice fiber optic lines cross the fault rupture, run through areas with liquefaction and (or) fire (and landslides, to a lesser extent), and may run along the length of three-quarters of the more than 100 heavily affected bridges. Collateral damage to fiber optic lines may result from damage to or repair of bridges and similarly from collocations with roadways, railways, and water, gas, and oil pipelines.

Meeting demand for voice and data services after a large earthquake is limited by network functionality losses from damage to infrastructure, power outages, and surges in demand for services. An assessment of prior disasters and our simple restoration model suggest that systems are initially overwhelmed by the increase in post-disaster demand despite resilience strategies of permanent backup power and management of user behavior that are critical soon after the disaster. The effectiveness of these two resilience strategies is short lived, but eventual arrivals of trucks with fuel and portable equipment are more able to sustain restoration that would otherwise be strongly influenced by the rate

of electric power restoration. Alameda County service restoration is reduced to serving 7 percent of demand because it incurs the heaviest damage, broadest power outages, and largest increase in demand for services. A slower restoration in Alameda County is caused by longer power outages and delays in truck arrivals. However, with the deployment of portable equipment and fuel delivery, it is possible for telecommunications service restoration to get ahead of electric power restoration. User experience would be variable depending on their location and restoration priorities, how they are connecting to networks, what types of telecommunications systems they are using, who or what website they are trying to access, and whether they have adequate power to run and recharge their electronic devices.

The percentage of demand for voice and data services that is met is at its lowest when most needed for public health and safety immediately after the earthquake, and likely below the outcomes of recent telecommunications outages caused by Public Safety Power Shutoffs in 2019 and 2020 to reduce risk of wildfires. Additional considerations include the reduced functionality of 9–1–1 public safety answering points, delays in fire reporting contributing to fire spread, dependence of other critical lifeline systems (notably transportation) on telecommunications services, disproportionate effects on socially vulnerable populations, and widespread economic losses from telecommunications disruptions through the digital economy. However, voice and data service disruption as a source of economic losses is dwarfed by much larger economic losses from property damage and transportation disruption such that telecommuting (enabled by telecommunications) could play a role in reducing billions of dollars of economic losses.

Opportunities to improve the restoration of voice and data services after an earthquake lie with the industry, governments, subscribers, and businesses and include the following.

- Mitigation of earthquake damages including attention to telecommunications infrastructure standards for ground-failure hazards and fire, and consistent standards for equipment installation.
- Mitigation of interactions with other infrastructure, including effects of widespread electric power outages on network functionality and collateral damage to fiber optic lines (for example, from bridge damage, derailed trains, or pipeline [water, oil, or gas] breaks).
- Attention to the many cellular sites on buildings regarding building codes, backup power, and inspection protocols.
- Industry's preparedness for restoration contingencies, especially potential fuel and labor shortages in the San Francisco Bay region.
- Readiness to use scientific earthquake hazard information in response and recovery decisions, including ShakeAlert warnings and afterslip and aftershock forecasts.
- User and (or) subscriber preparedness with sufficient power and data backups and management of their behavior to conserve bandwidth after a disaster.
- Attention to community telecommunications vulnerabilities, including the expansion of wireless small cells (with no backup power), implications of regulatory constraints, potential loss of 9–1–1 system functionality, competition with emergency response communications, and information and communication needs of socially vulnerable and (or) displaced populations.
- Business continuity practices for service outages and technological and organizational support for telecommuting after a disaster.

Introduction

The HayWired scenario—a moment magnitude (M_w) 7.0 rupture of the Hayward Fault and an aftershock sequence—is initiated in the east bay part of the San Francisco Bay region and occurs within 25 miles of Silicon Valley, a global center of internet commerce and communications technology. The HayWired scenario is named, in part, to recognize society's dependence on the wired and wireless communication technologies (telecommunications) and the networked information, computing, data storage, and processing technologies known collectively as information and communications technology (ICT). Following the Applied Technology Council (2016), we refer to these technologies collectively as telecommunications.

This study was conducted with the aim to inform San Francisco Bay region residents, public agencies, governing bodies, and enterprises about the potential disruption of voice and data services that would affect their lives during and after a large earthquake. This chapter addresses a broad audience and seeks to strike a balance between detailed and general descriptions; however, we recognize that some readers may prefer less or more technical detail. A scenario of potential telecommunications infrastructure hazard exposure or damage and voice and data service restoration can be used in exercises and planning along with comparable information for water supply, power supply and transportation (Porter, 2018; Jones and others, this volume). Results from this telecommunications study are also used in the economic consequence analyses (reported by Sue Wing and others, this volume) to examine effects of service losses on the digital economy in the San Francisco Bay region and the State of California. The overarching objectives are to highlight potential telecommunications infrastructure fragilities to multiple earthquake hazards, service restoration vulnerabilities, and opportunities for the industry and subscribers to improve the provision of telecommunications services after a large earthquake in the San Francisco Bay region (and any entity living near major faults).

Today's World of Telecommunications

Today, voice communications use the plain old telephone service (POTS), digital voice over internet protocol (VoIP), or a combination of the two. For many people, interpersonal

communication is also achieved through text messaging, application-based chat, email, and social media networks. Our physical lives are increasingly intertwined with our virtual lives online. The internet is where we can communicate, but also obtain and store information, pay bills, do banking, and shop for goods and services.

News is no longer obtained only from television and radio broadcasts, but also audio and video streaming over the internet. Ownership of broadcast radio receivers is declining—a 2016 report showed that the number of households that do not own a radio receiver outside of a car radio increased from 4 percent in 2008 to 21 percent in 2016 (Hill, 2016) and in the 18–34 age group reached 32 percent (Edison Research, 2016). These numbers match declining television viewership and ownership trends.

Platforms for our online activities range from desktop and laptop computers, to mobile devices such as tablets, smartphones, and smartwatches. Mobile devices host calendars, take and share photographs, record videos, provide navigation assistance to drivers and pedestrians, entertain, and even act as digital assistants capable of listening and responding to our verbal commands. Many of the advanced functions on smartphones require interactions over telecommunications networks, causing exponentially increased usage of those networks. For example, processing of voice commands for artificial intelligence assistants on smartphones is not done locally—an audio file is recorded and sent to a server for analysis and processing, then the response is sent back to the smartphone, which takes action or reads the result back to the user.

Remote sensors, telemetry and telecommand radio networks, data collection and analysis, and technologies such as Supervisory Control and Data Acquisition (SCADA) (DPS Telecom, 2016) provide automated control and management of the electric grid, natural gas, and water pipelines, and other critical infrastructure systems.[1] Automation systems that use commercial networks are used to control physical security, heat, light, and water for residents. Increasingly, more systems are based on the inter-networking of autonomous computing devices, data centers, artificial intelligence algorithms, actuators, and sensors—that is, the Internet of Things (IoT).

Telecommunications and Earthquakes

ShakeAlert, an earthquake early warning system for the west coast of the United States, uses telecommunications technologies to warn people of heavy shaking seconds after an earthquake has initiated (Strauss and others, this volume). Broadcast media is no longer the go-to solution for wide dissemination of information before, during, and after an emergency—it is being replaced with text messages, tweets, and the Wireless Emergency Alert (WEA) system that generates pop-up messages on smartphones (Federal Communications Commission, 2017a).

[1]Some infrastructure systems (such as electric, natural gas, and water utilities) operate SCADA on private networks, independent of commercial networks.

The capability of social media to provide insights into earthquake occurrences is the subject of the U.S. Geological Survey (USGS) Twitter Earthquake Dispatch (USGSted) project, which mines Twitter messages for keywords and geolocation data to determine if an earthquake has occurred (Crooks and others, 2013). The increasing number of network-connected devices means that even fitness trackers (presuming the data is gathered while protecting the privacy rights of the wearer) can be used to determine if an earthquake has occurred by mining the data to show that large numbers of people are suddenly awake and moving in the middle of the night (Mercer, 2014).

Disruption of Telecommunications Services

The last major disaster to affect the entire San Francisco Bay region, the 1989 Loma Prieta earthquake, occurred almost a decade before email came into common usage. How might the telecommunications networks, on which our modern world is based, be disrupted by a large earthquake like the HayWired scenario? Telecommunications networks, whether traditional or modern, fail during a large earthquake. In the HayWired scenario, equipment and structures are physically damaged, and connections are severed by ground shaking, ground movement, and cascading hazards of fire following the earthquake. Power outages are widespread and some backup power systems on equipment are lacking or fail. In addition, telecommunications networks are congested by heavy usage in the aftermath of the disaster. Not all of the San Francisco Bay region's telecommunications systems will work in the hours and days after a major earthquake, yet we commonly expect that these modern conveniences and monitoring advances will always be available.

Voice and data service disruptions affect both humans and the machines that support our modern lives. Service outages can severely disrupt the operations of other critical infrastructure, economic activities, and everyday life. Importantly, immediately after an earthquake strikes, network capacity losses and congestion disrupt voice and data services when they are most needed for public health and safety.

As the internet connects more of our infrastructure to telecommunications networks, the impact of outages potentially increases. Many critical services that may have been able to function effectively with only minimal telecommunications technology now rely on external information resources. For example, medical facilities may store electronic medical records in cloud services offsite. Patients may rely on remote monitoring of chronic conditions. On the positive side, the use of cloud services—located in geographically diverse and generally well-protected facilities—also enables companies to resume their operations from any location (for example, NZ Herald, 2012).

For a population that is accustomed to using the internet and mobile data to manage their lives, the impact of service outages will accentuate the emotional and mental challenges of an earthquake. In a small amount of literature on the emotional aspects of limited mobile phone use, Hoffner and others (2015) found that 70 percent of people recalled loneliness, anxiousness, or vulnerability when involuntarily separated from their mobile

phone. Regarding people's behavior, police have stated that cellular service and charged phones help with law enforcement after a disaster (T. Serio, Verizon Wireless, oral commun., 2014).

There are social disparities in disruptions of telecommunications that are increasingly serviced through cellular voice and data networks. In 2008, only 20 percent of U.S. households had exclusively cellular phone service (Blumberg and Luke, 2009); by the end of 2018, nearly 60 percent of households in the United States no longer had wired telephones (Blumberg and Luke, 2019), and for certain demographics (adults under age 34, Hispanic households, and people living below the poverty line), wireless phones are overwhelmingly the sole method of voice telephony. This is also true for data transmissions, where wireless is increasingly the preferred means of connection for people with incomes at or below the national poverty level. A 2016 survey found that the only connection to the internet for 14 percent of Californians is via a smartphone (California Emerging Technology Fund, 2017). Furthermore, in an emergency, wireline 9–1–1 phone calls are associated with a fixed location, but the location information of a mobile phone call is less specific for emergency responders (Federal Communications Commission, 2018), exacerbating the social vulnerabilities for certain demographics reliant on a cellular phone.

Study Approach

Compared to utilities and transportation systems, the disruption of telecommunications networks is challenging to investigate. Unlike traditional services such as physical and fixed single-operator networks for water supply, commercial power, highways, and commuter rail, telecommunications infrastructure differs in four crucial aspects: (1) it has multiple layers of functionality; (2) it has stronger dependencies than other infrastructure, in particular functional dependence on electric power; (3) infrastructure and services are commonly provided competitively, rather than by a public or single private utility, and are likely unregulated (Applied Technology Council, 2016); and (4) the demand for services increase above normal levels after a disaster (referred to as a demand surge). Another factor that complicates modeling network functionality is the constantly evolving technology, for example, the on-going convergence of voice and data networks using internet protocol (IP) technologies, the recent expansion of small cell technology for wireless sites, and the impending deployment of fifth generation (5G) cellular networks.

Nonetheless, similar to the analyses of other critical infrastructure systems, we assemble telecommunications infrastructure data and document failure modes; analyze potential infrastructure hazard exposure or damage for the HayWired earthquake scenario; and develop a simple model of voice and data service disruption that integrates effects of multiple earthquake hazards, power supply outages, demand surge, and service restoration strategies. The restoration strategies include permanent backup power on equipment, logistics of trucking in portable generators and (or) equipment to enhance network functionality, and management of subscriber behavior to reduce congestion in networks.

To complement spatial analyses and modeling, we facilitated conversations with a range of collaborators including industry representation, municipal information officers, and users or subscribers of voice and data services (for example, business, government, and individuals). Participation was instigated through two workshops and individual consultations. The first workshop hosted 18 industry experts and public emergency communication managers in February 2016, and the second workshop hosted approximately 60 industry experts, researchers, and emergency management practitioners (in government, critical infrastructure, and business roles) in September 2017. The second workshop rotated industry expertise through technical discussions and stakeholders (users) through coordination topics (see appendix 1).

Analyses and assumptions are grounded in observations from recent studies of global disasters, earthquakes in particular, but also other disasters in the United States. Earthquake disasters that provide information about damage to telecommunications infrastructure and service restoration include:

- California earthquakes
  - 1989 M_w 6.9 Loma Prieta earthquake in the San Francisco Bay region
  - 1994 M_w 6.7 Northridge earthquake in the San Fernando Valley region
  - 2014 M_w 6.0 South Napa earthquake in the San Francisco Bay region
- International earthquakes
  - 2010 M_w 8.8 Maule earthquake offshore of Biobío, Chile
  - 2010 M_w 7.1 Darfield earthquake, followed by the 2011 M_w 6.1 aftershock, in Christchurch, New Zealand
  - 2011 M_w 9.0 Tohoku earthquake and tsunami in Japan
  - 2015 M_w 7.8 Gorkha earthquake and aftershocks in Nepal
  - 2016 M_w 6.0 and M_w 7.0 Kumamoto earthquakes in Japan
  - 2018 M_w 6.6 Hokkaido earthquake in Japan.

Recent disasters in the United States that provide relevant information on telecommunications restoration dependencies and resilience strategies include:

- 2001 September 11 attacks
- 2005 Hurricane Katrina
- 2012 Hurricane Sandy
- 2017 wildfires in northern California (including the Tubbs Fire) and southern California (including the Thomas Fire)

- 2018 wildfires in northern California (including the Mendocino Complex Fire)
- 2019 Public Safety Power Shutoffs (PSPS) in California.

The 2019–2020 Ridgecrest, California, and the Puerto Rico earthquake sequences occurred after information on these events was compiled, and as a result are not incorporated into this study.

Our approach follows the principles of a Science Application for Risk Reduction (SAFRR) scenario (Porter and Sherrill, 2011; Hudnut and others, 2017) by providing a plausible outcome based on available science, disaster research, engineering knowledge, and consensus among experts. This chapter does not present a robust technical analysis (which is not currently practically or analytically feasible), but it does delve deeper and is more comprehensive than any known prior disaster scenario analysis of telecommunications infrastructure and services.

Chapter Overview

This report proceeds with basic descriptions of the telecommunications systems, various types of subscriber connectivity, and failure modes of equipment and transmission channels. The next section describes available telecommunications infrastructure data and results of analytical methods used to estimate multi-hazard exposure or damage to central offices, data centers, cellular sites, and fiber optic lines in the HayWired scenario. The following section provides estimates of residual network capacity and generates voice and data service restoration curves by county for cases of full dependence on commercial electric power supply, demand surge, and the various restoration strategies for the HayWired scenario. Numerous study limitations are acknowledged in the next section.

The last section summarizes results of telecommunications infrastructure exposure and damage and service restoration analyses for the HayWired scenario. Perspectives on societal consequences are drawn from the functionality of 9–1–1 call centers, and other HayWired analyses including the effect of communication delays in the spread of fire following earthquake, compounded vulnerabilities for populations at risk of displacement, and economic impacts of voice and data service outages. In conclusion, opportunities that emerged from a deeper examination of an earthquake scenario are emphasized to complement the Applied Technology Council's (2016) broader disaster assessment of telecommunications systems. Opportunities for the industry pertain to mitigating damage from multiple earthquake hazards, addressing dependencies on building sites and other lifeline infrastructure systems, preparing for restoration contingencies, working with governments, using hazard and risk communications, and managing subscriber behavior. Opportunities for improving societal resilience to service disruptions include preparing for emergency response communications, informing user behavior, and planning for business contingencies and continuity.

Telecommunications Systems, Subscriber Connectivity, and Infrastructure Failure Modes

This section provides some basic information about telecommunications systems; typical connectivity for businesses of different sizes, homes, and public safety answering points (PSAPs); and potential equipment and channel failure modes. The intention is to provide context for situating physical infrastructure in the multi-hazard landscape of the HayWired earthquake scenario, for estimating network capacity losses, and for considering societal impacts.

Telecommunications Systems

Telecommunications systems are composed of wired and wireless technology for voice communications and data transfer, storage, and processing. Wired systems use physical media to transmit voice and data at different frequencies. Copper wire lines pass information by conducting electromagnetic energy between transmitters and receivers. Fiber optic lines pass information by conducting pulses of light along strands of glass that are one-tenth the size of a human hair. Except for filling in, all new construction of fixed lines is likely to be fiber optic; copper and coaxial lines are rarely used for new construction, even in residential areas (Applied Technology Council, 2016) or for reconstruction after recent disasters (for example, Blagdon, 2013), but many of the original copper lines still remain.

Wireless systems (for example, cellular, satellite, and Wi-Fi) use radio waves instead of physical lines to provide service to end users. Most commonly, wireless systems extend the reach of voice and data services; ultimately the majority of these services depend on connectivity with physical wiring and fiber optic lines, although there are some sites that use high-frequency microwave links in lieu of fiber optic lines as the backhaul to the backbone network. There are also wireless data links known as optical short hop (OSH) that use laser transceivers that must be very precisely aligned; however, these are uncommon and used only for short distances.[2]

A complete description of modern communication systems is complex because they have been built up over time since the original plain old telephone system (POTS), which connects telephones to the public switched telephone network (PSTN), uses analog (continuous non-digital signal) technology over copper twisted pair wires to transmit voice. Telecommunications technology has evolved from single-purpose networks to a converged network that supports both analog and digital technology across wired and wireless systems for both voice communication and data transmission. For example, copper wires can use frequency splitting to carry

[2]OSH has more bandwidth than radio waves but has distance limitations of a few hundred meters. OSH is more expensive but may be cheaper than digging trenches or installing conduit in some places, and may be required in cases where digging is not an option.

both analog and digital transmissions; analog signals can be converted to digital signals and vice versa (by sampling and reconstruction, respectively), and digital modulation can host analog services (as in the case of VoIP telephony).

Understanding that various data and voice systems increasingly share copper pair, coaxial, and fiber optic lines and backbone infrastructure, the various types of equipment and channels needed to support various voice and data services can be illustrated in system diagrams of:

- copper-paired POTS and digital subscriber line (DSL) (fig. 1),
- wired data and VoIP (fig. 2),
- wireless (cellular voice, text, and data) (fig. 3), and
- internet (fig. 4).

Copper Pair Systems

Copper twisted pair wires transmit voice in the POTS and may also carry DSL (fig. 1). In the voice over copper pair system, the end user may be connected directly to the central

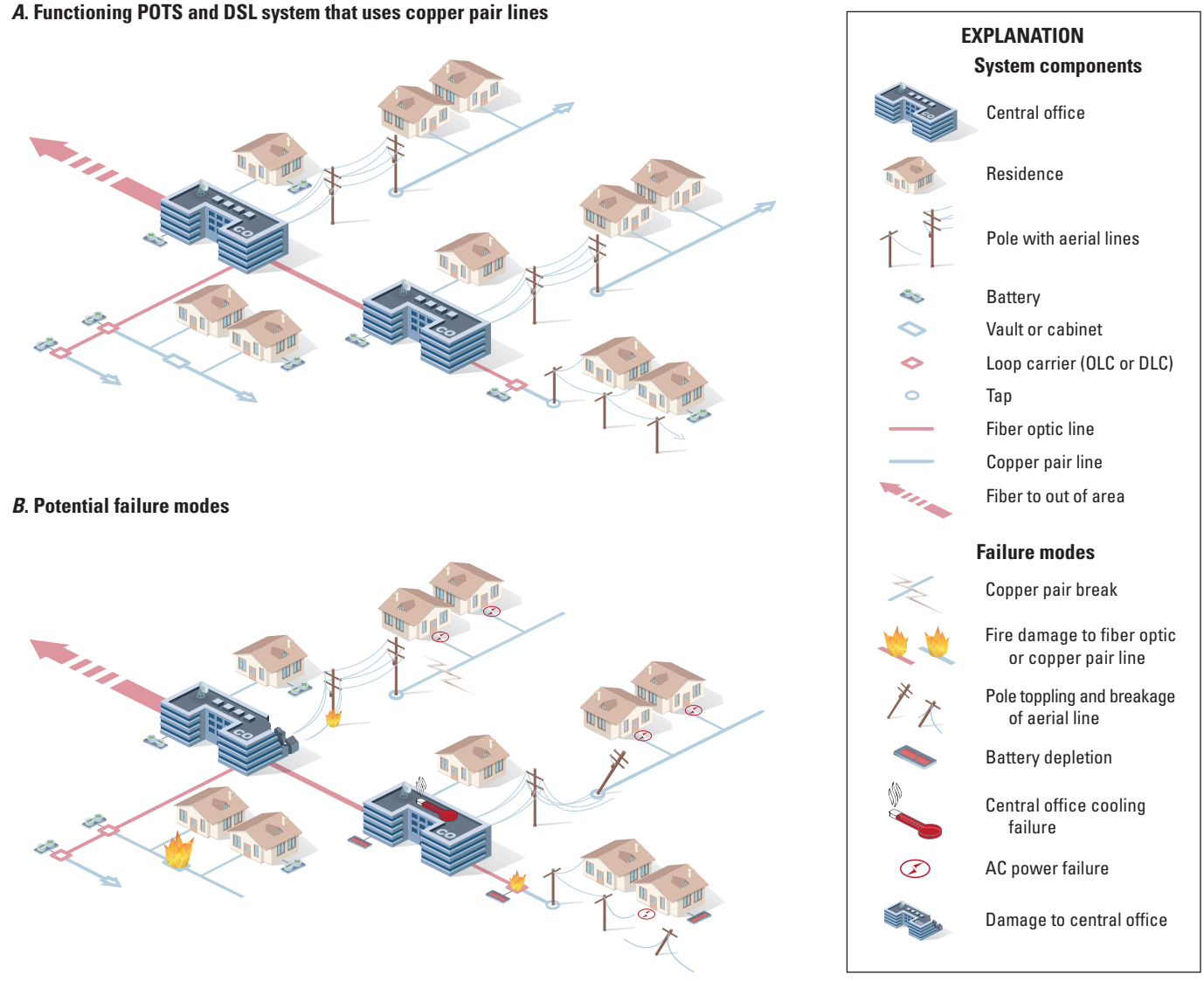


Figure 1. Schematic diagram illustrating (*A*) an example of a system that uses copper pair technology in plain old telephone service (POTS) and digital subscriber line (DSL), as well as (*B*) the system's potential failure modes. In this example, POTS and DSL may be carried over the same copper pair lines. Power for POTS is provided over the copper pair line to users from batteries at a central office. Power for DSL and cordless phones is provided by users in the form of AC power or a battery backup. POTS is sized to serve a fractional number of simultaneous users. AC, alternating current; OLC, optical loop carrier; DLC, digital loop carrier.

office,[3] or be extended by a loop carrier (or subscriber loop carrier). The connection from a telephone to a central office was originally called a loop—a term that dates back to the early days of the telegraph when central offices were the end point for local copper loops and housed switching equipment as well as connections to toll and routing centers for long-distance calling. Later implementations of this system moved provider equipment closer to subscribers; these systems are referred to as digital loop carriers (DLCs). In DLC systems, subscriber lines connect to loop carrier equipment, where the analog signal from the end user is digitized and multiplexed onto a data line between the loop carrier and a central office.[4] Optical loop

[3]Not all central offices are the same. For example, some central offices called tandem or toll switches only communicate to other central offices and have no connection to end users. As a result, these toll switches are more important and have a higher hierarchy than regular central offices.

[4]The method of multiplexing connections is also used in digital subscriber line (DSL) data service, where the DSLs are combined into a single data channel by using a digital subscriber line access multiplexer (DSLAM). This can be done in conjunction with DLC or OLC systems. The benefit of a DSLAM is that DSLs are limited to approximately 17,000 feet in length between the serving system and the subscriber. Data speed via DSL is inversely proportional to line length, so shortening the line length of a DSLAM allows faster subscriber speeds.

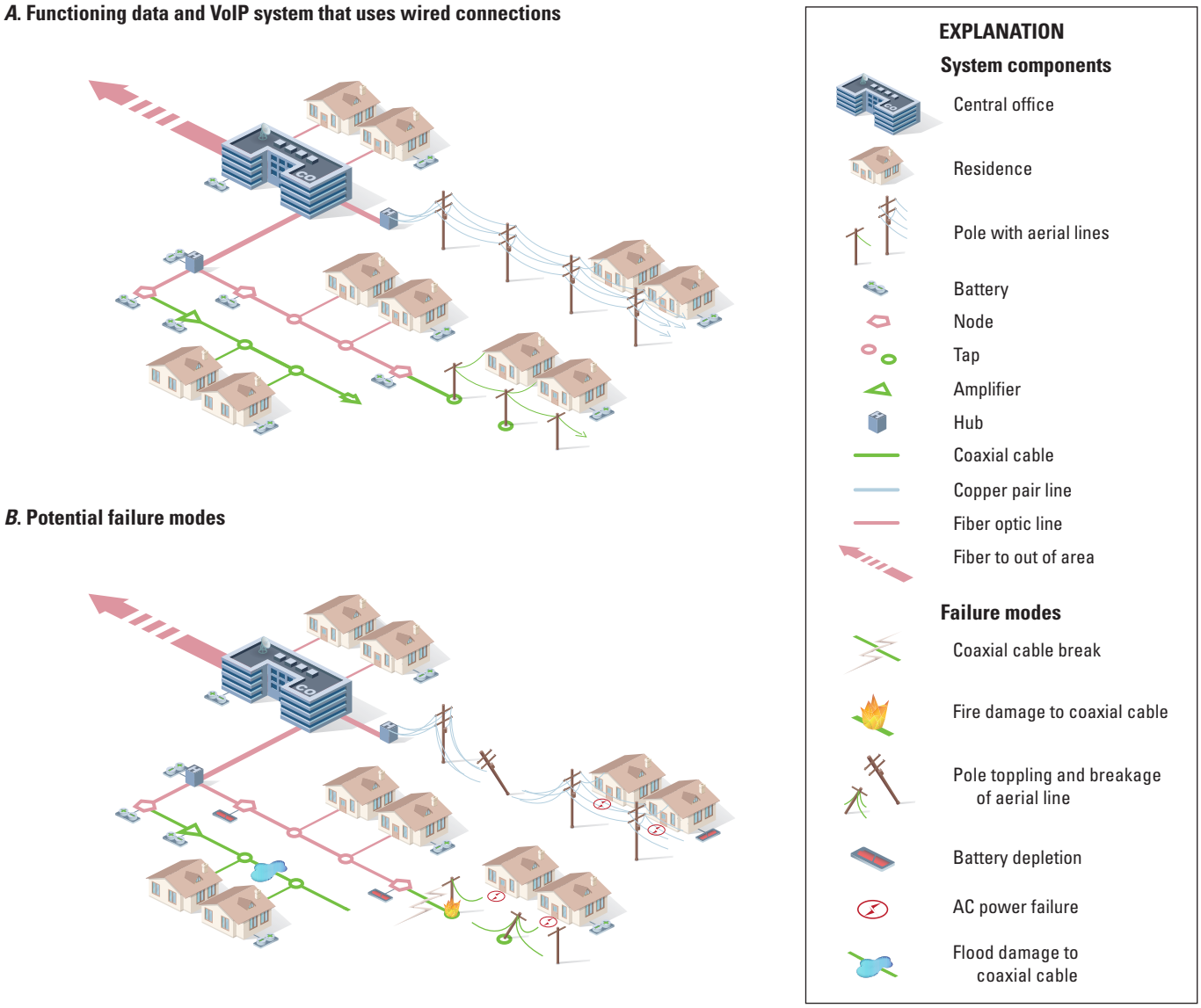


Figure 2. Schematic diagram illustrating (*A*) an example of a system that uses wired technology of data and voice over internet protocol (VoIP) connected via coaxial and fiber optic lines, as well as (*B*) the system's potential failure modes. In this example, data is carried on copper pair, coaxial, or fiber optic lines to gateway equipment, which optionally provides a telephone connection. Power for gateway equipment is provided by users in the form of AC power or battery backup. Users typically have cordless phones that also require power. Operator-provided battery backup may last only 3–4 hours. Inline amplifiers require power. AC, alternating current.

carriers (OLCs) are an even later implementation of this system (see fig. 2). They are commonly referred to as "fiber to the curb" because they user fiber optic lines between the loop carrier and central office and OLC equipment is typically installed in curbside cabinets in residential neighborhoods.

Power sources are needed to supply central offices and loop carriers with power. Whether subscribers are directly connected to a central office or to a loop carrier, they receive power for their POTS from the service provider. However, cordless phones (which are nearly ubiquitous in modern homes and small businesses that still have landline telephone service) require their own source of electric power for the base unit and the batteries need to be charged.

Data and Voice Over Internet Protocol (VoIP) Systems

Today, VoIP is gradually replacing the voice over copper pair technology of the POTS system. The VoIP system digitizes a user's voice, then transports it over a data network using a private internet protocol (IP) provided by carriers (as opposed to public internet). Digitized voice to and from subscribers is carried by the same copper wires as POTS using IP DSL (fig. 1) or IP coaxial lines using Data Over Cable Service Interface Specification (DOCSIS) or fiber optic lines (fig. 2).

Power sources are needed to supply central offices, hubs, and amplifiers with power. An important distinction between older POTS service and VoIP is that VoIP (and data) subscribers need to provide electrical power locally to their broadband equipment (commonly called modems or gateways). This equipment may have only rudimentary backup batteries—if they have a battery at all. Even if the gateway battery exists and is functioning, cordless phones attached to VoIP gateways still require their own source of electric power.

Cellular Voice, Data, and Text Messaging Systems

Cellular networks carry both digitized voice and text communications and data (fig. 3). Older cellular voice networks operated in similar fashion to wired PSTNs and are said to be circuit switched—each call between a phone and a cellular site is assigned to a dedicated frequency or digital channel. As the data speed and coverage of modern fourth generation (4G) cellular networks have improved, some carriers have begun to handle calls using voice over Long-Term Evolution (LTE), which provides better audio quality and allows the wireless carrier greater flexibility in managing their network capacity and resources.

At the heart of the wireless communication network, Mobile Telephone Switching Offices (MTSOs) contain a mobile switching center (MSC) that switches cell phones to the cellular site that provides the best reception and connects phones to central offices. In figure 3, we show that MSC buildings are constructed adjacent to central offices, but more commonly they are collocated with central offices in the same building. In the early days, when large PSTN frame racks were still dominant, the buildings could not fit more equipment so early MSCs were located nearby. As PSTN has given way to VoIP telephony, VoIP system equipment requires less space and MSCs are able to fit in central offices.

Cellular sites are the point of entry for wireless subscriber devices and also act as control points for management and monitoring of cellular calls and other services. Figure 3 illustrates macrocells (on lattice towers and monopoles) as well as distributed antenna systems (DAS) and small cells, collectively known as heterogeneous networks, or HetNets. HetNets first appeared as capacity enhancement and expansion technologies for 4G cellular networks. Over the past 5 to 6 years, carriers have deployed small wireless cells primarily on utility poles, streetlights, kiosks, trees, and buildings. Equipment is either mounted to the pole or placed in an equipment enclosure on a pedestal or in an underground vault. HetNets improve performance in small areas where cellular coverage is weak or there are large concentrations of users (such as in dense population and business centers, in public venues, or along roadways).

Cellular networks require electric power at cellular sites and along wired connections (for example, amplifiers on fiber optic lines) to function. Backup power is common at macrosite base stations and required at MSCs and central offices. Although HetNet technology provides a more dispersed point of entry and could help improve post-disaster telecommunications network performance, small cells in HetNets typically do not have backup electrical power systems because of size constraints and local ordinances. Individual users are responsible for charging their cellular devices.

The Internet

The public internet transfers data between computers and isolated networks are linked together using the IP standard. Internet exchange points (IXPs) are major exchange hubs (in buildings located in major cities around the world) where different networks interconnect for the exchange of data between networks owned and operated by commercial or public entities (Thompson, 2016). For example, the Federal Internet Exchange connects the U.S. Government's various networks with public networks. Four types of data centers have different levels of control of data transit (see sidebar 1). Fiber optic lines connect these centers to each other (fig. 4). Terrestrial microwave links may be used in place of fiber optic connections.

Internet-based services can be delivered using diverse technologies ranging from fiber optic and copper loops to cellular wireless and satellite (Applied Technology Council, 2016). Digital data originating from a computer may be transmitted by copper pair or DSL, coaxial cable[5] or DOCSIS, or fiber optic line. Cellular smartphones operate as a computer in the public internet system. A smartphone's data connection for internet access can occur in parallel with the carrier's voice connection, either via a Wi-Fi connection or a cellular data

[5]Coaxial cable is the same cable used for television and has an inner conductor (for example, copper plated steel wire) that is shielded to reduce traffic interference.

channel to the carrier's network. Cellular data services are more costly, but also more consistently available than Wi-Fi and do not require users to establish a connection.

In rural areas, internet service access to a network of copper twisted-pair DSL, coaxial DOCSIS, or fiber optic connections may not be available. In cases where internet service access is available, cost and performance are commonly negative factors. Rural users may obtain internet access from fixed wireless networks (also known as a wireless internet-service provider [ISP]) or satellite broadband networks (for example, HughesNet Gen 5) that substitute wireless data links for wired infrastructure. Figure 5 illustrates a satellite broadband system. Wireless ISP networks require electrical power at the ISP's transceiver sites (typically on hills or mountaintops). In both wireless ISP and satellite broadband use cases, the subscriber provides electrical power from their utility.

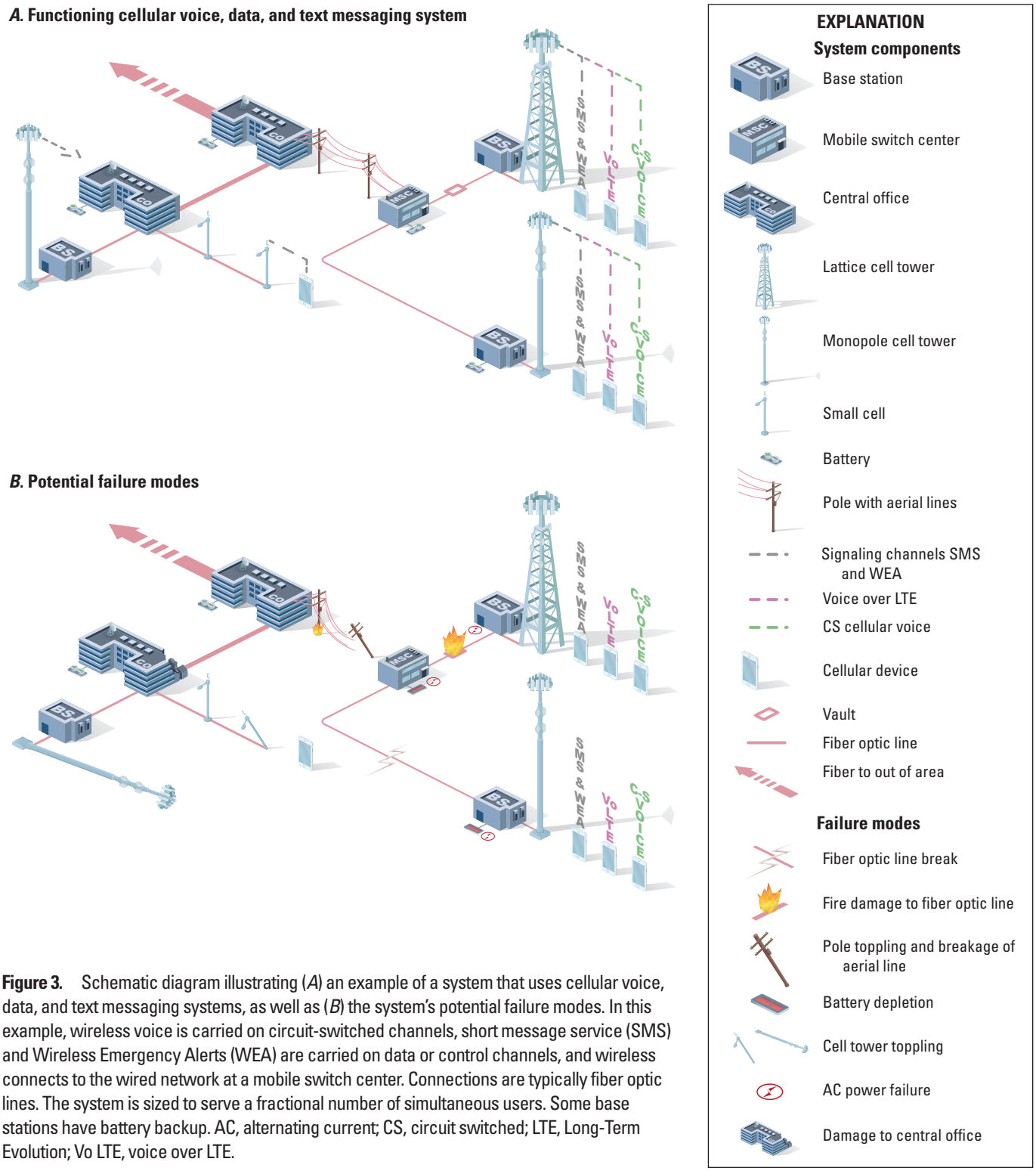


Figure 3. Schematic diagram illustrating (*A*) an example of a system that uses cellular voice, data, and text messaging systems, as well as (*B*) the system's potential failure modes. In this example, wireless voice is carried on circuit-switched channels, short message service (SMS) and Wireless Emergency Alerts (WEA) are carried on data or control channels, and wireless connects to the wired network at a mobile switch center. Connections are typically fiber optic lines. The system is sized to serve a fractional number of simultaneous users. Some base stations have battery backup. AC, alternating current; CS, circuit switched; LTE, Long-Term Evolution; Vo LTE, voice over LTE.

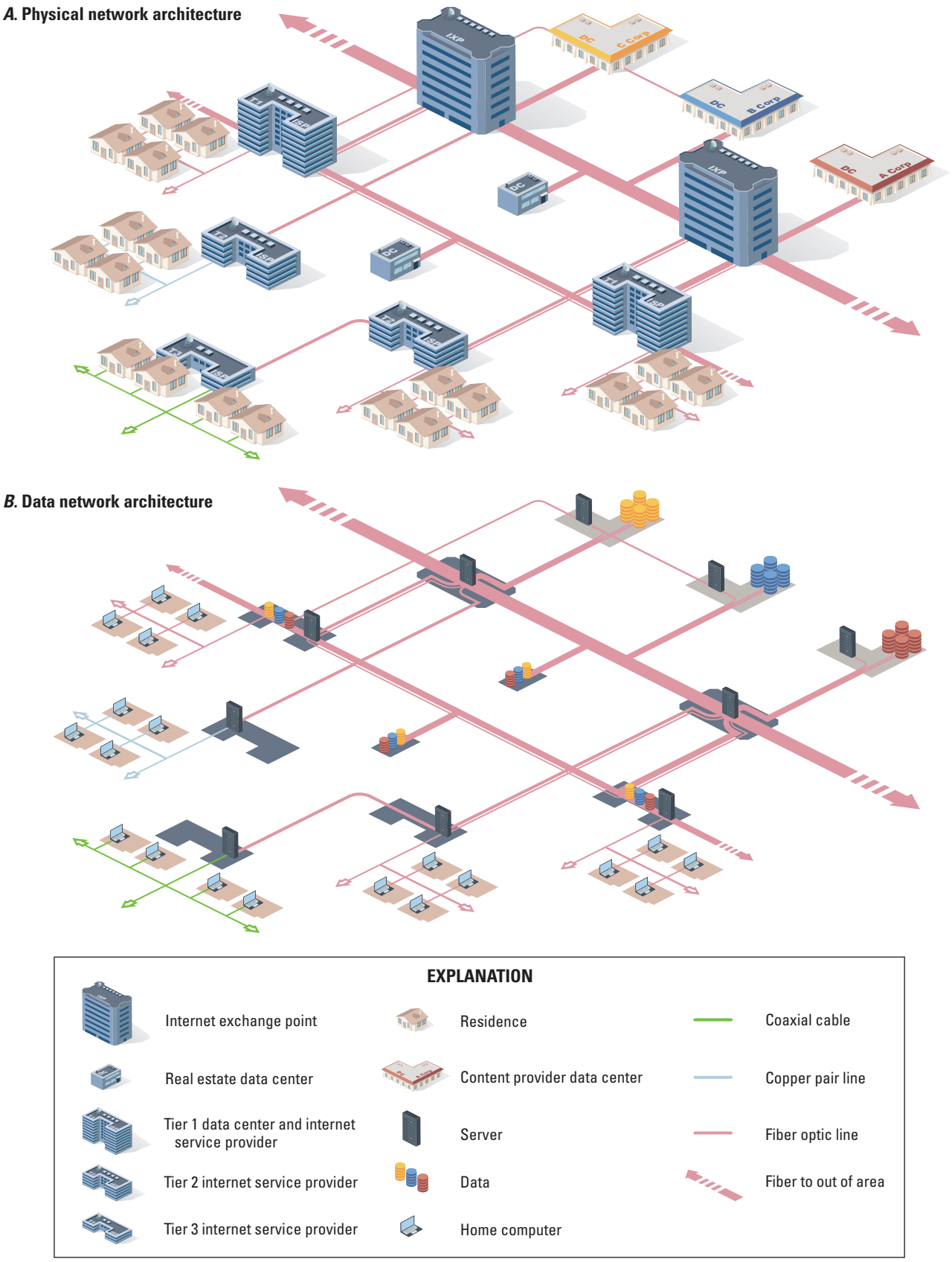


Figure 4. Schematic diagram illustrating an example of an internet-based system. The internet is a network of networks, connected together by common protocols that enable sharing of data in an office or anywhere around the world. Note that this representation of the internet is to show its parts, but not imply that it is isolated from other telecommunications systems, such as voice over internet protocol (VoIP) applications and cellular networks, that access the internet.

Sidebar 1—Data Center Rankings

Material adapted from Thompson (2016).

- Tier 1 network-provider data centers have their own data centers and have access to every network on the internet.
- Content-provider data centers (such as Google, Microsoft, Facebook, Amazon, and so on) are operated and rented by Tier 1 providers. For example, many smartphone application developers do not maintain their own servers, rather they host their systems at major data centers.
- Internet service provider (ISP) data centers facilitate transit and peering and commonly have data centers of their own. Tier 2 providers engage in the practice of peering with other networks, but also purchase internet protocol (IP) transit to reach some parts of the internet. Tier 2 providers are the most common ISPs, as it is much easier to purchase transit from a Tier 1 network than it is to peer with them and attempt to become a Tier 1 carrier. Tier 3 providers purchase IP transit solely from other networks to reach the internet. These data centers are smaller and commonly only house services for their direct customers.
- Collocation data centers or carrier hotels are built by companies that typically consider themselves to be in the real estate market. These companies sell power, cooling, and (or) network in addition to physical space for servers, routers, power management equipment, and wiring. They generally view their relationship with the customer as a traditional landlord and tenant model.

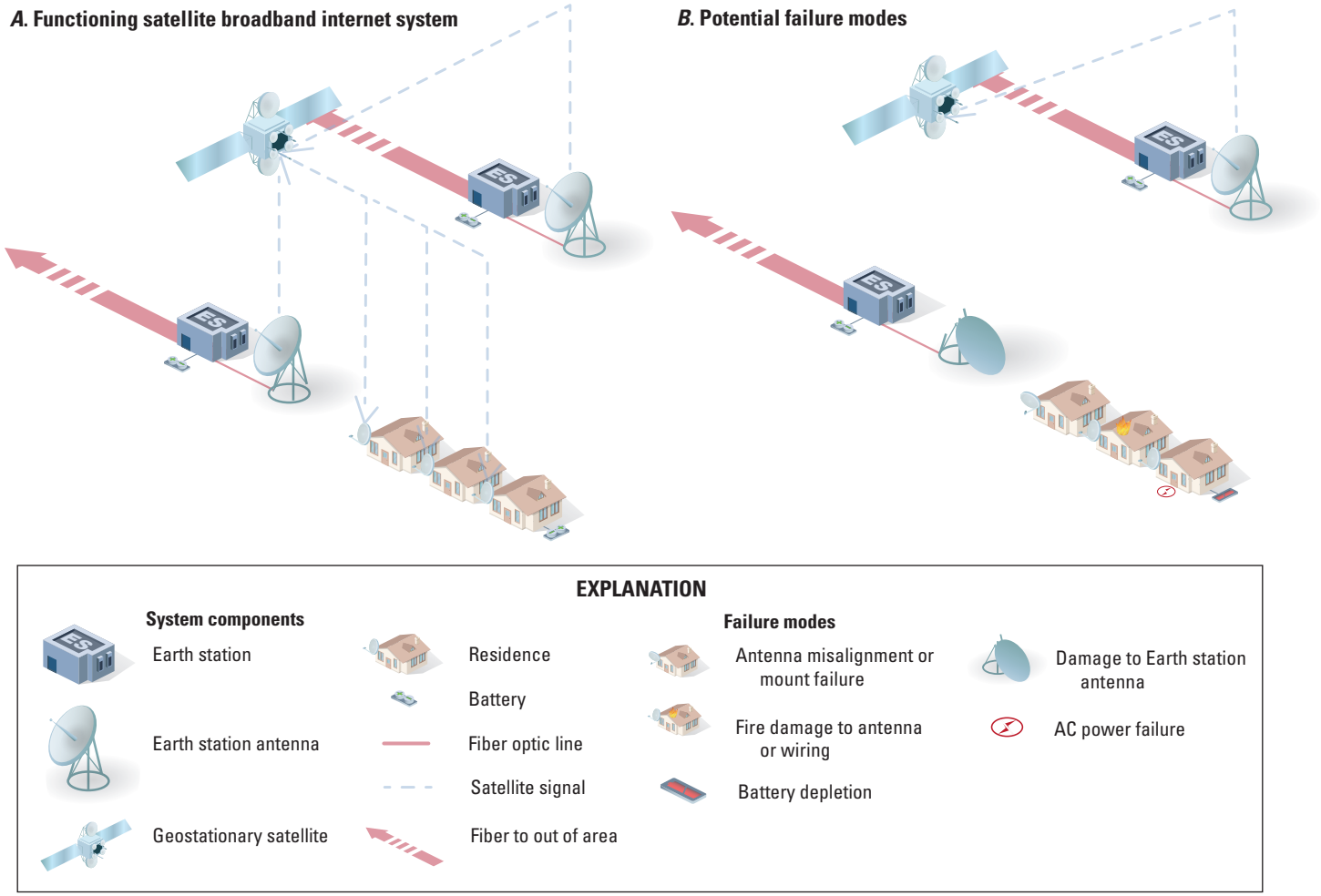


Figure 5. Schematic diagram illustrating (*A*) an example of a system that uses satellite broadband internet connection, as well as (*B*) potential failure modes. In this example, data is relayed via orbital satellites to ground-based equipment. Antennas are highly directional, thereby requiring precise alignment. Power for equipment is provided by users in the form of AC power or battery backup. Operator-provided battery backup may last only 3–4 hours. The system is sized to serve a fractional number of simultaneous users. AC, alternating current.

Subscriber Connectivity

Residential, government, and commercial subscribers have technological and provider service choices. The number of competitive offerings differ among geographic areas. In the San Francisco Bay region, subscriber choices vary across enterprises that range from large corporations with multiple sites to small startups operating from shared office space or even a private residence. Table 1 summarizes different types of connectivity and technology classifications for some primary users that are described below.

9–1–1 Calls—Public Safety Answering Points

The 9–1–1 public safety system was created to give people a nationally standardized and simple number for calls in case of emergency. All 9–1–1 calls are routed to public safety answering points (PSAPs) where 9–1–1 operators route the call to police, fire, or emergency medical services. Despite the movement in telecommunications toward digital voice telephony, PSAPs still operate on analog POTS lines and the PSTN system—as such, calls from digital telephone subscribers must be converted to analog technology prior to connection to the PSAP.

In an effort to modernize the 9–1–1 system, the Enhanced 9–1–1 (E9–1–1) system expanded the ability of PSAPs to handle calls from wireless callers. E9–1–1 was deployed in two phases. Phase I required wireless carriers to provide the PSAP with the 9–1–1 caller's telephone number and location of the cellular site from which the call was made; phase II required wireless carriers to provide more precise location information, depending on the type of wireless technology being used for the call. It should be noted that E9–1–1 requires a parallel data channel, in addition to the analog voice connection, between the wireless carrier's system and the PSAP—failure of that parallel data channel affects the ability of the PSAP to handle calls from wireless subscribers. Further enhancement to the 9–1–1 system will come from the Next Generation 9–1–1 (NG9–1–1) system, which will allow PSAPs to receive short message service (SMS) text messages and multimedia service messages (MMS) with support for images, videos, and other data files.

Home and Small Business Telephony

Although fiber optic lines to homes and small businesses are being deployed in both urban and suburban areas of major cities, copper wire systems have been around for many years—and will likely remain the dominant technology in

Table 1. Voice and data connections, primary users, and classification of technology.

[VoIP, voice over internet protocol; ISP, internet service provider; Tn, transmission system; DSn, digital signal line; ADSL, asymmetrical digital subscriber line; VDSL, very high bitrate digital subscriber line]

Voice, data, or VoIP connection	Primary user	Classification and method
Fiber optic	Large businesses, office parks, central offices, mobile switching centers, data centers	Optical waveguide (aerial, conduit[4])
Symmetrical: Tn, DSn[1]	Small- and medium-sized businesses, incubators	Wired copper pair (aerial, conduit)
Asymmetrical: digital subscriber lines (for example, ADSL or VDSL)[2]	Small businesses, home businesses, homes	Wired copper pair (aerial, conduit)
Asymmetrical-shared: DOCSIS[3]	Small businesses, home businesses, homes	Wired coaxial cable (aerial, conduit)
Public switched telephone network (voice only)	Small businesses, home businesses, homes, public safety answering points	Wired copper pair (aerial, conduit)
Wireless point-to-point and point-to-multipoint: Licensed or unlicensed spectrum (wireless ISPs)	Businesses (primarily as a backup method), homes (primarily in rural areas)	Wireless (directional antenna)
Cellular data	Businesses (backup method), employees in the field, homes	Smartphones, portable hotspots
Optical (short hop)	Large and medium businesses	Laser transceivers

[1]DSn and Tn are classifications of digital telecommunications circuits, where n is an integer. DSn technically refers to the rate and format of the signal, whereas the Tn designation refers to the equipment providing the signals and the physical lines carrying them. In practice, the two terms are used interchangeably, for example, DS1 and T1, DS3 and T3.

[2]xDSL: VDSL and ADSL2+ are most common in urban areas; ADSL2 is used in semi-rural areas. ADSL is largely obsolete in 2017. Telephone companies like AT&T, Verizon, and so on, use xDSL to deliver broadband along with either digital or plain old telephone service (POTS). Independent ISPs in the San Francisco Bay region, like Sonic.net and Cruzio, also use xDSL to deliver broadband service.

[3]DOCSIS refers to the standard for Data Over Cable Service Interface Specification. Cable television companies like Comcast, Charter, and so on, use DOCSIS to deliver broadband along with television signals.

[4]Conduit describes physical channels through which power, copper pairs, coaxial, or fiber optic lines are routed. It is typically underground or attached to physical objects like poles or building walls. Aerial lines or fiber are strung along poles—they are not contained in conduit.

use for years to come. However, the number of residential POTS subscriptions in the United States is decreasing steadily every year. (See data on switched access lines from Federal Communications Commission [2019].) Most voice telephony is now handled digitally by using VoIP over broadband (service communication networks that provide high-capacity data connections). The same copper wiring is used for POTS or VoIP over DSL (fig. 1). An important distinction is that POTS provides power to subscriber equipment over the wiring and can work even if electric utility power is disrupted.

Home-Based and Virtual Offices Requiring Broadband

The rise of the "gig economy" (Torpey and Hogan, 2016) has further driven demand for fast (high speed) and reliable internet connection (broadband). Intuit (2010) estimates that 25–30 percent of the U.S. workforce are contingent (non-permanent) workers and 80 percent of large corporations intend to continue to expand use of such flexible work arrangements. In the San Francisco Bay region, San Francisco was rated as the best city for opportunities for gig economy workers (Lieber and Puente, 2016) and the percentage in the work force could be higher than the nationwide average (K. Lister, Global Workplace Analytics, written commun., 2019). Home-based businesses and virtual offices are also common, and many workers telework (work remotely) one or more days per week.[6] Typically, VoIP and data connections are made via copper pair (xDSL[7]) or coaxial (DOCSIS) line service.

Small and Medium Businesses Requiring High Bandwidth

Small- and medium-sized businesses with more users than home-based and virtual offices require high bandwidth and typically use some form of connectivity via copper pair or coaxial line for connection via a modem to VoIP and the internet. Although not as fast as fiber optic line, copper pair and coaxial line are readily available and typically less expensive. Some sites have redundant copper pair wiring. The connections (for example, xDSL and DOCSIS) are converted to wired networking (ethernet) and wireless (Wi-Fi) for connecting user equipment to either internal or external data networks.

Central Offices, Data Centers, and Large Corporations Using Fiber Optic Lines

Central offices, mobile switching centers, data centers, and most large corporations use (if possible) fiber optic lines for connectivity (so-called fiber-lit buildings), because it offers the fastest speed, typically lower latency, highest security, and is relatively immune to disruption from nearby electromagnetic sources. Large corporations commonly have several buildings, or buildings at separate locations, which creates a requirement for both intranet (internal network) and internet (external or public network) connectivity. Fiber optic lines are converted to network cabling (ethernet) and (or) wireless (Wi-Fi) for data connection to user equipment. Most major businesses use VoIP phones, and connect their internal phones to the public network via digital private branch exchanges (PBXs) although there are also VoIP telephone systems. Fiber optic lines connect in-building equipment with a broadband provider (such as AT&T). Ultimately, voice calls route through the broadband network.

Enterprises that Require Reliable Connectivity

Enterprises that require constant connectivity commonly employ redundant connections to reduce the probability of failure. They may have fiber optic lines and copper pair or coaxial lines as a backup. Data centers reduce their vulnerability to severed fiber optic line by having redundant fiber optic line connections (B. Weihl, Facebook, oral commun., 2015). However, since the failure modes for lines are similar, businesses sometimes opt for wireless data as a contingency. With the increased availability of unlimited data plans on cellular networks, smartphones and hotspots (either via a smartphone or using a dedicated device) also became options for contingency connectivity. Wireless is not ideal for everyday business because of limited throughput and relatively expensive data plans and usage rates.

Physical Failure Modes

Failure modes for telecommunications systems are illustrated in figures 1–5 and are summarized below for telecommunications provider and subscriber equipment and channels.

Provider Equipment Failure Modes

Outside of central offices and data centers, network equipment and interconnection points are housed within roadside cabinets, pole-mounted cabinets, or in underground vaults. The purpose of these enclosures is to secure the equipment and interconnections against damage from weather, dust, sunlight, and vandalism. Some network equipment uses active cooling, and as a result enclosures are sometimes fitted with ventilation fans. Each enclosure method and ventilation system has benefits and drawbacks within the context of a disaster scenario. Equipment failure modes can include:

- Equipment damaged by collapse of supporting or containing structures or partial collapse of roofs, damage to exterior walls, or loosening of parapets or facades.
- Fire damage to supporting structures or equipment.
- Failure of mounts and brackets that attach equipment to towers, arms, or building structures.

[6]During final review of this work, the effects of the COVID-19 pandemic greatly inflated the numbers of teleworkers.

[7]xDSL is a generic term for a family of digital subscriber lines, including ADSL, ADSL2+, and VDSL.

- Toppling or positional shifting of battery or electronics racks.
- Stretching and breaking of coaxial line, fiber optic line, power cable, or control cable.
- Damage to electronics from water intrusion (fire suppression sprinklers; rainwater through damaged roofs, windows, or sidings; or flooding).
- Smoke and dust clogging air-intake filters and shutting down air-handling equipment and subsequently telecommunications equipment.
- Loss of primary power sources, and (if existent) failure of backup power to equipment in central offices, data centers, OLC and (or) DLCs, cabinets, or cooling equipment.
- Loss of water supply needed for central air conditioning to cool the equipment rooms and buildings that house telecommunications equipment.

Wired Channel Failure Modes

Copper wiring or fiber optic lines are routed between equipment sites either aerially by using utility poles, or underground by using direct-bury lines and (or) conduits. Fiber optic lines typically run underground or underwater and have maintenance vaults where signals can be amplified, split, and transmitted (Thompson, 2016). Each has benefits and drawbacks within the context of a disaster scenario. For example, aerial lines may be less susceptible to damage from ground failure than buried infrastructure but are more susceptible to damage from fires and pole toppling.

Copper pair, coaxial, and fiber optic lines are moderately resistant to longitudinal displacement because they typically have some give over any given installation path. (This is different from slack that is locked in a fiber optic storage device for repairs). They also have some flexibility and resistance to bending and shearing. All lines have common failure modes that degrade performance or knock out a transmission path, including:

- Substantial displacement and bending or shearing of conduit, or breakage and separation of joints, which is more likely in older infrastructure.
- Lack of electrical power to run in-line amplifiers and hubs.
- Discharge of backup batteries, reduced capacity of batteries caused by aging, or lack of backup batteries because of aesthetics, space, or low return on investment.

The resistance of copper pair, coaxial, and fiber optic lines to water intrusion and fire differ according to the following.

- Water intrusion is damaging to buried copper wiring although cable pressurization equipment is used to prevent corrosion (Kwasinski, 2012) and newer wiring has a gel inside to protect it from water (R. Schwabacher, AT&T, oral commun., 2016). Buried fiber optic lines and electrical components can be designed to handle water intrusion better than copper wiring (City of New York, 2013). However, damage has been observed if the fiber optic line remains too long underwater or if water enters a splice, and such damage may lead to excessive signal attenuation (A. Kwasinski, University of Pittsburgh, written commun., 2019).
- Copper pair and coaxial lines are typically heat tolerant but can be damaged by fire. Aerial fiber optic line is more easily damaged by heat from fire and buried fiber optic lines in vaults can be damaged if heat is drawn through electronic equipment vents.

Wireless Channel Failure Modes

Wireless data links are subject to some different failure modes than wired lines and include the following.

- Misalignment of antennas and laser transceivers caused by ground movement, mounting structure damage, or building, tower, or mast deformation at either the service or client location.
- Blocking of laser, microwave links, and satellite broadband by heavy rain, fog, cloud, or smoke.
- Discharge of backup batteries, reduced capacity of batteries caused by aging, or lack of backup batteries because of aesthetics, space, or low return on investment.

Subscriber Equipment Failure Modes

Subscriber equipment failure modes include the following.

- Lack of electrical power to run xDSL or DOCSIS gateways (routers or access points) or to run fiber optic transceivers, converters, routers, computers, and other devices.
- Damage to or inaccessibility of computer and other equipment.

Telecommunications Infrastructure Exposure and Damage from HayWired Earthquake Hazards

In this section, we review HayWired scenario hazards and observe telecommunications infrastructure failures caused by earthquake hazards. HayWired scenario hazard exposure analyses and some shaking damage estimates are performed for central offices, data centers, cellular towers, unanchored equipment, fiber optic lines, and surface streets (for copper lines). The potential fragility of public safety answering points (PSAPs) is also discussed because of their important role in emergency response immediately after an earthquake.

HayWired Scenario Hazards

The HayWired scenario is a moment magnitude (M_w) 7.0 mainshock on the Hayward Fault in the east bay part of the San Francisco Bay region, California, followed by an aftershock sequence. The shaking from the mainshock is strong to extreme and would be felt throughout the bay region and beyond (Aagaard, Boatwright, and others, 2017), causing an estimated $43 billion (in 2016 U.S. dollars) of building damage (Seligson and others, 2018).

The Hayward Fault rupture causes as much as 2 meters of slip at the ground surface north of the City of Fremont (Alameda County), but further slip of the fault (afterslip) would be expected. Cumulative afterslip of as much as 1.5 meters could occur at the surface at some locations along the fault for days, weeks, months, or even years, especially where the ground slipped less during the mainshock earthquake (Aagaard, Schwartz, and others, 2017). Slip at the surface disturbs structural foundations and can stretch or break infrastructure crossing the fault.

Shaking triggers liquefaction, which is when solid ground temporarily transforms into a softened or liquefied state, particularly in soft, water-saturated soils around the margins of San Francisco Bay and along streams (Jones and others, 2017). Our most detailed mapping of the liquefaction hazard for the HayWired scenario is described in appendix 1 of Jones and others (this volume). Shaking also triggers landslides, depending on slope, rock and soil strength, and shaking intensity (McCrink and Perez, 2017). Landslide hazards—probabilities and displacements of landslide initiations—are mapped by McCrink and Perez (2017) for the HayWired scenario. Liquefaction and landslides weaken structural foundations and warp or break infrastructure on and below the ground. For example, underground vaults could be stressed by ground shifting and (or) be damaged by water intrusion from broken water pipes.[8]

Building and infrastructure damage ignite fires and containment of fire is hampered by communication outages that delay the reporting of fires, fire truck resources and transportation disruptions that restrict access to fires, and broken water mains that diminish fire suppression resources (Scawthorn, 2018). For the HayWired scenario, the density of burned buildings is mapped by Jones and others (this volume) and lines could be scorched in these areas. Smoke and dust particles could clog filters at data centers that require clean air (M. Stoeffl, California Resilience Alliance, written commun., 2019).

The HayWired aftershock sequence includes 16 magnitude (M) 5 or greater earthquakes within 2 years (Wein and others, 2017). Aftershocks cause an estimated additional $10 billion (in 2016 U.S. dollars) of building damage and repeat liquefaction (Seligson and others, 2018), which poses safety concerns during rescue, inspection, and repair work, and are stressful to populations who experience them.

[8]See Porter (2018) for estimates of water distribution pipe breaks and leaks for the HayWired scenario.

Observations of Earthquake Damage

Earthquake damage to telecommunications infrastructure has been described as lighter than the devastation to its surroundings (Schiff, 1995) or relatively minor for central offices, cellular towers, and roadside broadband cabinets (Tang and others, 2014). Power outage as the cause of equipment malfunction has been frequently reported and is addressed in the next section about voice and data service restoration. Here, the focus is on direct damage from earthquake hazards.

Central offices have occasionally sustained extensive damage during previous earthquakes, but damage to their equipment and connections are more commonly reported. Tang (2008) compiled central office failures caused by building collapse from earthquakes in San Fernando (California, United States, 1971), Mexico City (Mexico, 1985), and Spitak (Armenia, 1988). Structural shaking damage to central offices from the 1994 Northridge earthquake in California were shored up but did not require evacuation or shut down of operations; the main causes of outages or isolation of local services were unseated and malfunctioning circuit boards, disk drive failures, shorts caused by unintended contacts, and loosened optical connectors (Schiff, 1995, p. 146). Recently, during the 2016 Kaikoura earthquake in New Zealand, the two affected telephone exchange buildings were not damaged, but in one, electronic boards had to be reset or replaced because of a broken rack mounting, and the other was isolated by fiber optic line breaks (Giovinazzi and others, 2017). Similarly, after the 2016 Kumamoto earthquake in Japan, there was no reported damage to exchange facilities except for hundreds of circuits that suffered from broken connections, caused by ground deformation, that were restored within 4 days (Tang and Eidinger, 2017).

Schiff (1995, p. 149) recognized the fragility of heating, venting, and air conditioning systems for cooling of central offices in the summer months in California, even if power and water services are still available. During the 1994 Northridge earthquake, most environmental systems within 8 miles of the epicenter sustained damage from broken water pipes to complete system failure attributed to poor structural quality and locations of heating, venting, and air conditioning systems on the highest levels of buildings. During the 2011 Christchurch earthquake in New Zealand, seismically supported equipment (network, power, and air conditioning) suffered no damage (Foster, 2011).

Data centers appear not to have suffered any crippling damage after earthquakes. They were reported to be online and operational after the 2011 Christchurch (New Zealand) earthquake, 2011 Tohoku (Japan) earthquake and tsunami, and 2014 South Napa (California) earthquake, but power outages and fuel shortages have been a threat to continued operations (Barwick, 2011; Niccolai, 2011; Informa, 2014). Although the Tokyo data centers were beyond the most affected tsunami area, they were tested by shaking and only five server racks were critically damaged (Niccolai, 2011). All server racks, cooling equipment, and so on are firmly secured to the floor in Japanese data centers, but the same cannot be said about data centers in the United States (Niccolai, 2011), even though this is a known

best practice when designing them. In Christchurch, data centers required clean up; occupancy could have been affected by lack of street power, water, and wastewater services, and one center had to restrict entry by personnel for safety reasons in the heavily affected central business district (Barwick, 2011).

After the 1994 Northridge earthquake, damage to cellular towers was described as minimal and microwave dish misalignment and severed landline interconnections were attended to within 3 days (Schiff, 1995, p. 152). The first instance of a self-supporting cellular tower folding in half of its height was observed after the 2016 Kumamoto earthquake in Japan (Tang and Eidinger, 2017). A few instances of damage to cellular towers from ground movement include a cellular tower destroyed by a rock fall and a monopole supporting wireless antennas tilted by liquefaction during the 2011 Christchurch earthquake in New Zealand (Eidinger and Tang, 2012). The 2015 Gorkha earthquake in Nepal misaligned 15 microwave links and landslides damaged fiber optic backhaul (Khanal, 2015). Therefore, dysfunction for some cellular sites have resulted from severed interconnecting lines (both metallic and fiber optic) caused by ground deformation (Tang and Eidinger, 2017). Sites on utility poles have been damaged by shaking and liquefaction (for example, fig. 6).

In Christchurch, roof-mounted cellular sites were more commonly affected: a cell tower on the roof of a collapsed building was destroyed, two rooftop cell sites were badly damaged, and another 26 rooftop cell sites (of two different providers) were out of service (Tang and others, 2014). Similarly, roof-mounted cellular site failures occurred when a building collapsed during both the 1995 Kobe (Japan) and 1999 Chi Chi (Taiwan) earthquakes (Tang, 2008), and more recently during the 2017 Puebla (Mexico) earthquake at a site operated by three carriers (A. Tang, L&T Consultant, written commun., 2017). Furthermore, sites on heavily damaged buildings are not immediately accessible after an earthquake (for example, fig. 7).

Damage to aerial and buried lines have resulted from transient shaking and permanent ground failure (from fault rupture, landslides, or liquefaction) and damaged bridge crossings (for example, Tang and others, 2014; Giovinazzi and others, 2017; Tang and Eidinger, 2017; Eidinger and Tang, 2019). During the 2016 Kaikoura earthquake in New Zealand, most of the damage to the telecommunications networks was to buried lines (mostly copper) that were stretched and broken as a result of ground motions, permanent ground displacement, fault rupture, and damaged bridge crossings (Giovinazzi and others, 2017). A major fiber optic line was severely damaged by six breaks that cut off communication outside of a rural township such that only local telephone communications over copper wires remained possible (Worthington, 2016). Similarly, in the 2016 Kumamoto earthquake, permanent ground displacement from landslides and damage to bridge crossings damaged landlines (including fiber optic line) (Tang and Eidinger, 2017). In Christchurch, liquefaction and associated flooding and shifting manholes stretched or damaged many buried public switched telephone network (PSTN) copper lines (Tang and others, 2014). Aerial lines were also stretched by poles that moved and tilted from shaking and (or) ground movement near streams (Giovinazzi and others, 2017). Wires that connect houses to poles have been damaged by pole failures (such as a toppled pole applying excess tension to the aerial lines and causing adjoining poles to lean at a high angle) and house collapses (Tang and Eidinger, 2017).

Fire following earthquake has damaged telecommunications infrastructure. For example, the Balboa Boulevard gas explosion and fire in the 1994 Northridge earthquake burned both power and



Figure 6. Photograph showing utility pole damage to a cellular site after the 2011 Christchurch, New Zealand, earthquake. The pole split along a fold seam midway up the pole; the head load is thought to be the issue (Wes Bonney, written commun., March 26, 2021). Photograph from Wes Bonney, Vodafone, New Zealand, February 22, 2011, used with permission.



Figure 7. Photograph showing cellular sites on a heavily damaged hotel after the 2009 L'Aquila, Italy, earthquake. Photograph by A. Tang, L&T Consultant, June 20, 2009, used with permission.

telecommunications lines (Schiff, 1995, p. 150). Fire from other disasters (for example, hurricanes and wildfires) have resulted in burning of aerial lines (Kwasinski, 2012; Tiffen, 2017). Recently, during the October 2017 wildfires in northern California, many aerial lines on poles were damaged by poles falling down, and even buried fiber optic lines were scorched through vault vents that provide ground-level access (Tiffen, 2017). In all, 77 cellular sites were damaged or disconnected by the fires, including a key cellular hub (Baron, 2017).

Methods

A description of analytical methods covers telecommunications infrastructure data sources; shaking damage estimation for buildings, towers, and equipment; and infrastructure exposure analyses for ground failure and fire hazards.

Telecommunications Infrastructure Data

We purchased a set of spatial data for cellular sites, fiber optic lines, wireless switching centers, and fiber-lit buildings (including central offices and data centers) from GeoTel Communications, LLC (GeoTel) (GeoTel Communications, 2018). On request, fiber optic lines were categorized as long-haul lines that transport strong signals traveling great distances and interoffice lines that are typically metropolitan connections among and from central offices and, nowadays, includes backhaul from cellular towers that are spliced to serve those in the area, such as business parks (E. Cabading, GeoTel Communications, oral commun., 2019). These data support a regional analysis to illustrate potential patterns of telecommunications infrastructure exposure or fragility to earthquake hazards.

Checking the data against imagery revealed that the GeoTel data contained some:

- Additional data (for example, radio broadcast arrays in cell tower data);
- Duplicate entries (for example, multiple listings of a shared cellular site by each carrier at the same location);
- Inconsistent categorization of assets (for example, antennas on buildings may be classified as building or occupancy type [for example, education or commercial]); and
- Missing data (for example, some internet exchange points were not represented in the data).

Some effort was expended to correct for these issues by using imagery to reclassify data, remove duplicates, verify antennas on a sample of buildings, and consult other datasets. Internet exchange points (IXPs) were cross-checked against two sources (a map of data centers from Data Center Map, available at https://www.datacentermap.com/ixps.html, and a map of IXPs from the Network Startup Resource Center, available at https://nsrc.org/ixp/NorthAmerica.html) and a few more IXPs were inserted to the GeoTel data center entries.

Copper wires for plain old telephone service (POTS) were first installed more than 100 years ago. As the population of the San Francisco Bay region grew, especially in the post-WWII era, hundreds if not thousands of miles of copper wiring were installed. This work is old enough that some records are now lost. Therefore, we assume that copper wires are mostly strung along pole lines or buried in public rights of way following surface roads along with various utilities.

Although some data for small cell sites in densely developed areas is becoming available, we did not attempt to build a comprehensive dataset for this analysis. No data was obtained for digital or optical loop carriers (DLCs and OLCs). No data was obtained to assess point-to-point high-frequency microwave connections. These types of point-to-point connections are used in the San Francisco Bay region across hills and canyons, and to connect to satellites.

PSAP locations were obtained from the Federal Communications Commission's 9–1–1 Master PSAP Registry (available at https://www.fcc.gov/general/9-1-1-master-psap-registry). Orphaned PSAPs were removed from the dataset. The PSAP locations were cross-referenced to public safety facilities (for example, police or fire) where they coincided in the Federal Emergency Management Agency's (FEMA) Hazus-MH 2.1 (hereafter referred to as Hazus) inventory data (D. Bausch, Federal Emergency Management Agency, written commun., 2014).

Physical Damage Estimation

In a state-of-the-practice damage analysis of a structure, a building's type and other engineering characteristic data would be taken from construction documents or examination of the building. Similarly, estimating physical damage to equipment requires knowledge of installation design and practices for that kind of equipment. For the present study, such data is not publicly available. Existing codes, standards, and guidelines covering a selection of telecommunications equipment and structures are summarized by the Applied Technology Council (2016). These and others are listed in sidebar 2.

However, the Applied Technology Council (2016) states that "design standards are voluntary (not mandated by law) but may be incorporated by reference into building codes, siting permits for towers, commercial contracts, or even financial auditing obligations, for example, for data center reliability." It refers to the Communications Security, Reliability, and Interoperability Council's (2014, p. 6) explanations for the voluntary nature of design standards that include "flexibility, innovation, and control in the management of different carriers' unique business models, cost, feasibility, and resource limitations." The Applied Technology Council (2016) concludes that "there does not appear to be any data on whether resiliency-related standards and best practices are widely followed by the communication industry. In particular, it is unclear to what extent outside plant, including fiber communication facilities, and central offices follow resiliency-related standards."

Sidebar 2—Telecommunications Infrastructure Design Guidelines and Regulations

Codes, standards, and guidelines for telecommunications infrastructure identified by the Applied Technology Council (2016) and from our own investigations include the following.

- Data center functionality and resiliency standards (by tier) have been established (Telecommunications Industry Association, 2014; Applied Technology Council, 2016).
- The industry standard for central offices—the Network Equipment Building System for levels of performance—may be supplemented by carrier-specific earthquake- and fire-resistant test methods and performance requirements (for example, GR-63 [Telcordia, 2012], GR-1089 [Telcordia, 2011], ATIS 0600329 [Alliance for Telecommunications Industry Solutions, 2014]) (see Applied Technology Council, 2016).
- The industry reference for fiber optic line is NECA/FOA 301 (Fiber Optic Administration, 2016) and it does not address building for seismic events or guidelines for laying fiber optic line across fault lines or through liquefaction- and landslide-susceptible areas.
- Design and maintenance standards for tower structures, mounts, and antennas were Telecommunications Industry Association's (TIA) TR-14 (TIA-222-G) (see Erichsen, n.d.) reinforced by construction and maintenance standards (American Society of Safety Engineers A10.48 and TIA-322). The standards divide tower structures into three classes, depending on whether they may present a hazard to human life and whether the services provided are optional or essential. Implementation of a 1.5 importance factor is set for structures that meet certain criteria.
    - The standard was revised to TIA-222-H during the course of this study. TIA-222-H incorporates long-period transitions as part of the earthquake design loads for telecommunications towers. This design criterion was taken specifically from the equivalent lateral force method from American Society of Civil Engineers (ASCE) 7 and is meant to account for structures with varying fundamental frequencies or periods (B. Lanier, American Tower Corporation, written commun., 2017). ASCE 7-18 and TIA-222-H design criteria accounts for amplification of shaking for cellular sites on buildings.
- TIA-TSB-5053 addresses antenna mount design loads applicable for extreme wind, extreme ice, and maintenance conditions to advise diverse suppliers with variable installation techniques. By default, the advisory encompasses shaking loads.
- Guidelines for cellular site foundations consider factors of liquefaction including soil parameters, some seismic parameters, and depth of the water table, as cited in the TIA-222-G standard; TIA-222-H cites minimum information that should be provided in a geotechnical report (B. Lanier, Telecommunications Industry Association, written commun., 2019).
- Guidelines for siting towers in landslide-prone or fire-threatened areas were not found.
- Guidelines are lacking for equipment racks that confine and organize equipment at telecommunications sites. Housings for electronic components at cellular sites are commonly pre-built, and are not standardized. Methods of procedures (MOPs) are typically based on the Telcordia GR-63-CORE and International Building Code (IBC) standards (Young, n.d.), and various carriers confirmed that stacked dry cell batteries should be bolted together and anchored in heavy steel containers designed for California building codes and lead-acid battery racks in plastic containers should be bolted to the floor.
- Utilities can place poles (that may support telecommunications equipment) in many different types of soil conditions, including sand, rock, clay, and dirt with various properties, and most of the poles set in the right-of-way are set in concrete or asphalt. The rule that exists for all placements is a prescribed setting depth that ranges from 5 to 10 feet in the ground, depending on the height of the pole. The recent California General Order 95 (Public Utilities Commission, 2018) could help with pole maintenance going forward because it requires all utilities to inspect wooden utility poles on a regular basis. The purpose of these inspections is to ensure that any safety concerns are addressed and corrected. One item on the check list is pole lean, which could indicate that the soil conditions have changed and any time this condition is identified, the requirement is to report it and correct it (W. Mueller, Extenet Systems, written commun., 2017). Other pole inspection items include sound timber, minimum circumference, and unacceptable damage. Pole maintenance could also reduce the likelihood of electric wires acting as a source of fire ignitions.
- Codes and standards for fire protection exist for telecommunications facilities that provide telephone, data, wireless, internet, and video services to the public (National Fire Protection Association [NFPA] 76) and for fire suppression and detection and building construction for information technology equipment (NFPA 75). The Applied Technology Council (2016, p. 5–19) notes that "[f]or fire alarms, NFPA 72 (NFPA, 2016) mandates in Section 10.6.7.2, that alarm systems, including communication components, can maintain operation on secondary power for 24 hours."

We proceed with describing assumptions and methods used to conservatively estimate shaking damage to telecommunications buildings, towers, and equipment for the HayWired scenario. Then, geographic information system (GIS) analyses are used to analyze exposure of all infrastructure (including lines) to the other HayWired scenario hazards of ground failures (surface rupture, liquefaction, or landslides), fire following earthquake, and aftershock shaking, as well as potential collateral damage to fiber optic lines from heavily damaged bridges. PSAP functionality is estimated using Hazus results for public safety facilities.

Shaking Damage Estimation for Central Offices and Data Centers

Structural engineers commonly estimate probabilistic damage to a building, structure, or equipment using a fragility function. A building is treated as having an uncertain capacity to resist a specified form of damage, such as structural collapse. Capacity is measured in terms of the uncertain environmental excitation (commonly a scalar measure of ground motion, such as peak ground acceleration) that the building can experience without suffering the specified damage. In some cases, the best available option is to estimate a central value of that fragility function, such that its median capacity has a 50 percent probability of non-exceedance for specific damage. For more information about fragility functions, see Porter (2020).

We are interested in the shaking hazard that is sufficient to damage buildings severely enough to cause them to be yellow tagged or red tagged. Tagging is building inspection that would occur after an earthquake by an engineer trained by the California Office of Emergency Services (Cal OES) and deputized by the city or other local jurisdiction to perform ATC-20 (Applied Technology Council, 2005) building safety evaluations. When the engineer sees that there is collapse or heightened collapse probability with aftershocks, the engineer applies a red placard to all the entrances to the building that declares the building to be unsafe to enter and occupy. Because it is illegal to enter the building to operate equipment, most likely the building remains nonfunctional until the repairs are completed, potentially months or years later. Yellow tagging means that the ATC-20 evaluator sees damage sufficient to restrict use, commonly either to a portion of the building or for limited duration, such as to remove property.

Engineers commonly associate red tagging with the complete structural damage state used by Hazus (Federal Emergency Management Agency, 2012), FEMA's damage-estimation tool (for example, Porter and Cobeen, 2009). Yellow tagging is commonly (though not universally or unambiguously) associated with the Hazus extensive structural damage state. Median capacities to resist red and yellow tagging are therefore taken from Hazus's fragility functions for complete and extensive structural damage.

The HayWired scenario damage assessment for central offices and data centers uses Hazus median capacities for proxy building types for central offices and data centers—that is, for the kinds of structures that commonly (though not universally) house that kind of facility. Central offices and mobile switching centers (which house voice switching and data transmission centers) are owned or rented by telecommunications service providers. In the San Francisco Bay region, central offices are likely built prior to the 1990s and are at least 25 years old. Although the critical function of these buildings was recognized earlier on and, as such, were built stronger than other buildings at the time, they are designed to older standards and to support heavier and larger equipment (Bell Systems, 1974). In one of the author's (K.A. Porter) professional experience, central offices tend to be low-rise stiff buildings (reinforced concrete, reinforced masonry, or tilt-up concrete), although some high-rise central offices do exist, such as the downtown San Jose wire center. Proxy building types for all central offices are the Hazus building type low-rise (one to three stories), moderate-code (1940s to 1970s construction), reinforced masonry construction with rigid diaphragms (floors and roofs), or alternatively moderate-code tilt-up concrete. Standard FEMA notation uses RM2Lm to indicate the former building type, PC1m for the latter. "RM2" denotes a lateral force resisting system, reinforced masonry construction with rigid diaphragms. "L" denotes low-rise building types and "m" denotes moderate code. "PC1" denotes tilt-up concrete, and "m" again refers to moderate code. (Until recently, tilt-up was always low-rise, hence the lack of a height-range term in its label.) We assume that our central office proxy building type is an equally weighted mix of RM2Lm and PC1m.

Compared to central offices, data centers and exchange points are commonly corporately owned and more modern (within 20 years old). Data centers can be in low-rise, mid-rise, or high-rise buildings, although again in K.A. Porter's professional experience, low-rise tilt-up buildings seem to be most common among San Francisco Bay region data centers. Buildings are more likely to be constructed for the building codes of the area, although because data centers may use existing buildings, some are built to moderate code. Seismic audits are not necessarily performed after the data center is initially built. We propose that moderate-code data centers are similar enough to central offices that we can reasonably use the same proxy building type for central offices to conservatively identify potential damage.

The structural response of both RM2Lm and PC1m buildings at low levels of ground motion (before significant degradation of stiffness) is reasonably estimated as a function of 5-percent-damped short-period (0.3-second) spectral acceleration (SA) response (abbreviated as SA 0.3 seconds, 5 percent). But at higher levels of ground motion, structural damage causes the structural system to soften, lengthening its period of vibration. At levels of ground motion sufficient to cause extensive or complete structural damage (in the sense used by Hazus [Federal Emergency Management Agency, 2012]), even these stiff low-rise buildings tend to be more sensitive to long-period motion. Their performance point in the sense of Hazus tends to lie on the constant-velocity portion of the idealized response spectrum, and 5-percent-damped elastic spectral acceleration response at 1.0 second period (abbreviated here as SA 1.0 second, 5 percent) tends to be a better indicator of damage (table 2). Methods described by Porter and Cobeen (2009) support this assumption.

Table 2. Median capacity for central offices in terms of 5-percent-damped elastic spectral acceleration response at a period of 1.0 second.

[RM2Lm denotes moderate-code low-rise (one to three stories) reinforced masonry construction with rigid diaphragms (floors and roofs), and PC1m denotes moderate code tilt-up concrete construction. *g*, acceleration due to gravity]

Damage state of central office	Hazus structure type		Average
	RM2Lm	PC1m	
Red tag	1.37*g*	1.22*g*	1.30*g*
Yellow tag	0.77*g*	0.64*g*	0.70*g*

Table 3. Median overturning capacity of common, unanchored central office equipment in terms of 5-percent-damped elastic spectral acceleration response at a period of 1.0 second.

[Alphanumeric codes refer to equipment classification from Applied Technology Council (2018). *g*, acceleration due to gravity]

Equipment	Median capacity
Chiller (D3031.013e)	0.72*g*
Cooling tower (D3031.023h)	1.52*g*
Diesel generator (D5092.031b)	0.90*g*
Distribution panel (D5012.031b)	2.16*g*
Low voltage switchgear (D5012.021c)	1.28*g*
Motor control center (D5012.013a)	0.73*g*
Transformer (D5011.013d)	3.05*g*

Shaking Damage Estimation for Unanchored Equipment

Direct failure of equipment could cease operation to cause functional failure of the central office. Porter and others (1993) offer logic diagrams related to the functional failure of central offices. Reasonable candidates are listed in table 3, along with their median capacities in terms of peak floor acceleration. (Here, overturning capacity refers to the uncertain excitation that the object can resist without overturning.) It is common that, even in a building where the operator is keenly aware of seismic risk, at least some of the equipment is not seismically installed; that is, it rests on the floor or on vibration isolators without restraint against overturning. It will tend to be this unrestrained equipment that overturns, fails, and causes the operational failure of the central office. We use the median capacity of the weakest link in the equipment system, such as the component that fails at the lowest level of excitation. Median overturning capacities in table 3 are expressed in terms of the peak acceleration of the floor on which the equipment rests. For a one-story central office, the equipment commonly rests on a slab at grade, so the peak floor acceleration is the same as the peak ground acceleration (PGA), which tends to be approximately equivalent to spectral response (SA 1.0 second, 5 percent). Notice that the lowest of the values in table 3 is approximately equal to the median yellow-tag capacity of RM2Lm and PC1m buildings, so completely and extensively damaged building states also imply possible damage to unanchored equipment. In the table, alphanumeric codes such as "D3031.013e" refer to the taxonomic classification for the equipment applied by FEMA P-58 (Applied Technology Council, 2018), the leading standard for second-generation performance-based earthquake engineering as of this writing.

Shaking Damage Estimation for Cellular Sites

Macrocellular site installations are classified approximately into five types:

- Self-supporting lattice towers (SST);
- Guyed lattice towers (GT);
- Monopole towers (MP), including stealth designs and most camouflage structures;
- Building-mounted tower (SST or GT), such as rooftop towers; and
- Building-mounted structures, such as those on parapets, outside walls, or facades.

Operational equipment for the cellular site is housed in vaults or container-style huts nearby.

Free-Standing Towers

Free-standing towers are SSTs, GTs, and MPs. Structural standards for telecommunications towers are defined by the Telecommunications Industry Association (TIA) via their TR-14 committee (Telecommunications Industry Association, 2012). Structural detailing of the foundations and communication structure to improve seismic survival is a standard element integrated into the development of commercial communication structures. Members of the TR-14 committee provided the median capacity values for free-standing towers in table 4. However, public communication structures and maintenance (for example, for rust) may not be of the same standard (USGS Telecommunications Phase 1 workshop, oral commun., 2016). The performance of the equipment (for example, antennas) on the structures was not considered, but equipment can be repaired faster than structural failures.

Seismic loads do not generally govern the design of tower structures. The wind loading requirements of the TIA-222-G standard generally requires a communication structure to support a larger lateral load than those induced by seismic events.[9] The median capacities in table 4 for SSTs and GTs exceed the seismic motion presumed in the HayWired scenario. This is consistent with evidence from the 2010 Haiti earthquake when the only company that remained operational almost exclusively utilized towers between 30 and 60 meters tall that were built to withstand hurricanes and earthquakes (Bilham, 2010; Corley, 2010) and the finding that cellular towers were in good condition after the recent 2016 Kaikoura earthquakes (Giovinazzi and others, 2017).

[9]This also holds for electric power transmission lines (if they host antennas and microwave dishes) (Wong and Miller, 2010).

Table 4. Median capacity for cellular towers in terms of 5-percent-damped elastic spectral acceleration response at a period of 1.0 second.

[Cellular tower median capacities provided by the Telecommunications Industry Association's TR-14 committee. SST, self-supporting lattice tower; GT, guyed tower; MP, monopole; ft, feet; n/a, not applicable; *g*, acceleration due to gravity]

Damage state	SSTs and GTs	Heavily loaded MPs <50 ft in height
High	n/a	1.5*g*
Moderate	2.5*g*	1.25*g*

However, the TIA analysis found that MPs less than 50 feet in height are less resistant to seismic forces than SSTs and GTs as they are more sensitive to loading per design standard and in some configurations had a lower median capacity (table 4). A critical component in the seismic analysis is loading—in other words, how much equipment weight is attached to a tower and at what height above ground. The fragility for these towers increases with more mass at the top (B. Lanier, American Tower Corporation, oral commun., 2016).

Rooftop Towers and Building-Mounted Antennas

Rooftop towers and building-mounted wireless facilities are more complicated to analyze than free-standing towers. The period of the antenna mounted on a building would likely be identical to that of the building. If the antennas were mounted on a sled or pole above the top of the building, the seismic forces would be amplified from the building response (although the spectral acceleration could be less because of the increased period). This is a similar response to the seismic loads imposed by a parapet. If the supporting structure is damaged (not collapsed), operations may continue as designed assuming the associated communication equipment is intact. Antennas can still work even if they are dislodged from their building mounts and may only need to be reoriented in the right direction (R. Altom, Verizon Wireless, oral commun., 2016).

Recently, concerns have been voiced that many cellular sites are attached to aging structures that may not meet the seismic requirements of modern building codes (Applied Technology Council, 2016). In most cases, the building design values that could influence the cellular site performance is not available and an analysis would need to be performed by the original building engineering design firm (B. Lanier, American Tower Corporation, written commun., 2019). To illustrate the potential inaccessibility of antennas and equipment on yellow-tagged and red-tagged buildings, we use the same median capacities for building damage listed in table 2 assumed for central offices and data centers.

Cellular Site Equipment

Even if towers and antenna mounting structures remain intact, locked equipment vaults or huts that are located nearby can be damaged by earthquake hazards. They contain radio equipment and are connected to the antennas by a coaxial line or waveguide. TIA's TR-14 committee defines standards for antennas and supporting structures, and the vaults and huts themselves are governed by local building codes. Yet, as noted above, no unified standard exists for hardening the equipment (batteries, components, racks, and electronics) against earthquakes inside these structures. In the absence of standards, we resort to illustrating the point by assuming the same median capacity for unanchored equipment in a central office (at SA of 1.0 second, 5 percent) of 0.7*g*.

Exposure of Infrastructure to Ground Failure, Fire, and Aftershock Shaking

GIS methods to map and tally exposure of infrastructure to HayWired surface rupture, liquefaction, landslides, fire, and aftershock shaking are adopted from Jones and others' (this volume) analyses of multiple lifeline infrastructure systems.

Ground Failure Exposure

Because fiber optic lines and copper lines cross the fault, damage would depend on the angle and amount of offset at the crossing. Hazus assumes that fiber optic lines are designed to have enough elasticity and resilience to bending to accommodate ground shaking and even moderate amounts of permanent ground deformations. However, fiber optic lines have been damaged in recent earthquakes, and carriers and workshop participants concurred that meters of ground displacement could break fiber optic lines. We use the results of Jones and others (this volume) for numbers of fiber optic lines and surface streets (as a proxy for copper lines) crossing the fault rupture as the subset of lines exposed to surface slip in the HayWired scenario.

Ground movements from liquefaction and landslide hazards are indicated by probabilities of occurring in the HayWired scenario (Jones and others, 2017; McCrink and Perez, 2017). Table 5 provides the probability ranges used for levels of intensity: low for nonzero probability less than 5 percent, moderate for probability at least 5 percent but less than 25 percent, and high for probability at least 25 percent. The ranges are chosen without any known relation between the probability of ground failure and damage to buried telecommunications equipment and lines or damage to site foundations. High hazard intensity is defined as 25 percent probability or greater because the Hazus software does not differentiate for probabilities larger than that.

A refinement for the fragility of buried fiber optic line in liquefaction-susceptible soils is informed by Sakaki and others (2014). They found damage rates of 3 and 1 percent

Table 5. Liquefaction and landslide probability hazard intensity ranges for the HayWired scenario mainshock in the San Francisco Bay region, California.

[Probability ranges from Jones and others (this volume). %, percent]

Hazard intensity	Probability range (%)
High liquefaction or landslide hazard	≥25
Moderate liquefaction or landslide hazard	5 to <25
Low liquefaction or landslide hazard	>0 to <5

for old standard fiber optic conduit in weak ground with 90 centimeters per second (cm/s) peak ground velocity (PGV) and with 30–90 cm/s PGV, respectively. These conditions are mapped for fiber optic line, although the GeoTel data does not distinguish between aerial and buried cables.

Fire Exposure

In the HayWired scenario, fire density is measured as the ratio of the burned building floor area to developed land area in an approximated fire station primary response area (delineated as a Voronoi area[10]) (Jones and others, this volume). Because land area in suburban tracts tends to be much larger than building area, fire density ranges in table 6 are small numbers.

Aftershock Exposure

The potential cumulative impact of aftershock shaking on infrastructure is mapped as an overlay of the number of times that aftershock shaking meets or exceeds 25 percent of the ground motion that appears in the design maps of the IBC, a lower bound for a moderate level of shaking. Further explanation is provided by Jones and others (this volume).

Collocation of Fiber Optic Lines on Bridges

Fiber optic lines collocated on heavily damaged California Department of Transportation bridges raises issues of potential collateral damage and coordination of repairs. The California Department of Transportation's bridge impact assessment is documented in appendix 5 of Jones and others (this volume). We do not know what precautions have been taken to protect fiber optic lines that run on bridges in a medium-high and high potential impact state from HayWired ground motions. Hart and others (1991) analyzed a fiber optic line affected by the 1989 Loma Prieta earthquake and found that the armored cable survived a bridge collapse, but fiber breaks from stress occurred where there were defects in the glass produced by fabrication or installation.

The California Department of Transportation does not have a record of infrastructure on its bridges. Using GIS, we located bridges within 50 meters of fiber optic lines and used satellite imagery to confirm that 50 meters selected the wider bridges. Next, we used the imagery to establish whether fiber optic line was running along the bridge (parallel to the bridge); bridges that had fiber optic line running under the bridge (for example, perpendicular to the bridge) were removed.

Functionality of Public Safety Answering Points

The functionality of public safety answering points (PSAPs) on day one, the first day after the mainshock earthquake, is estimated using Hazus damage results for the public safety facilities (for example, fire or police) (D. Bausch, Federal Emergency Management Agency, written commun., 2014)[11] in the same locations. The functionalities of other PSAPs with locations not found in the Hazus inventory were assigned a functionality range using the Hazus results for public safety facilities that had the closest hazard intensity profile for shaking and liquefaction.

Table 6. Fire hazard thresholds for the HayWired scenario mainshock in the San Francisco Bay region, California.

[Thresholds from Jones and others (this volume). Fire density refers to burned building square footage (Scawthorn, 2018) relative to the developed area containing the fires.]

Hazard intensity	Fire density range
High fire hazard	≥0.023
Moderate fire hazard	0.0085 to <0.023
Low fire hazard	>0 to <0.0085

HayWired Hazard Exposure and Damage Results

Central Offices and Wireless Switch Centers

The results of the HayWired scenario mainshock shaking damage estimation for central offices are shown in figure 8*A*. There are 5 red-tagged central offices that have one to four carriers in any one central office, such that there are 11 instances of carriers affected by a red-tagged central office (table 7). There are 9 yellow-tagged central offices involving 22 instances of carriers. These may be conservative assessments because AT&T reports that they have strengthened many facilities since the 1989 Loma Prieta earthquake (Lifelines Council, 2014), and therefore central offices could exceed the moderate-code assumption. Even so, unanchored equipment could turn over at any of the yellow- and red-tagged sites.

No central offices or wireless switches are found in the Hayward Fault trace zone of uncertainty. However, figure 8*B* depicts potential damage to central offices from liquefaction (and possible flooding) that may have been unknown at the time of the original siting of the central office. Three additional central offices, not shown to be red or yellow tagged from shaking, are located in high liquefaction probability (25 percent or greater) areas.

Furthermore, figures 8*B* and 8*C* show that among the five potentially red-tagged central offices, four of these offices are also subjected to a low probability (less than 5 percent) of landslide initiation, four are in areas with moderate liquefaction probability (between 5 and 25 percent), and two are exposed to the highest level of burned building density. Five of the yellow-tagged offices are also in areas with moderate liquefaction probability.

None of the wireless switching centers are indicated to be yellow or red tagged, or located in a high probability area for liquefaction, landslide, or fire; eleven are located in areas with moderate liquefaction (including four each in San Francisco and Santa Clara Counties) (fig. 9; table 8). Figures 8*D* and 9*D* assign the maximum level of hazard affecting each central office and each wireless switching center, respectively.

[10]A Voronoi area is a polygon whose sides are equidistant between the point the Voronoi area is centered around and any neighboring points. The Voronoi areas around fire stations are mapped in Scawthorn (2018).

[11]This Hazus run used HayWired mainshock shaking data and default liquefaction calculations in Hazus.

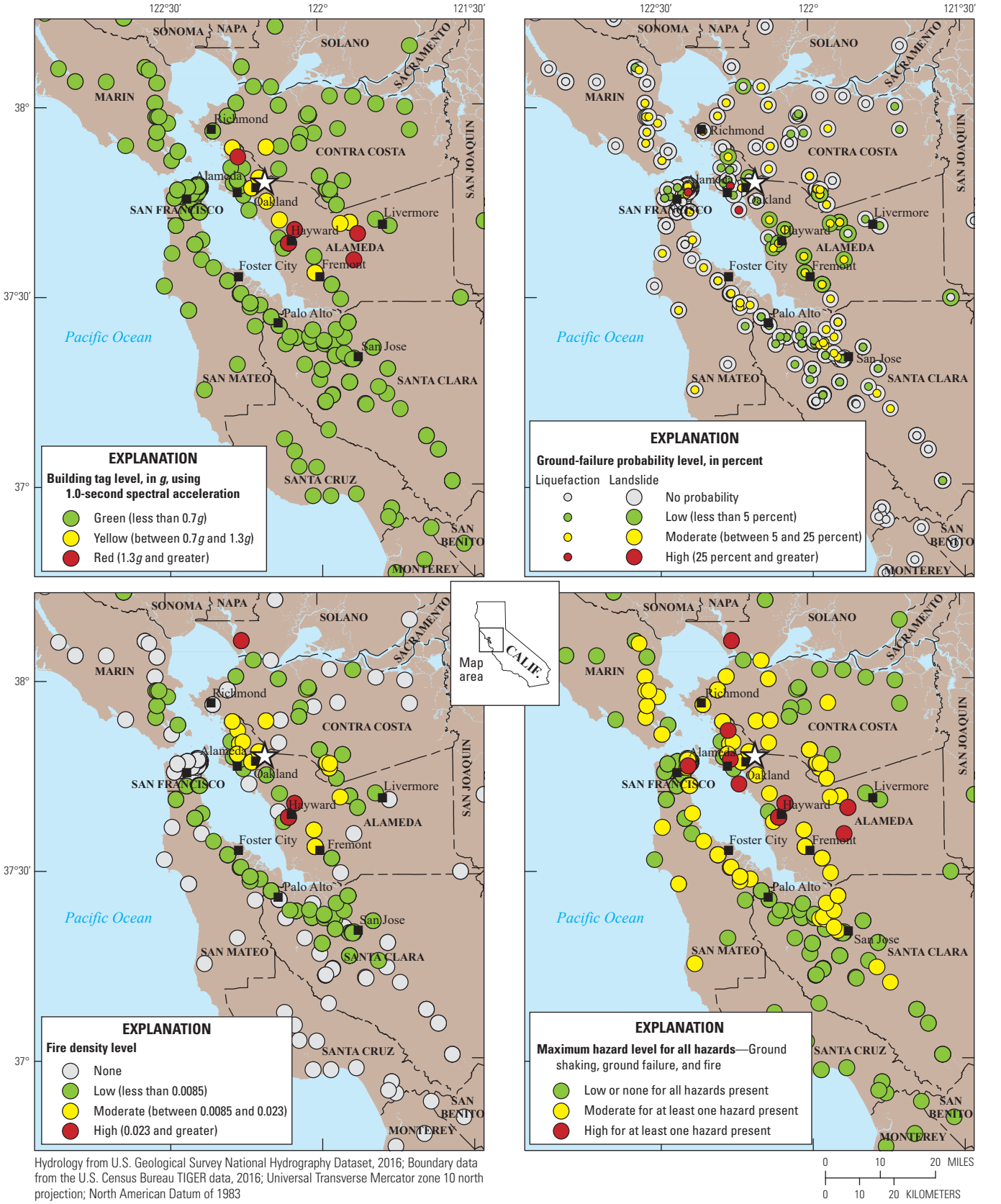
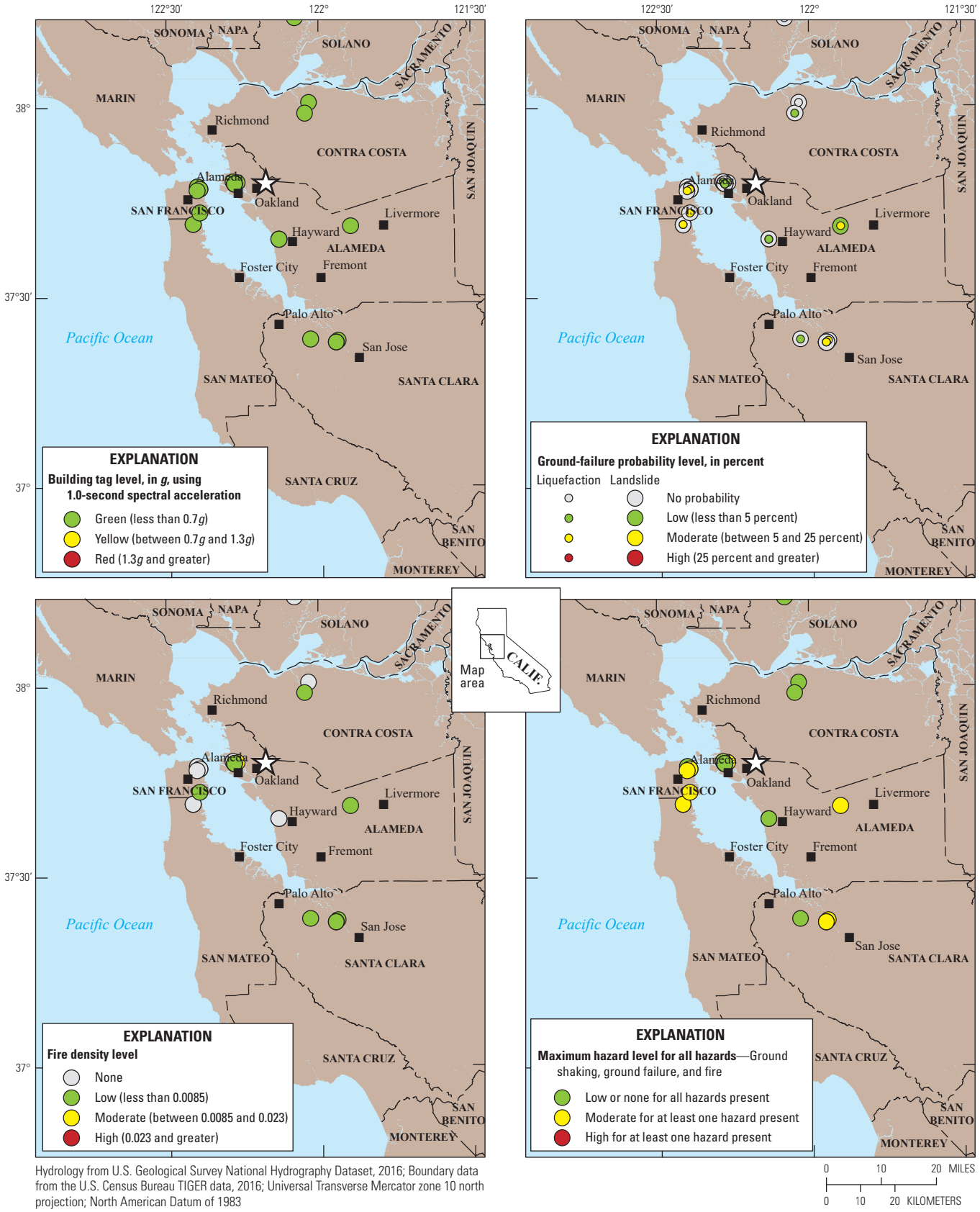


Figure 8. Maps showing damage and exposure to HayWired scenario mainshock hazards for central offices in the San Francisco Bay region, California. *A*, Map of potential building tagging from shaking for central offices assuming moderate code (overturning of unanchored equipment also possible in yellow-tagged and red-tagged buildings). *B*, Map of central office exposure to ground-failure hazards (liquefaction and landslide). *C*, Map of central office exposure to fire following earthquake hazards (represented by fire density level—burned-building square footage relative to the developed area containing the fires). *D*, Map of central offices affected by maximum level of hazard from shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016; Boundary data from the U.S. Census Bureau TIGER data, 2016; Universal Transverse Mercator zone 10 north projection; North American Datum of 1983

Figure 9. Maps showing damage and exposure to HayWired scenario mainshock hazards for wireless switches in the San Francisco Bay region, California. *A*, Map of potential building tagging from shaking for wireless switches assuming moderate code (overturning of unanchored equipment also possible in yellow-tagged and red-tagged buildings). *B*, Map of wireless switch exposure to ground-failure hazards (liquefaction and landslide). *C*, Map of wireless switch exposure to fire following earthquake hazards (represented by fire density level—burned-building square footage relative to the developed area containing the fires). *D*, Map of wireless switches affected by maximum level of hazard from shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.

Table 7. Counts by county of carriers in central offices that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Building tag level[1]			Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[2]			
	Green tag	Yellow tag	Red tag	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	34	20	11	9	21	32	3	31	34	0	0	8	22	28	7	0	9	42	14
Contra Costa	48	2	0	12	9	29	0	43	7	0	0	14	26	10	0	0	19	31	0
Marin	29	0	0	11	5	13	0	29	0	0	0	18	11	0	0	0	16	13	0
Merced	19	0	0	19	0	0	0	19	0	0	0	19	0	0	0	0	19	0	0
Monterey	29	0	0	29	0	0	0	29	0	0	0	29	0	0	0	0	29	0	0
Napa	12	0	0	8	4	0	0	12	0	0	0	12	0	0	0	0	12	0	0
Sacramento	100	0	0	100	0	0	0	100	0	0	0	100	0	0	0	0	100	0	0
San Benito	3	0	0	3	0	0	0	3	0	0	0	3	0	0	0	0	3	0	0
San Francisco	85	0	0	17	27	39	2	85	0	0	0	70	15	0	0	0	44	39	2
San Joaquin	56	0	0	56	0	0	0	56	0	0	0	56	0	0	0	0	56	0	0
San Mateo	33	0	0	11	1	21	0	33	0	0	0	8	25	0	0	0	12	21	0
Santa Clara	98	0	0	16	66	16	0	98	0	0	0	42	56	0	0	0	82	16	0
Santa Cruz	11	0	0	11	0	0	0	11	0	0	0	11	0	0	0	0	11	0	0
Solano	11	0	0	8	2	1	0	11	0	0	0	9	0	0	2	0	8	1	2
Sonoma	34	0	0	34	0	0	0	34	0	0	0	31	3	0	0	0	34	0	0
Stanislaus	26	0	0	26	0	0	0	26	0	0	0	26	0	0	0	0	26	0	0
Yolo	14	0	0	14	0	0	0	14	0	0	0	14	0	0	0	0	14	0	0

[1]Building tag level for central offices is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 2.

[2]Maximum hazard class provides the number of carriers in central offices and mobile switching centers where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Table 8. Counts by county of wireless switches that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Building tag level[1]			Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[2]			
	Green tag	Yellow tag	Red tag	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	8	0	0	0	7	1	0	7	1	0	0	3	4	1	0	0	6	2	0
Contra Costa	2	0	0	1	1	0	0	2	0	0	0	1	1	0	0	0	2	0	0
Marin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Merced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Monterey	5	0	0	5	0	0	0	5	0	0	0	5	0	0	0	0	5	0	0
Napa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sacramento	7	0	0	7	0	0	0	7	0	0	0	7	0	0	0	0	7	0	0
San Benito	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Francisco	6	0	0	2	0	4	0	6	0	0	0	5	1	0	0	0	2	4	0
San Joaquin	9	0	0	9	0	0	0	9	0	0	0	9	0	0	0	0	9	0	0
San Mateo	2	0	0	0	0	2	0	2	0	0	0	2	0	0	0	0	0	2	0
Santa Clara	5	0	0	0	1	4	0	5	0	0	0	0	5	0	0	0	1	4	0
Santa Cruz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solano	1	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0
Sonoma	1	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0
Stanislaus	2	0	0	2	0	0	0	2	0	0	0	2	0	0	0	0	2	0	0
Yolo	4	0	0	4	0	0	0	4	0	0	0	4	0	0	0	0	4	0	0

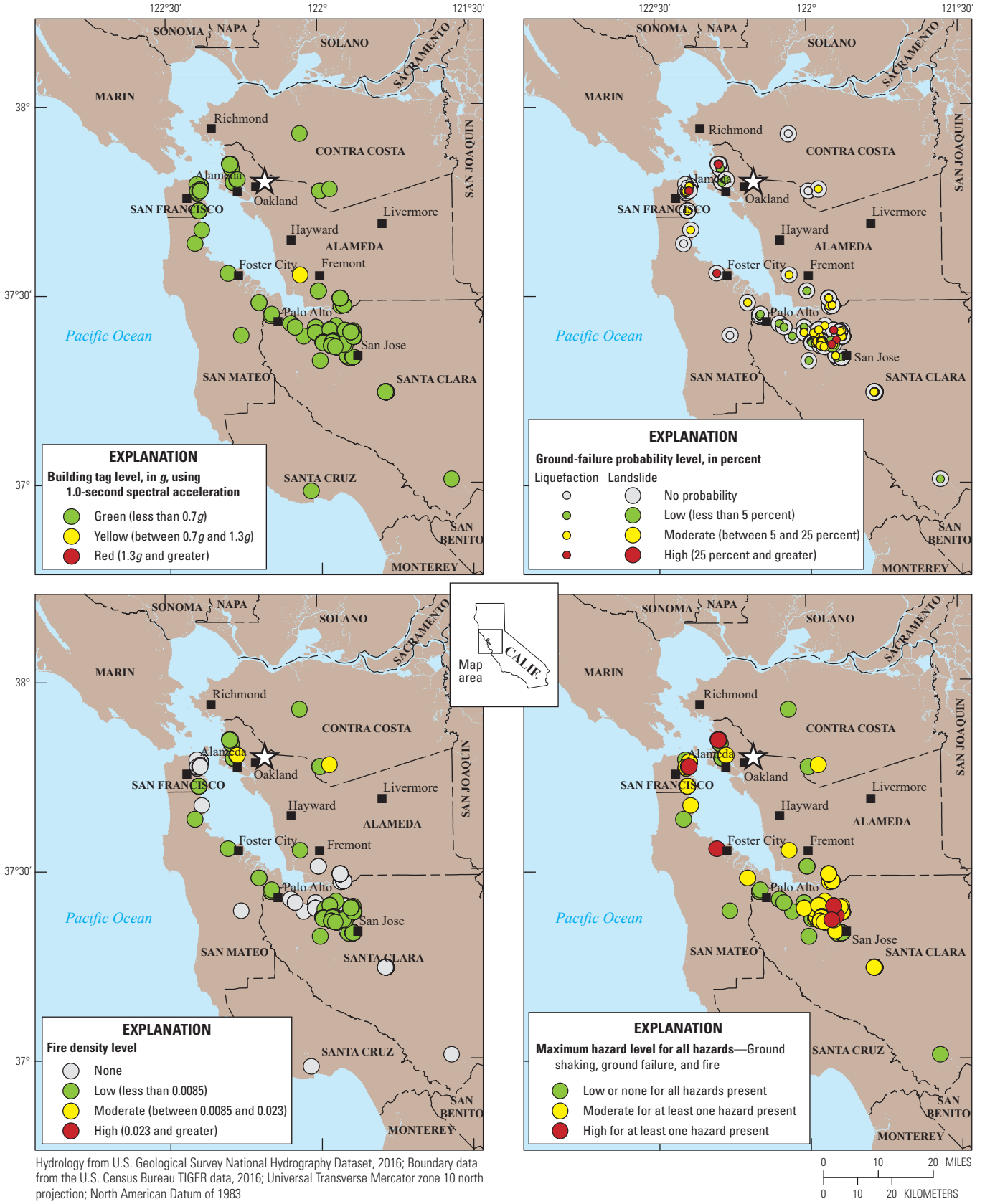
[1]Building tag level for wireless switches is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 2.

[2]Maximum hazard class provides the number of wireless switches where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Data Centers

No data centers are located in the Hayward Fault trace zone of uncertainty and only one data center is potentially yellow tagged from HayWired scenario mainshock shaking assuming it is built to moderate code (fig. 10*A*; table 9). Data centers are less exposed to fire following earthquake in the HayWired scenario; three are in areas with a moderate density of burned buildings (fig. 10*C*). One of these data centers is located on the east side of the foothills.

A potential hazard for data centers appears to be liquefiable soils, in San Francisco and Santa Clara Counties in particular (fig. 10*B*). Also, data centers are more exposed to repeated moderate level of shaking from HayWired scenario aftershocks than central offices (Jones and others, this volume). Each shaking incident is not heavy enough for yellow- or red-tag level of damage, but the cumulative effect of multiple events is unknown.



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016; Boundary data from the U.S. Census Bureau TIGER data, 2016; Universal Transverse Mercator zone 10 north projection; North American Datum of 1983

Figure 10. Maps showing damage and exposure to HayWired scenario mainshock hazards for data centers in the San Francisco Bay region, California. *A*, Map of potential building tagging from shaking for data centers assuming moderate code (overturning of unanchored equipment also possible in yellow-tagged and red-tagged buildings). *B*, Map of data center exposure to ground-failure hazards (liquefaction and landslide). *C*, Map of data center exposure to fire following earthquake hazards (represented by fire density level—burned-building square footage relative to the developed area containing the fires). *D*, Map of data centers affected by maximum level of hazard from shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.

Table 9. Counts by county of providers in data centers that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Building tag level[1]			Liquefaction exposure			Landslide exposure			Fire exposure			Maximum hazard class[2]		
	Green tag	Yellow tag	Red tag	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	36	1	0	0	12	23	2	37	0	0	0	25	10	2	0	0	10	25	2
Contra Costa	4	0	0	3	0	1	0	4	0	0	0	1	2	1	0	0	3	1	0
Marin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Merced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Monterey	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Napa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sacramento	24	0	0	24	0	0	0	24	0	0	0	24	0	0	0	24	24	0	0
San Benito	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Francisco	43	0	0	1	22	18	2	43	0	0	0	32	11	0	0	0	23	18	2
San Joaquin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Mateo	6	0	0	2	0	3	1	6	0	0	0	2	4	0	0	0	2	3	1
Santa Clara	305	0	0	0	171	128	6	304	1	0	0	45	260	0	0	0	171	128	6
Santa Cruz	1	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0
Solano	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sonoma	2	0	0	2	0	0	0	2	0	0	0	2	0	0	0	0	2	0	0
Stanislaus	2	0	0	2	0	0	0	2	0	0	0	2	0	0	0	0	2	0	0
Yolo	4	0	0	4	0	0	0	4	0	0	0	4	0	0	0	0	4	0	0

[1]Building tag level for data centers is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 2.

[2]Maximum hazard class provides the number of providers in data centers where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Cellular Sites

GeoTel data locate thousands of free-standing cellular sites (SSTs, GTs, and MPs) and rooftop towers or building-mounted antennas in the San Francisco Bay region. In urban areas, rooftop towers and building-mounted antennas tend to outnumber antennas on towers and monopoles. Table 10 shows the distribution of supporting structures throughout the San Francisco Bay region.

Free-Standing Towers

We find that wind load designs for large towers (SSTs and GTs) resist HayWired mainshock shaking (fig. 11*A*), but the structures may not be immune to liquefaction hazards (table 11; fig. 11*B*). There are cellular sites in high liquefaction probability areas on both sides of San Francisco Bay. Unlike the central offices, wireless switches, and data centers, several SSTs or GTs are in moderate landslide probability areas (fig. 11*B*), likely a result of siting in hilly areas (for height). HayWired fire following earthquake hazards threaten a cluster of SSTs or GTs in the north Richmond area (fig. 11*C*). The maximum level hazard affecting these sites are shown in figure 11*D*—any equipment that is not installed or maintained to survive seismic events could be vulnerable within a SA (1.0 second, 5 percent) of 0.7*g*, shown by the pink area.

Table 10. Counts by county of carriers at different types of cellular sites in the San Francisco Bay region, California.

County	Self-supporting or guyed towers	Monopoles	Rooftop towers and building-mounted antennas
Alameda	40	302	820
Contra Costa	87	201	394
Marin	11	54	92
Merced	52	65	127
Monterey	35	137	168
Napa	11	42	44
Sacramento	45	375	527
San Benito	8	21	26
San Francisco	5	15	268
San Joaquin	56	195	252
San Mateo	23	200	473
Santa Clara	31	403	1,094
Santa Cruz	7	55	63
Solano	28	123	177
Sonoma	15	144	194
Stanislaus	17	190	161
Yolo	15	73	85

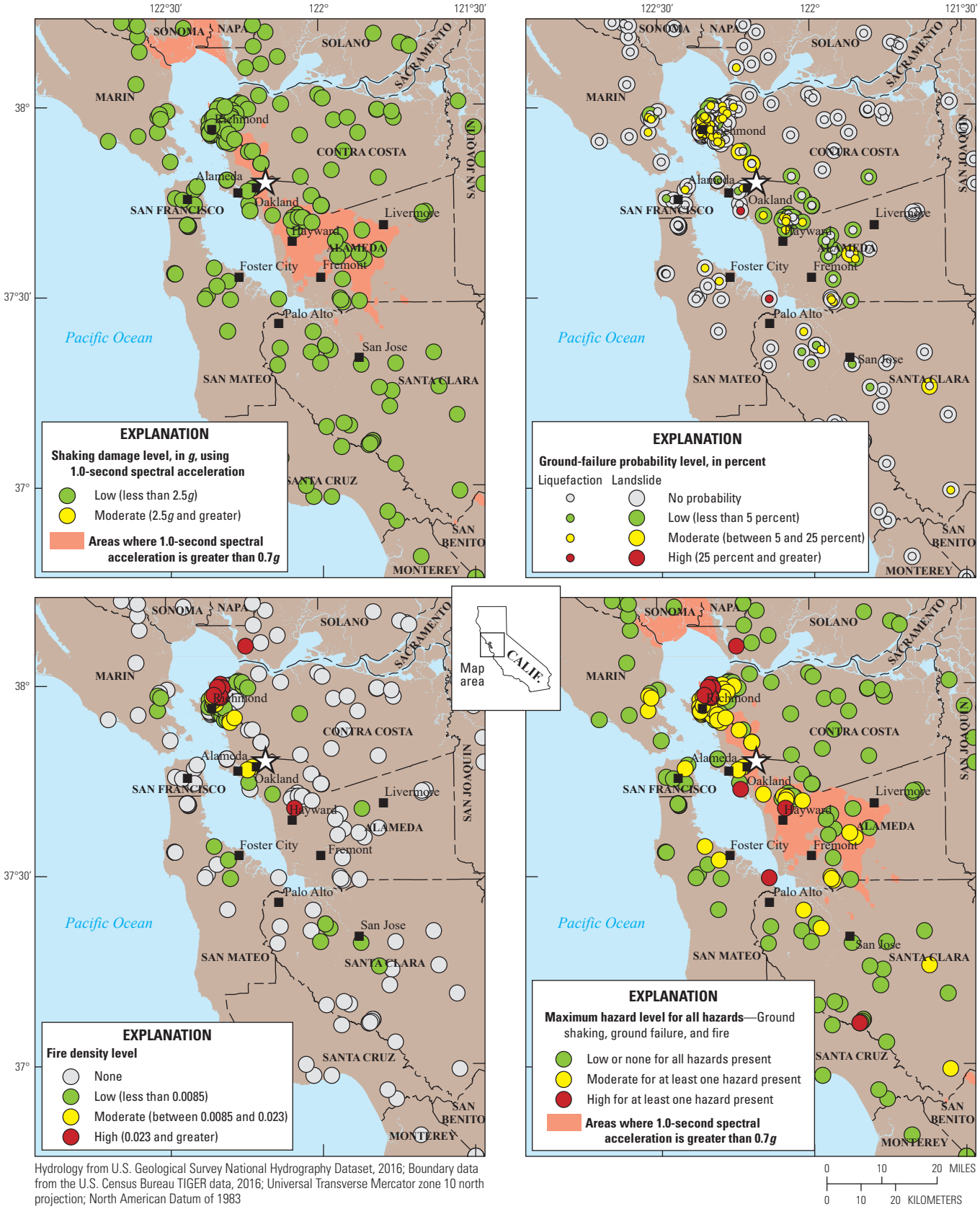


Figure 11. Maps showing damage and exposure to HayWired scenario mainshock hazards for self-supporting towers (SST) and guyed towers (GT) in the San Francisco Bay region, California. *A*, Map of potential damage to SSTs and GTs from shaking (overturning of unanchored equipment also possible in shaded areas). *B*, Map of SST and GT exposure to ground-failure hazards (liquefaction and landslide). *C*, Map of SST and GT exposure to fire following earthquake hazards (represented by fire density level—the burned-building square footage relative to the developed area containing the fires). *D*, Map of SST and GT affected by maximum level of hazard from shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.

Table 11. Counts by county of carriers on self-supporting towers (SST) and guyed towers (GT) that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Shaking hazard level[1]			Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[2]			
	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	40	0	0	24	4	11	1	14	24	2	0	34	3	2	1	0	25	13	2
Contra Costa	87	0	0	48	0	39	0	69	16	2	0	50	21	9	7	0	40	40	7
Marin	11	0	0	8	0	3	0	10	1	0	0	8	3	0	0	0	8	3	0
Merced	52	0	0	52	0	0	0	52	0	0	0	52	0	0	0	0	52	0	0
Monterey	35	0	0	35	0	0	0	35	0	0	0	35	0	0	0	0	35	0	0
Napa	11	0	0	10	1	0	0	11	0	0	0	11	0	0	0	0	11	0	0
Sacramento	45	0	0	45	0	0	0	45	0	0	0	45	0	0	0	0	45	0	0
San Benito	8	0	0	8	0	0	0	8	0	0	0	8	0	0	0	0	8	0	0
San Francisco	5	0	0	3	1	1	0	5	0	0	0	5	0	0	0	0	4	1	0
San Joaquin	56	0	0	56	0	0	0	56	0	0	0	56	0	0	0	0	56	0	0
San Mateo	23	0	0	20	0	2	1	23	0	0	0	20	3	0	0	0	20	2	1
Santa Clara	31	0	0	22	6	3	0	29	0	1	1	25	6	0	0	0	26	4	1
Santa Cruz	7	0	0	7	0	0	0	7	0	0	0	7	0	0	0	0	7	0	0
Solano	28	0	0	27	0	1	0	28	0	0	0	27	0	0	1	0	27	0	1
Sonoma	15	0	0	15	0	0	0	15	0	0	0	15	0	0	0	0	15	0	0
Stanislaus	17	0	0	17	0	0	0	17	0	0	0	17	0	0	0	0	17	0	0
Yolo	15	0	0	15	0	0	0	15	0	0	0	15	0	0	0	0	15	0	0

[1]Shaking hazard level for SSTs and GTs is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 4.

[2]Maximum hazard class provides the number of carriers on SSTs and GTs where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

A conservative shaking-damage assessment that assumes MPs do not adhere to some design standards (for example, load or distribution of it) is shown in figure 12*A*. Clusters of MPs exposed to strong shaking exist in the Hayward area and near Berkeley in Alameda County, as well as in southern Sonoma County adjacent to San Pablo Bay. Liquefaction and landslide hazards expand the areas for potential damage to MPs along the margins of San Francisco Bay and into the region's foothills (fig. 12*B*). Exposure to fire following earthquake overlaps and expands the conservative MP shaking-damage estimate (fig. 12*C*). In all, the maximum hazard level for each MP is shown in figure 12*D* and table 12. Any equipment that is not installed or maintained to survive seismic events could be vulnerable within a SA (1.0 second, 5 percent) of 0.7*g*, shown by the pink area.

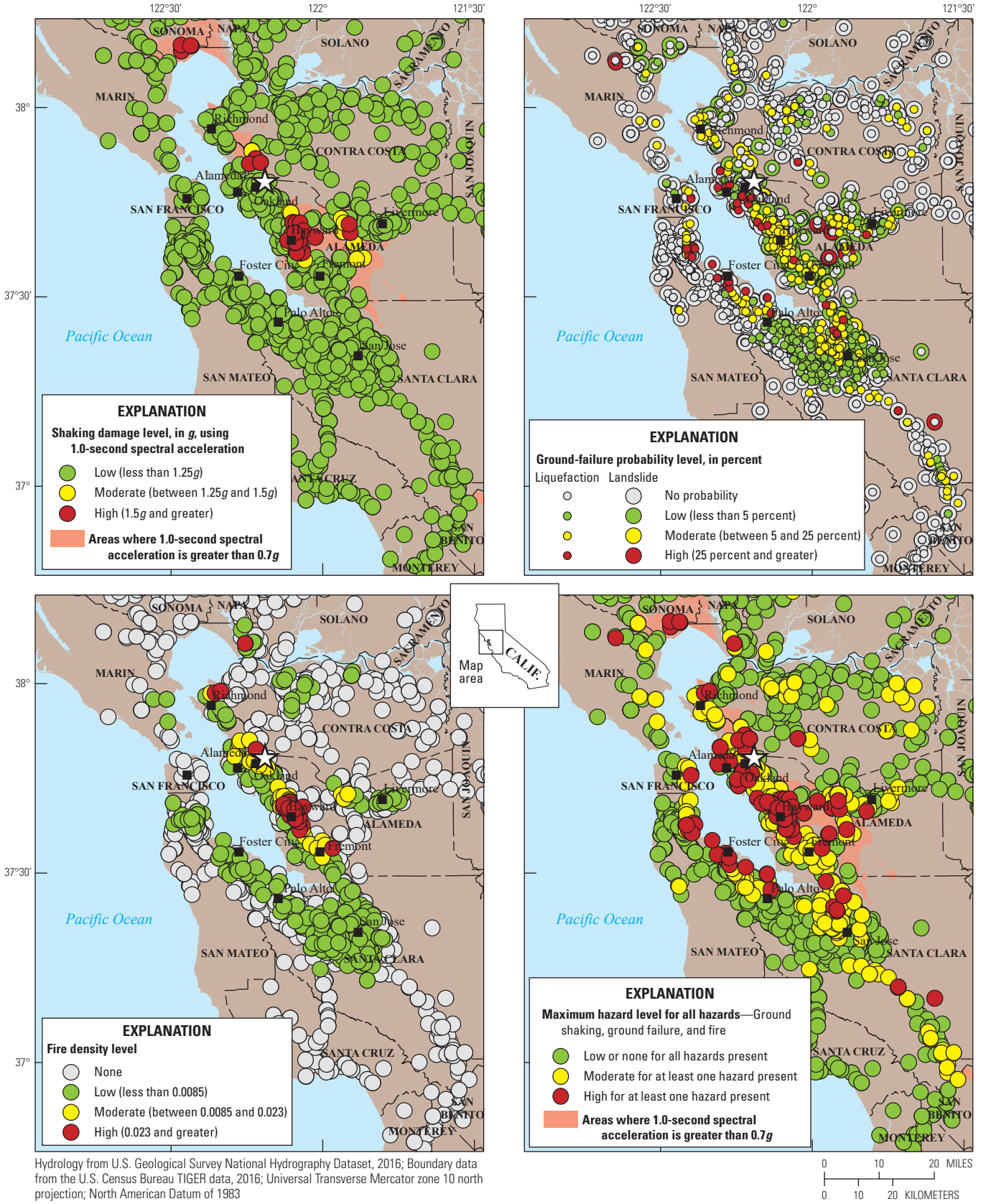


Figure 12. Maps showing damage and exposure to HayWired scenario mainshock hazards for monopoles (MPs) in the San Francisco Bay region, California. *A*, Map of potential damage to vulnerable MPs from shaking (overturning of unanchored equipment also possible in shaded areas). *B*, Map of MP exposure to ground-failure (liquefaction and landslide) hazards. *C*, Map of MP exposure to fire following earthquake hazards (represented by fire density level—the burned-building square footage relative to the developed area containing the fires). *D*, Map of MPs affected by maximum level of hazard from shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.

Table 12. Counts by county of carriers on monopoles (MPs) that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Shaking hazard level[1]			Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[2]			
	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	251	18	33	99	54	120	29	143	147	7	5	126	105	41	30	0	114	107	81
Contra Costa	194	2	5	136	21	42	2	179	19	3	0	165	33	1	2	0	149	43	9
Marin	54	0	0	43	1	10	0	44	9	0	1	50	4	0	0	0	43	10	1
Merced	65	0	0	65	0	0	0	65	0	0	0	65	0	0	0	0	65	0	0
Monterey	137	0	0	137	0	0	0	137	0	0	0	137	0	0	0	0	137	0	0
Napa	42	0	0	42	0	0	0	42	0	0	0	42	0	0	0	0	42	0	0
Sacramento	375	0	0	375	0	0	0	375	0	0	0	375	0	0	0	0	375	0	0
San Benito	21	0	0	20	0	1	0	21	0	0	0	21	0	0	0	0	20	1	0
San Francisco	15	0	0	7	3	4	1	15	0	0	0	15	0	0	0	0	10	4	1
San Joaquin	195	0	0	195	0	0	0	195	0	0	0	195	0	0	0	0	195	0	0
San Mateo	200	0	0	143	5	33	19	200	0	0	0	130	70	0	0	0	148	33	19
Santa Clara	403	0	0	65	238	90	10	378	22	2	1	204	199	0	0	0	300	92	11
Santa Cruz	55	0	0	55	0	0	0	55	0	0	0	55	0	0	0	0	55	0	0
Solano	123	0	0	113	3	7	0	123	0	0	0	113	8	0	2	0	116	5	2
Sonoma	139	0	5	141	3	0	0	141	3	0	0	144	0	0	0	0	139	0	5
Stanislaus	190	0	0	190	0	0	0	190	0	0	0	190	0	0	0	0	190	0	0
Yolo	73	0	0	73	0	0	0	73	0	0	0	73	0	0	0	0	73	0	0

[1]Shaking hazard level for MPs is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 4.

[2]Maximum hazard class provides the number of carriers on MPs where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Rooftop Towers and Building-Mounted Antennas

A conservative estimate of damages or restricted access to rooftop towers and building-mounted antennas and equipment using building damage estimates (table 13; fig. 13*A*) aligns with the areas that were highlighted for potential damages to MPs.

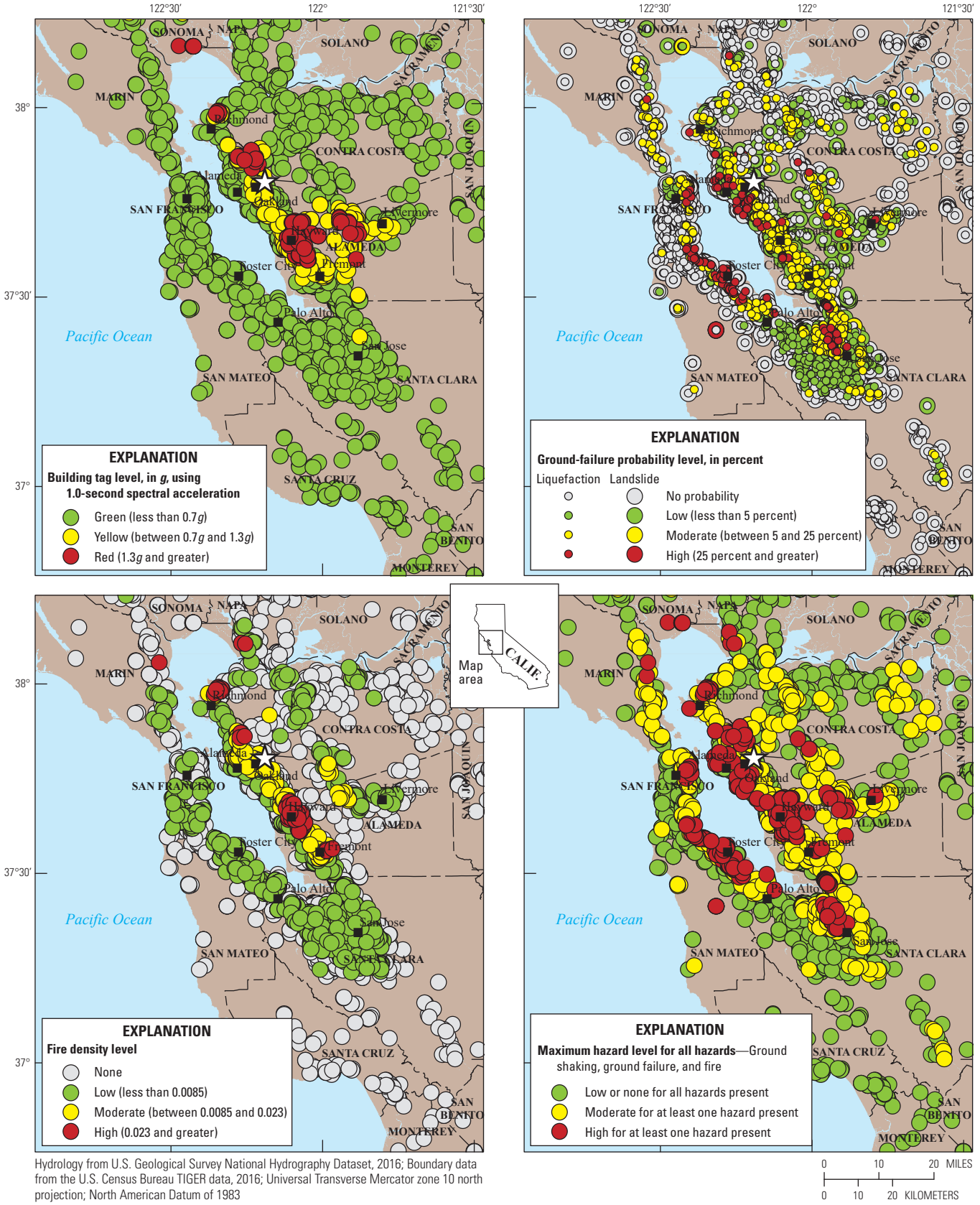


Figure 13. Maps showing damage and exposure to HayWired scenario mainshock hazards for rooftop towers and building-mounted antennas in the San Francisco Bay region, California. *A*, Map of potential damage to rooftop towers and building-mounted antennas from shaking (overturning of unanchored equipment also possible in yellow-tagged and red-tagged buildings). *B*, Map of rooftop tower and building-mounted antenna exposure to ground-failure (liquefaction and landslide) hazards. *C*, Map of rooftop tower and building-mounted antenna exposure to fire following earthquake hazards (represented by fire density level—the burned-building square footage relative to the developed area containing the fires). *D*, Map of rooftop towers and building-mounted antennas affected by maximum level of hazard for shaking, ground failure, and fire. White star shows the mainshock epicenter. *g*, acceleration due to gravity.

Table 13. Counts by county of carriers on rooftop towers and building-mounted antennas that are exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting them.

County	Building tag level[1]			Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[2]			
	Green tag	Yellow tag	Red tag	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	448	229	143	125	199	408	88	446	370	4	0	263	317	181	59	0	194	383	243
Contra Costa	363	15	16	205	68	118	3	343	46	4	1	258	107	15	14	0	242	126	26
Marin	92	0	0	36	9	46	1	89	3	0	0	76	15	0	1	0	44	46	2
Merced	127	0	0	127	0	0	0	127	0	0	0	127	0	0	0	0	127	0	0
Monterey	168	0	0	168	0	0	0	168	0	0	0	168	0	0	0	0	168	0	0
Napa	44	0	0	41	3	0	0	44	0	0	0	44	0	0	0	0	44	0	0
Sacramento	527	0	0	527	0	0	0	527	0	0	0	527	0	0	0	0	527	0	0
San Benito	26	0	0	26	0	0	0	26	0	0	0	26	0	0	0	0	26	0	0
San Francisco	268	0	0	67	82	92	27	268	0	0	0	233	35	0	0	0	149	92	27
San Joaquin	252	0	0	252	0	0	0	252	0	0	0	252	0	0	0	0	252	0	0
San Mateo	473	0	0	207	45	113	108	470	1	0	2	191	282	0	0	0	250	113	110
Santa Clara	1,092	2	0	74	553	389	78	1,070	22	1	1	333	761	0	0	0	623	392	79
Santa Cruz	63	0	0	63	0	0	0	63	0	0	0	63	0	0	0	0	63	0	0
Solano	177	0	0	150	14	11	2	176	1	0	0	164	11	0	2	0	163	10	4
Sonoma	183	4	7	187	7	0	0	185	2	6	1	192	2	0	0	0	182	4	8
Stanislaus	161	0	0	161	0	0	0	161	0	0	0	161	0	0	0	0	161	0	0
Yolo	85	0	0	85	0	0	0	85	0	0	0	85	0	0	0	0	85	0	0

[1]Building tag level for rooftop towers and building-mounted antennas is determined based on 1.0-second spectral acceleration (5 percent damped). Threshold values are in table 2.

[2]Maximum hazard class provides the number of carriers on rooftop antennas and building-mounted antennas where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are shaking damage, landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Summary of Cellular Site Damage Assessment

All potential vulnerabilities for cellular sites are combined in figure 14. The sites are mapped for the maximum assessment from shaking, ground movement (liquefaction and landslide), and fire. It shows concentrations of potential damages from shaking near the Hayward Fault and the Livermore basin, from liquefaction around San Francisco Bay margins and along streams, and from fire spread in Hayward, northern Richmond, and areas in Napa and Solano Counties. There are relatively few exposures of cellular sites to moderate or high landslide probabilities.

Wired Channels

Fiber Optic Lines

Fiber optic lines are mapped against the HayWired scenario fault rupture, liquefaction and landslide probabilities, and fire density in figure 15. Jones and others (this volume) identify 227 incidences of fiber optic lines crossing the Hayward Fault that could be affected by slip and 123 of those incidences are potentially exposed to coseismic slip at the time of the HayWired mainshock. The lengths of fiber optic line exposed to the other hazards are: 1,324 kilometers (km) in areas with liquefaction probability of 25 percent or greater, 830 km in areas with landslide probability of 25 percent or greater, and 663 km in the most densely burned areas. In addition, more than three-quarters of the medium-high or high potential impact bridges appear to carry fiber optic lines—that is, 37 of 51 high potential impact bridges and 50 of 60 medium-high potential impact bridges. Approximately 15 percent of the bridges in the San Francisco Bay region are estimated to carry fiber optic lines—meaning that a disproportionate number of potentially damaged bridges are carrying fiber optic lines.

Tables 14 and 15 show the hazard exposure for interoffice and long-haul fiber optic lines across counties. Notably, most of the landslide exposure involves interoffice fiber optic lines and occurs in Alameda and Contra Costa Counties in particular; in contrast, long-haul fiber optic lines are more exposed to high liquefaction probability and (or) fire density in these counties, and are relatively less exposed to landslides in the region as a whole.

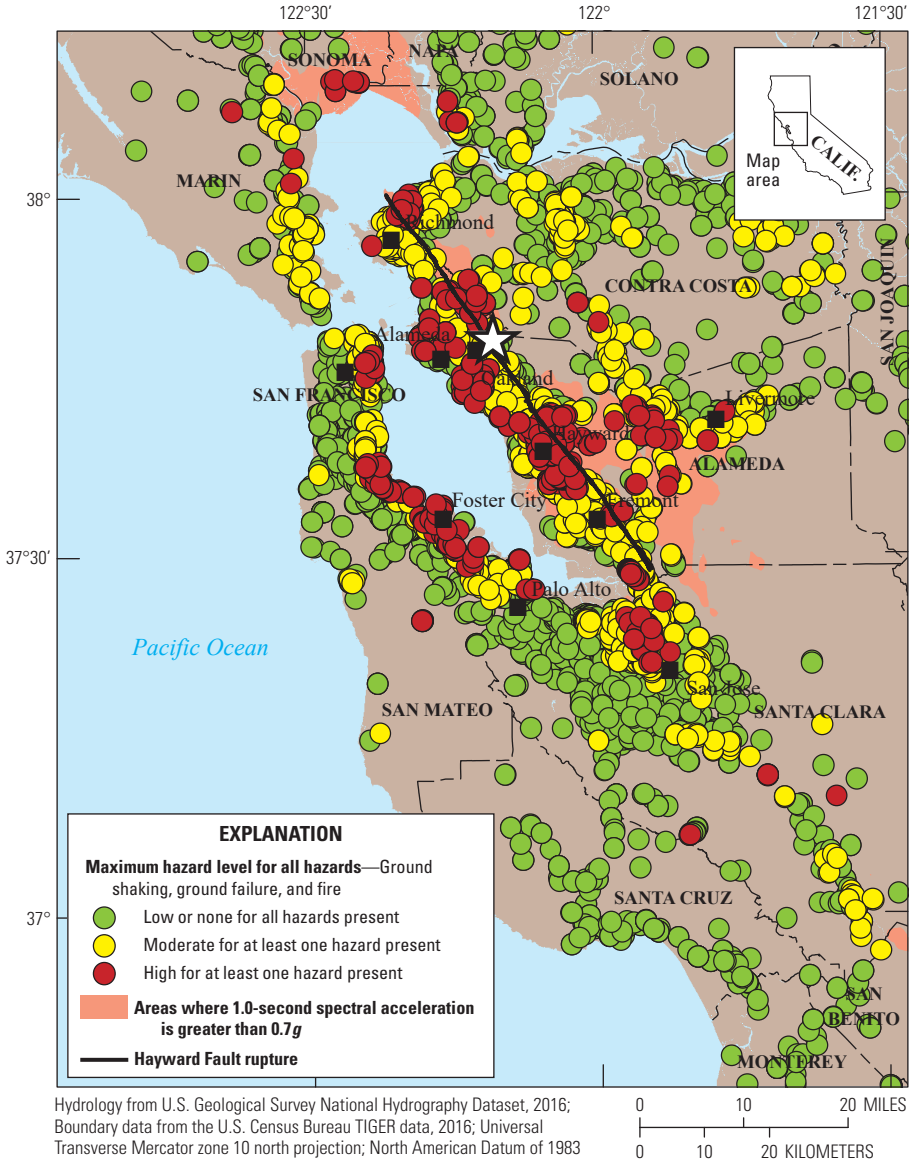


Figure 14. Map showing combined hazards for all types of cellular sites for the HayWired scenario mainshock in the San Francisco Bay region, California. Each cellular site is identified based on the highest level of hazard mapped for shaking, liquefaction and landslide probability, and fire density (burned-building square footage relative to the developed area containing the fires). White star shows the mainshock epicenter. *g*, acceleration due to gravity.

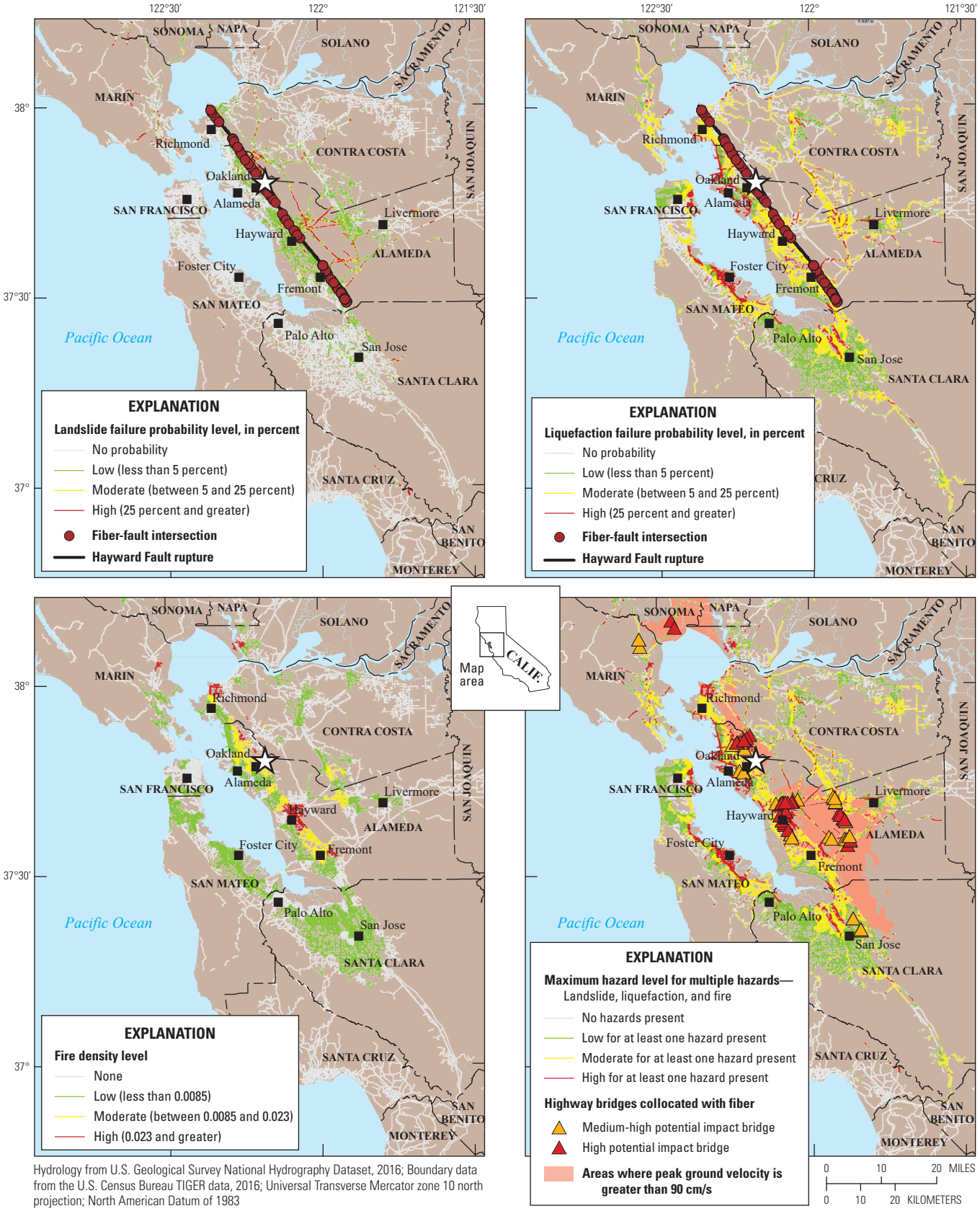


Figure 15. Maps showing the exposure of fiber optic lines to rupture fault crossings, liquefaction and landslide probability, fire density, and affected bridges for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Map of fiber optic line exposure to landslide hazards. *B*, Map of fiber optic line exposure to liquefaction hazards. *C*, Map of fiber optic line exposure to fire density hazards (defined as the burned-building square footage relative to the developed area containing the fires). *D*, Map of bridges classified as medium-high or high potential impact that carry fiber optic lines relative to multiple HayWired scenario mainshock hazards (landslide, liquefaction, and fire density). White star shows the mainshock epicenter. cm/s, centimeters per second.

Table 14. Lengths, in kilometers, of long-haul fiber optic lines, by county, exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting each length of line.

[Values in kilometers]

County	Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[1]			
	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	198	233	789	156	656	691	16	13	403	538	270	164	111	228	707	329
Contra Costa	228	20	210	81	399	138	1	<1	340	99	17	83	111	97	175	156
Marin	9	7	54	0	65	4	<1	0	69	0	0	0	8	8	54	0
Merced	405	0	0	0	405	0	0	0	405	0	0	0	405	0	0	0
Monterey	1,044	0	0	0	1,044	0	0	0	1,044	0	0	0	1,044	0	0	0
Napa	129	<1	27	0	154	2	0	0	154	2	0	0	124	5	27	0
Sacramento	442	0	0	0	442	0	0	0	442	0	0	0	442	0	0	0
San Benito	13	0	0	0	13	0	0	0	13	0	0	0	13	0	0	0
San Francisco	11	1	3	10	24	<1	<1	<1	16	9	0	0	4	8	3	10
San Joaquin	418	0	0	0	418	0	0	0	418	0	0	0	418	0	0	0
San Mateo	43	55	63	7	169	<1	0	0	54	115	0	0	19	79	63	7
Santa Clara	123	232	255	6	596	19	<1	<1	372	244	0	0	120	235	254	7
Santa Cruz	25	<1	0	0	25	0	0	0	25	0	0	0	25	<1	0	0
Solano	436	41	94	<1	569	2	<1	<1	552	12	0	7	424	52	88	7
Sonoma	176	90	<1	0	231	32	4	<1	258	9	0	0	150	113	5	<1
Stanislaus	251	0	0	0	251	0	0	0	251	0	0	0	251	0	0	0
Yolo	320	0	0	0	320	0	0	0	320	0	0	0	320	0	0	0

[1]Maximum hazard class provides the length of long-haul fiber optic lines where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Table 15. Lengths, in kilometers, of interoffice fiber optic lines, by county, exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting each length of line.

[Values in kilometers]

County	Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[1]			
	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	3,085	1,237	2,811	356	3,111	3,409	391	579	4,331	1,642	1,181	336	568	2,421	3,235	1,265
Contra Costa	10,811	1,058	1,391	89	11,250	1,764	142	193	12,374	837	103	35	8,546	2,927	1,558	317
Marin	622	77	309	6	937	39	10	28	733	262	0	19	477	168	316	53
Merced	962	0	0	0	962	0	0	0	962	0	0	0	962	0	0	0
Monterey	1,953	0	0	0	1,953	0	0	0	1,953	0	0	0	1,953	0	0	0
Napa	280	6	3	0	288	<1	<1	<1	285	4	0	0	276	9	3	<1
Sacramento	4,671	0	0	0	4,671	0	0	0	4,671	0	0	0	4,671	0	0	0
San Benito	578	0	<1	0	578	0	0	0	578	0	0	0	578	0	<1	0
San Francisco	542	331	385	129	1,386	<1	<1	<1	1,124	263	0	0	375	498	385	129
San Joaquin	2,078	0	<1	0	2,078	0	0	0	2,078	0	0	0	2,078	0	<1	0
San Mateo	1,027	236	786	299	2,333	16	<1	<1	762	1,587	0	0	462	802	786	300
Santa Clara	367	2,926	1,407	182	4,765	107	3	6	1,694	3,188	0	0	300	2,985	1,409	187
Santa Cruz	1,523	<1	0	0	1,506	8	1	8	1,523	0	0	0	1,505	8	1	8
Solano	951	60	41	3	1,052	3	<1	<1	969	68	0	19	881	117	37	21
Sonoma	1,078	1	<1	0	1,068	9	<1	1	1,048	32	0	0	1,035	42	1	1
Stanislaus	1,326	0	0	0	1,326	0	0	0	1,326	0	0	0	1,326	0	0	0
Yolo	954	0	0	0	954	0	0	0	954	0	0	0	954	0	0	0

[1]Maximum hazard class provides the length of interoffice fiber optic lines where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Applying PGV thresholds for damage rates for old standard fiber optic lines in weak ground (indicated by liquefaction probability), figure 16 maps the lines, which if old, could be more susceptible to damage than newer lines (Sakaki and others, 2014).

- Higher damage rates (for example, 3 percent) for old lines are potentially in areas with PGV greater than 90 cm/s and 25 percent or greater probability of liquefaction (red fiber optic lines) and are in a few spots in Contra Costa and Alameda Counties near the bay margins and streams.
- Damage rates (for example, 1 percent) for old lines are potentially in areas where PGV is moderate (30 to 90 cm/s) and the liquefaction hazard is high (25 percent or greater probability) (pink lines) or where PGV is greater than 90 cm/s and liquefaction hazard is moderate (between 5 and 25 percent probability) (bright yellow lines).

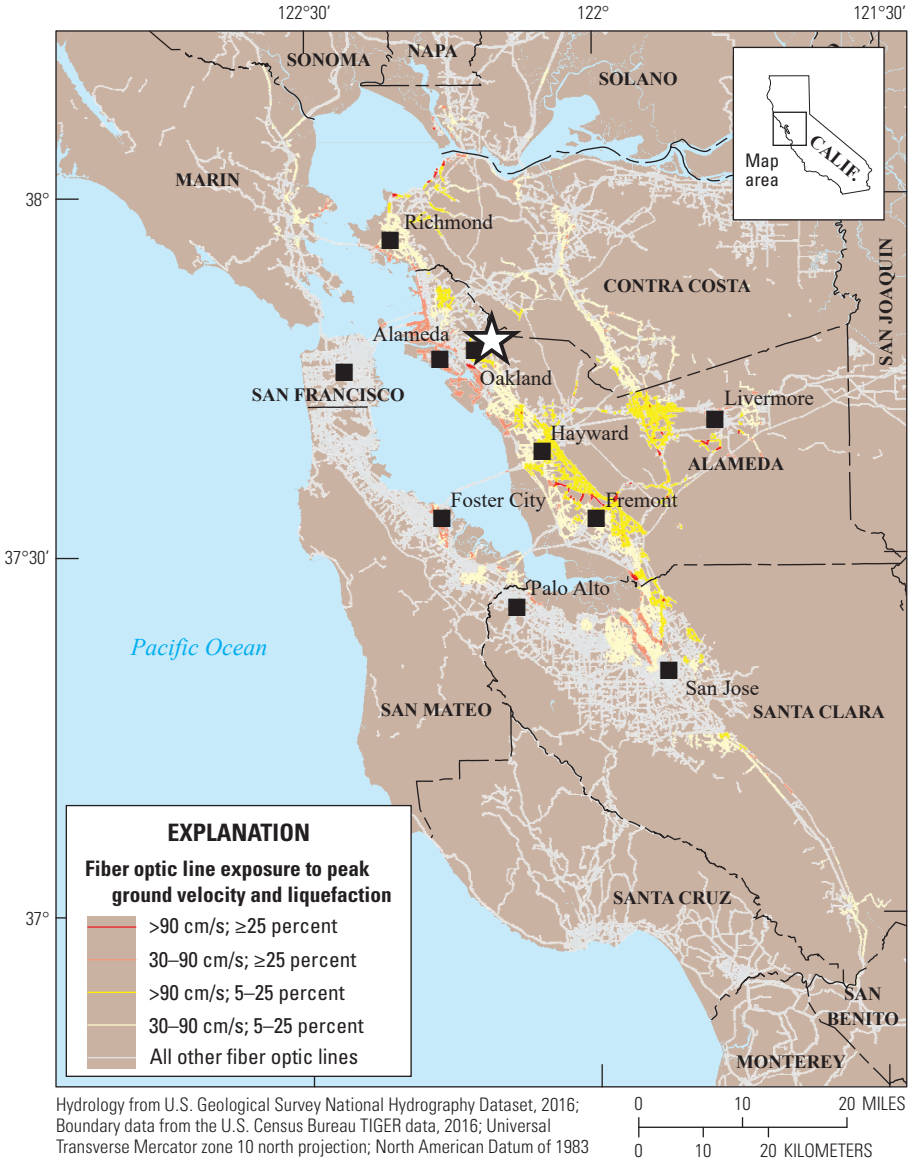


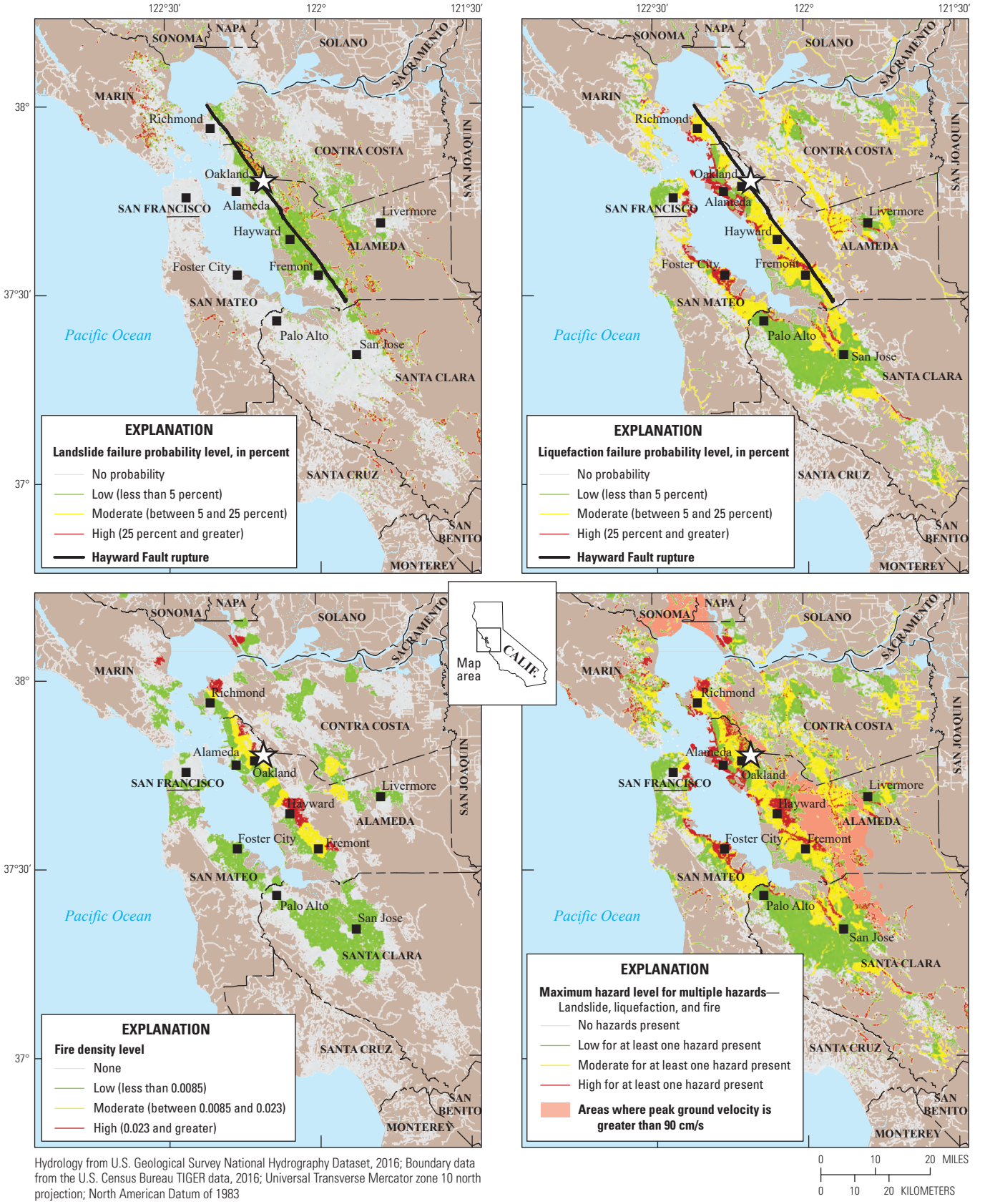
Figure 16. Map of the San Francisco Bay region, California, showing fiber optic line running through HayWired scenario mainshock shaking and liquefaction hazards above thresholds for failure rates for old conduit. Thresholds from Sakaki and others (2014). Thresholds for peak ground velocity are in centimeters per second (cm/s) and liquefaction exposure is given as a percentage. White star shows the mainshock epicenter.

Copper Pair and Coaxial Lines

Where there are surface streets, copper pair and coaxial lines may also be present. Figure 17 and table 16 show the exposure of surface streets to ground movement from fault rupture, liquefaction, and (or) landslides for the HayWired mainshock. There are 424 surface streets crossing the fault, 270 are offset by HayWired coseismic slip, and afterslip may further affect surface street crossings (Jones and others, this volume). There are about 1,500 km (2 percent) of surface streets running through areas with a liquefaction probability of 25 percent or greater for the HayWired mainshock. Another 276 km of surface streets are exposed to HayWired mainshock landslides with a probability of 25 percent or greater and 777 km of surface streets run through the areas with the highest fire density (Jones and others, this volume). The dominant hazard affecting surface streets (as a proxy for copper and coaxial lines) varies across counties: liquefaction in Alameda, San Francisco, San Mateo, and Santa Clara Counties; fire in Contra Costa County; and landslides in Marin County.

Public Safety Answering Points

Table 17 presents results for functionality of facilities hosting public safety answering points (PSAPs) on day one, the first day after the mainshock earthquake. Facilities in Alameda, Contra Costa and Santa Clara Counties have less than 25 percent functionality on day one and as much as 42 percent of Alameda County facilities fall within this low level of functionality. Contra Costa and Alameda Counties do not have any PSAP facilities with more than 75 percent functionality on day one. Some of these facilities are located in high probability liquefaction areas: one in Alameda County and four in San Mateo County. In addition, four facilities that host PSAPs are in the most densely burned building areas in Alameda County.



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016; Boundary data from the U.S. Census Bureau TIGER data, 2016; Universal Transverse Mercator zone 10 north projection; North American Datum of 1983

Figure 17. Maps showing the exposure of surface streets (a proxy for copper and coaxial lines) to liquefaction and landslide probability, fire density, and the maximum hazard exposure for all mapped hazards for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Map of surface street exposure to landslide hazards. *B*, Map of surface street exposure to liquefaction hazards. *C*, Map of surface street exposure to fire density hazards (defined as the burned-building square footage relative to the developed area containing the fires). *D*, Map of surface street exposure relative to multiple HayWired scenario mainshock hazards (landslide, liquefaction, and fire density). White star shows the mainshock epicenter. cm/s, centimeters per second.

Table 16. Lengths, in kilometers, of surface streets, by county, exposed to HayWired scenario mainshock hazards (San Francisco Bay region, California) and the maximum hazard exposure level affecting each route.

County	Liquefaction exposure				Landslide exposure				Fire exposure				Maximum hazard class[1]			
	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High	None	Low	Moderate	High
Alameda	2,114	1,048	3,061	720	3,404	3,293	138	109	2,677	2,121	1,628	518	420	1,830	3,356	1,338
Contra Costa	3,140	961	1,698	79	5,270	570	23	15	4,062	1,459	255	102	1,977	1,882	1,822	197
Marin	1,830	217	437	20	2,302	121	21	58	1,951	503	0	50	1,381	550	445	128
Merced	4,328	0	0	0	4,328	0	0	0	4,328	0	0	0	4,328	0	0	0
Monterey	4,405	0	0	0	4,405	0	0	0	4,405	0	0	0	4,405	0	0	0
Napa	1,208	35	18	0	1,259	2	<1	<1	1,235	27	0	0	1,182	60	19	<1
Sacramento	7,879	0	0	0	7,879	0	0	0	7,879	0	0	0	7,879	0	0	0
San Benito	805	<1	<1	0	805	0	0	0	805	0	0	0	805	<1	<1	0
San Francisco	866	550	169	128	1,710	2	<1	<1	1,248	465	0	0	594	821	170	128
San Joaquin	5,181	0	<1	0	5,181	0	0	0	5,181	0	0	0	5,181	0	<1	0
San Mateo	2,153	227	879	420	3,649	20	3	7	1,890	1,789	0	0	1,369	1,001	881	428
Santa Clara	2,515	4,936	1,417	138	8,519	372	40	75	4,853	4,153	0	0	1,994	5,345	1,455	212
Santa Cruz	2,274	0	0	0	2,256	9	1	7	2,274	0	0	0	2,256	9	1	7
Solano	2,773	177	157	18	3,123	2	<1	<1	2,761	258	0	107	2,491	391	130	113
Sonoma	4,808	38	0	0	4,809	27	6	4	4,773	74	0	0	4,710	127	6	4
Stanislaus	4,291	0	0	0	4,291	0	0	0	4,291	0	0	0	4,291	0	0	0
Yolo	1,913	0	0	0	1,913	0	0	0	1,913	0	0	0	1,913	0	0	0

[1]Maximum hazard class provides the length of surface streets where the maximum hazard exposure level corresponds to the class in the column header. The hazards considered for this set of columns are landslide, liquefaction, and fire. The "none" column counts points not exposed to any of the hazards included in the analysis; the "low" column counts points exposed only to low hazards for any hazards present; the "moderate" column counts points exposed to at least one moderate hazard for any hazards present; and the "high" column counts points exposed to at least one high hazard for any hazards present.

Table 17. Functionality on day one (the first day after the HayWired earthquake scenario mainshock in the San Francisco Bay region, California) of facilities located with public safety answering points (PSAPs) according to Hazus analysis of mainshock shaking and default liquefaction (no groundwater adjustment) at collocated police and fire facilities.

[Data from D. Bausch, Federal Emergency Management Agency, written commun., 2014. PSAPs in alternative locations were assigned a status from the facility with the closest shaking and liquefaction hazard profile. %, percent]

County	Functionality				Percent of facilities with PSAPs that are less than 25% functional
	<25%	25–50%	50–75%	>75%	
Alameda	8	10	1	0	42%
Contra Costa	2	3	6	0	18%
San Francisco	0	1	2	1	0%
San Mateo	0	4	7	2	0%
Santa Clara	1	4	5	3	8%

Exposure to Aftershock Shaking

Aftershocks, which are by definition a smaller magnitude earthquake than the mainshock, can produce shaking intensities greater than the mainshock in localized areas near the aftershock epicenter. There are a few areas where this is the case in the HayWired aftershock sequence (Seligson and others, 2018). We find that the shaking of each aftershock is not intense enough to impair the function of uncompromised central offices, data centers, and unanchored equipment but the cumulative effects are unknown. An area that is hit most often by aftershocks in the HayWired scenario straddles the cities of Menlo Park, Palo Alto, Mountain View, and Sunnyvale in San Mateo and Santa Clara Counties. It also illustrates a case of a cellular tower and fiber optic lines that are exposed to 25 percent or greater probability of liquefaction from the mainshock, where liquefaction could repeat multiple times owing to multiple aftershock events (fig. 18).

Voice and Data Service Restoration

When discussing disaster scenarios, people commonly ask whether phone and internet service will continue working in the aftermath. This sounds like a simple enough question, but a response is very complicated. The physical network of equipment and wired and wireless connections can be mapped (like a roadway system), but the information flows are more difficult to follow (like the routes that cars take). The Applied Technology Council notes that "[w]hile there are performance standards for

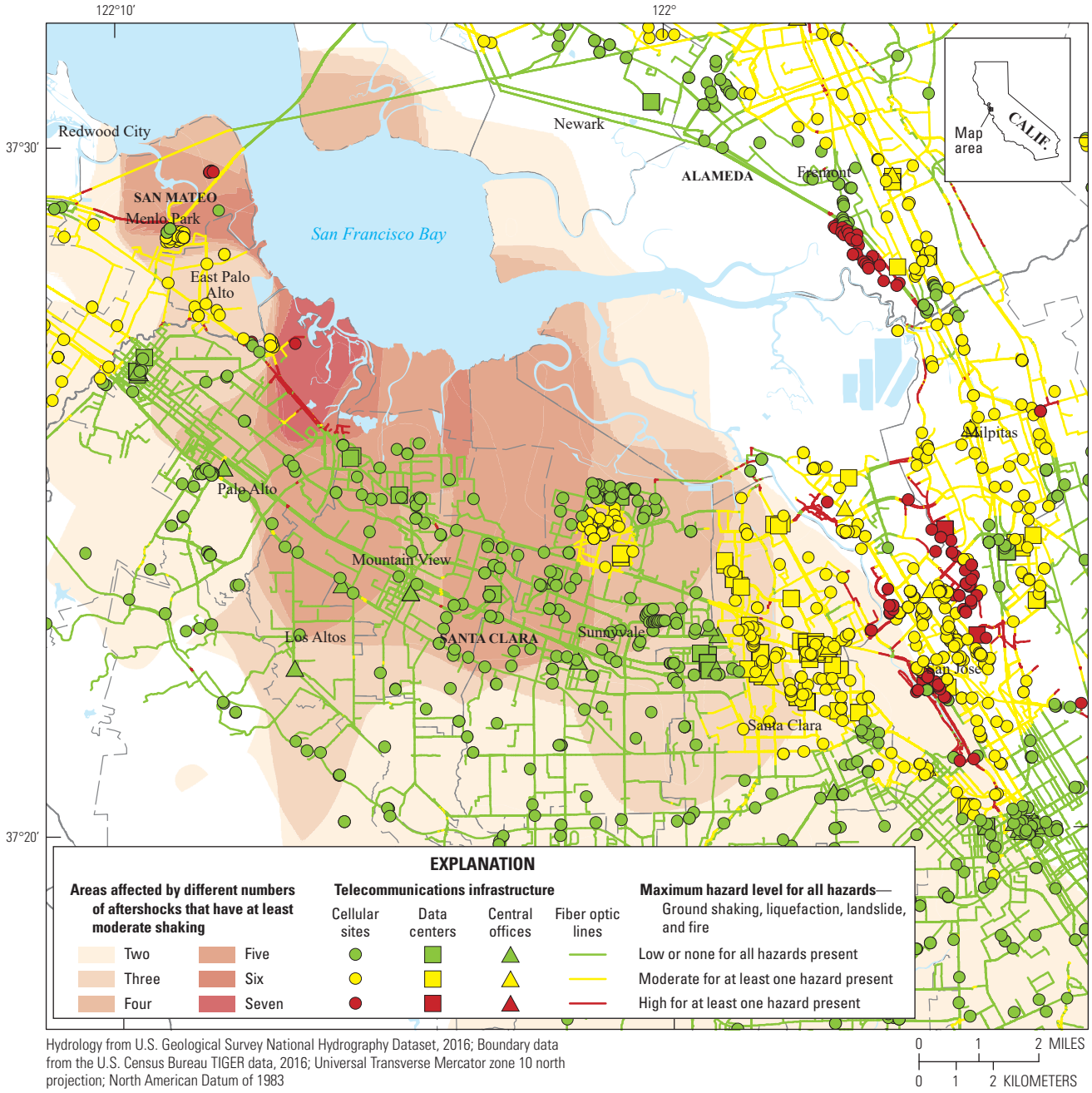


Figure 18. Map showing HayWired scenario mainshock impacts from all hazards (ground shaking, liquefaction, landslide, and fire following earthquake) to telecommunications infrastructure compared to exposure to aftershock shaking in San Mateo and Santa Clara Counties.

individual components of communication systems up to the level of a data center, there appear to be no simulation tools that estimate the influence of design choices and recovery strategies, provide resources for overall lifeline performance, or predict the likely recovery timeline" (Applied Technology Council, 2016). The capability to model stresses on physical infrastructure and effects on information flow is a topic that some researchers are pursuing (V. Krishnamurthy, University of Pittsburgh, written commun., 2021).

In our simple model of service restoration, voice and data are treated as one because they have become indistinguishable (for example, cellular data is used for broadband and some voice calls, and Wi-Fi can now be used for voice telephony). Service restoration is defined as the percentage of voice and data services demanded that can be served.[12] Demand served is a product of telecommunications network functionality and the volume of demand for voice and data services. Network capacity after an earthquake is the residual capacity after

[12]This concept of demand served differs from other measures of network reliability and availability (for example, see Applied Technology Council, 2016) that focus on the performance of the networks.

damage to infrastructure. Network functionality may be further compromised by power outages. Conversely, network functionality may be augmented by resilience measures. For example, decoupling dependence of equipment on electric power by using backup power options increases uptime and reestablishing network capacity can be hastened by truck deliveries of portable equipment, including gensets, cells on wheels (COWs), cells on light trucks (COLTs), and microwave links. On the other hand, demand surge from increased communication and information seeking after a disaster congests and degrades network performance such that managing user behavior could improve the demand served.

We proceed by first compiling available information about landline, mobile phone, and internet network functionalities and service restoration times after recent disasters. Next, for the HayWired scenario, we analyze a base case of demand served over time by county that incorporates

- physical damage (informed by infrastructure hazard exposure and damage from the previous section),
- demand surge (informed by available data from prior disasters), and
- complete dependence on electric power restoration (described in appendix 3 of Jones and others, this volume).

Next, we sequentially add the effects of

- permanent backup battery and generator power sources,
- capabilities for trucks to deliver portable equipment (at the same rate as truck arrival after Hurricane Sandy), and
- managing user behavior to reduce congestion.

These cases illustrate the effects of various resilience measures on demand served and are used in an analysis of macroeconomic impacts of voice and data service disruptions (Sue Wing and others, this volume).

Voice and Data Service Restoration After Disasters

Reports on recent international earthquakes and U.S. hurricanes provide reference points for phone and internet service restoration.

Service Restoration after Earthquakes

After recent earthquakes, the bulk of voice and data services have been reported as restored to normal on the order of days to weeks. There are some discrepancies among reported infrastructure restoration, "back to normal" services, and user experience with phone and internet services. For example, services may be said to have returned to normal, but not necessarily to original levels of functionality (if people left the area) or consistent with users' experiences.

- After the 2010 Maule earthquake in Chile, communications were reported as returned to normal within 7 days (Tang and others, 2011), but data collected by Krishnamurthy and others (2016) convey that after one week:
  - Landline service was about 80 percent and mobile service was about 50 percent restored in the Biobío region.
  - Landline service was about 95 percent and mobile service was about 75 percent restored in the Maule region.
  - The slower infrastructure restoration in the Biobío region reflected more damage from shaking in a more populated and developed area than in the Maule region. Also, in the Maule region there was more extensive use of portable diesel generators (gensets) and COWs.
- After the 2010 Darfield (New Zealand) earthquake, communication systems were reported as back to normal after 3 days (Tang and others, 2014).
- After the more impactful 2011 Christchurch (New Zealand) earthquake, communications were considered back to normal after 9 days. Compared to the Darfield earthquake, the longer restoration time was dictated by a longer electric power restoration time (Tang and others, 2014). From the perspective of people working from home, reliable service took longer.
  - Telephone services were disrupted for 13 and 3.4 percent of the staff working from home after 1 week and 3 weeks, respectively.
  - Internet services slightly lagged behind telephone service—17 and 6 percent of staff reported internet disruptions after 1 week and 3 weeks, respectively.
  - Telephone, power, and internet services were reliable for all customers within 2 months (Donnelly and Proctor-Thomson, 2013).
- After the 2011 Tohoku earthquake and tsunami in Japan, pre-earthquake mobile and landline telecommunications infrastructure were restored within 14 to 17 days, except for mobile facilities whose base stations were destroyed (Krishnamurthy and others, 2016).
- After the 2015 Kumamoto earthquake, the recovery of cellular sites was a little bit slower than previous *M*6 earthquakes in Japan because of difficult access to some areas and aftershocks (Tang and Eidinger, 2017):
  - About 85 percent of the cellular sites were restored within 4 days after the mainshock.
  - 99 percent of normal operations were recovered within 12 days.

Service Restoration after Hurricanes

After Hurricane Katrina, an event with centralized (rather than distributed) damage, cellular telephony service was almost fully operational after 1 week along the Gulf Coast and partially operational in New Orleans and Plaquemines Parish; the diversity and flexibility of mobile networks and priority to restore them outstripped the restoration of PSTN networks (Kwasinski and others, 2006).

After Hurricane Sandy, the number of cellular site outages decreased from 25 percent to 19 percent over the course of the first day, and steadily improved over the next few days, except for isolated outages that lingered where electric power remained unavailable and where the storm caused more widespread damage (Davidson and Santorelli, 2012). The Communications Sector Coordinating Council (CSCC) reported that Verizon was operating at 94 percent capacity immediately after Hurricane Sandy and at 99 percent capacity 5 days later (T. Serio, Verizon Wireless, oral commun., 2014).

As for internet services after Hurricane Sandy, 10 percent of the network in metropolitan areas was offline (Davidson and Santorelli, 2012). Flood damage to data centers and service providers (including InterNAP) resulted in unavailable websites and online services for almost a week (Davidson and Santorelli, 2012). Heidemann and others (2013) pinged networks for responses and detected a doubling of baseline U.S. internet outages when the hurricane made landfall. They traced the sources of the outages to the States of New York and New Jersey and found that it took about 4 days to recover to normal performance levels. Overall, it appears that most services after Hurricane Sandy were restored within a week except for isolated cases of internet and phone outages, which lasted for months (Smith, 2013).

Simple Model of Voice and Data Demand Served

A simple model of voice and data service restoration begins with a base case. This worst case illustrates a lower bound for service restoration for counties in the San Francisco Bay region, and we subsequently build in various resilience capabilities.

Base Case: Residual Capacity, Power Outages, Demand Surge

The base case assumes that demand served is constrained by residual network capacity, is fully dependent on and follows the restoration of electric power, and is degraded by congestion caused by a surge in demand for voice and data services. We develop assumptions for each of these factors and combine the effects into estimates of demand served over time.

Residual Network Capacity

After an earthquake, residual capacity is the percentage of pre-earthquake network capacity remaining after physical damage. The convergence of the voice (landline and cellular) and data (internet, cloud, VoIP, and so on) networks makes it difficult to identify the total capacity of the networks because they cannot be isolated as single components of a particular carrier's system owing to interoperability. In addition, network design has diversity as well as controls that help to reduce loss of information flow when parts of the physical system are compromised (sidebar 3). On the other hand, networks may have single points of failure, both well known and hidden, that could cause widespread outages during and after hazard events (Applied Technology Council, 2016) (sidebar 4). However, the largest single point of failure would likely manifest from failure of the electric power grid, which is addressed below in the context of power dependency.

Sidebar 3—Examples of Resilient Network Design

- Central office operations can be diverted and performed at other central offices that have circuits available (for example, Davidson and Santorelli, 2012).
- Subscribers may be covered by multiple cellular service areas; cell coverage overlaps to enable the signal to be handed over as the user moves from one area to another without a disruption in service. This means that a cellular site can be lost without affecting coverage in an overlapping area, but cellular data speeds may be slowed from the loss of capacity, and fewer customers may be able to make calls at the same time (R. Altom, Verizon Wireless, oral commun., 2016).
- Carriers build in redundant entry points to self-healing fiber ring networks that might help in the case where fiber optic lines cross a fault multiple times.
- Path diversity is built into the system via independent connections to a network backbone. Wireless networks can serve as backup for broken lines (Applied Technology Council, 2016).
- Data centers use data replication and failover to preserve data and access to it—the process of transferring operational control of a corporation within seconds to a remote location (for example, Perry 2016). Many service providers have data centers outside of the region and access to data can be transferred to them, although with some increased latency (M. Thompson, Argonne National Labs, oral commun., 2017).
- The Transmission Control Protocol (TCP), one of the primary communications protocols used on the internet, is designed as an end-to-end protocol, meaning that it attempts to guarantee message delivery from sender to receiver despite changes or outages in the intervening network nodes. This protocol allows networks that use TCP to be highly resistant to failures, albeit slower, when multiple paths from sender to receiver exist.

Sidebar 4—Examples of Single Points of Failure for Parts of a Network

- Because of the process known as traffic grooming, carriers may inadvertently route circuits that were meant to be geographically diverse through the same physical line.
- Transmission Control Protocol data flow has the potential to fail if a concentration of high-capacity routes between a particular sender and receiver become unavailable (Thompson and Evans, 2016).
- Possible critical points of failure for the internet include single fiber optic line cuts (in the absence of diversity) (Thompson and Evans, 2016) and disruption to internet exchange points that house important connections (Murphy, 2015).
- For cellular networks, damage to wired or wireless backhaul feeding a macrocell site (or cluster of sites) is a potential single point of failure for the site or cluster, unless the site or cluster has a redundant wired or wireless backhaul connection.
- During Hurricane Katrina, wireless services were affected by public switched telephone network failure because it was the backbone for many of the networks (Kwasinski and others, 2006).
- Damage to a single site shared by multiple carriers (known as colocation facilities) could put a large number of customers on different carriers out of service.
- Customers could be out of service because of failures in their distribution networks[13] (last mile) with no alternative connection to the backbone network or from being directly connected to a central office that fails.

Estimate of Residual Network Capacity After the HayWired Mainshock

Without tools to estimate network capacity, we first elicited industry expert consensus about the residual capacity of the networks after the HayWired mainshock. In a workshop, industry experts postulated residual network capacity as a function of shaking intensity (table 18). For each county, we calculated the average Modified Mercalli Index (MMI) score affecting the county and assigned the residual capacity from table 18.

To include the effects of multiple hazards (such as liquefaction as well as shaking), we developed a second approach to assign capacity reductions to facilities and channels and combine them into a representation of network capacity. We consider that a user of the networks requires an exchange type of facility (like a data center, central office, or mobile switching center), a local channel (like a cellular tower or fiber optic or copper line), and a long-haul channel (like long-haul fiber optic line). Because of resilience in the networks, we assume that residual capacity is governed by the average residual capacities of each type of requirement.

Table 18. Average industry estimate of likely residual network capacity caused by earthquake damage (listed by shaking intensity).

[MMI, Modified Mercalli Intensity; %, percent]

	MMI VII Very strong shaking	MMI VIII Severe shaking	MMI IX or X Violent or extreme shaking
Network capacity after the earthquake	80%	70%	50%

Our HayWired scenario mainshock damage analysis provides estimates for numbers of extensive (for example, yellow-tagged building) or complete (for example, red-tagged building) damage to central offices, data centers, and three types of cellular sites. For the estimation of capacity losses, we assumed that red-tag damage corresponds to 100 percent loss of equipment capacity and yellow-tag damage represents a loss of 22 percent of equipment capacity.[14] Our liquefaction and landslide exposure analyses yield numbers of facilities and lengths of interoffice and long-haul fiber that are exposed to the probability of these ground failures. The capacity loss from ground-failure hazards is assumed to be functionally consistent with the probability range as follows.

- 30 percent capacity loss for 25 percent and greater chance of ground failure,
- 15 percent capacity loss for between 5 and 25 percent chance of ground failure, and
- 2.5 percent capacity loss for 0.1 to 5 percent chance of ground failure.

For each county, each infrastructure capacity loss from each earthquake hazard is summed and capped at 100 percent capacity loss (for example, if complete damage from shaking and 30 percent probability of ground failure coincide). In table 19, we show that the largest exchange-type capacity loss estimate is for central offices in Alameda and Contra Costa Counties and for data centers in San Francisco, San Mateo, and Santa Clara Counties. The largest capacity loss estimate for transmission channels is cellular sites on buildings in all counties, but only 2 percent above capacity loss estimates for interoffice fiber in most counties, except in the more heavily affected Alameda and Contra Costa Counties.

We make a very high-level calculation of residual network capacity for each county from the product of:

- the average percentage of residual capacity of central offices and data centers;

[13]Last-mile wired connections are primarily copper twisted pairs (for voice, digital subscriber line, and legacy data services), coaxial (for cable television), and fiber (for cable television, business data services, cellular backhaul, and internet access).

[14]A range of functionality coincides with extensive damage. The 22 percent value derives from an estimate of average functionality of yellow-tagged buildings after the 2014 South Napa earthquake by one of the authors, K.A. Porter.

Table 19. Estimates of residual capacity of facilities and transmission channels after the HayWired scenario mainshock in the San Francisco Bay region, California, using damage and ground-failure probability functionality assumptions.

[Values are percentages]

County	Data center	Central office	Self-supporting or guyed towers	Monopoles	Cellular sites on buildings	Long-haul fiber optic line	Interoffice fiber optic line
Alameda	88	65	93	76	64	86	88
Contra Costa	96	90	92	93	90	89	97
Marin	100	93	96	96	92	88	94
Merced	100	100	100	100	100	100	100
Monterey	100	100	100	100	100	100	100
Napa	100	99	100	100	100	97	100
Sacramento	100	100	100	100	100	100	100
San Benito	100	100	100	99	100	100	100
San Francisco	91	92	97	94	91	86	92
San Joaquin	100	100	100	100	100	100	100
San Mateo	88	90	97	95	89	92	91
Santa Clara	92	96	97	94	91	92	93
Santa Cruz	100	100	100	100	100	100	100
Solano	100	98	99	99	99	97	99
Sonoma	100	100	100	96	95	99	100
Stanislaus	100	100	100	100	100	100	100
Yolo	100	100	100	100	100	100	100

- the average percentage of residual capacity of cellular sites and interoffice connections; and
- the percentage of residual capacity of long-haul fiber optic lines.

In table 20, we compare the results of these calculations with industry estimates. The differences between the two pertain to: (1) the inclusion of ground failure that lowers residual capacity in San Francisco and San Mateo Counties where the shaking hazard is relatively less intense than liquefaction hazards, and (2) industry consensus on residual capacity for shaking levels (MMI) is lower than using the reduced capacity calculation described above (notably in Contra Costa and Santa Clara Counties). We carry forward our residual capacity estimate because they are in the same ballpark as the industry estimates and they are differentiated by liquefaction and landslide as well as shaking hazards.

Dependence on Electric Power Restoration

Power outages were the primary reason for telecommunications capacity loss and service interruption after the 2011 Christchurch (New Zealand) earthquake, many other major earthquakes around the world (Schiff, 1995, p. 155; Tang and others, 2014; Krishnamurthy and others, 2016; Tang and Eidinger, 2017), and hurricanes (Kwasinski and others, 2006; Davidson and Santorelli, 2012). After both the 2011 M_w 9.0 Tohoku (Japan) earthquake and the 2010 M_w 8.8 Maule (Chile) earthquake, power outages and lack of permanent onsite generators (exacerbated by theft) were the most common failure modes, more common than damaged infrastructure and

Table 20. Estimates of residual network capacity after the HayWired scenario mainshock in the San Francisco Bay region, California, using the high-level calculation based on all earthquake hazards and industry consensus based on shaking (MMI level).

[Values are percentages. MMI, Modified Mercalli Intensity]

County	Residual network capacity	
	As a product of exchanges and channel capacities	From MMI-based industry consensus
Alameda	53	50
Contra Costa	77	60
Marin	80	70
Merced	100	80
Monterey	100	95
Napa	97	80
Sacramento	100	100
San Benito	100	80
San Francisco	74	95
San Joaquin	100	95
San Mateo	76	95
Santa Clara	81	60
Santa Cruz	100	80
Solano	96	95
Sonoma	97	95
Stanislaus	100	100
Yolo	100	100

batteries, antenna misalignment, and isolation due to failed links caused by repeater damage and severed fiber optic lines (Krishnamurthy and others, 2016). Another issue for large facilities is that power for air conditioning equipment is backed up by diesel generators only (not batteries), so it is possible for sites to experience outages during disasters because of thermal issues even when telecommunications batteries still have remaining charge (Kwasinski, 2010). Thermal inertia may cause a site to increase its temperature from around 18 to 55 degrees Celsius in about 5 or 6 hours, though the time could be stretched to 8 hours by using fans or shutting down less critical services to reduce the heat sources (A. Kwasinski, University of Pittsburgh, written commun., 2020).

Estimate of Network Capacity Dependent on Electric Power Restoration

We model the dependence of network functionality on electric power restoration as manifesting in two ways. First, functional equipment needs electric power to operate, and second, the repair of damaged telecommunications equipment is paced by electric power restoration—if the power company can get in to restore power, then the telecommunications industry can follow within a few days depending on the severity of damage (for example, Krishnamurthy and others, 2016). Figure 19 shows the dependence of a telecommunications pole repair on a power pole repair.

For the HayWired scenario, Hazus electric power restoration results are published in appendix 3 of Jones and others (this volume). Figure 20 displays the electric power restoration curves during the first month for the nine counties adjacent to San Francisco Bay. The restoration is not necessarily as smooth as depicted. For example, after the South Napa earthquake, most power was on, but then a few hours later it was all off because the Pacific Gas and Electric utility turned off power until they cleared areas from threats from gas leaks. As areas were cleared for gas leaks, power was restored. Consequently, although telecommunications networks were otherwise working, when power went down, communication disruptions increased.

We assume that restoration of telecommunications lags behind electric power restoration, in a manner similar to the findings of Krishnamurthy and others (2016) after the Maule (Chile) earthquake. That is, approximately a 2-day lag behind power restoration in the harder-hit Biobío region and approximately a 1-day lag in the Maule region. For the HayWired scenario, we apply a 2-day lag in the hardest hit county (Alameda); a 1-day lag in other counties that touch San Francisco Bay (Contra Costa, Marin, Santa Clara, San Francisco, San Mateo, Solano, and Sonoma), and a 0-day lag in the remaining and least affected counties. After 1 month, we assume that the cumulative restoration of power and voice and data services are the same. As a reference point, for people working at home in Christchurch 20 days after the 2011 *M*6.3 earthquake, the average percentages of phone and internet service restoration equaled power service restoration percentages (Donnelly and Proctor-Thomson, 2013).



Figure 19. Photographs showing repair dependence between telecommunications and electrical power poles. After the 2014 South Napa, California, earthquake, a wooden telecommunications pole was observed to have been quickly repaired with a 2×6 support and tied to the adjacent power pole. *A*, Photograph of full pole with repair. *B*, Close-up view of wooden support repair. Photographs by A. Tang, L&T Consultant, October 20, 2015, used with permission.

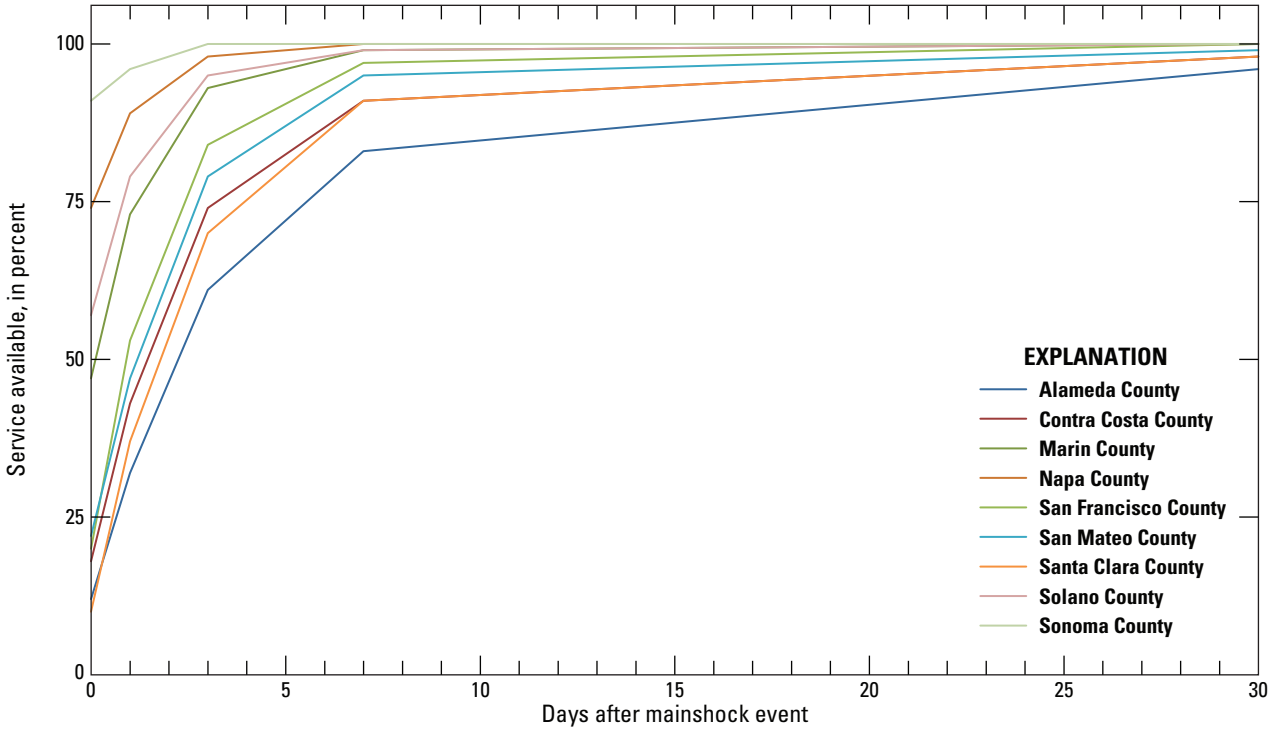


Figure 20. Line graph showing the electric power restoration curve by county for the HayWired scenario mainshock in the nine counties adjacent to San Francisco Bay, California. From Jones and others (this volume).

Service Degradation from Demand Surge

In the aftermath of a significant earthquake, large numbers of users will try to use the telecommunications network simultaneously for voice calls and text messaging, causing congestion (Bark, 2011). People call more in a disaster compared to their usual use of voice, text, and social media (Satoh and others, 2018). Even moderate earthquakes in California (for example, 2007 Alum Rock, 2008 Chino Hills, and 2014 South Napa) resulted in outages of cellular networks when people reacting to the earthquakes flooded the system with calls (for example, Xia and Lin, 2015).

Congestion arises because the telecommunications network is designed with the presumption that only a fraction of the subscribers will simultaneously try to make calls at any given time, such as a normal peak demand from 8 percent of customers. The networks are clogged further by people retrying when they cannot get through and concerned friends and relatives around the world attempting to communicate with residents in the affected areas. Users with smartphones capable of recording high-resolution photographs and video that upload large files to social media sites or streaming news video could also contribute to heavy loads on cellular and temporary Wi-Fi networks. As available bandwidth goes down overall, the efficiency drops because the number of collisions increases (for example, data packets that collide must be retransmitted)—thus creating more traffic.

We used reports on recent disasters and industry input to inform our estimate of the surge in demand for information and communication services. Tang and others (2014) document that call volume after the daytime February 2011 earthquake in Christchurch, New Zealand, was nearly 10 times above normal at peak (and 4 to 5 times more than the call volume after the nighttime September 2010 Canterbury earthquake). After the Tohoku earthquake (Japan), a mobile provider reported that outgoing and incoming calls increased by 60 and 40 times soon after in the devastated area (Ministry of Internal Affairs and Communications [Japan], 2011). In New York City after 9/11, call demand was observed to be 13 times the demand the day before and 92 percent of cellular call attempts were initially blocked. The average blocked call rate of 75 percent for the day indicated a decline in demand surge with time (O'Rourke and others, 2003). Furthermore, the demand surge and call block rate declined with distance from the center of the 9/11 disaster. Similarly, Jia and others (2017) detected text messaging application usage spikes after the 2013 Ya'an (China) earthquake and found that the spikes were lower in areas with lower shaking intensities and usage declined with time.

Internet bandwidth usage after earthquakes has been observed to initially and briefly drop off and then increase beyond normal use. After the 2014 M_w 6.0 South Napa

(California) earthquake, normal internet usage dropped off for 18 minutes in affected Napa and Sonoma Counties (especially those on desktops, likely because of power outages) and then returned to just above 100 percent of normal demand. Internet usage increased as much as 3 times elsewhere in the San Francisco Bay region in the middle of the night (Kamprath, 2014). Similarly, after the 2011 Tohoku earthquake and tsunami, 20 percent of Japan's total internet traffic dropped immediately because of power outages, followed by a spike in traffic, and most bandwidth was filled by people streaming video (for example, looking at news) (for example, Fukuda and others, 2011). Packet traffic was measured to increase by about 4 times as much as the previous week and 85 percent of emails were delayed, but 90 percent were delivered within 80 minutes (Internet and Television Association, 2012). Likewise, internet traffic increased during and after Hurricane Sandy because of increased video streaming, telecommuting, and searches for recovery news (Davidson and Santorelli, 2012).

Estimate of Demand Surge After the HayWired Mainshock

For the HayWired scenario mainshock, industry experts posited the fraction of demand surge that could be met by pre-earthquake network capacity in areas affected by MMI IX and X shaking over time (see fourth column of table 21). The worst case of only 10 percent of demand surge served by pre-earthquake network capacity is in the realm of previous observations. To mimic the findings of lower demand surge in less affected areas, we scale the fraction that could be met for MMI IX and X areas by 1.5 and for MMI VIII and VII by 2; the resulting demand surge fractions are shown in table 21.

Demand Served Restoration Estimation Method: Base Case

The base case for demand served in each county is constructed using the following steps.

1. Immediately after the earthquake, network capacity is reduced to residual network capacity because of damage to infrastructure (as explained above).

2. The residual network capacity is supplied with power in proportion to power restoration for each county. That is, we multiply the residual capacity (table 19) by the percentage of customers with power at time 0 (fig. 20).

3. The effect of demand surge is imposed by multiplying the residual capacity (step 2) by the fraction of demand surge that can be met by pre-earthquake network capacity.

4. Over time, network functionality is restored after electric power is restored with the assigned time lags for each county. The effect of demand surge also drops off over time according to table 21.

5. After 1 month, there are no effects of demand surge and network capacity is restored on the same day as power in all counties.

Table 21. Fraction of demand surge that could be served by pre-earthquake network capacity after the HayWired scenario mainshock in the San Francisco Bay region, California, by shaking intensity.

[Values are percentages. MMI, Modified Mercalli Intensity]

Impact resulting from user behavior	MMI VII: Very strong shaking	MMI VIII: Severe shaking	MMI IX or X: Violent or extreme shaking
Soon after the earthquake	20	15	10
1 day later	100	75	50
1 week later	100	100	95
1 month later	100	100	100

Resilience Case of Permanent Backup Power

Permanent (or fixed) backup power provides critical protection from electric power outages. During commercial power outages, switching facilities, data centers, and cell towers rely on the delivery of diesel fuel by truck to keep backup generators running (Applied Technology Council, 2016). Necessary assumptions for this resilience case are the prevalence of backup batteries and generators; the availability of backup power at the time of need; the length of time that backup power lasts; and the ability for trucks to acquire fuel, access sites, and refuel permanent generators before they run out of fuel.

Backup Power Options, Prevalence, and Running Time

The core components of telecommunications systems (data centers, central offices, and most—but not all—macrocell towers) have backup power (batteries, generators, and [or] fuel cells). Typically, these facilities may have as much as 4 to 8 hours of battery backup, 24 hours of generator fuel at cell sites, and 72 hours of generator fuel (possibly as much as 128 hours of fuel) at central offices and data centers. A Christchurch exchange had batteries that were sized to last as long as 8 hours in the absence of an onsite generator (Tang and others, 2014). Verizon reports that 100 percent of their macrocellular sites in northern California have backup batteries and 90 percent of macrocellular sites have diesel and natural gas generators (R. Altom, Verizon Wireless, oral commun., 2016). However, one of Verizon's lowest penetration rates in the country is in the City and County of San Francisco, where only 14 percent of their macrocellular sites have permanent backup generators (D. Mieler, City and County of San Francisco Office of Resilience and Capital Planning, written commun., 2019).

For all carriers, the main exceptions for backup power supplies are cellular sites on rooftops (limited by floor loading of the batteries) and roadside equipment (limited by space). In the past, wireless carriers were fairly aggressive about installing backup power for buildings that host their sites and selecting sites that were close to critical locations, such as hospitals. Over time, as the focus for wireless site deployment has moved closer to population centers and especially residential areas, suitability of a site for backup power became less of a consideration than

providing desired signal coverage, meeting business and economic expectations, and conforming to local government regulations. Reasons for restrictions on backup generators include fire safety, aesthetics, space, and noise from testing.

For the components of the distribution system, batteries are smaller or less prevalent than they are for the core components. For roadside cabinets and rural huts in Christchurch, battery reserves ranged from 2 hours at urban sites to 5 hours at rural sites (Tang and others, 2014). After the 2010 Maule earthquake in Chile, reserve battery power in most distributed network facilities was depleted after 3 hours (Earthquake Engineering Research Institute, 2010). Backup power supplies for small cells are typically not approved by municipal permitting processes (R. Altom, Verizon Wireless, oral commun., 2016).

Batteries may last less time than expected because lead-acid, absorbent glass mat type batteries can lose capacity with age, and under heavy use (for example, the type of use that occurs after a disaster) they discharge faster. After the 2011 Christchurch earthquake, batteries did not perform as well as they did after the 2010 Darfield mainshock, likely because the mainshock had disrupted power 5 months earlier and accelerated the aging of batteries (Tang and others, 2014).

Given the range of backup power installations, including none, we assume a combined effect on network functionality equivalent to 50 percent with a battery only and 50 percent with a generator. We assume that batteries drain on the first day and that generators run for 3 days before needing to be refueled.

Fuel Delivery to Permanent Generators

The arrival of fuel trucks depends on available labor and equipment, roadway conditions, and security issues. In Christchurch, road access to refuel cabinets was difficult because of road closures, roads damaged by liquefaction and landslides, and traffic congestion (Fenwick, 2011); a central office in the cordoned area of Christchurch required fuel delivery by helicopter (Tang and others, 2014). After the 2010 Maule (Chile) earthquake, damage to roads and bridges made access to cell sites and remote offices that were relying on battery reserve power difficult to access once the batteries had discharged (Tang and others, 2011). After Hurricane Katrina, civil unrest affected access to several BellSouth central offices and fuel trucks met obstacles of inaccessible routes and security checkpoints (Kwasinski and others, 2006). During the Hurricane Sandy response, companies were unable to access damaged sites because of downed trees, flooding, or other physical impediments (for example, damaged roofs housing cell towers) (Davidson and Santorelli, 2012).

The Lifelines Council (2014) concluded that damage to regional roads and city streets would strongly affect restoration of telecommunications services. A HayWired scenario hazard exposure and damage analysis for roadways (Jones and others, this volume) indicate very limited access in some areas because of heavily damaged bridges and landslides on roadways. Near the bay shoreline, liquefaction damage to driving surfaces—especially sand boils and cracks from lateral spreading—would require repair vehicles to drive very slowly, but not necessarily obstruct them.

A critical contingency in the San Francisco Bay region event is the uncertainty of fuel supply within the first 10 days of a large earthquake (G. Schremp, California Energy Commission, written commun., 2018; Jones and others, this volume). As recent hurricanes demonstrate, there is a serious gap for the industry between expectations for the availability of fuel and the threat to fuel supplies from disasters. Even if the fuel gets to its destination, there have been cases when it was misdirected to the wrong generator.

Another consideration for the San Francisco Bay region is the potential lack of availability of skilled labor to construct, maintain, repair and upgrade, fuel, and manage telecommunications systems. Skill sets range from advanced university degrees to construction and manual labor. It is perceived that the technology boom and housing costs are already driving competition for these talents in the San Francisco Bay region such that the availability of qualified personnel is an ongoing issue. Locating human resources to recover from a HayWired-type earthquake is expected to be very challenging. One of the authors (D.T. Witkowski) knows contractors that came to the San Francisco Bay region from out of state during the response to the 2019 Public Safety Power Shutoffs (PSPSs). Access to sites may be further obstructed by delays in credentialing contract labor and (or) when buildings are secured for safety and inspection.

In our model, we assume that permanent generators can be refueled using first-truck delay data from a Hurricane Sandy study by Krishnamurthy and Kwasinski (2014). The setting of Hurricane Sandy is similar to the San Francisco Bay region in terms of density of large cities, importance of bridge access, and presence of centers of world industry that depend on telecommunications services (A. Kwasinski, University of Pittsburgh, written commun., 2018). Although warnings for hurricanes enable pre-staging of fuel trucks and equipment, the excitation of that hazard lasts longer (for example, a day) than the seconds of an earthquake, which could make up some of the time lost from not being able to pre-stage, except where there is fire following the earthquake. Krishnamurthy and Kwasinski (2014) report triangular distributions of truck entry delay days described by the minimum, average, and maximum number of days in three Hurricane Sandy impact zones (where 1 is the most affected) (see table 22). We note that the minimum delay of 2 days for the most affected area is consistent with the

Table 22. Fuel truck delivery delays (in days) to sites in three zones of impact from Hurricane Sandy in the northeastern United States.

[Data from Krishnamurthy and Kwasinski (2014). The time for the first trucks to arrive at a site is a triangular distribution described by the minimum, maximum, and average number of days]

Zone of impact	Minimum	Average	Maximum
1	2	4.3	7
2	1	3	5
3	1	2	3

mobilization and placement of large AT&T trailers containing telecommunications equipment at a site in New Jersey within 48 hours of the 9/11 attack (O'Rourke and others, 2003). We use the zone 1 data for Alameda County, zone 2 data for other counties adjacent to San Francisco Bay, and zone 3 data in the least affected counties—the same geographical divide used to assign telecommunications restoration time lags after power restoration in the base case.

Backup power equipment itself may fail to work because of insufficient testing and maintenance, overheating and sulfation (a change in chemistry in the case of batteries), or damage by the earthquake event (for example, Kwasinski and others, 2006; Fenwick, 2011; Davidson and Santorelli, 2012). After the 2014 South Napa earthquake, a central office had a nonfunctioning generator, but was still able to run on battery systems until generators and a cooling system were installed (Noyes, 2014). Less fortunate were the central office operations that were interrupted when Hurricane Sandy floods damaged backup power equipment including onsite diesel generators and fuel pumps in their basement or first floor (Kwasinski, 2012). Closer to home, during the 2019 PSPSs, a San Mateo County radio shop had to contend with two generator failures (out of 11 sites with generators) and after calling 27 sources in California could not find replacement generators (A. David, County of San Mateo, oral commun., 2019).

Grant and others (1996) found that stand-by diesel generators at U.S. commercial nuclear power plants had an 85 percent availability when operated for more than 24 hours. Failure modes included being out of service for maintenance, failure to start, and failure to keep running. In our model, we simply assume permanent batteries and generators are 90 percent available.

Demand Served Restoration Estimation Method: Permanent Backup Power

Demand served by the telecommunications network with backup power is estimated using the following steps to build on the base case.

1. Permanent backup power is effectively present in the proportion of 50 percent of network functionality with a battery that runs out within 1 day and 50 percent of network functionality with a generator and 3 days of fuel.

2. Backup power is 90 percent available; 10 percent of backup power is assumed to malfunction. At time zero, the network functionality is the base case plus 90 percent of the residual capacity that is without electric power but running on permanent and available backup power.

3. After 1 day, the batteries drain such that 50 percent of the residual capacity that is without commercial power is reduced to the power-dependent restoration case (applying steps 2 and 4 of the base case).

4. After 3 days, when generators run out of fuel, fuel trucks are able to refuel generators according to the triangular distribution of the county's impact zone (table 22). In zone 3, all generators are refueled without a lag, in zone 2 half of the generators are out of fuel for 1 or 2 days, and in zone 3 more than half of the generators are out of fuel for 1 to 4 days. Sites with generators that are not refueled within 3 days fall back to the base case of power-dependent restoration.

Resilience Case of Portable Equipment

Portable (or deployable) equipment, including gensets and telecommunications equipment, are trucked in after disasters. After Hurricane Sandy, Verizon used as many as 1,500 generators, consuming 100,000 gallons of fuel each day (Cheng, 2012). After the 2011 Christchurch earthquake, more than 500 gensets were needed and it took a few days to source them.

Portable cellular sites on wheels (COWs) or light trucks (COLTs), typically used to provide supplemental cellular voice and data capacity for large gatherings (sports events, tradeshows, music festivals, and so on), can substitute for damaged sites or augment coverage in critical areas. For example, a temporary wireless antenna was erected in northern New Jersey to support financial institutions and stock exchanges after Hurricane Sandy (Davidson and Santorelli, 2012) (fig. 21).

COWs and COLTs require electric power (although they typically have on-board batteries and generators) and connect to the network via either fiber optic lines or wireless data links. In areas with persistent outages, AT&T has connected portable satellite connections to cellular towers until fiber optic connections or terrestrial wireless links can be restored (Davidson and Santorelli, 2012).

In the rarer cases of an inoperable central office, a digital loop carrier (DLC) could be installed and connected to an operational central office with a fiber optic line to replace the damaged central office operations. A more expensive option of a switch on wheels (SOW) may be preferable for reliability, functionality, reducing congestion, and better telecommunications traffic distribution (Kwasinski and others, 2006). More recently, mobile telephone exchanges (MTXs) have been used to backup central office failure. AT&T has several trailers composing a core network (Fitchard, 2014). The links for these MTXs are either by microwave, high-speed copper or fiber lines, and (or) satellite.

As with fuel deliveries, roadway conditions, security checkpoints, the number of technician teams working in parallel, and the difficulty of resourcing fuel and spare parts or replacements influence the arrival of trucks at sites. We assume that carriers can deliver gensets and other portable equipment into counties at the same rate as fuel trucks (described above). We also apply the 90 percent backup-power availability rate assuming that similar hitches can apply to portable equipment as with permanent backup power and that there are impracticalities of setting up generators on rooftops and next to roadside wireless equipment cabinets (for example, Eidinger and Tang, 2012).

Demand Served Restoration Estimation Method: Portable Equipment

Demand served by using trucked-in portable equipment is estimated as follows.

1. Residual capacity without commercial power or permanent and available backup power is brought back online at the rate that first trucks arrive in the county's impact zone each day after the earthquake (table 21), with 90 percent backup power availability until restoration occurs according to the power-dependent case.

2. Damaged capacity is also restored at the rate of first truck arrivals and 90 percent backup power availability while it is without commercial power.

Resilience Case of Managing User Behavior

Providers have some means to manage some use of networks. Once a portable cellular site (COW or COLT) is activated, carriers have limited control over who uses it, but they can control types of uses. For example, in Christchurch, New Zealand, wireless carriers shut off the 3G data service to conserve battery power, but did not inhibit text messaging (Fenwick, 2011).



Figure 21. Photograph showing a cell on light truck outside Freedom Tower (renamed the One World Trade Center) in New York City after Hurricane Sandy. Photograph by A. Kwasinski, University of Pittsburgh, November 2012, used with permission.

Wireless carriers can control usage by limiting the data rates available to various users. This technique, called "throttling," can be done on a per-user basis, and can be used to reserve network capacity for public safety, first responders, and emergency personnel. This allows carriers to provide connectivity for basic usage of applications, websites, and so on, but prevents streaming of high-impact content, like videos. In the aftermath of an earthquake where impacts have degraded performance, wireless carriers may activate throttling until normal operation is restored, so users should expect that high-bandwidth applications, like video chat, may not work. However, during the 2018 Mendocino Complex fire, Verizon throttled a safety department's unlimited data plan that slowed speeds above a set limit at a critical time. The department had to upgrade; subsequently, Verizon admitted they had made a support error (Dwyer, 2018).

Satoh and others (2018) found that an alternative technique of restricting people's call initiation to 6-minute time periods within each hour prompts them to reduce their call duration and redials. Experimental results found a potential 30 percent reduction in call duration. This is an example of imposing a restriction with a positive behavioral change that could help reduce congestion.

Human instinct in a crisis causes people to seek information and communicate their status, so telling people to minimize their use of cellular phones and the internet could be counterintuitive. The 2010 Canterbury earthquakes in New Zealand provided evidence that people were willing to respect advice to use text messaging for non-critical communications. The news media cooperated to keep voice capacity available for emergency responders (Tang and others, 2014). News media can also help by providing regular updates and public service messages via radio and television.

Some public messaging advice for users during a disaster has been compiled by the Federal Communications Commission and the Federal Emergency Management Agency (Federal Communications Commission, 2017b). Social science research has found that people forget what to do in a crisis and need concise reminders (for example, Covello, 2003; Wein and others, 2016). An outcome of HayWired workshop discussions were examples of easy-to-understand and implementable public service messages that could be used to remind residents about how to conserve use of the telecommunications network in and around affected areas (sidebar 5).

Recall that in the base case, demand served was tempered by the fraction of demand surge that could be met by pre-earthquake capacity. To demonstrate effects of various user behavior management tactics the fraction of demand surge met is increased by 10 percent.

Sidebar 5—Conserving Use of the Telecommunications Network

- Use 9–1–1 in emergencies. Don't post calls for help on social media.[15]
- Post your status to the American Red Cross "Safe and Well" system via the internet (American Red Cross, 2021), or go to a Red Cross shelter site to register your status.
- Text, don't talk.[16] Unless calling 9–1–1 in an emergency, do not make voice phone calls unless absolutely needed.
- Post your safety status on social media (for example, Facebook) via wired broadband but avoid the temptation to use social media for other activities.
- Hold on to photographs and videos. After a disaster, communication networks can be overloaded—avoid uploading photographs (and especially video) over cellular data networks.
- Change your telephone and cellular voicemail messages to provide updates on your status.
- When seeking news and information, broadcast radio is best.[17] Try to avoid using data.
- If radio and television are not an option, use wired broadband (DSL, cable, or fiber) to access websites, but avoid streaming video or newscasts.[18]
- Use broadband or Wi-Fi for data. Turn off mobile data unless absolutely needed.
- As a last resort, use your cellular data if available, but limit usage.

Demand Served Restoration Estimation Method: User Behavior Management

Demand served with some user behavior management is illustrated by:

1. Increasing the fraction of demand surge met by pre-earthquake capacity in table 21 by 10 percent (capped at 100 percent).

[15]During Hurricane Harvey, residents of Texas reportedly posted calls for help to the U.S. Coast Guard via Twitter.

[16]Sending text SMS messages has minimal impact to cellular networks and will help reserve network capacity for emergency calls and public safety personnel.

[17]Radios are battery powered and have no impact on data networks. Televisions require electric power, which may not be available.

[18]Streaming exacerbates congestion in strained data networks.

Resilience Case of All Capabilities

Discussed above, the three resilience measures of permanent backup power, portable equipment, and user behavior management are combined to arrive at our most optimistic outcome for demand served by:

1. Applying portable equipment on top of the permanent backup power case. Functionality lost from damaged and (or) unavailable backup power system is restored at the rate first trucks arrive in the county each day after the earthquake (table 21), and;
2. Applying user behavior management by scaling up the fraction of demand surge met by pre-earthquake capacity by 10 percent.

Voice and Data Demand Served

We present the results of the simple restoration model for the HayWired scenario followed by a discussion of notable uncertainties in the restoration curves. We also explain why subscriber experience during the restoration period could be variable.

Restoration Curves

In figure 22, the base case result for demand served in Alameda County is shown against the effects of each resilience capability in succession of adding permanent power supply backup, portable equipment and fuel, and user behavior management. Without backup power, Alameda County, as the hardest hit county, has 7 percent initial demand served (which happens to correspond to the 93 percent initial blocked cellular calls in New York City after 9/11).

Relative to the base case of power-dependent network capacity, figure 22 illustrates the immediate service improvement provided by permanent batteries and generators. The service loss from drained batteries during the first day is evident in the reduced slope of the restoration curve after day one. (It is not necessarily a drop in demand served because the surge of user demand has decreased from the day before and some power services have been restored). We see a delay in the improvement from portable equipment use because we assume the first trucks arrive at the end of day two through to the end of day seven in the most affected county. The use of portable equipment allows demand served to surpass electric power restoration on day five in this example. Therefore, it is possible for voice and data demand to be served ahead of electric power services and users would need to have backup power for their devices to realize this outcome. The benefit of user behavior management is not particularly evident initially because the networks are still overwhelmed by demand surge. The effectiveness of user behavior management increases with time (because it accentuates reductions in congestion), but the effect tapers off as demand surge declines back to normal levels. Optimistically, all three resilience capabilities result in 98 percent

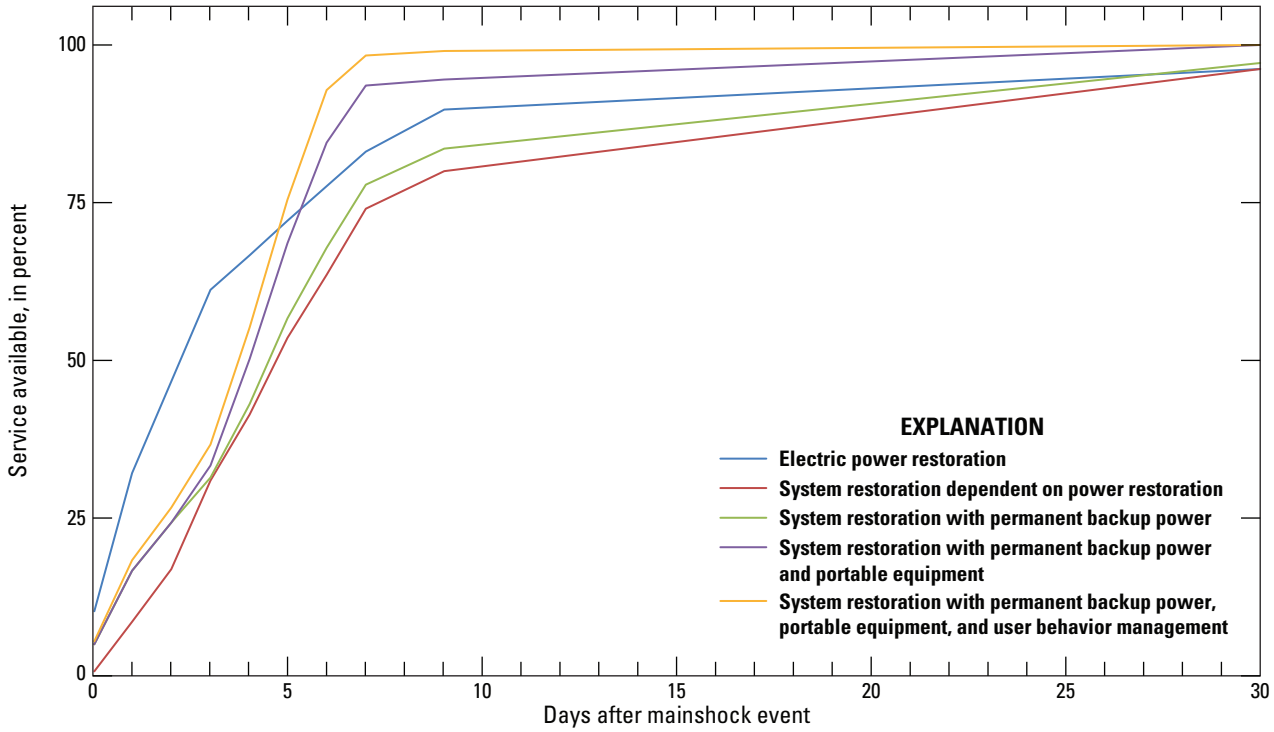


Figure 22. Line graph showing voice and data demand served and power restoration curves for Alameda County for the HayWired scenario mainshock in the San Francisco Bay region, California. Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management) achieves the most optimistic outcome.

of voice and data demand served in Alameda County at 1 week after the mainshock earthquake. Given the logistical uncertainties, the base case provides the least optimistic outcome of 73 percent voice and data demand served after 1 week in Alameda County.

A familiar curve for telecommunications network capacity is one that neglects the effect of demand surge (for example, Lifelines Council, 2014). Removing the effect of demand surge, shown in figure 23, reveals the drop in network functionality when batteries run out. A comparison of figures 22 (demand served) and 23 (functionality) illustrates that congestion from demand surge is responsible for large losses of service soon after the disaster. This comparison aligns with the concepts of physical functionality and service-oriented operability which inform different aspects of resilience (Davis, 2021).

Across counties, figure 24 shows a range of optimistic restoration curves that show effects of different residual network capacities; rates of electric power restoration, fuel and portable equipment truck re-entry times; and volumes of demand surge. Our optimistic estimate is that voice and data demand served could be satisfied in the least affected counties within a few days and within a week in the other counties except for the most affected county. Alameda County suffers from compounding factors of the most damage to telecommunications infrastructure, slowest electric power restoration, and longer times for trucks to enter to deliver fuel and portable equipment.

Restoration curves for the nine counties adjacent to the San Francisco Bay are provided in appendix 2 and by Wein (2021). For example, 1 week after the mainshock, the power-dependent base case shows 85 percent demand served in Contra Costa and Santa Clara Counties (figs. 2.1 and 2.6 in appendix 2) and 90 to 95 percent demand served for San Mateo and San Francisco Counties (figs. 2.4 and 2.5 in appendix 2).

Our results are within the realm of service restoration times after previous earthquakes and Hurricane Sandy. Another point of reference is the Lifelines Council (2014) study that consulted with carriers to estimate telecommunications restoration in the City and County of San Francisco after an *M*7.8 earthquake scenario on the San Andreas Fault. Their result (without demand surge) depicts service restoration at 60 percent immediately after the earthquake caused by damage and power outages, which drops to 30 percent after 2 days as batteries deplete and backup generators run out of fuel, and is followed by a steep restoration of telecommunications services that tracks power restoration (without a lag) to about 97 percent by the end of the first week and with complete service restoration taking as long as a month. The study noted that post-earthquake system functionality is expected to be high (in the range of 90 percent) where there is a strong supply of batteries, generators, and diversity in the connections.

Restoration Model Uncertainties

We have made various assumptions about residual network capacity, telecommunications restoration relative to power restoration, demand surge and user behavior management,

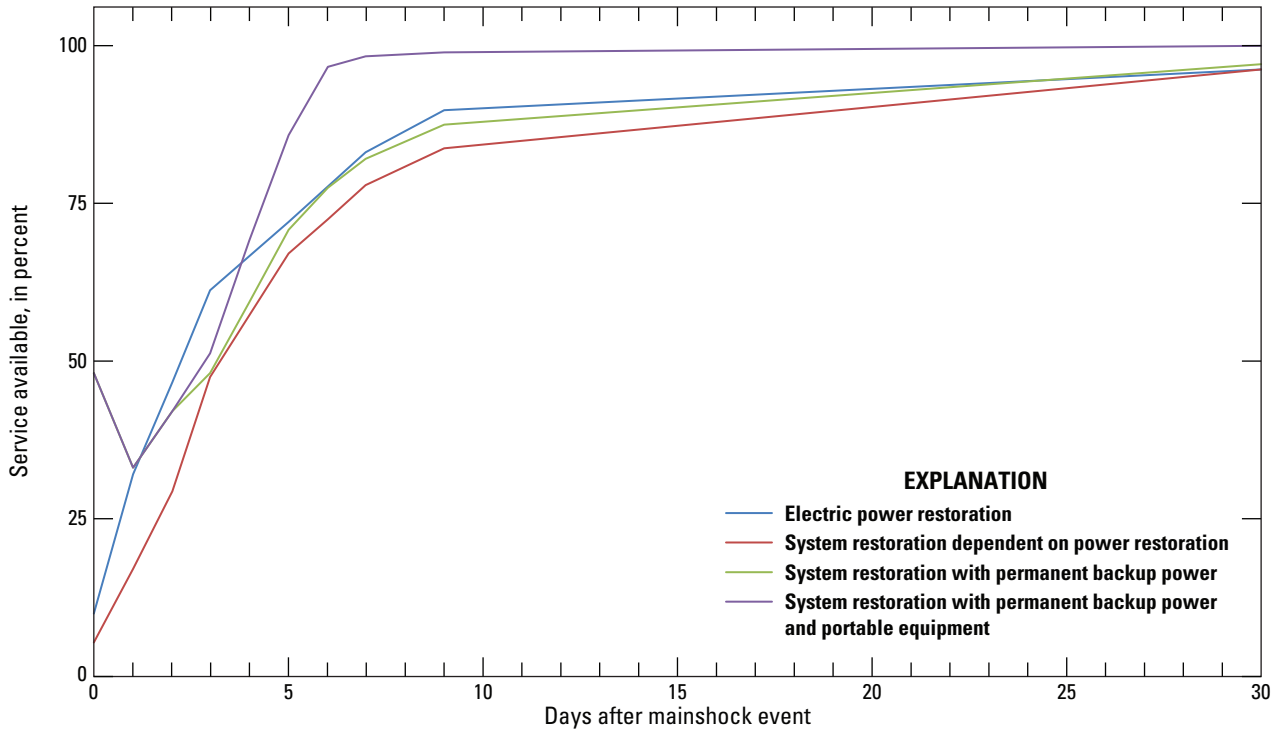


Figure 23. Line graph showing voice and data demand served and power restoration curves when the effect of demand surge is removed for Alameda County for the HayWired scenario mainshock in the San Francisco Bay region, California. The effects of two resilience tactics (permanent power backup and portable equipment) are shown.

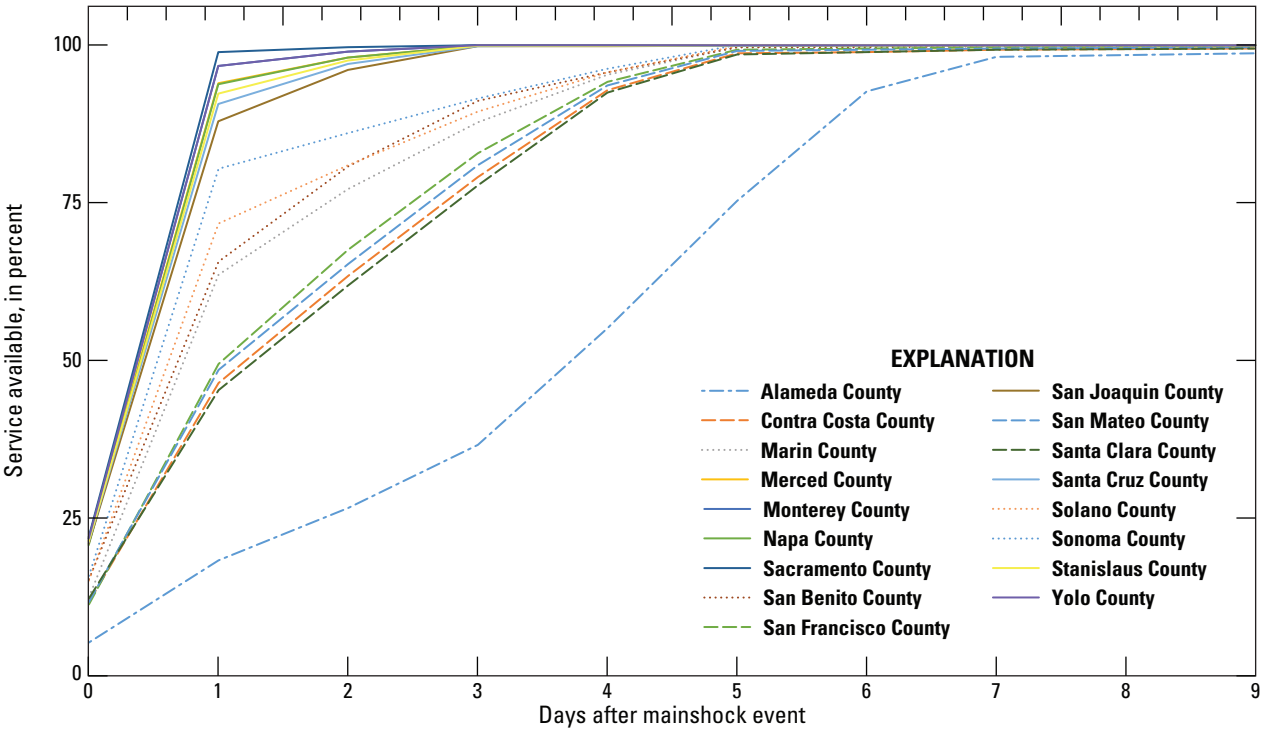


Figure 24. Line graph showing optimistic voice and data restoration curves when three resilience capabilities are implemented for the HayWired scenario mainshock in the San Francisco Bay region, California. The resilience capabilities are use of batteries and (or) generators, deployment of portable equipment (including cells on wheels [COWs] and cells on light truck [COLTs]), and management of user behavior.

prevalence and availability of backup power, and arrival time of first trucks with fuel and portable equipment. Parameter settings for these assumptions could be altered in the model constructed to estimate demand served.

In cited literature on disasters, telecommunications outages are most commonly attributed to power outages. Therefore, uncertainty in commercial power restoration is a primary source of uncertainty for voice and data demand served. The prevalence and performance of backup power supplies throughout the network is another critical source of uncertainty before the first trucks arrive. In addition, equivalent capacity for lost wireless sites has also been provided by increasing the radio frequency range allocated to telecommunications providers, as was done after the attacks on 9/11 (O'Rourke and others, 2003). We have not incorporated this effect into this study, which was effective soon after the 9/11 disaster.

The logistics of telecommunications restoration are represented by a distribution of days for the first trucks to arrive at sites in our model and the various uncertainties are also potentially large. The logistical uncertainties include availability of skilled labor (mutual aid, contractors, and employees) and accommodation of their needs for housing, sanitation, food, water, and broadband; transportation, safety, and security access to sites; and availability and delivery efficiency of fuel, gensets, and other portable equipment to sites. If first truck arrivals play out more like they did during Hurricane Katrina than during Hurricane Sandy (see Krishnamurthy and Kwasinski, 2014), the demand served would be restored at slower rates.

Fire following earthquake in the HayWired scenario (Scawthorn, 2018) is another uncertainty for further damage, larger losses of residual network capacity, and longer truck entry delays that would reduce the demand served throughout the service restoration. The relative exposure of telecommunications infrastructure to fire hazards varies by county. The more exposed components are fiber optic lines and monopoles in Alameda County; long-haul fiber optic lines, SSTs, and GTs in Contra Costa County; and central offices in Solano County. Fire damage would mostly concern aerial lines, although buried lines have also been damaged through equipment vents (Tiffen, 2017).

HayWired scenario aftershocks (Wein and others, 2017) do not independently cause severe damage, but associated power outages, cumulative damage, and degraded battery performance would set back the restoration of demand served in Alameda and Contra Costa Counties during the first few weeks, and potentially intermittently disrupt voice and data services in Santa Clara County during the first 6 months. Service restoration after aftershocks could be more quickly enabled if equipment is pre-staged in anticipation of aftershocks.

Depending on the season, water supply outages could affect evaporative cooling of data centers and large central offices that rely on makeup well and municipal water supplies. In the San Francisco Bay region, during cool weather data centers can be air-cooled, otherwise they need evaporative water cooling (B. Weihl, Facebook, oral commun., 2015). They generally have buffer water tanks that could last for a few days (for example, Foster, 2011) and water use would not be at peak demand in April (the month of the HayWired scenario). If water is needed for cooling, backup supplies last 1 week, and replenishment is not prioritized thereafter; in the HayWired scenario there could be more than a 50 percent chance that the backup water supplies are depleted in Alameda, Contra Costa, and San Mateo Counties and a 25 percent chance of backup water depletion in Santa Clara and San Francisco Counties (see HayWired water supply restoration in Porter, 2018).

Variability of Subscriber Experience

A telecommunications carrier (who wished to remain anonymous) cautioned that it is difficult to say how long service will be out, but likely weeks for peripheral parts of the system as it will take some time to bring in crews and mutual aid. As such, restoration will be focused on certain priority areas, such as dense population centers. We surmise that user experience could vary according to the following.

- *Provider and location*.—If a provider at a local cell tower exhausts its backup fuel supply, or did not have a backup generator in the first place, subscribers served by that tower may experience service disruptions whereas subscribers served by other sites may not (Applied Technology Council, 2016).
- *Subscriber support and coordination*.—Providers have taken measures to expand customer access to available services (sidebar 6).

Sidebar 6—Examples of Carrier Response to Supporting User Access

Services by carriers have been expanded by opening Wi-Fi to rival internet provider subscribers and setting up Wi-Fi hotspots with telephones and charging stations (Davidson and Santorelli, 2012; Roberts, 2014; BBC News, 2016). Also, residences and businesses have shared connections by removing passwords from their Wi-Fi routers (Davidson and Santorelli, 2012; BBC News, 2016). Wi-Fi calling (for those that have the capability) can also be enabled. Carriers have offered free and (or) lenient service charges to ensure that affected subscribers could use their mobile devices to make or receive calls, and to access data services (National Business Review staff, 2011; Davidson and Santorelli, 2012). In New Zealand, a telecommunications carrier shipped in a significant number of phones that could operate by using power provided via the plain old telephone service lines and these phones were distributed via Telecom Hub centers and retail stores free of charge (Eidinger and Tang, 2012; Tang and others, 2014). More advanced technology (tablets and smartphones) with access to free Wi-Fi was distributed at emergency shelters in Japan (Tang and Eidinger, 2017).

- *Service restoration priorities*.—Services are restored using the Telecommunications System Priority (TSP) program to ensure that critical services receive the highest priority and to minimize service disruptions to central offices and focus on recovery of technology (for example, AT&T, 2005). Conversely, if only a feeder line from a central office to a neighborhood is affected, the neighborhood outage could receive a lower repair priority.
- *Subscriber priorities*.—Currently, the Government Emergency Telecommunications Service (GETS) and Wireless Priority Service (WPS) provide priority access to landline and cellular communications services when communication networks are congested after a disaster (see Cybersecurity and Infrastructure Security Agency, n.d.), but there are limitations because the service cannot preempt and cannot deny service to users, which means that the resources used to process call requests (for example, the cellular signaling channels) can still be saturated by large numbers of people trying to make calls as well as compete with text messages that are also carried on the signaling channels.
- *Types of services*.—Text messaging is likely more available than cellular phone calls. Some websites might be unavailable (for example, InterNAP was down after Hurricane Sandy).
- *Subscriber demographics*.—Households with annual incomes below $50,000 increasingly rely on cellular data for access to the internet (McHenry, 2016) and likely lack other options (for example, to switch to in-home broadband) so the impact of cellular outages on lower income users would be greater.
- *Property damage*.—If property damage restricts use of buildings it will by extension restrict the use of broadband in those buildings, even if broadband service remains operational.
- *Subscriber preparedness for power outages*.—Only the analog POTS telephone system provides power over subscriber lines. Cordless phones and answering machines, DSL modems, DOCSIS cable modems, and VoIP gateways do not work without power. Backup power for residential and small business network equipment is crucial to maintain and restore communication capabilities at scale (Applied Technology Council, 2016).

Knowledge Gaps and Study Limitations

Knowledge gaps and study limitations apply to all aspects of our HayWired scenario analysis of physical infrastructure fragilities and voice and data service restoration. Before we address these knowledge gaps, it is important to remember that there are uncertainties and unknowns in how the Hayward Fault will rupture in the next earthquake. Although scientists are sure that the Hayward Fault will rupture again, they cannot say when and how the fault will rupture in the next large earthquake on the Hayward Fault. Therefore, the HayWired scenario analysis characterizes situations that might arise in any San Francisco Bay region earthquake.

Earthquake Hazard Uncertainties

The hypocenter in the HayWired scenario is under the City of Oakland, but the hypocenter of the next large earthquake on the Hayward Fault could occur at other places along the fault. A rupture from a different hypocenter would affect the directivity of the shaking intensity throughout the San Francisco Bay region (Aagaard, Boatwright, and others, 2017). Likewise, the amount of slip at each point along the fault at the time of the earthquake will affect the pattern of shaking intensity and damage to the copper pair, coaxial, and fiber optic lines crossing it. The new work on liquefaction and landslide probability assessments for the mainshock have data and methodological limitations that are documented in those chapters in volumes 1 and 3 of the HayWired earthquake scenario (Jones and others, 2017; McCrink and Perez, 2017; Jones and others, this volume). In addition, the aftershock sequence could play out in an infinite number of ways. Aftershocks would likely occur within 30 miles of the epicenter, but the sequence could remain active in this area or migrate to the east, the north, or around San Francisco Bay (as it does in the HayWired scenario aftershock sequence) (Wein and others, 2017). The uncertainties in fire following earthquake are large; the numbers of burned buildings could be more or less, and fire could spread through the wildland-urban interface. There are many factors that affect fire ignitions and containment, including building stock, wind, number of fire trucks, and aspects of response (communications, roadway access, and water supply) that are also affected by other earthquake hazards (Scawthorn, 2018).

Another unknown is the impact of the earthquake sequence on the Sacramento-San Joaquin Delta levee system with respect to fiber optic conduits and amplifiers and repeaters that run through that area to serve Contra Costa County emergency services. Finally, human-caused hazards could create cascading failure and security problems if hackers take advantage of post-earthquake chaos as a cover to launch cyberattacks (for example, take advantage of victims by setting up malicious sites) or if thieves remove copper pair, coaxial, and fiber optic lines (for example, Greenberg, 2019) and gensets.

Limitations of Study Scope

The scope of this study considers only physical components of telecommunications networks. A discussion of the software for routing, management, access control, and many other functions, located either in routing or switching equipment or separate servers, is in the Applied Technology Council's (2016) assessment. We are unaware of software incidents during an

earthquake and recognize that such an occurrence could have a more far-reaching effect.

Although we focus on two-way communication and data transmission, in an emergency, one-way wireless communication via AM and FM radio and television provides an alternative and critical source of information independent of telecommunications systems. The lower radio frequencies of television and radio broadcasts use omni-directional antennas that are not sensitive to misalignment. Indeed, radio services held up during the 2011 Christchurch earthquake in New Zealand (Mowll, 2012). In the HayWired scenario, television transmitters are not located in the most hazardous areas or exposed to the most intense landslides or fire following hazards, although 11 (less than 3 percent) AM and FM radio antennas are located in high liquefaction probability areas (Jones and others, this volume). A deeper analysis could examine exposure of fiber optic lines and coaxial data lines connecting transmission equipment, broadcast studios, and broadcast towers to earthquake hazards.

Data Limitations of Evolving Telecommunications Infrastructure Data

Unlike the analyses of water supply and transportation system infrastructures (used by Porter, 2018, and Jones and others, this volume), telecommunications technology is constantly evolving (Applied Technology Council, 2016) and no one entity can provide complete telecommunications infrastructure data. It is impractical for wireless carriers to collaborate or share data because of sensitivity of their information, overlapping network infrastructure, and the competitiveness of their industry. GeoTel periodically updates a collection of telecommunications infrastructure data and we used a 2018 version (see Telecommunications Infrastructure Data section under Methods).

The GeoTel data do not capture OLCs or DLCs, microwave links, or the trend of small cells. In 2008, most cellular infrastructure was handled by large macrotowers covering many square miles, but today, wireless telecommunications are increasingly reliant on heterogeneous network (HetNet) technologies, such as distributed-antenna systems (DAS) and small cells, and this technology trend will continue as the industry continues to expand the 4G network and transitions to 5G beginning in 2020.

Scant Telecommunications Infrastructure Design and Fragility Data

Neither age data nor other design parameters for facilities and equipment installation exist in the GeoTel data. We used Hazus fragility information to estimate shaking damage to central offices, data centers, unanchored equipment, and PSAP facilities. For purposes of selecting Hazus fragility information to use, we assumed that central offices and data centers are generally one to three stories tall, were built between about 1940 and the 1990s, and have walls of reinforced masonry construction plus rigid floor and roof diaphragms or have tilt-up reinforced concrete panel walls. We used the same default fragilities for buildings supporting cellular sites for illustrative purposes. With help from industry advisors, we estimated shaking damage to cellular towers (SSTs, GTs, and monopoles) by comparing seismic loads with wind load design standards in the TIA-222-G standard. We represented the risk of overturning unanchored equipment in a central office using the minimum median capacity of typical central office equipment and loosely applied the same shaking threshold for all types of telecommunications equipment. We mapped infrastructure with respect to ground-failure probabilities and fire density to indicate potential hazard exposure falling short of integrating damage estimation across hazards.

Little is known about the fragility of optical fiber line to earthquake hazards, except for one study of shaking and liquefaction hazards. Furthermore, Applied Technology Council (2016) recommends conducting studies to compare mean time between failure and mean time to repair for buried versus aerial installations of fiber optic lines to test the hypothesis that buried fiber optic lines are more resilient. We are unaware of any such studies to date.

Although aftershock shaking is generally less intense than the mainshock shaking in the HayWired scenario, we were unable to account for weakening of structures and equipment or aging of the backup batteries throughout the sequence that would reduce their performance during an aftershock sequence.

Simple Model of Network Capacity and Service Restoration Times

Even if component fragilities and functionality (including uncertainties of power supplies and backup power) were better understood in the region, there is no capability to show how the networks will perform with component capacity losses in the context of network diversity, single points of failure, and correlated failures. The Applied Technology Council (2016) recommends developing computational models and tools for simulating the impact of disruptive hazard events on telecommunications design choices and restoration strategies using realistic recovery assumptions. Modeling real telecommunications systems and the effects of stresses on them is a nascent field. Simulations are being developed to answer questions about the probability of cascading outages within networks and to assess effects of call duration and how much call blocking (if a state of emergency is declared) might be necessary when a network is stressed. Researchers also aim to provide guidance on the number of COWs and COLTs to dispatch after disasters and during evacuations (V. Krishnamurthy, University of Pittsburgh, written commun., 2017). The Applied Technology Council (2016) identifies the lack of data, metrics, and tools to measure, monitor, and diagnose network system performance. Although the Federal Communications Commission gathers data about large-scale network outages both during normal operation and after hazard events, the data are currently not available for root-cause analysis or to estimate recovery times (Applied Technology Council, 2016).

Voice and data service restoration times are needed to examine impacts to emergency response, businesses resumption, community recovery, and the digital and regional economies. Therefore, we assemble a simple model of voice and data demand served for the purpose of estimating restoration times for the HayWired scenario and investigating the effectiveness of resilience measures. We use the notion of demand served that encompasses network functionality and demand surge. Data and models needed to describe the elements of voice and data service restoration include the following:

- Functionality of telecommunications infrastructure components damaged by multiple earthquake hazards and the effect on the residual network capacity;
- The prevalence, availability, and running times of backup power options and dependence of telecommunications equipment on uncertain electric power restoration;
- Dependence of cooling equipment in data centers and central offices on water supply restoration;
- Arrival times of the first trucks carrying fuel, gensets, and portable equipment to compromised sites; and
- Spatiotemporal demand surge for voice and data services after an earthquake and effectiveness of user behavior management.

Summary and Conclusion

Analyses of telecommunications infrastructure and service restoration for the HayWired earthquake scenario complements the Applied Technology Council's (2016) effort that broadly considers telecommunications standards, guidelines, and performance criteria; lifeline infrastructure interdependencies and societal impacts; and research and operational recommendations for disaster recovery. The Applied Technology Council's (2016) assessment concerns various hazard events and derives primarily from recent hurricane events in the United States, whereas the HayWired scenario more extensively examines the multiple hazards of an earthquake sequence in the San Francisco Bay region.

This chapter describes the culminating effects of a large earthquake on commercial voice and data services considering:

- Capacity losses from damage to telecommunications infrastructure caused by ground shaking, ground failure or movement (surface fault rupture, liquefaction, and landslides), and fire following earthquake.
- Amplification of network functionality losses from electrical power supply outages and battery and (or) generator backup power-supply failures.
- Network congestion from surges in demand for voice and data services, caused by subscriber activity that is above network-design capacity following a large earthquake.
- Logistical delays in deploying portable equipment, replacement parts, and fuel for power generation to failed sites.

In this final section, we first summarize the telecommunications infrastructure exposure to or damage from HayWired scenario hazards and service restoration estimates. We then draw insights on societal impacts from the reduced functionality of public safety answering point (PSAP) facilities and from other HayWired chapters regarding delays in reporting fires following an earthquake, interactions of telecommunications infrastructure with other lifeline infrastructures, information and communication needs of displaced populations, and economic consequences of voice and data service outages. In conclusion, we compile opportunities to improve the performance of telecommunications networks and restoration of services after a large earthquake by the industry, and resilience opportunities for governments, subscribers, and enterprises.

Telecommunications Infrastructure Hazard Exposure and Damage

Resilient telecommunications networks are composed of

- structures, equipment, and communication channels built to resist hazards according to their primary use;
- diverse backhaul connecting edge equipment to the core of a network;
- redundant interconnection points between operators;
- failover facilities; and
- reliable access to power and water supply (where needed for cooling).

As noted in the section on knowledge gaps, examination of resilience is limited by the paucity of performance metrics and resilience standards, response exercises, and simulations and models to test, monitor, and report network functionality and operability when some components fail. The HayWired analyses are only able to indicate potential hazard exposure or damage to certain infrastructure components. Findings of these analyses are summarized below for:

- central offices, wireless switches, and data centers;
- macrocellular sites;
- any unanchored equipment;
- wired and wireless channels

To summarize multiple earthquake hazard impacts on infrastructure components, we expand the Applied Technology Council's (2016) ratings for (low or high) hazard threat or preventable damage.

Central Offices, Wireless Switches, and Data Centers

For the HayWired scenario, assuming a moderate building code for typical central office buildings (reinforced masonry construction that have rigid diaphragms or tilt-up concrete), shaking damage estimates suggests nine central offices could be restricted use (yellow tag) and five central offices could be unsafe to enter or occupy (red tag) affecting more than 30 instances of carriers in central offices. Assuming the same building types for data centers, there could be only one that is yellow tagged because of the location of these facilities. Relatively more data centers are located on the San Francisco Peninsula and in the south bay, further away from the ground shaking and fire hazards caused by the Hayward Fault rupture scenario. However, more data centers are located in high (25 percent or greater) liquefaction probability areas, including six in Santa Clara County. Data centers are also exposed to the largest aftershocks in the HayWired scenario earthquake sequence. Wireless carrier switch locations appear to be largely out of harm's way for this particular scenario.

Data centers may also outperform central offices based on Applied Technology Council's (2016) finding that data centers are the only communication-related entities that have a comprehensive, verifiable set of standards with auditing. A new data center in San Jose features earthquake-proof design (see https://www.ragingwire.com/wholesale-data-centers/silicon-valley-california). Although carriers have indicated investments into earthquake mitigation of San Francisco Bay region central offices, the specifics of the seismic performance of the offices are unknown to the authors.

Cellular Sites

Working with the Telecommunications Industry Association (TIA), we find self-supporting towers (SSTs) and guyed towers (GTs) designed per the TIA-222-G standard to resist high wind loads are also expected to resist the seismic loads of the HayWired scenario. The exposure of the approximately 500 towers to other HayWired scenario hazards are relatively small in number: seven are exposed to a high level of fire density in Contra Costa County, one tower is in a high liquefaction probability area in both Alameda and San Mateo Counties, and one tower is in a high landslide probability area in Santa Clara County.

In the study region, there are a large number of cellular sites (approximately 2,500) that are classified as monopoles. Of these, about 30 in each case are potentially vulnerable to shaking damage, high liquefaction probability, and (or) high level of fire density in Alameda County. The weight of the equipment (load) and height of the pole (less than 50 feet) are important considerations for avoiding shaking damage at monopole sites. We were not able to evaluate the growing trend of cellular network densification using heterogeneous network (for example, small cell) wireless sites deployed on streetlight or utility poles.

The most common location for siting of antennas or towers in the San Francisco Bay region is on buildings; approximately 5,000 buildings support cellular sites. These sites are subject to seismic building performance that could be structurally more fragile than freestanding towers, as seen in previous disasters. In the HayWired scenario, ground shaking is the dominant hazard for building-located cellular sites but building age and type data have not been associated with sites. Assuming the same building construction as for central offices and data centers, 45 percent of 820 buildings supporting cellular sites in Alameda County will receive a yellow or red tag, for example. Other hazard exposures include 7 percent of building sites in Alameda County in areas with a high density of burned buildings; 23 percent of 266 building sites in San Mateo County exposed to high (25 percent or greater) liquefaction probability; and one or two building sites in high (25 percent or greater) landslide probability areas in Contra Costa, San Mateo, Santa Clara, and Sonoma Counties. Although damage to the building does not presume damage to the cellular site, it could limit or restrict access to the site.

Overall, we expect older and (or) poorly maintained cellular towers and building sites will be more vulnerable to earthquake hazards than newer structures. The latest TIA design guidelines classify tower structures according to the importance of the cellular tower to the network and published safety of the structure in ANSI/TIA-222-G and ASCE 7 (Lanier and Garrett, 2017). The updated standard (TIA-222-H) now provides guidelines for long period motions of tall tower structures, including monopoles (B. Lanier, American Tower Corporation, written commun., 2019). TIA-222-G/H cite minimum technical information to use in designing cellular site foundations (B. Lanier, American Tower Corporation, written commun., 2019). However, when selecting a building for cellular siting it is fair to say that seismic building performance is not a primary criterion for site selection; the wireless industry primarily considers several factors, including location relative to needed coverage, lease rates, costs of preparation and construction, and so on (T. Page, Crown Castle International, oral commun., 2019).

Unanchored Equipment

The vulnerability of unanchored equipment, including heating, ventilation, and air conditioning systems (which performed poorly during the 1994 Northridge earthquake [Schiff, 1995]), corresponds to the shaking threshold for yellow-tagged moderate code buildings of the types assumed for data centers and central offices in our HayWired scenario analysis. Based on prior earthquake observations, unanchored equipment and other equipment failures are more common than damage to containing or supporting structures. Inconsistent wireless industry standards for anchoring equipment, tethering battery racks and equipment, and so on, within vaults and buildings create unknowns about their potential performance during an earthquake.

Wired and Wireless Channels

HayWired workshops in 2017–2018 and Applied Technology Council (2016) established that backhaul from cellular sites to the backbone and core networks is as important as site performance during an earthquake to maintain functionality. Copper lines, fiber optic lines, and microwave links have been damaged by shaking, ground-failure hazards (landslide, liquefaction, and [or] fault offset), and (or) fire from earthquakes (see Telecommunications Infrastructure Exposure and Damage from HayWired Earthquake Hazards section).

In the HayWired scenario, hundreds of interoffice or long-haul fiber optic lines cross the Hayward Fault and are exposed to as much as 2 meters of surface offset from fault surface rupture and afterslip (Aagaard, Schwartz, and others, 2017). More than 1,000 kilometers of interoffice fiber optic line and more than 300 kilometers of long-haul fiber optic line run through areas with liquefaction, fire following earthquake, and (or) landslide hazards. Long-haul fiber optic line is relatively more exposed to high (25 percent or greater) liquefaction probability and high burned-building density (exposing 4 percent of lines in the region in each case), and interoffice fiber optic line is relatively more exposed to high (25 percent or greater) landslide initiation probability (exposing 2 percent of these lines in the region). Surface streets (along which copper and coaxial lines commonly run from DLCs and OLCs) are similarly exposed to these same hazards. Design guidelines are lacking for buried fiber optic line regarding ground failure hazards, including fault crossings. The Applied Technology Council (2016) concludes that fiber backbone, first- and last-mile impacts, and preventions are unknown for earthquakes.

In addition, collateral damage could result from lines collocated on bridges and power poles, along transportation corridors, and along water and energy pipeline routes that are damaged by earthquake hazards. In the HayWired analysis of collocated lifeline infrastructure (Jones and others, this volume), interoffice fiber optic line is commonly collocated with other infrastructure (oil and gas, electric power, water and waste-water transmission systems, and roadways and railway lines) in about 10,000 places in areas with one or more high-intensity hazard. Long-haul fiber optic line appears to be collocated in about 1,300 places, and 800 of these collocations are with other types of transmission infrastructure. However, based on available data, we do not know whether fiber optic line is an aerial or buried installation.

A particular example is fiber optic lines running along bridges that could be damaged by shaking or ground failure. Using geographic information systems (GIS) and bridge shaking damage estimates (Jones and others, appendix 5, this volume), we estimated that fiber optic line may be collocated on 37 and 50 medium-high and high potential impact bridges, respectively, in the HayWired scenario. Another possible transportation interaction is damage to fiber optic line in a railway easement from a train derailment (for example, Ratner, 2001) caused by shaking.

There is a further risk of causing more damage to collocated buried infrastructure during repairs. Crews using backhoes to repair buried water or natural gas pipelines have accidentally damaged buried copper or fiber optic line. Workshop participants reported that the Underground Services Alert clearinghouse of precise wire and fiber line locations are updated infrequently—not often enough to be a reliable source during an emergency.

Summary of Hazard Impacts on Infrastructure

Table 23 summarizes the impacts of earthquake hazards on key components of telecommunications networks. The table is adapted from one by the Applied Technology Council (2016). The single earthquake column in that table is expanded into five earthquake hazards here. Impact levels are characterized as low or high, where low indicates that most elements will continue to function after the exposure to the hazard, and high indicates a large fraction of the exposed components are affected. Some are preventable owing to the existence of regulations (for example, data centers) and guidelines (for example, towers). Compared to Applied Technology Council's (2016) table, submarine lines and landings are excluded because they are not in the HayWired scenario study region (for example, Burrington, 2015), and software is excluded because we have no further information. Three rows are added to include DLCs and OLCs, building-mounted or supported cellular sites, and unanchored equipment.

Network Functionality and Demand for Services

Voice and data services are inseparable for analysis purposes owing to convergence of communication and information systems. The abilities of telecommunications networks to meet demand are affected by

- residual capacity after earthquake damage,
- equipment failure from power outages, and
- congestion from surge in demand for services after a large earthquake.

Strategies that increase network functionality include permanent (fixed) backup power on equipment, delivery of fuel and deployment of portable equipment to sites, and management of user behavior. The effects of a large earthquake are greater than recent Public Safety Power Shutoffs (PSPS) because of damage to telecommunications infrastructure, larger expected demand for services, and damage to other infrastructure, creating fuel shortages and logistical problems in addition to electric power outages.

Residual Network Capacity

Residual network capacity in each county is approximated from the product of the residual capacity estimates for central offices or data centers, cellular towers or interoffice fiber optic lines, and long-haul fiber optic lines considering all hazards. The

Table 23. Major telecommunications infrastructure components and exposure levels to earthquake hazards in the HayWired earthquake scenario in the San Francisco Bay region, California.

[Modified from the Applied Technology Council (2016). Exposure is designated as preventable (in other words, no impact) if appropriate code and standards could prevent impacts. DLC, digital loop carrier; OLC, optical loop carrier; n/a, not applicable]

Telecommunications infrastructure component	Ground shaking	Fault offset from coseismic slip and afterslip	Liquefaction	Landslide	Fire following earthquake
Last mile, aerial copper line, and fiber line	Low (except falling debris on lines or weak pole base)	Low	Low (except for inadequate pole foundations)	High	High
Last mile and buried copper line	Low	High	Low (except for manholes and collateral water utility damage)	High	Low
DLCs and OLCs	Low	n/a	Low (except for inadequate foundations)	High	High
Backbone, middle and last mile, and buried fiber optic line	Low	High	Low (except old fiber lines and manholes)	High	Low (except heat entering through vault vents)
Data centers	Preventable via regulations	n/a	Preventable via building codes	n/a	Preventable
Central offices	Preventable or unknown	n/a (closest office is 0.2 miles from fault zone)	High (where sited before hazard was understood)	n/a	Preventable
Free-standing towers, monopoles, and poles	Preventable via guidelines (for loads)	n/a	Preventable via guidelines	High	High
Cellular sites on buildings	High (for sites on vulnerable buildings)	n/a	Low	High	High (for wood-frame buildings)
Equipment	Preventable (but inconsistent standards)	n/a	Low (except water damage)	High	Preventable (except smoke damage)

estimated residual network capacity ranges from 53 percent in Alameda County, to between 74 and 97 percent in the other eight counties that are adjacent to San Francisco Bay, and to 100 percent for counties in the larger region.

Electric Power Supply Dependence

In the HayWired scenario, electric power outages are estimated to affect about 2 million customers throughout the San Francisco Bay region, which is similar to the unprecedented PSPSs during the California fire season in 2019. Electric power restoration is estimated to take days in the less affected counties to weeks in the more affected counties. Power outages are initially widespread and telecommunications equipment is more commonly affected by power outages than earthquake damage in all counties; therefore they are the dominant cause of functionality losses. If equipment is fully dependent on electric power supply, power outages reduce residual network functionality to less than 10 percent in Alameda and Santa Clara Counties. If we assume damaged telecommunications equipment is restored with a lag behind power restoration (for example, by 2 days in the most heavily damaged county of Alameda), after 1 day,

- Alameda County network functionality is restored to 17 percent.
- The network functionality in the other eight counties adjacent to San Francisco Bay is restored between 30 and 90 percent.
- The network functionality in the counties in the rest of the region is restored between 60 and 90 percent.

Permanent Backup Power

In the case of electric power outages, we assume that backup power installations replace the lost network functionality equivalent to a 50-50 presence of generators that have 3 days of fuel and batteries that drain within the first day with 90 percent availability.[19] Compared to the case of fully dependent electric power restoration, permanent backup power increases network functionality in Alameda County to 48 percent (that is, 90 percent of the residual capacity) on the first day. One week later, generators sustain about a 7 percent increase in network functionality over the electric power-dependent case, assuming fuel deliveries to permanent generators are accomplished within 2 to 7 days. Other counties

[19]Staff and budget cuts since the 2008 recession could have resulted in increased potential failure rates of backup power. Uninterruptable power supply failures are another consideration.

show similar patterns of improvement from permanent backup power, but the improvement relative to the electric power-dependent case peaks earlier than it does in Alameda County owing to faster electric power restoration that reduces the need for backup power in those counties.

Fuel Delivery and Portable Equipment Deployment

Industry preparedness and response is represented by modeling portable equipment deployment and fuel deliveries to sites with equipment and (or) power failures that occur at the same rates that the first trucks arrived after Hurricane Sandy. Inherent in the first truck arrival rates are contingencies of fuel supply, labor supply, and site access; the industry expressed less concern about availability of materials and equipment. In Alameda County, the model estimates as much as a 20 percent increase in network functionality over the electric-power-dependent case (peaking on day six) from fuel and equipment delivery to failed sites when the first trucks arrive between 2 and 7 days after the earthquake. The telecommunications system could outperform the electric power system on day four. The network functionality improvements from the industry response occur quicker in other counties because first truck arrivals are modeled to happen between 1 and 5 days after the earthquake.

Network Congestion

A surge in subscriber demand after a disaster can exceed residual network capacity, and even the network design capacity before the disaster. In our model, the percentage of post-earthquake demand that can be served by pre-event design capacity is initially assumed to be 10 percent in the most affected county of Alameda. The demand surge is assumed to decline with time and distance from the earthquake. In Alameda County, the demand surge initially reduces the demand served in the fully power-dependent network to almost zero, and to 7 percent for the case of permanent backup power. Two days after the earthquake, the network is about 40 percent functional (batteries have run out) but demand served increases to 25 percent because demand surge has declined. In the permanent backup-power case, demand served is initially below 20 percent in other counties, but demand served restores faster than in Alameda County owing to faster electric power restorations, faster industry responses, and lower levels of demand surge.

If we assume that demand surge can be reduced by 10 percent from carriers doing what they can to control subscribers' use of the networks and subscribers conforming to advice to reduce phone calls and other actions to conserve bandwidth, the model shows little initial benefit in Alameda County because the networks are still overwhelmed. However, user behavior management offers about a 9 percent increase in demand served 6 days later when network functionality has restored to 96 percent and demand only slightly exceeds the network design capacity. Similarly, in other counties, a 10 percent reduction in demand surge does not markedly relieve congestion on the first day. This illustrates how communications are crippled when they are most needed for health and safety responses immediately after a disaster.

Societal Consequences

The percentage of voice and data demand served has societal consequences for public health and safety, restoration of other critical lifeline services, and enterprise recovery (Applied Technology Council, 2016). We flesh out some of these societal impacts using the public safety answering point (PSAP) functionality analyses in this chapter and other HayWired chapters about fire hazards, communities at risk, and economic impacts.

Health and Safety

As is typical after a large earthquake, the safety of populations is most threatened when communication failures are the greatest owing to reduced network functionality and surges in demand for services (for example, Yamamura and others, 2014). During the hours and days after a disaster, commercial telecommunications networks are needed for emergency response communications to alert, warn, and inform the public about their safety, resources (such as food, shelter, or medical care), and restrictions or advisories (such as road closures or boil-water advisories) (Applied Technology Council, 2016), as well as for some of their own internal response communications. The problem is well known, and all U.S. States and territories have opted into FirstNet (https://www.firstnet.com/home), a network built through a public-private partnership with AT&T, that dedicates wireless broadband for emergency responders, and possibly provides some improvements to commercial networks at the same time (for example, backup power at shared sites). The migration of public safety broadband to FirstNet has initiated in the cities of San Jose and San Francisco (for example, AT&T, 2019) and is being tested in other Hayward Fault communities, including the City of Oakland. During the adoption phase of FirstNet, the biggest concern is coverage (C. Reynolds, Bay Area Regional Interoperable Communications System [BayRICS], written commun., 2020).

Other health and safety issues are

- Loss of functionality of PSAPs, further degrading 9–1–1 services,
- Delayed reporting of fires after a large earthquake,
- Inequitable services for socially vulnerable populations with fewer options, and
- Services for individuals with access and functional needs.

9–1–1 After an Earthquake

During and soon after disasters, PSAPs handle 9–1–1 calls for emergency services. In the HayWired scenario, facilities hosting PSAPs are not fully functional after the

M_w 7 earthquake, particularly in the hardest hit county of Alameda, where 42 percent of buildings that host PSAPs are estimated to be less than 25 percent functional on day one. The performance of 9–1–1 will depend on the extent that San Francisco Bay region PSAPs maintain critical 9–1–1 circuit diversity, central office backup power, diverse network monitoring, and backup internet or sites to improve their availability (per Federal Communications Commission, 2015, 2016; and Office of the Federal Register, 2015).

Fire Reporting

Scawthorn's (2018) modeling of fire following earthquake for the HayWired scenario assumes that 9–1–1 systems and PSAPs are completely overwhelmed, and persons calling in to report fires cannot get through, such that responses are delayed until either fire companies themselves observe smoke from a fire, or a resident travels (drives, runs, and so on) to the fire station or company and reports the fire (a still alarm). Meanwhile, fires spread, and this has been the experience in major earthquakes (C. Scawthorn, SPA Risk LLC, written commun., 2019).

Vulnerable Populations

Socially vulnerable populations have a greater prevalence of housing-related and income-related challenges (for example, lack of home ownership, high housing cost burden, lower household incomes) and literacy challenges (for example, lower levels of education and more non-English speakers) (section B of Johnson and others, this volume). These populations disproportionately reside in areas of heavier and concentrated building damage in the HayWired scenario (section B of Johnson and others, this volume).

Socially vulnerable populations are also more likely to have only wireless connections and lower cost plans with fewer features (Anderson and Hitlin, 2016; California Emerging Technology Fund, 2017; Blumberg and Luke, 2019). Certain populations (young adults, Hispanics, renters, multifamily households, and households that have income levels below the Federal poverty line) are more likely to have given up wired telephones (whether POTS or VoIP) and have wireless only for voice service (Anderson and Hitlin, 2016; Blumberg and Luke, 2019). Households that have incomes below $50,000 per year are increasingly likely to rely on cellular data for access to the internet (McHenry, 2016). During the post-earthquake response and recovery phases, many of these people will not have the option of switching to in-home broadband for voice and data services—because they do not have it to begin with. During the 2020 pandemic, we learned that people without home broadband could not engage in distance learning, telehealth, or telework (Vogels and others, 2020; Galperin and others, 2021).

Furthermore, socially vulnerable populations residing in heavily damaged areas are prone to displacement (section B of Johnson and others, this volume). The ability for people to return home is governed by authorities allowing access that largely influences the pace and place for the recovery, including upgrades of telecommunications services (V. Krishnamurthy, University of Pittsburgh, written commun., 2017). The telecommunications recovery process has been less favorable for areas that have socially vulnerable populations after a disaster—even without a disaster, these communities currently lag behind on installations of fiber to the curb.

Populations with Access and Functional Needs

Although households that have individuals with disabilities are not disproportionately affected by concentrated building damage in the HayWired scenario (section B of Johnson and others, this volume), they are identified as having below-average rates of in-home broadband services (California Emerging Technology Fund, 2017) and therefore fewer options. Electric power and telecommunications outages compromise their ability to maintain their health, receive mobility assistance, and call for help.

Enterprise Recovery

Everyday business and other enterprise operations (non-profits and government) are generally affected by telecommunications disruptions for between 1 and 12 weeks after disaster events (Applied Technology Council, 2016). The Applied Technology Council (2016) proposes research be conducted to understand the economic impacts of sustained communication outages. Sue Wing and others (this volume) models 6 months of business interruption losses measured as gross state product (GSP) losses from the telecommunications service disruptions determined in this chapter. Inversely, the provision of telecommunications services enables teleworking to reduce business interruption losses from property damage and transportation disruptions (Sue Wing and others [this volume] and Kroll and others [this volume], respectively). We elaborate on these two aspects for the HayWired scenario below.

Business Interruption Losses from Telecommunications Service Disruptions

Sue Wing and others (this volume) isolate the impact of voice and data service disruption on the macroeconomy by modeling the ripple effects of the service disruption through the sectors that supply and purchase goods and services from each other in the San Francisco Bay region and California economies. Top purchasers of telecommunications and data processing and hosting sectors include telecommunications; professional scientific and technical services; publishing, motion pictures, and broadcasting; and finance, insurance, real estate, and leasing sectors (Sue Wing and others, this volume).

In the case of electric-power-dependent telecommunications restoration, the $350 million loss of GSP is larger than the losses from electric power. However, these losses may be reduced by the implementation of various resilience measures, including carrier responses and business continuity practices. Permanent backup power on telecommunications equipment and subscriber behavior management are effective immediately; although short-lived,

each show a reduction of about $50 million of GSP losses. The deployment of portable equipment and fuel delivery, albeit delayed, achieves a larger reduction of $150 million of business interruption losses.

Alternatively, supposing that none of these industry measures are implemented and enterprises instead use workarounds of paper records, data backup, and cash transactions to continue business with an effectiveness equivalent to 20 percent increase in voice and data services, the GSP losses are also reduced by $150 million. The effects of resilience measures are not additive, but if all are implemented, the GSP losses from telecommunications disruptions are reduced from $350 million to $37 million. To put these losses in perspective, GSP losses from property damage caused by the earthquake sequence and fire contribute 98 percent of the total estimated $43 billion GSP losses.

Business Interruption Loss Reductions from Telework

Using the prevalence of telework in industry sectors, Sue Wing and others (this volume) found that telework reduced GSP losses from telecommunications service disruption by about $5 million, but more effectively reduced business interruption losses from property damages by about $3 billion or 6 percent of the estimated 6-month $43 billion of GSP losses. Kroll and others (this volume) found that halving the implementation of telecommuting in the case of highway and rapid transit transportation disruptions increased total gross regional product (GRP) losses by $4 billion or a 6 percent increase of the estimated total $67 billion of multi-year GRP losses. These results illustrate the important role of telecommunications services for teleworking that enhances economic resilience. However, the ability of employees to work remotely relies on telecommunications providers restoring internet service or at least high-quality mobile data services to homes and alternative workplaces (also see Applied Technology Council, 2016) and shifts in demand. During the 2020 pandemic, use of home-based broadband increased and was pushed out to the edges of the networks (Shanmugaraj, 2021).

Interactions with Other Lifeline Infrastructure Systems

Other lifeline infrastructure systems depend on telecommunications to monitor and operate transportation, water, and energy systems, and communicate about their statuses (Applied Technology Council, 2016). For example, during the 2014 South Napa earthquake, the supervisory control and data acquisition system for monitoring water tank levels failed owing to power outages in the absence of backup power (J. Eldredge, City of Napa, written commun., 2017). The dependence of critical infrastructure operations on telecommunications services can be seen in the economic analysis of Sue Wing and others (this volume). Electric power and various transportation sectors are among the top purchasers of telecommunications services, amounting to about 1 percent of their gross output. HayWired telecommunications service outages reduce 6-month outputs of water and various transportation sectors by approximately 0.02 to 0.25 percent (depending on implementation of resilience measures), but output losses in the electricity and gas sectors are less sensitive.

Opportunities for Increasing Resilience

Findings from the HayWired scenario, an earthquake sequence initiated by a moment magnitude (M_w) 7.0 earthquake on the Hayward Fault, are used to identify and reinforce opportunities for improving the performance of San Francisco Bay region telecommunications networks and societal resilience to service disruptions. The following points, derived from HayWired scenario analyses and workshops, complement and overlap with those in the Applied Technology Council (2016) report about disasters, earthquake reconnaissance reports, and Bay Area Urban Area Security Initiative and other local government communications resilience programs. For providers of voice and data services, opportunities pertain to mitigating damage from multiple earthquake hazards, addressing dependencies on building sites and other lifeline infrastructure systems, preparing for restoration contingencies, using earthquake risk communications, working with governments, and managing user behavior. Societal resilience to voice and data service disruptions could be increased by emergency response planning, user preparedness, and business continuity planning.

Resilience Opportunities for Voice and Data Service Providers

1. Mitigating Damage from Multiple Earthquake Hazards

1.1. Mitigating Shaking Damage

In the HayWired scenario, ground shaking is strong throughout the San Francisco Bay region, and violent near the fault and in sedimentary basins in the east bay. Telecommunications infrastructure that is most vulnerable to very strong or higher intensities of shaking includes older infrastructure, central offices (owing to unknown retrofit and siting standards), unanchored equipment, poles that are heavily loaded with equipment, and sites on seismically vulnerable buildings.

- Performance-based retrofits and building codes, TIA design guidelines, and development of a set of consistent standards for securing equipment and battery racks[20] are

[20]Network Equipment-Building System GR-63 guidance for central office equipment provides a starting point for securing equipment (A. Tang, L&T Consultant, written commun., 2018).

all mitigation actions that could be taken to reduce damage to telecommunications infrastructure from shaking.

- With education, standards could be required by contracts to ensure equipment is properly installed to resist seismic events.

1.2. Mitigating Ground Failure Damage

In the HayWired scenario analysis, telecommunications infrastructure is mapped on fault rupture and surface offset as well as liquefaction and landslide probabilities to illustrate exposures of fiber optic and copper lines, monopoles and cellular sites on buildings, and central offices and data centers in the San Francisco Bay region.

- The performance of telecommunications infrastructure could be improved with increased knowledge about ground failure hazards and geotechnical design guidance for
  - Transitions from copper to fiber optic lines and (or) aerial to buried lines;
  - Redundant and diverse backhaul, backbone, and inter-networking connections between central offices and data centers on opposite sides of the fault; and
  - Structure and pole foundations, vaults, and manholes at sites susceptible to liquefaction and landslide hazards (see also Tang and others, 2014).

1.3. Considering Fire Following Earthquake

Fire after an earthquake concentrates and spreads building damage (especially among densely spaced wood buildings) that may affect cellular sites in the area. Fire threatens aerial lines more than buried lines but produces heat that could enter underground vaults via vents to melt lines. Smoke and soot could clog filters and interfere with heating, ventilation, and air conditioning systems.

- The telecommunications industry could be made aware of how to prevent fire ignitions from earthquake shaking and ground movement and to prepare for conflagrations after an earthquake.
- The telecommunications industry could consider fire hazards in the built environment when siting and designing equipment. For example, for vaults with active ventilation, the use of pyrostats—which will turn on fans for cooling but also shut down fans if the air temperature indicates a fire—could help reduce heat damage.
- One complicating factor of fire spread after earthquakes is the inability to report fires when communications fail, and this interaction warrants further study.

2. Addressing Dependencies on Building Sites and Other Lifeline Infrastructure Systems

2.1. Mitigating Risks to Cellular Sites on Buildings

Seismically vulnerable buildings during an earthquake present multiple threats to cellular sites owing to large numbers of sites on buildings in the urbanized San Francisco Bay region, constraints on backup power equipment loads on top of buildings, and municipal building inspection policies that delay entry to telecommunications sites. In the past, wireless carriers were aggressive about installing backup power for buildings hosting their sites that were close to critical locations, such as government buildings and hospitals. As wireless site deployment has moved closer to population centers and especially residential areas, suitability of a site is now driven more by availability and business considerations.

- The industry could prioritize seismic building performance in siting equipment and network designs, emphasize the importance of backup power with building owners, and discuss building inspection policies with local governments in addition to the current site selection criteria of signal coverage, service expectations, and conforming to other local government regulations.
- Buildings conforming to modern building codes provide an added resiliency benefit for cellular sites located on them.

2.2. Mitigating Collateral Infrastructure Damage

Interoffice and long-haul fiber optic lines are collocated with other types of lifeline infrastructure in HayWired earthquake high-hazard-intensity areas throughout the San Francisco Bay region.

- The trend to replace buried and aerial copper wiring with buried fiber optic lines provides a stronger defense against flooding damage from water distribution pipeline breaks and fire following earthquake, respectively.
- Pole construction standards (for example, General Order 95 in California [Public Utilities Commission, 2018]) could potentially improve resiliency where infrastructure is shared.
- Lines along bridges could be designed to resist bridge damage, including installations with slack at bridge abutments (Eidinger and Tang, 2019) and redundant routes to ensure connectivity (Tang and Eidinger, 2017).
- Maintaining current knowledge of infrastructure collocations could reduce damage from digging to make repairs and help coordinate “dig once” policies.

2.3. Decoupling Telecommunications Equipment Dependence on Commercial Electric Power

Widespread commercial electric power outages after a large earthquake can cause more equipment failures than damage to equipment from the earthquake hazards themselves. Backup power is not always available when needed and during an earthquake sequence, backup batteries may last less time than expected because lead-acid, absorbent glass mat type batteries can lose capacity with heavy use—known as damage by deep discharge (see Tang and others, 2014). Data centers and central offices operating heating, ventilation, and (or) air conditioning that require large amounts of electric power would need alternative power sources. Backup power is more limited in the last-mile distribution system from DLCs and OLCs to subscribers. HetNet (DAS and small cell) sites, deployed in the public rights-of-way near population centers, do not have permanent backup power in order to minimize cabinet size and improve visual and auditory aesthetics. The potential loss of network functionality from loss of electrical power for HetNet wireless facilities cannot be understated because network buildout is shifting from macrocells and monopoles toward network densification using DAS and small cells.

- Diesel fuel is the most efficient way to store energy (Kwasinski, 2009). Replenishment plans for on-site fuel storage could factor in multi-hazards (for example, a large earthquake occurring toward the end of a fire season of Public Safety Power Shutoffs).
- Hybrid fuel generators (for example, using natural gas) reduce the need for onsite fuel storage, but they could be a less effective redundancy in an earthquake (compared to a hurricane) where ground failure concurrently damages the gas distribution system or gas is shut off to reduce fire hazards after an earthquake.
- Use of solar panels and rechargeable batteries is increasingly more feasible and could reduce the most common causes of infrastructure failure: power supply loss, generator failures, and fuel replenishment during restoration.[21]
- Effective generator testing (for example, testing that exceeds 1 hour) and battery maintenance before and during the earthquake sequence could improve availability of backup power when needed.
- Backup power solutions for small cell sites are needed. The use of digital power (also known as packetized power) could be an inexpensive way to keep communication components powered at a distance by generators, or possibly via fuel cells. Another option is to build small cell networks that can be easily powered by portable generators, which can be brought in as needed during response and recovery.
- Providers could plan and exercise for power supply solutions for a large earthquake during Public Safety Power Shutoffs.
- Microgrids that provide a continuous power solution are changing the power supply landscape. Microgrids for telecommunications[22] could be evaluated for their reliability during a widespread electric power outage after an earthquake.

2.4. Understanding Water Supply Dependencies

Heating, ventilation, and air conditioning systems use water for cooling. In the HayWired scenario, water supply restoration takes a few days to as much as 6 months.

- To better understand the water dependency for heating, ventilation, and air conditioning systems, the water supplies, usage rates, and inventories during the summer months could be assessed for data centers and central offices in the San Francisco Bay region.

3. Preparing for Telecommunications Restoration Contingencies

3.1. Planning for and Coordinating Limited Fuel Supply

Fuel supply is a large logistical uncertainty owing to time to restart refineries after an earthquake, the somewhat isolated fuel system in the San Francisco Bay region, California Air Resource Board compliancy for generator fuel, disruptions to alternative fuel transportation systems, and inefficient fuel deliveries to sites.

- Fuel needs and delivery for data centers, central offices, and cellular sites could be assessed in the San Francisco Bay region and integrated with the assessment of water and electric power utility backup fuel needs.
- Plans for shortages of California Air Resources Board compliant gasoline fuel could be developed.
- Telecommunications providers, wireless site owners and operators, and network data center operators could plan for at least 10 days of fuel shortages and develop several points of contact for fuel sourcing and transportation.
- Fuel delivery could be coordinated among multiple carriers and site owners and operators who share the same cellular sites to improve efficiency and reduce congestion on roads (see also Kwasinski and others, 2006).

[21] A large array of solar panels is needed to power a data center, but data centers are generally installing solar panels to supplement power supply. Only a few are installing solar panels in quantities sufficient to fully power a data center for environmental sustainability reasons.

[22] NTT (Japan) and Verizon (Garden City, New York) are telecommunications service providers deploying microgrids (A. Kwasinski, University of Pittsburgh, written commun., 2018).

3.2. Improving Cooperation with Electric Power Companies

In the absence of available backup power, restoration of voice and data services depends on and lags behind electric power restoration in affected areas.

- A lesson learned for telecommunications companies after the Canterbury, New Zealand, earthquake was the need to engage with power utilities before the next disaster (Peter Anderson, Jacobs, written commun., 2021).
- Better reporting of power service restoration status and plans (for example, rotating outage blocks) and coordination of hierarchical repairs on shared infrastructure could improve the allocation of gensets and efficiency of telecommunications service restoration.[23]

3.3. Planning for Inaccessibility of Sites

Inaccessible telecommunications sites after an earthquake may differ from those identified by the Applied Technology Council (2016) for hurricanes, which focus on coastal areas and floodplains.

- Backup power planning could consider isolation of telecommunications equipment from roads blocked by landslides, dangerous or cordoned areas subject to aftershocks, bridge damage to major transportation routes, detours resulting from fires, prohibited entry of red-tagged buildings, and hazardous material spills.

3.4. Planning for Skilled Labor Supply

Skilled labor for telecommunications restoration and repair is expected to be in short supply in the San Francisco Bay region owing to increased demand for these skills, competition from other jobs in the technology sector, and high housing costs that limit workers' ability to live locally.

- Knowing that large earthquakes are an inevitability in the San Francisco Bay region, an assessment of people as critical infrastructure and current talent gaps could be conducted.
- The knowledge gained from after-action analysis of non-earthquake disasters (fires, floods, hurricanes, and so on) could provide training opportunities for earthquake response.
- Planning to take care of the people who address service outages could be coordinated with communities—displaced and temporary contract labor will need food, shelter, sanitation, communications, and other support, or these people will have to be transported to and from other areas, causing delays and extended repair times.
- Local labor for transport and refueling could help if they are trained in advance, instead of flying in generator delivery and refueling contractors from other areas of the United States.[24]

3.5. Planning for Supplying and Sharing Spare Parts

Nearly all commercial telecommunications providers are members of the Communications Information Sharing and Analysis Center, operating through the Department of Homeland Security and the Cybersecurity and Infrastructure Security Agency as the National Coordinating Center for Communications (NCC). Through NCC, commercial telecommunications providers may engage in spare-part sharing in cases where supply chain issues negatively affect response and recovery efforts. (S. Kisting, Proactive Telecommunications Solutions, LLC, written commun., 2020)

4. Working with Governments

4.1. Identifying Community Infrastructure Vulnerabilities

Outside of a disaster, there are tensions between communities and the telecommunications industry, including battles around local control versus Federal Communications Commission orders, and vocal concerns about the safety of high-frequency electromagnetic fields around cellular sites and perceived negative impacts of wireless facilities to property values in the San Francisco Bay region (Witkowski, 2019).

- Local jurisdictions with amateur radio members (see sidebar 7) could investigate community telecommunications infrastructure with providers to understand reliance on and potential effects of equipment failures (including power backup) on neighborhoods (also see Applied Technology Council, 2016).
- Public safety agencies could work with their providers to understand potential impacts to and backup needs for emergency operation centers and public safety broadband systems, including FirstNet.

4.2. Preparing for Telecommunications Restoration

Relations between communities and telecommunications providers are unofficial (also see Bay Area Urban Areas Security Initiative, 2015) and commonly contentious, as mentioned above. Most interactions between them are transactional and occur via local government's public works and planning departments, in the context of specific applications for deployment of wireless facilities. During recent Public Safety Power Shutoffs, telecommunications providers did not have contacts for local emergency operations centers (California Public Utilities Commission hearing, oral commun., 2019).

[23]Some State laws, such as Act 12-148 (State of Connecticut, 2012), mandate close cooperation between electric and telecommunications utilities (Applied Technology Council, 2016).

[24]During the 2019 Public Safety Power Shutdowns, cellular providers brought in contract crews to transport generators and fuel to cellular sites in the blackout zones. In some cases, these crews were flown in from places like North Carolina, because the contractors in those areas have prior experience in refueling operations during hurricane response.

- To increase resiliency, local governments and agencies could hold interviews, workshops, and exercises with communications providers and utilities, focused on planning for telecommunications restoration. One example is a San Francisco Lifelines Council effort to examine telecommunications restoration with providers (D. Mieler, City and County of San Francisco Office of Resilience and Capital Planning, written commun., 2019). Joint workshop and exercise objectives (informed by Corey Reynolds, BayRICS, written commun., 2019) may include:
  - Coordination between cities, towns, counties, and the State on telecommunications restoration priorities.
  - Deciding what and how information will be shared among telecommunications industry representatives, local city and county emergency operations centers, and the State.[25]
  - Consideration of a pathway for data center and content providers to contribute to resilience efforts and (or) communicate criticality during an emergency (for example, Thompson and Evans, 2016). This would be a paradigm change to recognize the role of telecommunications operators and providers in a disaster response beyond the Federal Communications Commission regulated 9–1–1, E9–1–1, and NG9–1–1 services.
  - Shared understanding of restoration and recovery processes and needs of the commercial telecommunications providers, carriers, site owners and operators, and contractors.
  - Pre-planning by carriers and local governments and agencies for
    - Fast credentialing of outside contractors and pre-defining the process for contractors to request law enforcement escorts to reduce criminal activity (for example, when contractors are transporting high value items, such as solar panels, generators, or fuel).
    - Locations for deployment of mobile assets.
    - Exploring capabilities and plans to restore telecommunications services to customers and targets (for example, number of customers restored within 1 week) together by using a local version of what is known as a "threat and hazard identification and risk assessment," similar to the Bay Area Urban Areas Security Initiative assessment completed every 3 years for the San Francisco Bay region.
    - Overcoming regulatory hurdles and permit processing of new and upgrades of older equipment that delay restoration of services. Local governments and telecommunications providers could pre-define what equipment would be replaced if damage occurs, and pre-process sets of contingency applications and permits.

[25]For example, State Senate Bill 670 proposes telecommunications providers be required to notify the California Governor's Office of Emergency Services within 60 minutes of discovery whenever an outage occurs that limits the provider's customers' ability to make 9–1–1 calls or receive emergency notifications (California State Senate, 2019). The California Governor's Office of Emergency Services would notify applicable county emergency services, sheriffs, and PSAPs (California Governor's Office of Emergency Services, 2019).

5. Using Earthquake Risk Communications

5.1. ShakeAlert Earthquake Early Warning System

Warning of the strongest shaking may be received with only seconds of notice in the San Francisco Bay region (for example, via the ShakeAlert earthquake early warning system), given sufficient distance from the epicenter (Strauss and others, this volume). In the HayWired scenario, ShakeAlert could provide as much as 25 seconds of warning of very strong (or more intense) ground shaking or prompt confirmation of an earthquake occurrence in the San Francisco Bay region (Strauss and others, this volume).

- The telecommunications industry could investigate the use of ShakeAlert in protecting their assets, data collection networks, and people. For example, it could:
  - Initiate and (or) automate data failover seconds earlier than it would otherwise;
  - Shut down equipment, drives, and computers, initiating backups, and so on; or
  - Warn people in trenches or on towers to protect the safety of crews.
- There are some interactions and consequences to explore should the electric power company use ShakeAlert to turn off power to reduce damage ahead of heavy shaking. In that instance, backup power on telecommunications equipment could be of utmost importance for complete delivery and receipt of ShakeAlerts.

5.2. Aftershock Forecasts

Once a large earthquake has occurred, USGS aftershock forecasts will provide expected ranges of numbers and magnitudes of aftershocks within specific time frames (next day, within a week, and so on). For example, a HayWired scenario aftershock forecast following the mainshock includes a statement, "within the next week, about 470 magnitude M_w 3 or larger aftershocks could be felt throughout the Bay Area, and about 5 aftershocks could be damaging" (Wein and others, 2017). During HayWired workshops, the telecommunications industry expressed interest in maps of aftershock forecasts in the future.

- The industry could consider use of aftershock forecasts in restoration decisions, such as
  - Where to leave portable equipment in place to "pre-stage" for aftershocks;

- When to monitor and maintain backup batteries and fuel inventories; and
- When to schedule repairs to protect labor resources from climbing towers in risky areas during an earthquake sequence.

5.3. Afterslip Forecasts

Another type of forecast is related to slip of the fault after a rupture, a possibility for the Hayward Fault. The rate of slip would decline with time. For the HayWired scenario, afterslip is estimated to offset the ground on either side of the fault by as much as 1.5 meters over time, culminating with a total (coseismic and after) slip of as much as 2 meters (Aagaard, Schwartz and others, 2017). Afterslip forecasts for locations along the fault rupture would estimate the amount of slip expected at the site over days, weeks, and months.

- The industry could investigate use of afterslip forecasts in restoration decisions regarding lines and microwave antenna alignment crossings between communications equipment on either side of the Hayward Fault.

6. Managing User Behavior of Commercial Networks

After a large earthquake, there will be a surge in demand for voice and data services as people check on each other, report problems, and obtain information. Simultaneously, telecommunications network functionality will be reduced, resulting in congestion from overload. Not only will subscribers be unable to connect, but emergency responders will also be competing for the same services.

- Carriers could educate users (for example, in schools and via various types of media) and remind subscribers during disasters (via SMS messaging) what to expect in terms of network performance, public safety priorities, possible throttling (limiting both throughput and total data usage), issues with making voice calls, recommendations to use text messaging instead of voice calls, and so on.

Resilience Opportunities for Users of Voice and Data Services

7. Preparing for Emergency Response

7.1. Improving Resilience of 9–1–1 Call Services

Public safety answering points (PSAPs) that receive 9–1–1 calls may have reduced functionality, be overloaded with emergency phone calls, and (or) be understaffed.

- Investigation of expected PSAP facility functionality, including communication channels and availability of backup units before and during a large earthquake, could help improve the performance of the 9–1–1 system (also see Applied Technology Council, 2016).
- Reducing 9–1–1 calls for help could result from
  - Encouraging effective use of ShakeAlert to reduce injuries or entrapment.
  - Programs that prepare neighborhood residents with radio capabilities and to help their neighbors (for example, amateur radio operators training Community Emergency Response Teams (see sidebar 7).
- Enhancements to the 9–1–1 system (such as NG9–1–1 for wired telephones and E9–1–1 for wireless phones) are expected to improve disaster response by helping to manage call overload, transferring of 9–1–1 calls, and using location tracking for proper jurisdictional responses (Office of Emergency Medical Services, 2017).

7.2. Enhancing Emergency Response Communications

FirstNet is being implemented to dedicate bandwidth to communications among emergency responders and public safety agencies. Other strategies for increasing capacity of emergency response communications include

- Local jurisdictions purchasing portable backup equipment, like mobile satellite trailers that operate independently of local terrestrial networks by transmitting data wirelessly to enhance communications during response and restoration (C. Reynolds, BayRICS, written commun., 2019).
- Private tech companies supporting disaster relief operations, such as Cisco NERV (Cisco, 2016) that interconnects a wide variety of communication networks from satellite links to cellular networks and two-way radio.
- Leveraging amateur radio members for solutions to broken communication links and additional communications capacity (see sidebar 7).
- Local jurisdictions arranging backup power for emergency command vehicles and an emergency communications node with a privately owned microgrid (K. Dueker, City of Palo Alto, oral commun., 2019).

7.3. Improving Communication of Alerts

Earthquakes occur without warning and ShakeAlert potentially provides seconds of warning for the heaviest shaking for people who are far enough away from the epicenter. After an earthquake, the public will need to receive warnings about fires, landslides, aftershocks, as well as other important notifications related to public health (for example, drinking water), weather, traffic, shelter and emergency assistance information, notification of community meetings, and so on.

Sidebar 7—Roles for the Amateur Radio Community

A disaster response resource for local government is the amateur radio community, which may have experience with the process of building both temporary and permanent networks, including obtaining permits, signing contracts with tower or building owners, installing antennas, attending to lightning protection, installing and maintaining batteries, and so on. They provided communications when existing systems failed during the 1989 Loma Prieta earthquake, the 2001 9/11 attacks, hurricanes, floods, wildfires, and recently to more reliably establish a data communication network with the American Red Cross for communication of Safe and Well updates in Puerto Rico after Hurricane Maria (Murphy and Krupa, 2017). Amateur radio can step in if the link is broken between residents and the emergency operations center for 9–1–1 emergencies (for example, Presley, 2019).

In the San Francisco Bay region, people in the amateur radio community have led the Disaster Preparedness Initiative (Joint Venture Silicon Valley, 2011), have written about Survivable Social Networks[26] (Iannucci and others, 2013), and created a regional network that can support both fixed and portable data communications stations to link government and private emergency operations centers sites (for example, see San Jose Wireless Emergency Network [available at https://sjraces.org/?page_id=311], Amateur Radio Emergency Data Network [available at https://www.arednmesh.org], and Santa Clara Emergency Wireless Network [available at https://www.scc-ares-races.org/aresraces.htm]).

Amateur radio members can help prepare communities by

- Participating in joint workshops and exercises about community telecommunications vulnerabilities and commercial service restoration processes (A. Ramirez and M. Kim-Molina, Bay Area Urban Areas Security Initiative, oral commun., 2019; also see Bay Area Urban Areas Security Initiative, 2019, for a regional training and exercise program).
- Training residents to use radios in their neighborhoods with predetermined channels in and out of neighborhoods (for example, Palo Alto's emergency services volunteer program).

[26]These are islands of connectivity that can provide local communications for neighbors when commercial networks are down and that can link to other Survivable Social Network nodes in a mesh network.

- Jurisdictions could promote and communicate the importance of the public signing up for opt-in alerting and public safety notifications (such as "reverse 9–1–1" systems). The Bay Area Urban Areas Security Initiative is working to improve the disparate regional reverse 9–1–1 systems through its Bay Area Alert and Warning Toolkit (available at http://www.bayareauasi.org/alertandwarning).
- Jurisdictions could encourage the public to receive alerts through various modalities (such as ShakeAlert, application-based alerting, SMS alerting, fixed and mobile sirens, and National Oceanic and Atmospheric Administration [NOAA] weather radio).
- Jurisdictions could participate in tests and exercises of public alerting systems for an earthquake scenario.

7.4. Attending to Vulnerable Populations

Socially vulnerable populations are disproportionately affected by damage to housing and buildings in their neighborhoods in the HayWired scenario. Lower income populations are more vulnerable to wireless network outages because of their greater reliance on mobile devices and fewer connectivity options (for example, broadband). Language barriers may interfere with messages that do get through. Individuals with access and functional needs can be particularly reliant on electric power and telecommunications services to maintain their health, receive mobility assistance, and call for help.

- Emergency managers could
  - Prepare messages about how to prepare to communicate before, during, and after an earthquake for population groups respecting different languages, cultures, age demographics, and people with disabilities in their communities.
  - Design websites with emergency information for smartphones and tablets because users may not be able to access the internet using a desktop computer.
- Redundant wireless coverage, fiber broadband service to economically disadvantaged areas, and municipal-owned community Wi-Fi could help provide services to populations that need them most after a large earthquake. For example, during the 2020 pandemic, school districts provided cellular hotspots with prepaid SIM cards to students with access and functional needs who did not have home broadband.
- Improved identification of individuals with access and functional needs could guide Community Emergency Response Teams in making wellness checks.

7.5. Planning for Evacuations and Displaced Populations

Hundreds of thousands of people are at risk of evacuation or displacement by earthquake damage and fire after a large earthquake in the San Francisco Bay region.

- Shelters and community resource centers could be equipped with sufficient and secure voice and data services, power supplies and electrical outlets, and USB chargers (also see Lifelines Council, 2014).
- Cities and communities could exercise and plan for facilitating communications during evacuations and tracking the movement of people over time.

8. User Preparedness

8.1. Preparing for Power Outages

Users and subscribers are responsible for backup power of their devices and broadband gateways. Most subscribers can no longer rely on power supplied from a central office as they did with the traditional landline telephony (POTS) systems. The industry's use of temporary portable equipment to restore services during response means that telecommunications services may be available to a subscriber even though electric power is not restored. The positive benefit of recent PSPSs is that some residents have now experienced widespread power outages, which had not occurred since the 1989 Loma Prieta earthquake or in the age of the internet.

- For those that have not experienced power shutoffs, a day without (using) power exercise could help users better understand their battery backup needs for laptops, mobile devices, and broadband gateways. See appendix 3 for guidance on installing an uninterruptable power supply.

8.2. Being Informed About Using Voice and Data Services

After a large earthquake, the usage of voice and data services spike, exceed network design capacity, and cause congestion. Usage is concentrated in the disaster-affected area because people contact their friends and family out of concern for their safety.

- Users of telecommunications services could learn about triaging uses of information and communication channels to help manage system overload. See sidebar 6 and tips posted by the Federal Communications Commission and the Federal Emergency Management Agency at https://www.fcc.gov/emergency.

9. Planning for Business Contingencies and Continuity

9.1. Reducing Business Interruption from Telecommunications Outages

Voice and data service disruptions could potentially have larger and more widespread impacts on businesses and the digital and broader economies than other utility outages. Telecommunications industry resilience measures of backup power are effective immediately for residual capacity but short-lived; the delivery of fuel and (or) portable equipment to sites is more effective at reducing economic losses from telecommunications service disruption.

- While telecommunications services are being restored to meet demand that has changed in volume and location, business continuity practices such as conservation of bandwidth and substitution for electronic processes (for example, using paper and local data backup[27]) could help to reduce business and economic losses.

9.2. Reducing Business Interruption with Teleworking

In the HayWired scenario, most of the business and economic losses result from earthquake damage to buildings and their contents and transportation systems disrupting commutes. Teleworking assumptions reduce losses by about 6 percent. Teleworking in response to the ongoing COVID-19 viral pandemic has suggested even greater potential efficacy.

- Teleworker arrangements at alternative workplaces and using cloud and other telecommunications services reduce business and economic impacts from property damage and transportation system disruptions.

However, the telecommunications industry would need to respond to changes in redistribution of demand for various services across the networks in an equitable manner.

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[27]Based on an informal survey with Silicon Valley municipal governments, data replication and fail-over is not a given for smaller operations such as cities, counties, and mid-sized companies.

- Telecommunications carriers (wired, wireless, build, fix and reactive)—AT&T, Verizon, Comcast, Crown Castle International, and Extenet Systems
- Telecommunications providers and internet exchanges, level 3, State, Federal government
- Internet content providers and aggregators—Facebook
- Data storage and serving (Amazon), corporate and city Chief Information Officers
- Electric, natural gas, and water utilities
- Public safety communications, including city and county offices of emergency service
- Amateur radio operators, including the City of Cupertino Amateur Radio Emergency Service and City of San Jose Radio Amateur Civil Emergency Service
- Oversight—California Public Utilities Commission (regarding power and telecommunications)
- California Office of Emergency Services office of Access and Functional Needs—Vance Taylor
- Telecommunications and Internet Security Officers
- U.S. Geological Survey physical scientists

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Glossary

Asynchronous digital subscriber line (ADSL) is a technology standard for transferring broadband data over twisted-pair copper wiring to home and small business subscribers.

AT&T is a multinational conglomerate holding company, and the world's largest telecommunications company. AT&T traces its ancestry to the Bell Telephone Company, which was renamed the American Telephone and Telegraph Company in 1885, and later became AT&T Corporation. In 1984, as part of a consent decree in *United States v. AT&T*, AT&T Corporation's local operations were split into seven regional Bell operating companies. Over time, five of the operating companies merged to form AT&T Inc.

Broadband is data that transfers at minimum speeds of 25 megabits per second (Mbps) download, 3 Mbps upload (per the Federal Communications Commission's 2015 definition).

Cellular is a network of radio sites that provide voice and data service using wireless technologies. The term refers to the regular spacing of sites, each with a coverage area, arranged so that subscribers can move from site to site without losing connection.

Coaxial line (coax) is a physical medium used to carry modulated radio frequency signals. Coaxial line is used by cable utilities to deliver video and broadband data to subscribers.

Colocation refers to the installation of wireless equipment and antennas for multiple technologies and (or) competing carriers to a single tower or wireless facility. When spelled "collocation," the term also refers to different types of infrastructure at the same location.

Copper pair line (copper pair) is a physical medium used to carry plain old telephone service (POTS) telephony and modulated radio frequency signals for various digital subscriber line services (xDSL). Copper pair line is used by telephony utilities to deliver broadband data to subscribers.

Data Over Cable Service Interface Specification (DOCSIS) is a digital data line technology and standard for transferring broadband data over coaxial line to home and small business subscribers.

Digital signal line (DSn) is a digital data line technology for transfer of information over physical T-carrier lines. Levels of service range from DS0 (64 kilobits per second [kbps]) to DS5 (400.352 Mbps).

Digital subscriber line (DSL) carries digital data over a telephone line. There are several variants of DSL, collectively called xDSL.

Distributed antenna system can be indoor (typically called DAS) or outdoor (usually called o-DAS).

Fiber optic line is a digital data line technology for transmission of information using pulses of light (optical).

Gig economy is the economic shift of workers away from full-time, long-term employment to transient short-term jobs or "gigs"—sometimes called the contractor economy.

Heterogeneous network (HetNet) is a system of dissimilar wireless technologies operating as a whole.

Information and communications technology (ICT) is a broad term used to describe the integration of information technology (servers, data storage, and data processing) with the networks used to link them together.

International Telecommunications Union (ITU) is the technology standardization and coordination arm of the United Nations.

Internet exchange points (IXPs) are locations where privately owned, publicly owned, academic, and government-owned networks connect together.

Internet of Thing (IoT) is the connection of stand-alone nodes, systems, and devices to the internet.

Internet protocol (IP) is the standard for data interconnection over the internet.

Lattice tower is a type of communications tower constructed from a lattice of metal sections—can be either guyed (GT) or self-supporting (SST).

Long-Term Evolution (LTE) is the name given to the 4G radio interface standard published by the Third Generation Partnership Project (3GPP).

Macrocellular site tower is a large tower (either guyed or freestanding) that supports communications equipment and antennas.

Monopole (MP) is a type of wireless tower; disguised versions of monopole are named for the objects they resemble, including monopines, monopalms, monocacti, and so on.

NECA/FOA 301 is a standard for the installation and testing of fiber optic lines.

Optical short hop (OSH) is a system where lasers are used instead of wires or fiber optic lines to create a data link.

Pacific Gas and Electric is an investor-owned electric and natural gas utility that serves nearly all cities, towns, and counties in northern California.

Plain old telephone service (POTS) is an older subscriber service that carries analog voice signals over copper pair wiring. POTS provides both signals and power to subscriber telephones. POTS connects to the public switched telephone network (PSTN) system for call processing, switching, and signaling.

Private branch exchange (PBX) is an older system used in workplaces to create an internal phone network. Connects to the public switched telephone network (PSTN) for calling in and out of the internal network.

Public switched telephone network (PSTN) is an older system for carrying and handling voice telephony.

Radio Amateur Civil Emergency Service (RACES) is a radio sevice that operates from oversight from the Federal Emergency Management Agency and the Federal Communications Commission.

Small cell is a type of communications equipment that operates at lower power levels than a macrocellular site. Small cells typically cover areas from a single room to several hundred meters in radius. They are commonly attached to other structures, such as building roof perimeters, street lights, and utility poles.

T-carrier is a physical copper line used to transport multiplexed communication channels.

Transmission Control Protocol (TCP) is one of the main components of internet protocol (IP) technology.

Wireless is a generic term for telecommunications channels of voice or data using radio frequency (RF) or microwave signals.

xDSL is a generalized term for various classes of digital subscriber line (DSL) services. Common classes are ADSL2, ADSL2+, VDSL, VDSL2+, and G.fast.

Appendixes 1–3

Appendix 1. Program of the U.S. Geological Survey's Telecommunications Phase 2 Workshop

HayWired Telecomm/ICT Workshop Agenda

General Session (8:00 a.m.–10:00 a.m.)

- Opening, welcome, and housekeeping (David Witkowski, 15 minutes)
- Presentation on HayWired roll-out plan (Dale Cox, 15 minutes)
- Presentation: Lessons from Recent Disasters (Scott Kisting, 15 minutes)
- Presentation: Haywired Telecom/ICT Chapter (David Witkowski and Anne Wein, 45 minutes with question-and-answer session)
- Morning track agenda and introduction of track leads (David Witkowski and Anne Wein, 15 minutes)

Working Lunch (12:00 p.m.–1:00 p.m.)

- 12:15 p.m.: Vision Presentation (Russ Hancock, Joint Venture Silicon Valley, 15 minutes)
- Afternoon track agenda and introduction of track leads
- Technical track groups prepare top 5 points
- Practitioner track leads can prepare for their sessions

General Session (2:30 p.m.–5:00 p.m.)

- 2:30 p.m.–3:00 p.m., snack break and track lead preparation
- 3:00 p.m.–4:30 p.m., top 5 points from track leads and question and answer session
- 4:30 p.m.–5:00 p.m., wrap-up, next steps, invite to continue dialog, methods for remaining in touch (Google group, Slack, Wiki, and so on), commitment to April 18th, 2018

Table 1.1. Workshop morning schedule.

[comms, communications; EEW, earthquake early warning]

Group	Meeting room	Point person	Technical tracks			
			Track M1 **Existing standards, mitigations, and HayWired impacts**	**Track M2** **Existing functional dependencies and user behaviors**	**Track M3** **Restoration strategies, dependencies and recovery planning**	**Track M4** **Uses of EEW; afterslip and aftershock information**
			Lead: Keith Porter **Notes: Dale Cox**	**Lead: Vaidy Krishnamurthy** **Notes: Michael Germeraad**	**Lead: Corey Reynolds** **Notes: Gerald Kiernan**	**Leads: Sara McBride, Andrew Michael** **Notes: Susan Benjamin**
Group A: Voice comms	Rambo front	John Erichsen	10:00–10:30 a.m.	11:30 a.m.–12:00 p.m.	11:00–11:30 a.m.	10:30–11:00 a.m.
Group B: Data comms	Rambo rear	Benny Lee	10:30–11:00 a.m.	10:00–10:30 a.m.	11:30 a.m.–12:00 p.m.	11:00–11:30 a.m.
Group C: Data networks	California room	Bill Pugh	11:00–11:30 a.m.	10:30–11:00 a.m.	10:00–10:30 a.m.	11:30 a.m.–12:00 p.m.
Group D: Cloud and services	Nevada room	Anton Batalla	11:30 a.m.–12:00 p.m.	11:00–11:30 a.m.	10:30–11:00 a.m.	10:00–10:30 a.m.

Table 1.2. Workshop afternoon schedule.

[Telecom, telecommunications; ICT, information communication technology]

Group	Meeting room	Point person	Practitioner tracks		
			Track P1 **Interagency coordination to enhance (voice and data) performance and restoration**	**Track P2** **Telecomm and ICT (voice and data) trends**	**Track P3** **Impacts from telecom and ICT outages and preparedness**
			Lead: Scott Kisting **Notes: Stephanie Ross**	**Lead: David Witkowski** **Notes: Juliette Finzi Hart**	**Lead: Paula Scalingi** **Notes: Jamie Jones**
Group 1: Government	Rambo	John Erichsen	1:00–1:30 p.m.	2:00–2:30 p.m.	1:30–2:00 p.m.
Group 2: Critical infrastructure	California room	Benny Lee	1:30–2:00 p.m.	1:00–1:30 p.m.	2:00–2:30 p.m.
Group 3: Public and business	Nevada room	Bill Pugh	2:00–2:30 p.m.	1:30–2:00 p.m.	1:00–1:30 p.m.

Appendix 2. Demand Served Restoration Curves by County

Figures in this appendix show demand served restoration curves with and without demand surge for all counties adjacent to the San Francisco Bay except for Alameda County (the curves for Alameda County are on p. 53–54 of the main text).

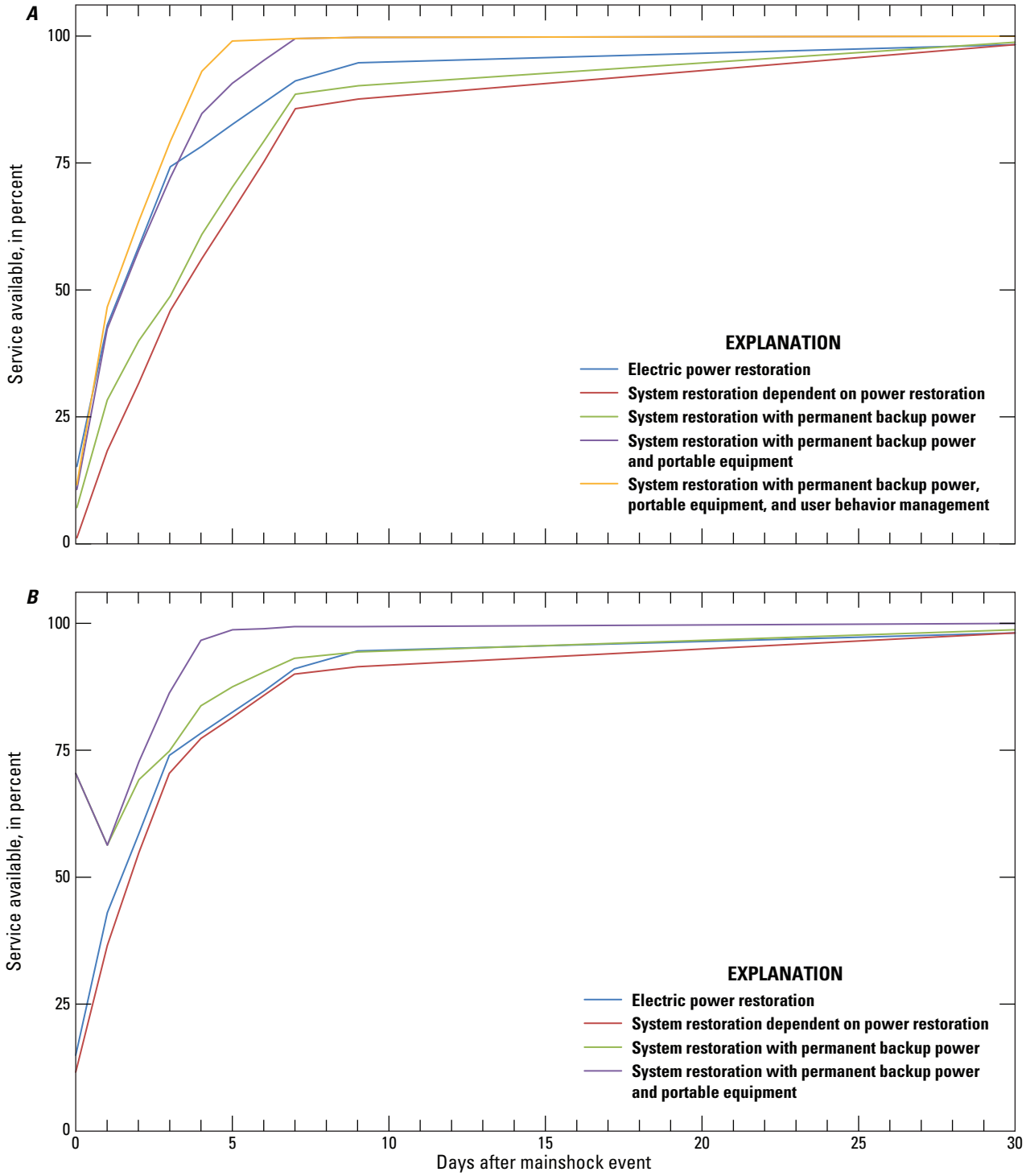


Figure 2.1. Line graphs showing voice and data demand served and power restoration curves for Contra Costa County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

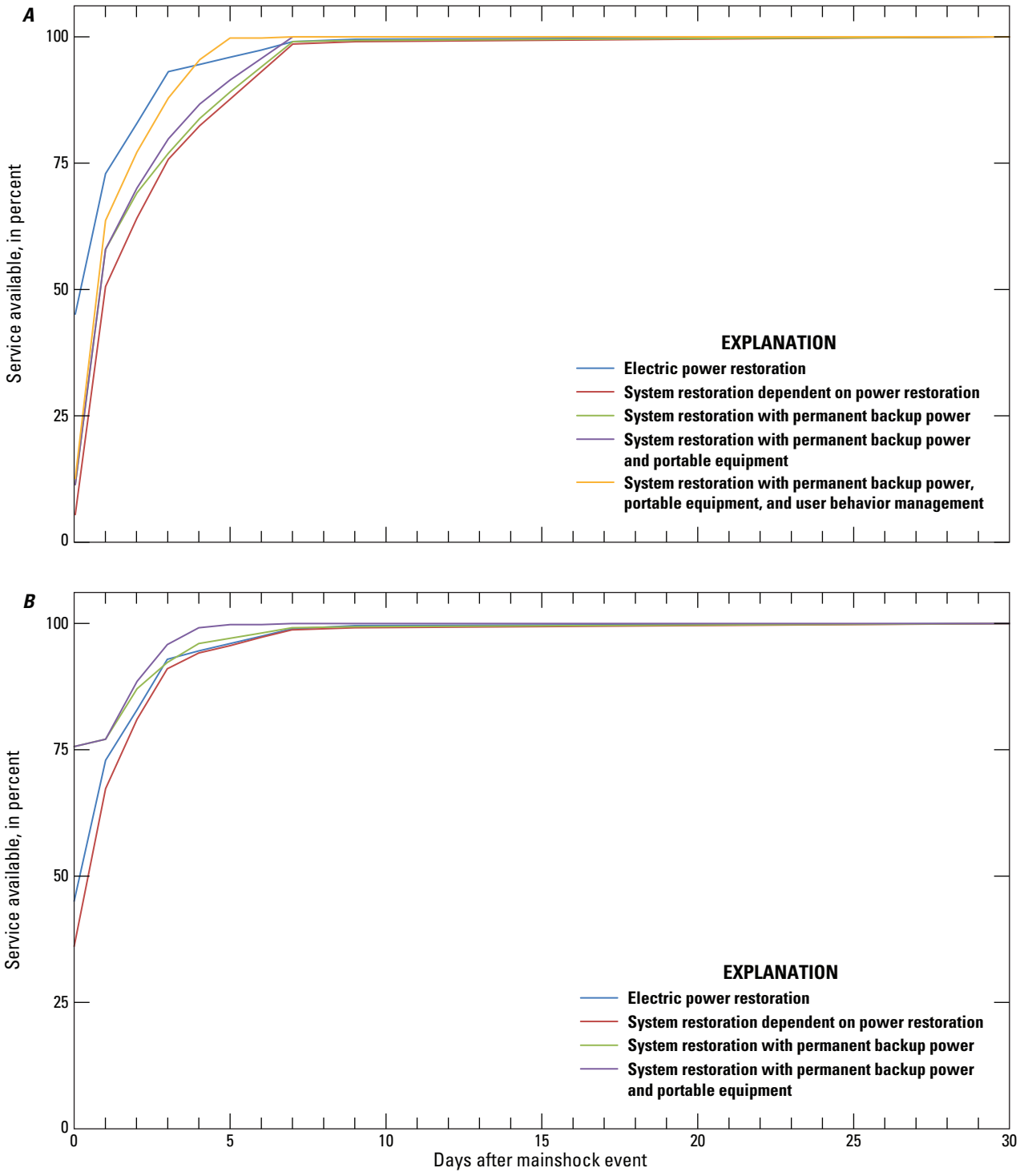


Figure 2.2. Line graphs showing voice and data demand served and power restoration curves for Marin County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

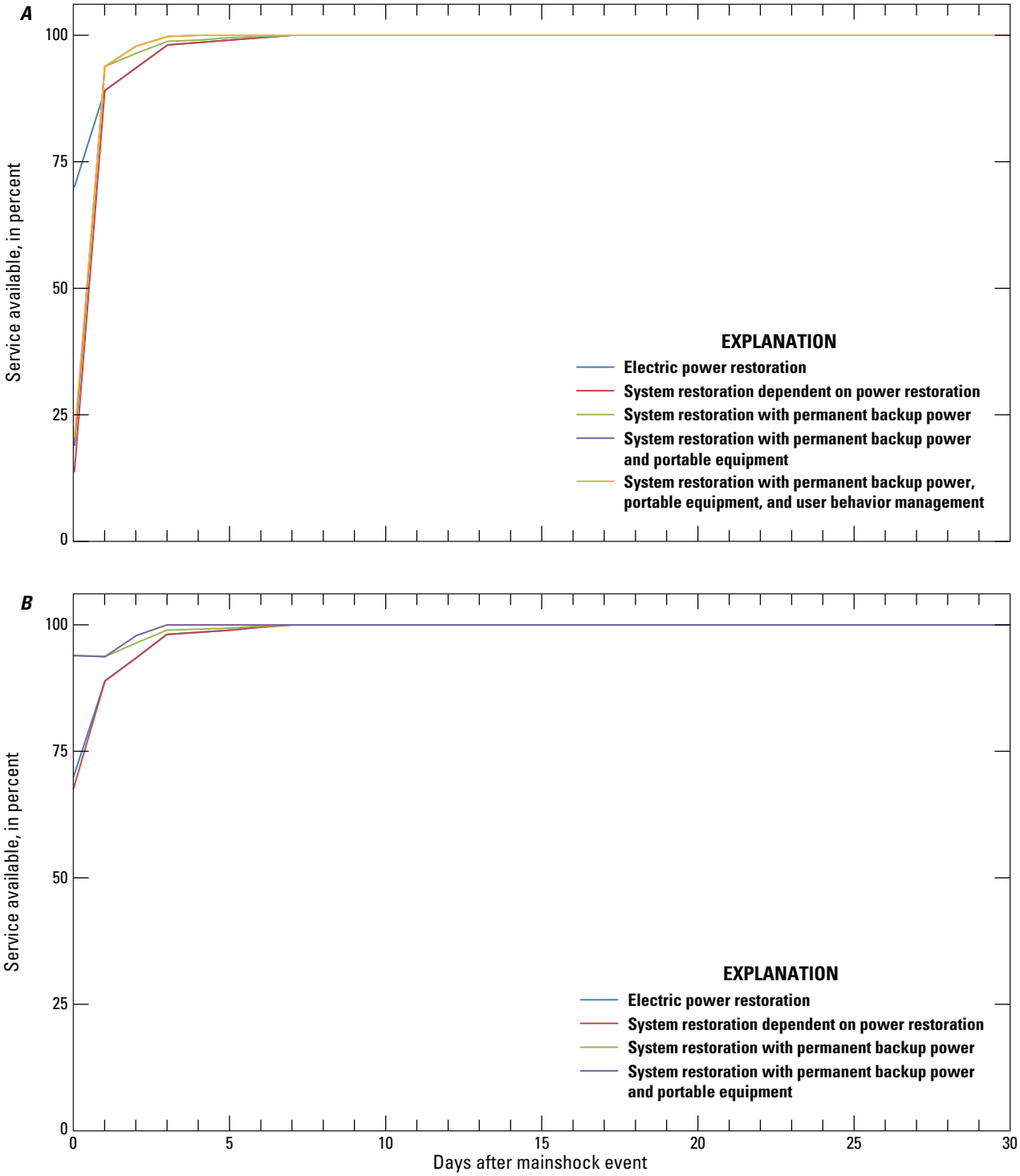


Figure 2.3. Line graphs showing voice and data demand served and power restoration curves for Napa County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

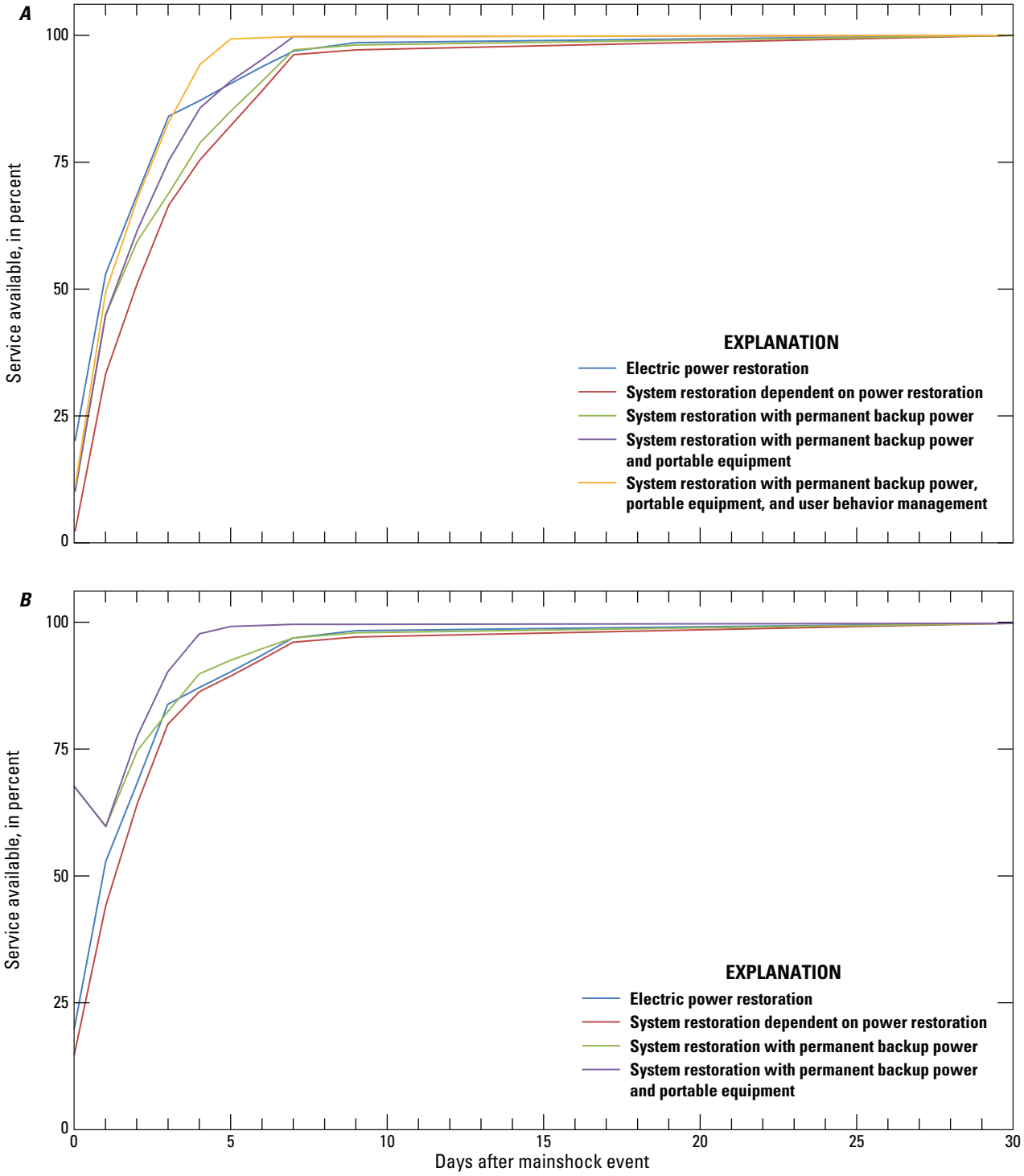


Figure 2.4. Line graphs showing voice and data demand served and power restoration curves for San Francisco County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

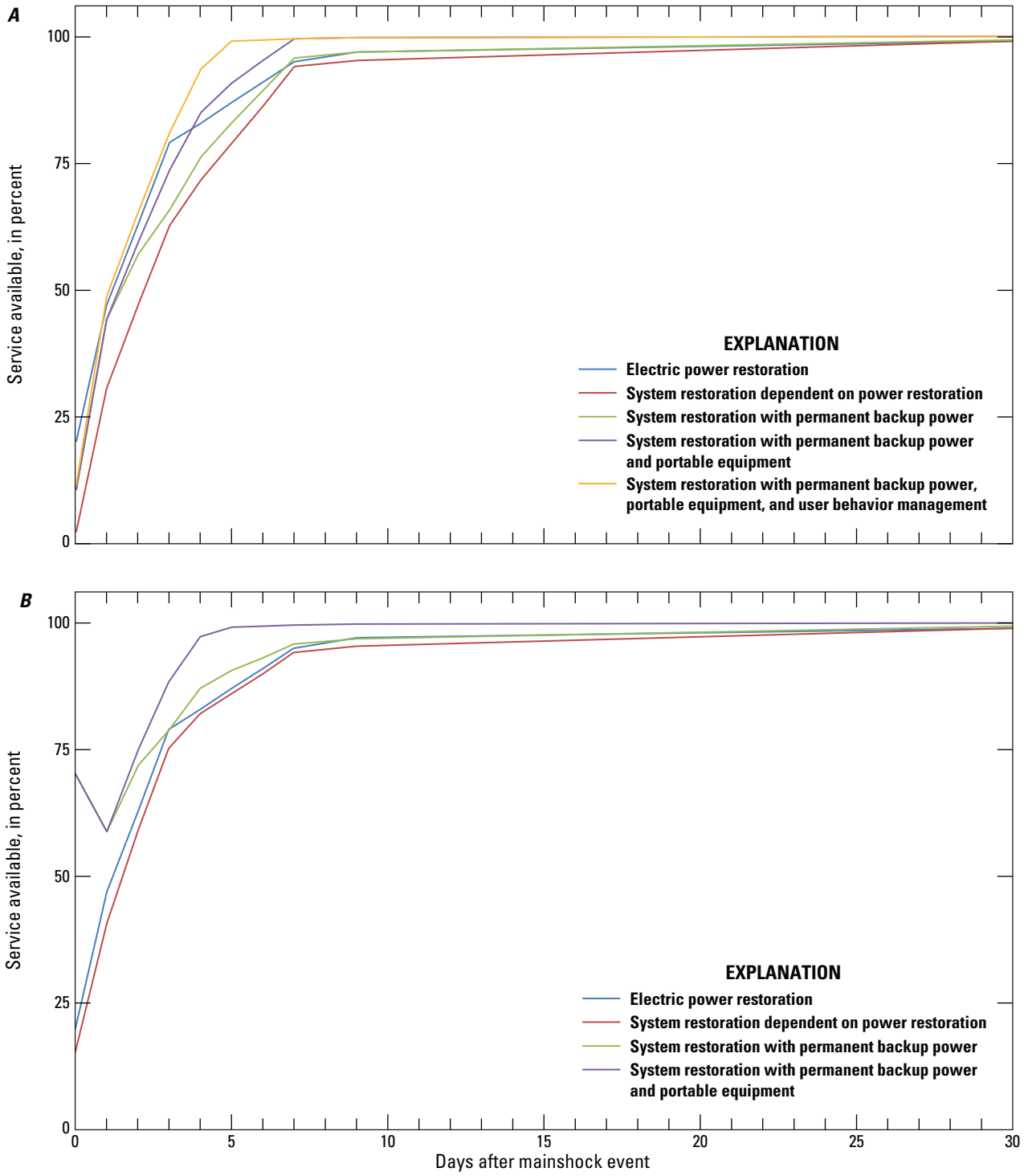


Figure 2.5. Line graphs showing voice and data demand served and power restoration curves for San Mateo County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

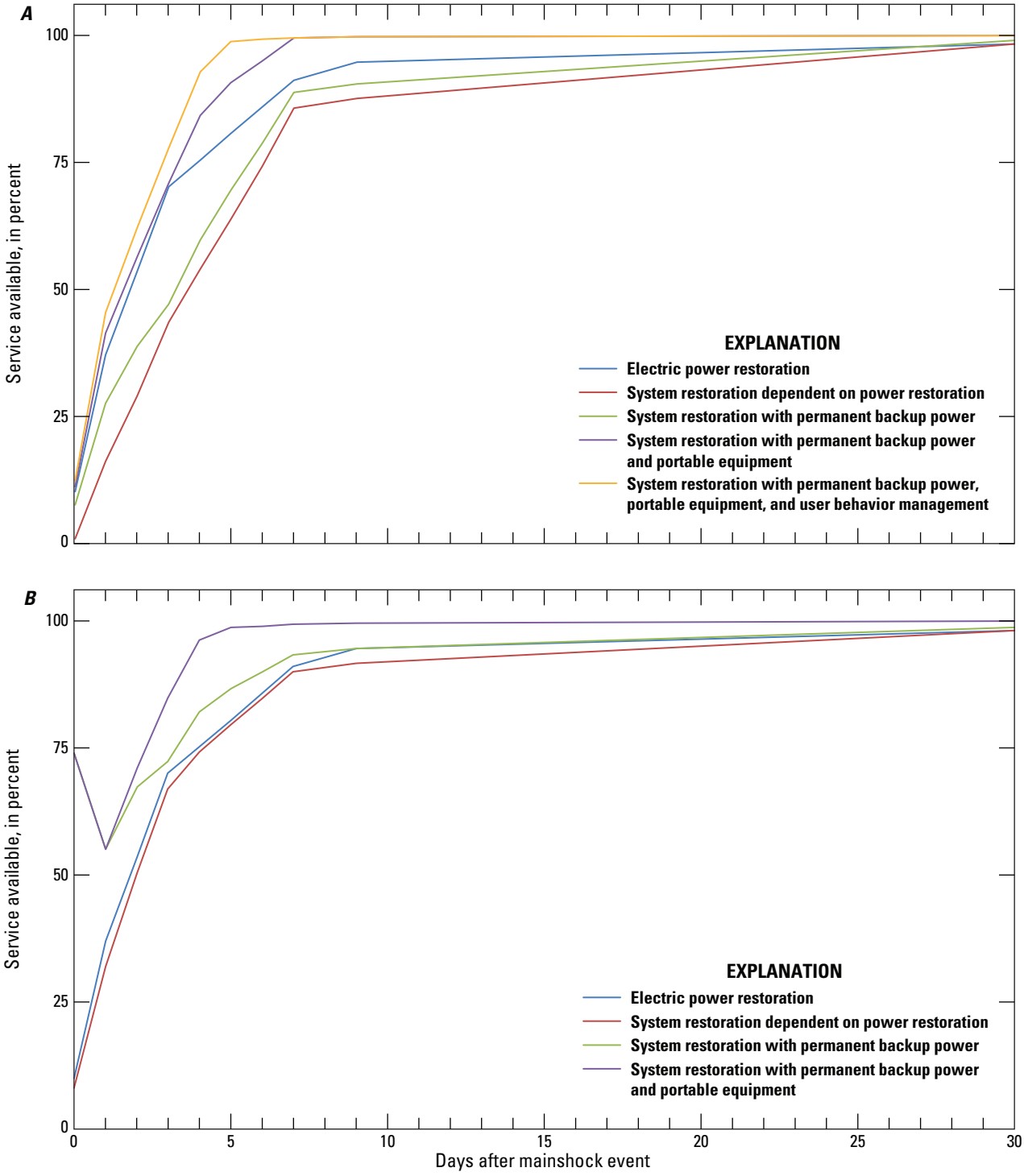


Figure 2.6. Line graphs showing voice and data demand served and power restoration curves for Santa Clara County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

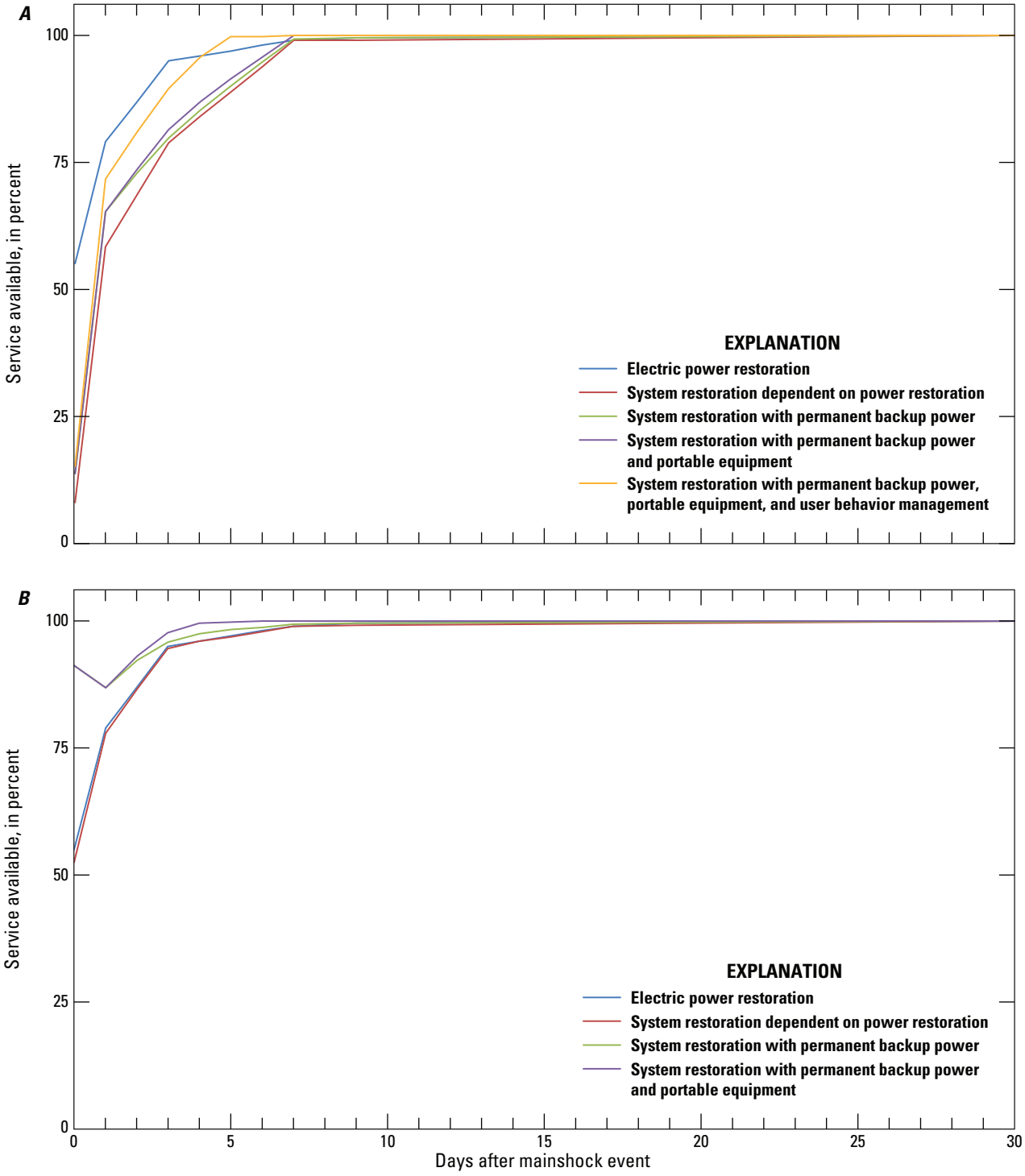


Figure 2.7. Line graphs showing voice and data demand served and power restoration curves for Solano County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

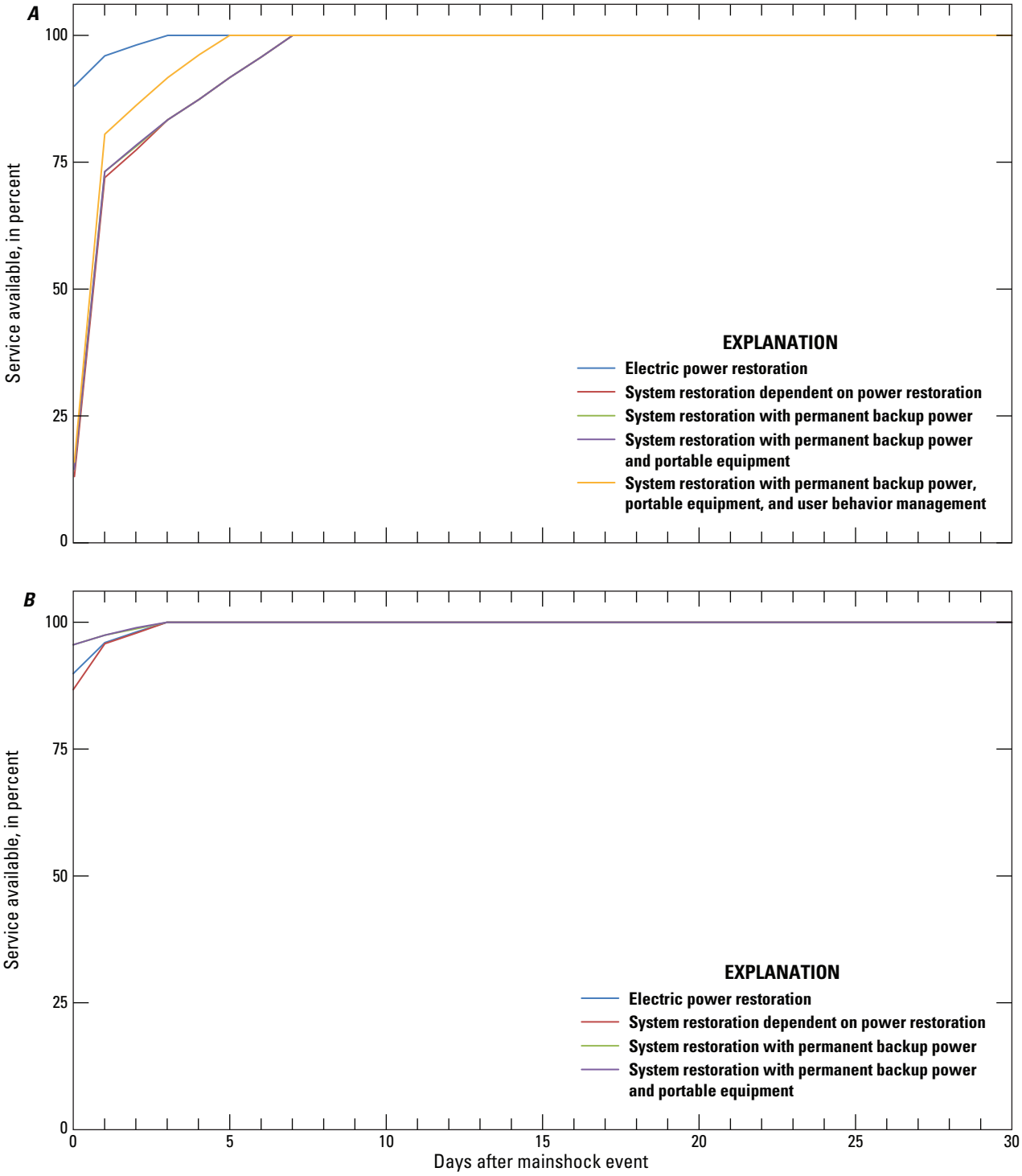


Figure 2.8. Line graphs showing voice and data demand served and power restoration curves for Sonoma County for the HayWired scenario mainshock in the San Francisco Bay region, California. *A*, Implementation of three resilience tactics (permanent power backup, portable equipment, and user behavior management), with demand surge included in the estimation. *B*, Implementation of two resilience tactics (permanent power backup and portable equipment) with the effect of demand surge removed from the estimation.

Appendix 3. Home Uninterruptible Power Supply Set Up

Most modern voice over internet protocol (VoIP) gateways do not have internal backup batteries, and most subscribers do not have an uninterruptible power supply (UPS) to keep their gateways and cordless phones running in the absence of electric power. Sidebar 8 and figure 3.1 illustrate how to set up a UPS.[1]

[1]Subscribers who receive broadband and telephone service over a copper pair line (xDSL) or coaxial line (DOCSIS) must provide local backup power, using a UPS, to the router or gateway. Subscribers who receive broadband and telephone service over fiber optic lines must provide local backup power, using a UPS, to either the router or gateway and also to the optical network terminal (ONT) that interfaces with the router or gateway to the fiber line.

Sidebar 8—How Large a UPS Would I Need?

This is not a simple question, because the answer depends on several factors:

- Where do you live?
- How stable is your local electrical grid in the event of an earthquake?
- How long do you expect to want or need power?
- How much space do you have for equipment, and how much weight can the shelf where it will sit support?
- How much power does your equipment consume?
- How much are you willing to spend?

As of November 2017, a typical consumer-grade UPS that provides approximately 350 voltamperes (VA) per hour of capacity costs just under $50 U.S. dollars. In 2015, the power consumption for a Pace 5268AC (as tested by a coauthor of this report [D.T. Witkowski]) was measured at 13 VA, a standard measure of power consumption that considers the efficiency of the power adapter. The author's UPS was rated (with a new battery at time of purchase) to provide 350 VA of capacity—which means that the UPS can keep the 5268AC running for just under 27 hours. The author later measured power consumption of another gateway, the ARRIS BGW210, at 23 VA—which drops the runtime of that same UPS down to just over 15 hours. Reduced capacity from battery aging will further reduce that runtime—to be safe, the author estimates runtime at only 12 hours. This runtime falls short of the Department of Homeland Security's Ready.gov recommendation that citizens prepare for 72 hours of self-sufficiency (Department of Homeland Security, 2017). To reach 24 hours of runtime, the 350-VA UPS would have to be upgraded to at least 550 VA, or even more to account for battery aging. To meet the recommended 72 hours of disruption at 23 VA, a UPS would require just under 1,700 VA capacity. The author located a UPS with 2,200 VA capacity (list price in November 2017) for $750 U.S. dollars—and it weighs 112 pounds. Will the average user be able to afford this UPS to have 72 hours of capacity, and are they willing to carry in over 100 pounds of UPS to get it? Furthermore, this approximate estimate does not account for the power consumption of a cordless phone. Additional equipment such as wired routers and Network Attached Storage (NAS) drives will further reduce runtime.

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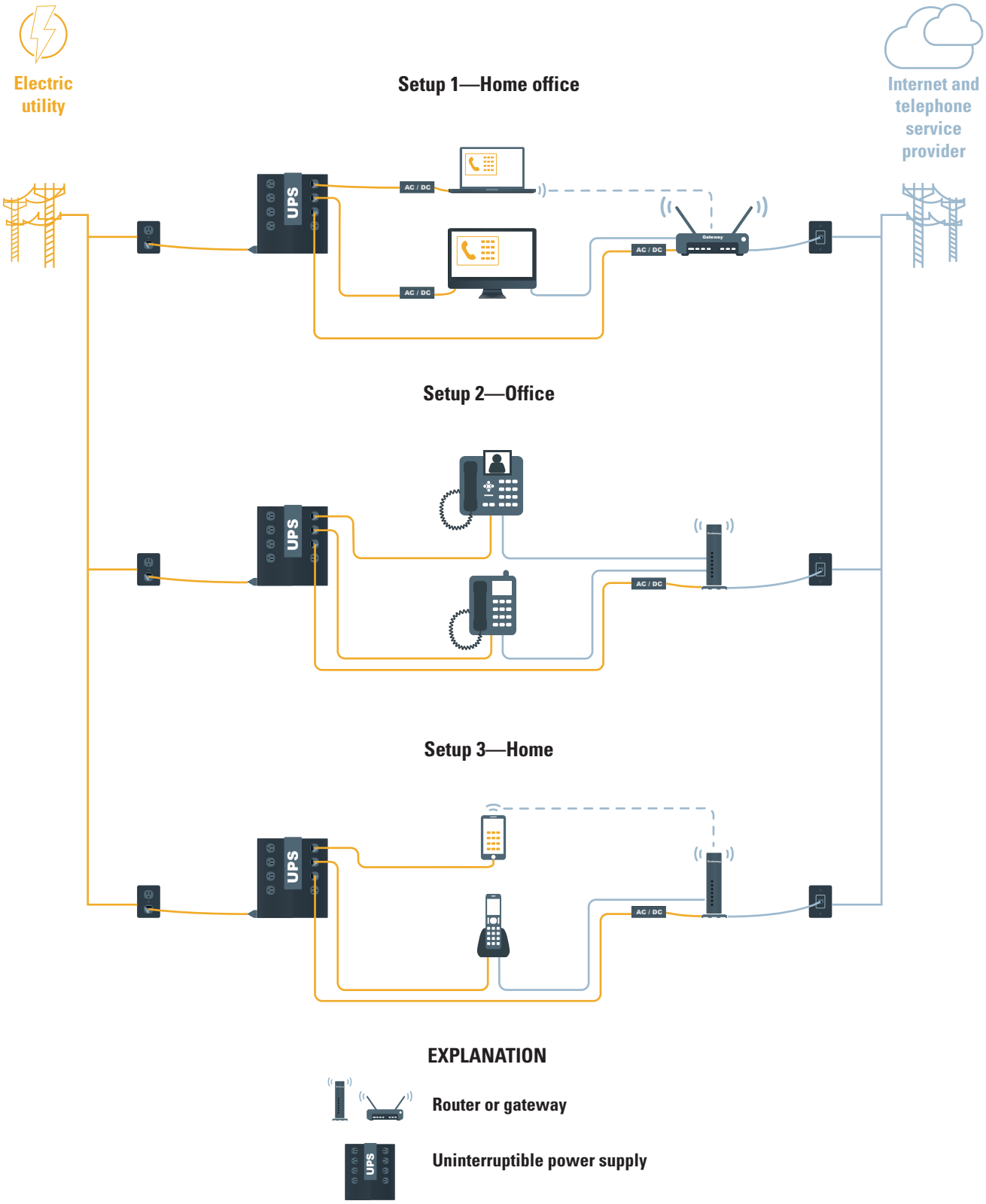


Figure 3.1. Schematic diagram illustrating examples of modern telephone resiliency setups for uninterruptible power supply (UPS). Setup 1 is for a home office that has a desktop or laptop computer that uses softphone. Setup 2 is for an office that has a desktop internet protocol (IP) phone as well as a desktop analog phone. Setup 3 is for a home that has a cordless analog phone as well as a cell phone that uses Voice over Internet Protocol (VoIP) applications.

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Chapter T

Lifeline Infrastructure and Collocation Exposure to the HayWired Earthquake Scenario—A Summary of Hazards and Potential Service Disruptions

By Jamie L. Jones, Anne M. Wein, Amy E. Schweikert, and Laurel R. Ballanti

Abstract

This chapter provides a comprehensive exposure analysis of five interacting lifeline infrastructure systems (comprised of facilities and conveyances) to six different HayWired earthquake scenario hazards. The lifeline infrastructure systems examined are transportation, water supply and wastewater, oil and gas, electric power, and telecommunications. The hazards considered are the HayWired mainshock ground shaking, surface rupture (represented as coseismic slip and afterslip), liquefaction, landslides, fire following the earthquake, and aftershocks. New geographic information system methods were developed to: (1) create a more detailed liquefaction probability map for the San Francisco Bay region that is not limited to a census-tract scale; (2) map relative levels of earthquake hazard intensities into a single multi-hazard intensity map; and (3) map collocation and density of infrastructure systems in a multi-hazard environment. Using these new methods, we look at the interaction between lifeline infrastructure systems and hazards in several ways: the exposure of single lifeline infrastructure types to single hazards; the exposure of single lifeline infrastructure systems to combinations of multiple hazards; and potential interactions between systems in hazardous areas after an earthquake. Finally, we compile lifeline infrastructure restoration times that have been acquired from various collaborations with providers and comment on the capabilities to consider multiple hazards and interactions between systems.

Hazard exposures vary by lifeline infrastructure. Eleven internet exchange points and five oil refineries are the most exposed (comprising 27 and 20 percent of sites, respectively) to high shaking intensity (defined as above 50 percent of the ground motion in the low-rise building design maps of the International Building Code). Liquefaction hazards are the primary hazard at the three international airports, seaports, water treatment plants, and one refinery in terms of affected area and severity during the HayWired mainshock (and likely for some nearby aftershocks). Oil and gas pipelines run parallel to and cross various transportation infrastructure and fiber optic cables in some areas with high liquefaction probability. Across all infrastructure, only 22 facilities were found in the fault zone, but hundreds of roadways and fiber optic cables cross the surface rupture and (or) are further exposed to afterslip. Also, there is infrastructure in the fault zone that is potentially exposed to all five hazards at once: these include a few bridges and cellular sites, and less than a few kilometers of roadways, fiber optic cables, and oil and gas pipelines. Contrary to the outcome of the 1989 Loma Prieta earthquake in California, safe egress from the east bay (especially away from ensuing fires) might well be west across the trans-bay bridges rather than to the east owing to fault rupture and landslide hazards. Because of the urban nature of fire following an earthquake in the HayWired scenario, Bay Area Rapid Transit (BART) facilities are relatively more exposed to higher fire-density areas. Long-haul fiber optic cables are relatively more present in high and very high multi-hazard areas. Five percent or more of petroleum, oil, or lubricant terminals, storage facilities, or tank farms; internet exchange points; fiber-lit buildings; cellular sites; natural gas compressor stations; microwave towers; and AM radio antennas are potentially exposed to three hazards (shaking, liquefaction, and fire) simultaneously. Most commonly, collocated infrastructure in hazardous areas involves surface streets or interoffice fiber (distribution infrastructure), although transmission infrastructure collocations among highways, railways, natural gas and petroleum pipelines, and high-voltage electric infrastructure may be a higher priority to repair following an earthquake. More societally critical infrastructure collocations occur around ports (specifically, the Port of Oakland and San Francisco International Airport) and in high building-density areas.

Service restoration time estimates indicate that BART stations and train yards will take longer (a few years) than highway bridges (as long as 10 months) to restore in the most heavily impacted areas, and water supply restoration times (as long as 6 months) extend beyond gas and electric power (weeks to a month) and voice and data (days to weeks) service restoration times. Restoration times could be extended by additional damages from fires following the earthquake, aftershocks, collateral damage, and repair delays from collocated infrastructure and other restoration dependencies.

This chapter offers an analytical approach to support planning and coordination among organizations of lifeline infrastructure providers, communities, government officials, businesses, and public safety. These results could assist agencies with identifying areas where they may benefit from working together to minimize damage and system disruption in several ways. This research provides: (1) comprehensive and standardized hazard exposure analyses to complement shaking-only or unavailable damage assessments of lifeline infrastructure systems, (2) a set of data layers for use in the development of information sharing tools, (3) potential exposure of collocated infrastructure to multiple hazards to inform and facilitate dialogue among organizations about increased societal risks for cascading failures and complex restoration interactions, and (4) windows into potential interactions that could arise following a major earthquake to suggest emergency management exercises among organizations. Finally, this work aligns with the proposed goals of a Regional Lifeline Council for the San Francisco Bay region.

Introduction

The economically vibrant, densely populated area around the Hayward Fault in the San Francisco Bay region in California presents a challenge in preparing and planning for a large earthquake. Lifeline infrastructure systems, such as transportation, electric power, oil and gas, water supply and wastewater, and telecommunications systems are the backbone infrastructure for economic and social activities (Perkins and Hutchings, 2010; The Lifelines Council, 2014; Applied Technology Council, 2016). Furthermore, economic and social activities increasingly rely on connected and complex systems of infrastructure. Electric power and telecommunications infrastructure are prime examples of interconnected infrastructure, as are transportation routes that also serve as right-of-ways for lifeline infrastructure (for example, pipes and conduits for water, wastewater, telecommunications, electric power, oil, and natural gas) (Applied Technology Council, 2016). Furthermore, the efficiency of systems has increased with more recent technological dependencies, such as remote monitoring of water and natural gas systems using sensors that require electricity and telecommunications infrastructure.

Interactions within and between lifeline infrastructure systems are vulnerable during and after an earthquake (The Lifelines Council, 2014): there are functional dependencies when one infrastructure relies on another (for example, telecommunications use electric power), geographic dependencies where collocated infrastructure can damage or delay the restoration of another (for example, utility lines beneath surface streets), substitution dependencies where capacity loss for one shifts demand to another (for example, roads and rails can both transport people and goods), and restoration dependencies when one needs the other to complete repairs (for example, transportation networks are required to access damaged infrastructure). Lifeline infrastructure interactions can also cause unexpected cascading failures. For example, in 1989, a train derailment in the Cajon Pass, north of the City of Los Angeles, damaged a nearby gasoline transmission pipeline and the subsequent explosion resulted in many destroyed homes and lost lives (Applied Technology Council, 2016). This example elucidates the importance of being able to anticipate, plan, and prepare for less predictable and less visible, potentially disastrous, lifeline infrastructure system interactions related to damages, services, and restoration. Arellano and others (2003) and Scalingi (2015) provide other examples and find that many of the impacts of seismic events have been caused by unforeseen (or previously unknown) interactions between lifeline systems. Furthermore, The Lifelines Council (2014) highlight hubs of collocated infrastructure systems as important areas of vulnerability and in need of further consideration in emergency management planning.

The San Francisco Bay region has been receptive to and proactive about earthquake risk from damages to lifeline infrastructure (Brocher and others, 2018), but interactions among infrastructure systems remain a challenge to assess and address before, during, and after a large earthquake. Applied Technology Council (2016) summarizes interdependency modeling capabilities at multiple scales that include optimization of restoration, functional dependencies, and simulations (both in the market and economy), especially regarding lifelines paired with power. They observe that infrastructure recovery models tend to neglect collocated infrastructure, resource limitations, and multiple and extended time horizons.

In practice, coordination among lifeline infrastructure systems that are affected by multiple earthquake hazards requires a cross-system, cross-organizational, and integrated approach to planning that is difficult to implement (Applied Technology Council, 2016). However, each lifeline infrastructure operator and provider has distinctive institutional procedures, operations, and operating areas. They lack a common set of service and restoration goals, scenarios for exercises, and comparable methods of assessment using standardized units. Sharing data for regional planning and preparedness can be cumbersome as a result of these inconsistencies (Scalingi, 2015). Exercises and disaster events are further limited by the inability of infrastructure owners and managers to easily and securely share infrastructure data (Scalingi, 2015; Applied Technology Council, 2016). Consequently, many areas and details of physical collocation are unknown.

According to Grain (2014), there is great value in well-designed, informative exercises that can test the efficacy of contingencies and preparedness plans. A post-event workshop on the 2014 South Napa (California) earthquake (Scalingi, 2015) gathered stakeholders and experts from across many jurisdictions and identified several immediate priorities. More dialogue between lifeline infrastructure managers about interdependencies and interactions was identified as the first priority. The second priority was a common approach, process, and standard for assessing vulnerabilities. The final priority identified during the 2014 workshop was to address the constraints on sharing information (including a secure information tool) to better coordinate restoration and allocating scarce resources (including personnel, fuel, electricity, communications, and transportation).

In the San Francisco Bay region, earthquake scenarios have been used as a common approach to assess and facilitate dialogue about the vulnerabilities of lifeline infrastructure systems and the interactions among them. The Lifelines Council (2014) chose a San Andreas Fault earthquake as the basis for their study for the City of San Francisco. Germeraad and others (2014) used publicly available lifeline infrastructure data with three important and representative earthquake scenarios in the bay region to investigate potential transportation and utility system vulnerabilities.

The HayWired scenario provides the most comprehensive set of hazard data to date for an earthquake scenario. The HayWired mainshock is a hypothetical moment magnitude (M_w) 7.0 earthquake on the Hayward Fault in the east bay part of California's San Francisco Bay area occurring at 4:18 p.m. on April 18, 2018. The HayWired earthquake hazards are: fault rupture and slip (during and after the event), ground shaking intensity, liquefaction probability, landslide probability, and fire following the earthquake for the mainshock, and two years of aftershocks (Detweiler and Wein, 2017; Scawthorn, 2018). We determined that the HayWired scenario can be used to illustrate a standardized assessment of multiple types of lifeline infrastructure (including collocated infrastructure) exposed to multiple hazards.

We approached the assessment by assembling critical San Francisco Bay region lifeline infrastructure stakeholders in 2014. We proposed that each stakeholder evaluate the performance of their infrastructure for the HayWired earthquake scenario hazards and share estimates of service restoration times and assumptions behind their estimates, including the use of shared, but scarce, resources (for example, labor, material, and accommodations). Each stakeholder's contribution was affected by availability of analytical tools, sensitivity of information, and uneasiness with appearing to promise restoration times that are dependent on many uncertain factors (including lifeline interactions). Thus, lifeline infrastructure damage and restoration analyses varied. They were: (1) conducted by stakeholders using in-house tools but not made publicly available, (2) conducted by the Federal Emergency Management Agency using Hazus-MH 2.1 (hereafter referred to as Hazus), (3) conducted by stakeholders for some hazards (dictated by assessment tool capabilities) and shared, and (or) (4) produced with additional assistance through HayWired collaborations. Hazus electric power, Bay Area Rapid Transit (BART), and California Department of Transportation (Caltrans) assessments are documented in appendixes 3–5 of this chapter. HayWired collaborative infrastructure damage and restoration assessments for water supply and telecommunications are in Porter (2018) and Wein, Witkowski, and others (this volume), respectively.

Although Hazus was our contingency plan for examining electric power, the tool was not used as a standardized assessment because it does not support all infrastructure and hazards (for example, fiber optic cables crossing surface rupture) and coarsely evaluates hazards at the scale of census tracts rather than utilizing more detailed hazard maps. Thus, our approach constructs a comparable and standardized multi-hazard exposure analysis for lifeline infrastructure systems. Available data for transportation, water supply and wastewater, oil and gas, electric power, and telecommunications systems were mapped against each mainshock hazard and aftershock shaking intensities. We contend with multiple mainshock hazards by reducing ground shaking, surface rupture, liquefaction, landslides, and fire following the earthquake into low, moderate, and high hazard intensity and combining them into a multi-hazard intensity landscape. Results for each system provide counts of facilities and lengths of conveyances exposed to each hazard intensity as well as the mainshock multi-hazard intensity. These results complement infrastructure damage assessments that were conducted for a subset of the hazards.

From the baseline infrastructure hazard exposure analyses, we were able to proceed with the next level of complexity; that is, density and multi-hazard exposure of collocated lifeline infrastructure of different types to show geographical interactions. We produced maps of collocations involving all lifeline infrastructure, transmission infrastructure, and possibly more societally critical infrastructure with respect to multiple hazards. We referred to The Lifelines Council (2014) framework for lifeline infrastructure interactions (general [within systems], functional, substitution, and restoration) as well as geographical interactions. We updated The Lifelines Council (2014) lifeline interaction table with input from HayWired workshop discussions, and we illustrated interactions between collocated infrastructure in hazardous sites of the HayWired scenario.

Utility and transportation service restoration times were compiled from other parts of the HayWired scenario (Porter, 2018, for water supply; Wein, Witkowski, and others, this volume, for telecommunications) and appendixes of this chapter (stakeholder analyses from BART and Caltrans; Hazus analysis for electric power). We reflect on the extent to which these estimates embody effects of multiple hazards and lifeline interactions.

In summary (also illustrated as a graphic in fig. 1), the following steps are taken.

1. Identify individual lifeline infrastructure systems
   - A. Analyze exposure of each infrastructure system to each earthquake hazard and fire following the earthquake
   - B. Analyze exposure of each infrastructure system to multiple hazards
2. Identify collocated lifeline infrastructure
   - A. Determine density of collocation infrastructure
   - B. Analyze exposure of collocated infrastructure (all, transmission, and potentially more critical for society) to multiple hazards
3. Assess lifeline infrastructure interactions
   - A. Update lifeline interactions informed by HayWired activities
   - B. Provide illustrations of lifeline infrastructure interactions
4. Compile lifeline infrastructure service restoration information.

In addition to the scientific uncertainties (Detweiler and Wein, 2017), the knowledge and data gaps in our work pertain to hazard mapping thresholds, infrastructure data and attributes, infrastructure fragilities, and collocated infrastructure. We conclude with a summary of potential lifeline infrastructure system exposures to earthquake hazards in the San Francisco Bay region. We posit that the methods and data developed here can be used to facilitate deeper analyses of lifeline interactions in a multi-hazard setting and to provide situations for exercises and materials for developing information-sharing tools. Finally, this demonstration of lifeline infrastructure analysis informs the current policy initiative for a proposed San Francisco Bay area regional lifeline council.

First, we describe and classify each of the HayWired earthquake scenario hazards (surface rupture and slip, ground shaking, liquefaction, landslides, and fire following the earthquake for the mainshock; and ground shaking for aftershocks) and data sources for the infrastructure systems (transportation, water supply and wastewater, oil and gas, electric power, and telecommunications). We follow with results of the exposure of each lifeline infrastructure system to each hazard intensity. Subsequent sections of this chapter expand on this baseline analysis to draw additional conclusions about multiple hazards affecting interdependent lifeline infrastructure in the San Francisco Bay region.

Lifeline Infrastructure Exposure to HayWired Earthquake Scenario Hazards

The first level of lifeline exposure analysis looks at how individual lifeline infrastructure systems (composed of facilities and conveyances) are exposed to each HayWired earthquake scenario hazard. This single lifeline-single hazard assessment serves as a baseline for understanding potential impacts to lifeline infrastructure; hazard exposure analysis offers a comprehensive and standardized approach, but it does not estimate damages to infrastructure.

HayWired Hazard Descriptions and Classifications

The main source of earthquake hazard data is HayWired v. 1 (Detweiler and Wein, 2017), as well as an expanded liquefaction probability map (appendix 1) and a fire density map (explained below). The hazards and data sources are summarized in table 1. Each hazard (except fault rupture) is classified into low-, moderate-, and high-intensity exposure. These classifications are designed to simplify the complexities of multi-hazard analyses. These are relative classifications of hazard intensity within our study area for the HayWired scenario.

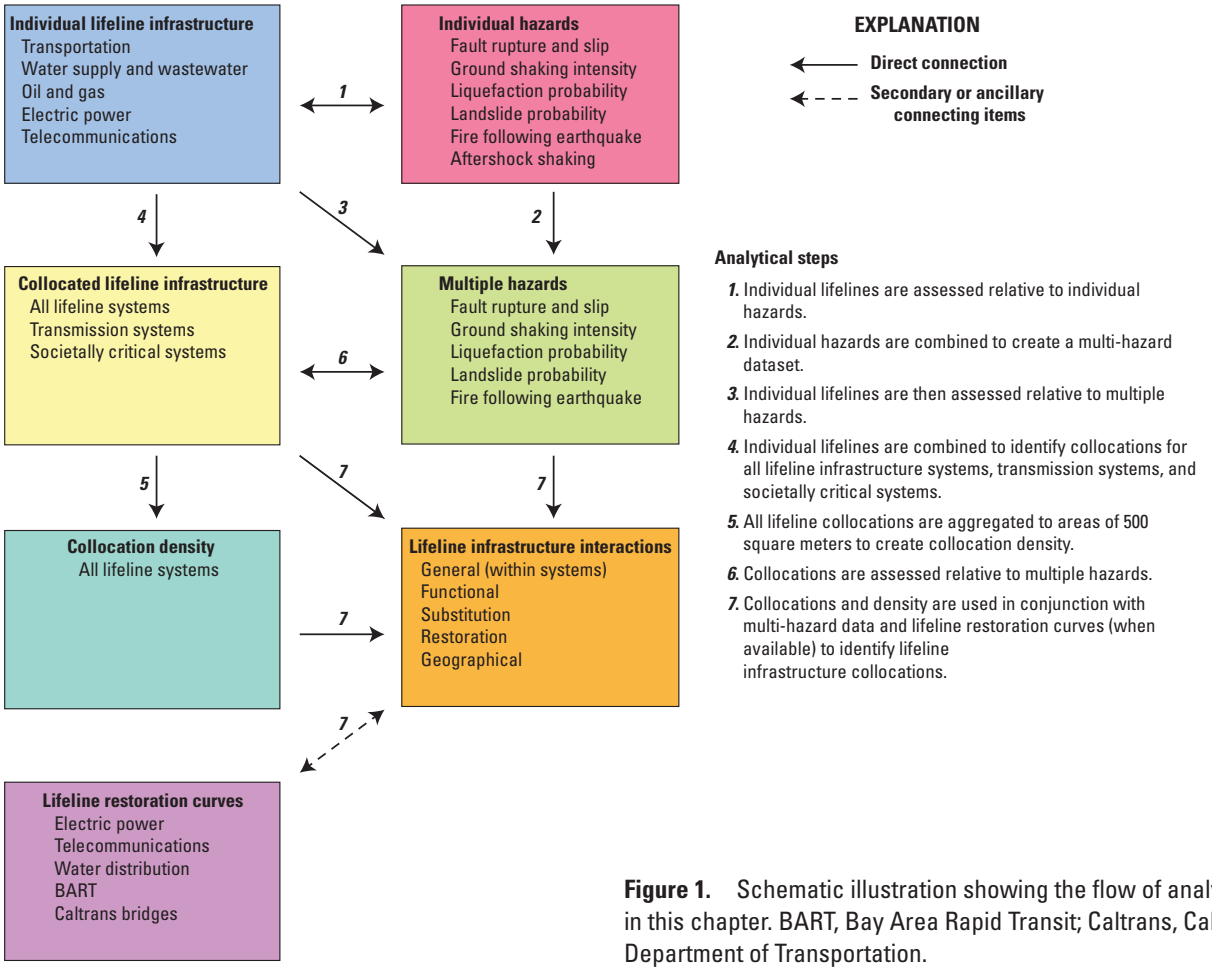


Figure 1. Schematic illustration showing the flow of analyses in this chapter. BART, Bay Area Rapid Transit; Caltrans, California Department of Transportation.

Table 1. Summary of hazards resulting from the HayWired earthquake scenario in the San Francisco Bay region, California.

[km, kilometers; km^2, square kilometers; m^2, square meters; cm/s, centimeters per second]

Hazard	Original data source	Summary description
Ground shaking (mainshock)	HayWired v. 1, chap. C—"HayWired scenario mainshock ground motions" by Aagaard, Boatwright, and others (2017)	Magnitude of mainshock measured in 0.3 second period of vibration for spectral acceleration at approximately 1.5 km^2 resolution (1.2 km^2 longitudinal, 1.8 km^2 latitudinal). Calculated for 51,372 km^2.
Fault rupture (mainshock)	HayWired v. 1, chap. D—" HayWired scenario mainshock coseismic and postseismic surface fault slip" by Aagaard, Schwartz, and others (2017)	Fault rupture that caused coseismic slip (during an earthquake) or afterslip (following an earthquake) at the ground's surface. Total fault length that experienced surficial coseismic slip or afterslip is 83 km, of which 63 km experienced surficial coseismic slip.
Liquefaction (mainshock)	HayWired v. 1, chap. E—"HayWired scenario mainshock—Liquefaction probability mapping" by Jones and others (2017) HayWired v. 3, this chap., appendix 1—"HayWired liquefaction modeling expansion methodology"	Probability of liquefaction estimated at 50 m^2 resolution in Jones and others' (2017) study area (susceptibility data used at same 50-m^2 resolution). Total area of modeled extent with non-zero occurrence probability is 3,144 km^2, of which 1,181 km^2 is based on Jones and others' findings.
Landslide (mainshock)	HayWired v. 1, chap. F—"HayWired scenario mainshock—Earthquake-induced landslide hazards" by McCrink and Perez (2017)	Probability of landslide estimated at 10 m^2 geographic scale modeled in areas where peak ground velocity exceeds 20 cm/s. Total area of modeled extent with non-zero occurrence probability is 2,915 km^2.
Ground shaking (aftershocks)	HayWired v. 1, chap. G—"HayWired scenario aftershock sequence" by Wein and others (2017)	Seven of the 16 largest aftershocks occur within 2 years of the mainshock event, and are the only ones that have ground shaking of moderate and (or) high-intensity classification.
Fire (following the mainshock)	HayWired v. 2, chap. P—"Fire following the HayWired scenario mainshock" by Scawthorn (2018)	Density of burned buildings estimated in developed land tracts. Total area of modeled extent with non-zero density is 1,220 km^2.

Fault Rupture

The surface slip caused by a fault rupturing is described as coseismic slip (the displacement that occurs during an earthquake) and afterslip (the subsequent slip of the fault occurring over the days, weeks, and months following a large fault rupture). Surface slip disturbs any lifeline infrastructure crossing the fault. Coseismic slip followed by afterslip may require a series of repairs to facilities and networks that straddle the fault. This situation recently arose, for example, after the 2014 South Napa earthquake in California (Hudnut and others, 2014). Scientists observed that afterslip tended to occur along the fault rupture where coseismic slip was less pronounced (Hudnut and others, 2014; Lienkaemper and others, 2016).

The HayWired scenario rupture of the Hayward Fault begins beneath the city of Oakland and extends from San Pablo Bay in Contra Costa County to southern Fremont in Alameda County over a total distance of 83 kilometers (km) (Aagaard, Schwartz, and others, 2017). The coseismic surface slip ranges from no measurable surface slip to about 2.1 meters (m), whereas afterslip from the HayWired scenario could measure between 0.5 and 1.5 m. Afterslip may cause rupture at the surface along the entire fault rupture zone even where coseismic slip only occurred beneath the surface (Aagaard, Schwartz, and others, 2017). Figure 2 shows the fault rupture used for the HayWired scenario along with the linear transmission lifeline infrastructure assessed in this chapter—figure 2*A* is the full study area and figure 2*B* is focused on the area where fault rupture is modeled to occur. See appendix 2 for an illustration of clusters of lifeline infrastructure crossing the fault along its length. The amount of offset that may cause damage varies widely across infrastructure types exposed—for example, brittle pipelines may be damaged by even a few millimeters of offset (K. Porter, University of Colorado at Boulder, written commun., 2017). Therefore, the classification of the fault rupture hazard intensity is binary: either the area has measurable (non-zero) coseismic surface slip (classified as high hazard intensity) or does not. However, damage from fault offset varies widely. For example, electric power transmission lines are included in the fault offset hazard for consistency, although such damage is likely minimal. In this case, transmission lines are generally suspended with flexibility between supporting towers that are not located on faults and the natural horizontal frequency for electric transmission towers is low to withstand high winds (which are generally stronger forces than earthquake shaking) (Federal Emergency Management Agency, 1990). In contrast, the building of structures in the fault zone is constrained by the Alquist-Priolo Act of 1972 (Perkins and Hutchings, 2010; California Department of Conservation, 2017). This reduces,



Figure 2 (pages 118–119). Maps of the San Francisco Bay region, California, showing transmission infrastructure relative to rupture of the Hayward Fault during the HayWired earthquake scenario mainshock. Many transmission infrastructure lifelines cross the fault, including natural gas and petroleum pipelines, water supply transmission systems, highways and secondary roads, electric power transmission lines, and long-haul fiber optic cables. These maps also illustrate the density of certain infrastructure around more urbanized areas in the study region (defined by the black bounding box in *A*). Where linear features cross the fault, the intersection points are colored to be consistent with the linear infrastructure they correspond to (for example, a yellow point denotes where a natural gas or petroleum pipeline crosses the fault). *A*, Regional view of the Hayward Fault rupture and infrastructure relative to the study region. *B*, Zoomed-in view of the locations where infrastructure assets cross the Hayward Fault rupture. M_w, moment magnitude.

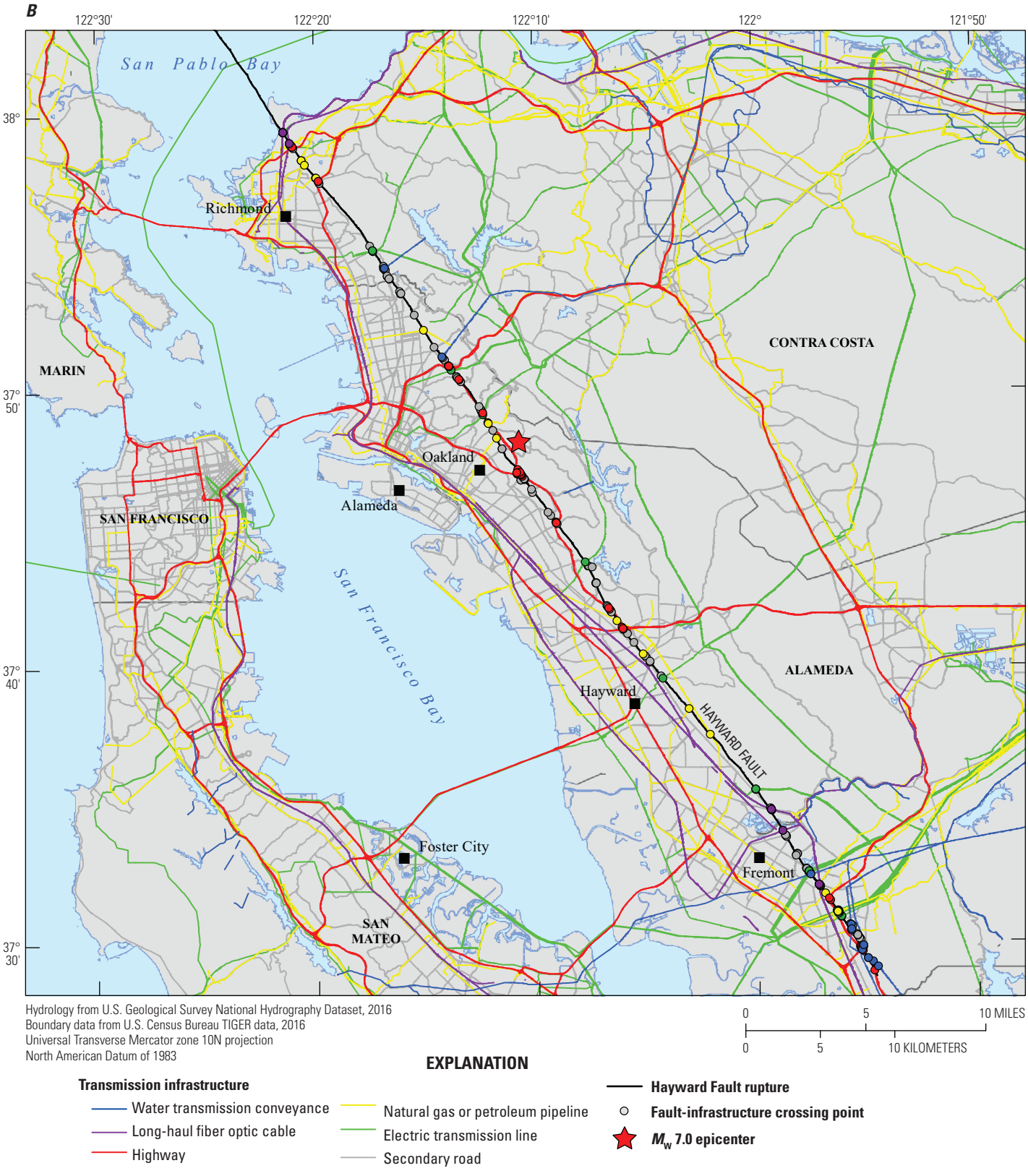


Figure 2 (pages 118–119).—Continued

but does not eliminate, the presence of lifeline infrastructure facilities in the fault zone. The whole length of the fault is considered a high-intensity fault rupture hazard with respect to total surface slip (coseismic slip and afterslip).

To use this information in an assessment of lifeline infrastructure exposure, the coseismic slip from Aagaard and others' (2010) model for the HayWired scenario is transferred to the most recent representation of the fault trace (Lienkaemper, 2007). The mapped fault trace provided in these geographic information system (GIS) data was aligned with surface slip data (discussed in Aagaard, Schwartz, and others, 2017). This was done by associating the centroid of each fault segment in the Lienkaemper (2007) dataset to the closest segment of the HayWired surface slip dataset using a spatial join in the GIS software. The fault trace dataset includes a field specifying the positional uncertainty of the mapped fault trace; the trace was buffered in the GIS using the positional uncertainty values to define a zone for the location of the Hayward Fault. The end result was the surface slip along the fault trace within a zone of uncertainty around the Hayward Fault. This means that parallel segments of the Lienkaemper (2007) fault trace were all assigned the same surface slip value from the HayWired surface slip dataset. In reality, the slip on parallel segments could be loaded on one segment or distributed across parallel segments. In our fault-crossing analyses, we assume some of the coseismic slip occurs on all parallel segments up to the amount for the zone of uncertainty.

Ground Shaking

Ground shaking is typically the most extensive earthquake hazard and occurs both as mainshock and aftershock shaking. In the HayWired scenario, ground shaking was modeled using two methods—a largely physics-based model for the mainshock (Aagaard, Boatwright, and others, 2017) and ShakeMap for the aftershocks (Wein and others, 2017). The implications of the differences between the two methods are explained in Porter (2017). The study area for this analysis is the extent used in the physics based model (Aagaard and others, 2010), which covers a total area of 51,372 square kilometers (km^2).

The measurement of ground shaking used in this chapter is spectral acceleration (SA) at a 0.3 second period of vibration. This measurement of SA corresponds to the amplitude of earthquake shaking that resonates most with low-rise buildings (buildings between 1 and 4 stories in height, which represent the vast majority of structures in the region) and is used in this analysis because it is consistent across a range of geographic comparisons, accounts for differences such as soil type, and is an appropriate measure for infrastructure asset owners and operators to assess potential damages (Federal Emergency Management Agency, 2006). The thresholds for moderate and high shaking are defined by shaking that is at least 25 and 50 percent, respectively, of the ground motion in the design maps of the International Building Code (K. Porter, University of Colorado at Boulder, oral commun., 2014). For example, in the formulas in table 2, 0.25 corresponds to 25 percent of the design map motions; S_s is the ground motion in the International Building Code for the seismic design of low-rise buildings on rock sites; and $F_a(S_s)$ is a factor to account for the way soil tends to amplify earthquake motion above what a site on rock would experience. So, a building that experiences motion of $0.25 \times F_a(S_s) \times S_s$ is experiencing motion that is at least 25 percent of the very rare motion shown in the design maps in the building code. Fewer than 1 building in 2,000 would collapse below this level of motion, but about 1 building in 500 might be damaged to the extent of being unfit for human occupation (red-tagged), and perhaps as many as 1 in 40 could be identified as habitable for only short periods (yellow-tagged) at 25 percent of the mapped motion. More information about the International Building Code design maps and the formulas can be found in Federal Emergency Management Agency (2003) and Federal Emergency Management Agency (2009).

Mainshock Ground Shaking

Figure 3*A* displays the relative shaking intensity using SA classifications at a 0.3 second period of vibration, as described in table 2. As shown in figure 3*A*, most areas with high-intensity shaking exist within approximately 30 km of the HayWired scenario epicenter and include most of Alameda County as well as some areas in Contra Costa, Santa Clara, and San Joaquin Counties. Figure 3*B* is the same HayWired ground-shaking scenario intensity but shown relative to the U.S. Geological Survey (USGS) ShakeMap representation of the Modified Mercalli Intensity (MMI) scale. As shown in figure 3*B*, most areas of high-intensity ground shaking have MMI values of VIII or IX and small areas experience high-intensity ground shaking associated with MMI values of VI–VII. MMI values of VIII and IX are considered "severe" and

Table 2. Shaking-potential hazard intensity classification for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[km^2, square kilometers; S_s, short-period 5 percent damped maximum considered earthquake spectral response acceleration; $S_{a(0.3)}$, 0.3 second period 5 percent damped earthquake spectral acceleration; F_a, short period average spectral amplification factor]

Intensity classification	Formula	Estimated geographic extent (km^2)
Low	$S_a(0.3) \leq 0.25 \times F_a(S_s) \times S_s$	31,665
Moderate	$0.50 \times F_a(S_s) \times S_s > S_a(0.3) > 0.25 \times F_a(S_s) \times S_s$	18,052
High	$S_a(0.3) > 0.50 \times F_a(S_s) \times S_s$	1,655

"violent," with moderate to heavy damage predicted. Some areas of moderate-intensity ground shaking (fig. 3*A*) have corresponding MMI values of VIII and IX as well (shown in bright yellow in fig. 3*B*). Most areas of low-intensity and some areas of moderate-intensity ground shaking correspond to MMI values of IV and V (light to moderate perceived shaking), indicating none to very minimal damage, as shown in figure 3*B* as the lightest shades of yellow and green (MMI values based on Aagaard, Boatwright, and others, 2017). Please note that SA is not directly comparable to MMI; SA approximates the shaking a building experiences, whereas MMI is a representation of an earthquake's intensity.

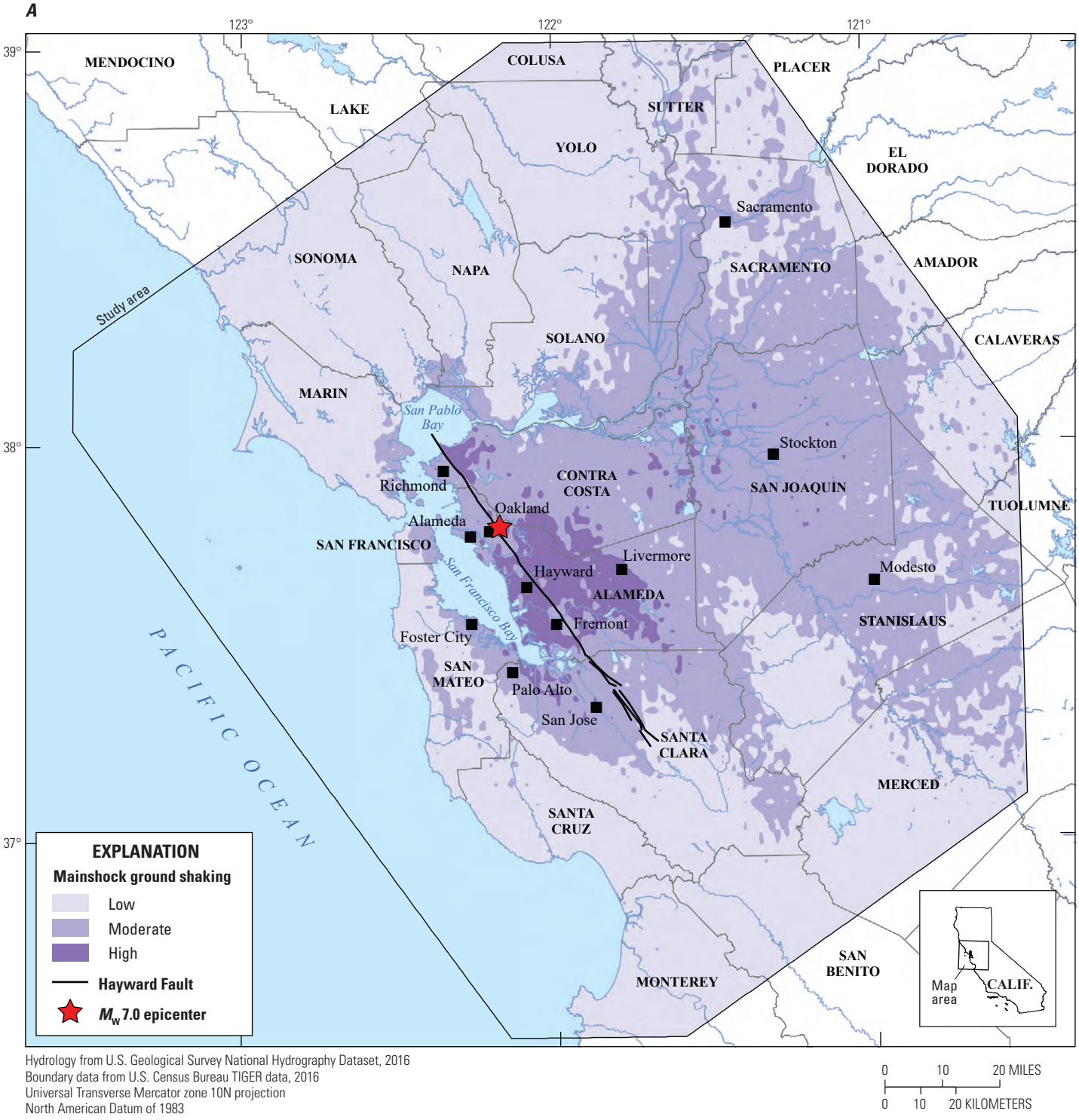
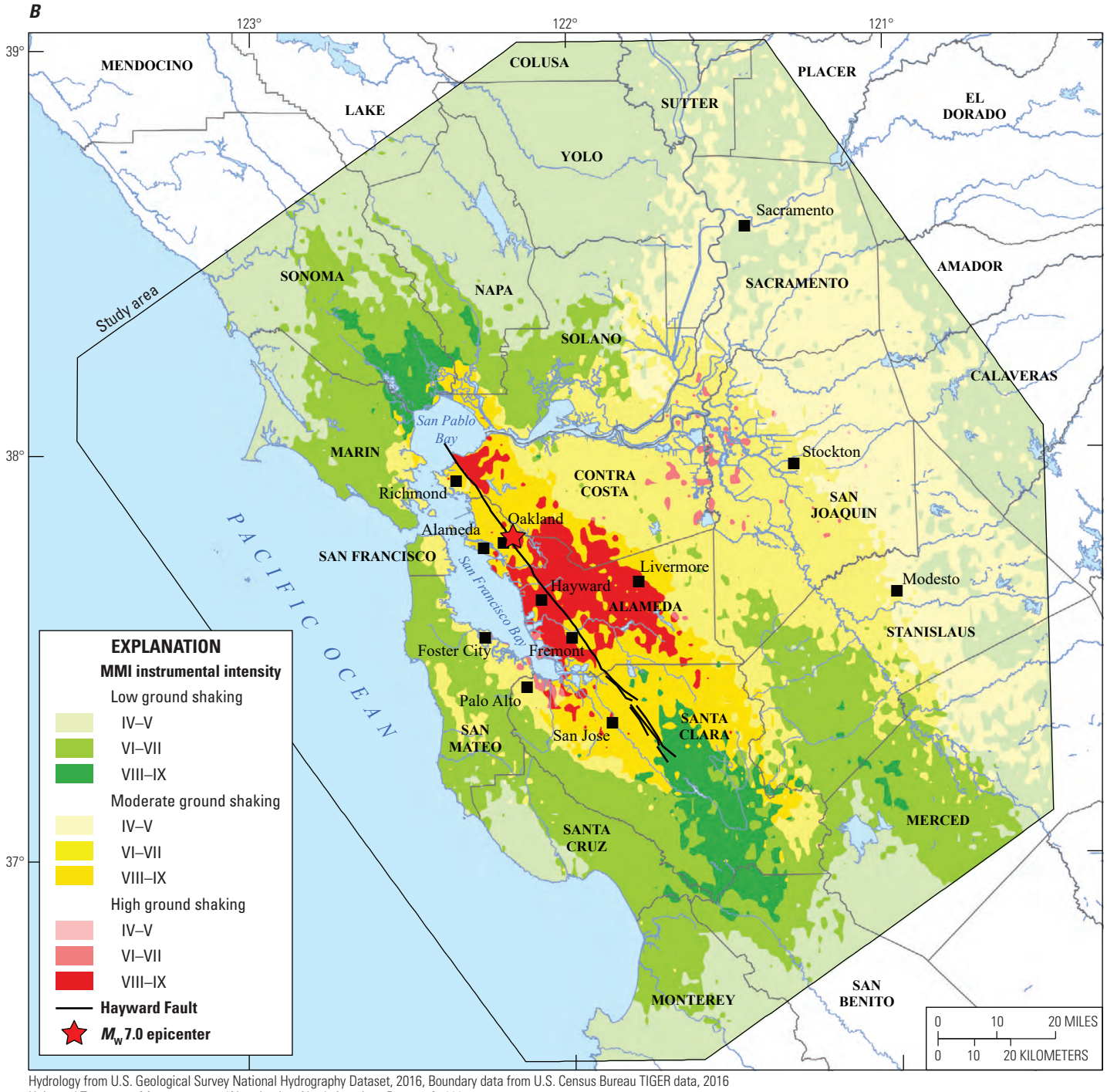


Figure 3 (pages 121–122). Maps of the San Francisco Bay region, California, showing ground shaking as a result of the HayWired earthquake scenario mainshock on the Hayward Fault. *A*, Ground-shaking classifications used in this chapter. *B*, Ground shaking classifications compared to ShakeMap Modified Mercalli Intensity (MMI) instrumental intensity values. M_w, moment magnitude.

Aftershock Ground Shaking

The HayWired earthquake scenario sequence includes a simulation of two years of aftershocks following the mainshock, although aftershocks after a large Hayward Fault earthquake could continue for many additional years (Wein and others, 2017). A total of 16 aftershocks in the HayWired aftershock sequence were modeled to have a magnitude (*M*) of at least 5. In this assessment of lifeline exposure, only seven of the 16 *M*5 or greater aftershocks are used—only these seven aftershocks cause at least moderate ground shaking and they occur within one year of the mainshock (table 3). Only one aftershock (*M*6.4 in Cupertino) produces high-intensity ground shaking.

Particularly important for the analysis of aftershocks is the timing, magnitude, and number of aftershocks that occur in the hours, days, weeks, and months following the mainshock. Figure 4 maps how many earthquakes that produce moderate or high ground-shaking intensity affect a single geographic region, indicating repeated ground shaking



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016, Boundary data from U.S. Census Bureau TIGER data, 2016
Universal Transverse Mercator zone 10N projection, North American Datum of 1983

Figure 3 (pages 121–122). —Continued

Table 3. Modeled aftershocks with moderate or high ground shaking for the HayWired earthquake scenario in the San Francisco Bay region, California.

[Locations listed are approximate based on nearest major city, see figure 4. *M*, magnitude]

Aftershock description	Number of days after mainshock
M6.2, May 28, 2018, 4:47 a.m., Palo Alto	40
M5.7, May 28, 2018, 11:53 p.m., Palo Alto	40
M5.2, June 23, 2018, 8:27 p.m., Palo Alto	66
M5.3, July 1, 2018, 11:19 a.m., Palo Alto	74
M6.0, September 30, 2018, 8:16 p.m., Mountain View	165
M6.4, October 1, 2018, 12:33 a.m., Cupertino	166
M5.4, October 1, 2018, 2:24 a.m., Sunnyvale	166

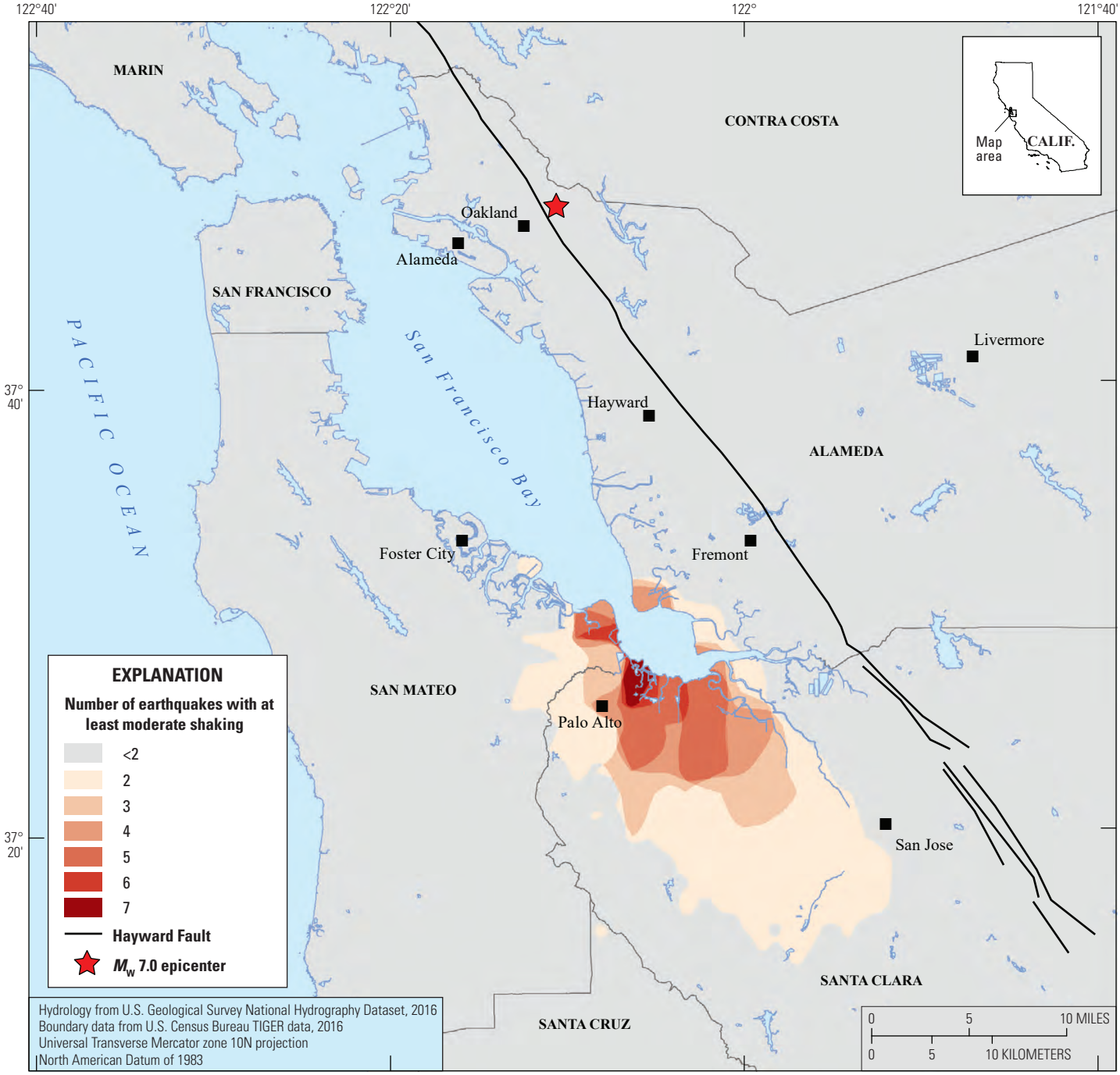


Figure 4. Map of the San Francisco Bay region, California, showing areas affected by overlapping aftershock ground shaking for the HayWired earthquake scenario. Some areas experience multiple aftershocks in addition to the mainshock, especially the bay side areas near Palo Alto, and some areas experience moderate and (or) high ground shaking that occurs five, six, or seven times in the year following the HayWired scenario mainshock. M_w, moment magnitude.

over time. As shown in figure 4, all the aftershocks that result in moderate or high ground shaking occur in the southern part of San Francisco Bay, where some areas experience multiple events of at least moderate-intensity ground shaking (indicated in dark red).

Liquefaction

Liquefaction is a form of ground failure induced by an earthquake in areas where loose, water-saturated ground composed of sand or silt becomes temporarily softened or liquefied, behaving like quicksand (Perkins and Hutchings, 2010; Jones and others, 2017). In areas where intense ground shaking occurs and specific hydrologic and geologic conditions exist, liquefaction is probable (though not likely to occur in all areas with liquefaction susceptibility). When liquefaction occurs, it can cause severe damage to infrastructure above and below ground, including structures, roads, water pipes, and electric power lines. Historically, liquefaction from earthquakes has been a source of damage in the San Francisco Bay region, including the 1868 Hayward, 1906 San Francisco, and 1989 Loma Prieta earthquakes (Knudsen and others, 2000).

We expanded upon the liquefaction probability map in Jones and others (2017) to map liquefaction probability within census tracts where Hazus results were used. Census tract-level Hazus results were modified based on liquefaction susceptibility data from Knudsen and others (2000)—tract liquefaction probabilities were estimated by susceptibility class and then mapped to each susceptibility class in each tract. The final liquefaction probability dataset covers 3,144 km^2 in area (with non-zero liquefaction probability). For a more detailed description, please refer to appendix 1.

The liquefaction intensity classification is defined in table 4 and mapped in figure 5. The classification for low intensity (less than 5 percent probability) excludes areas with zero probability of liquefaction. The high-intensity liquefaction threshold is set at 25 percent; whereas some areas from Jones and others' (2017) model see much higher liquefaction probabilities, 25 percent is the Hazus cap and thus used to capture the high range of liquefaction probability. Moderate intensity is between 5 and 25 percent probability of liquefaction.

Table 4. Liquefaction hazard intensity classification for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Probability refers to the percentage of land in a given geographic area affected by liquefaction. Thresholds are designed for classification and discussion purposes only and are not intended to provide guidance. %, percent; km^2, square kilometers]

Intensity classification	Liquefaction probability (%)	Estimated geographic extent (km^2)
Low	<5	1,438
Moderate	5 to <25	1,513
High	≥25	193

Table 5. Landslide hazard intensity classification for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Probability refers to the percentage of land in a given geographic area affected by slope failure. Thresholds are designed for classification and discussion purposes only and are not intended to provide guidance. %, percent; km^2, square kilometers]

Intensity classification	Landslide probability (%)	Estimated geographic extent (km^2)
Low	<5	1,780
Moderate	5 to <25	344
High	≥25	791

Landslides

Landslides are induced by shaking in combination with geologic characteristics (for example, material strength) and slope gradient of the land. Landslides can cause damage to lifeline infrastructure above and below ground (roads, rail, pipelines, buried fiber optics, and so on). McCrink and Perez (2017) completed landslide modeling for ten counties in the region assessed in the HayWired scenario; the landslide modeling covers 2,195 km^2. According to McCrink and Perez (2017), because uniform 1:24,000 scale geologic mapping does not yet exist for the entire HayWired scenario study region, an unpublished, statewide, generalized geologic compilation map was used to extract the 10-county study region used in their analysis. They used geologic material strength, slope gradient, ground shaking maps, and other variables to produce landslide probability maps in areas where the HayWired mainshock peak ground velocity (PGV) exceeds 20 centimeters per second. See McCrink and Perez (2017) for modeling parameters, details, and a discussion of limitations.

The probability of landslides caused by the HayWired mainshock is mapped using the same probability threshold categories used for the liquefaction hazard in order to be consistent across both types of ground failure (table 5). The high hazard class for landslides covers a larger area than the moderate hazard class (that is scattered throughout the region and not as large pockets) owing to more area in hilly terrain with high probabilities (and little development). Similarly, areas with zero probability of landslide are omitted. Figure 6 displays the study region and landslide probability classifications.

Fire Following Earthquake

Fires following earthquakes are common, and large conflagrations are possible—a notable example is the 1906 San Francisco earthquake. Approximately 80 percent of the total damage following the 1906 earthquake was attributed to post-earthquake fires, even when compared to ground shaking damage. Scawthorn (2018) lays out the conditions for fires following an earthquake in terms of the simultaneous correlated effects of a large earthquake: numerous ignitions,

degraded building fire-resistive features, overwhelmed and potentially damaged communication and transportation routes, low or no water pressure in water-supply mains for fire response, multiple fires beyond the capacity of local fire companies to respond to in a timely manner, and the effects of wind on spreading fires. These factors, combined with an aging and (or) wooden urban and suburban building stock, create the potential for costly fire following earthquake events and are acknowledged as a vulnerability in the San Francisco Bay region.

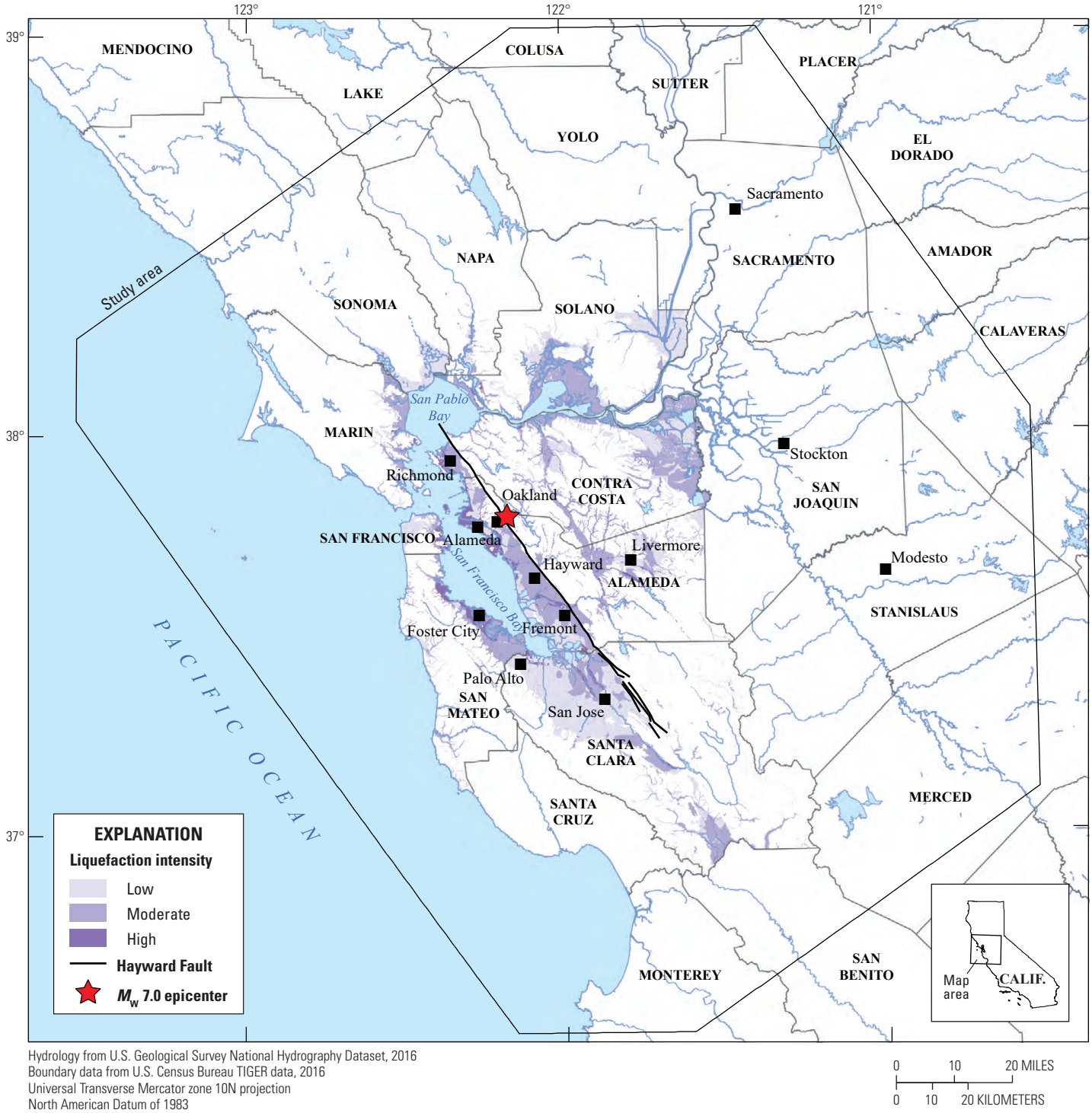


Figure 5. Map of the San Francisco Bay region, California, showing the liquefaction probability modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. Liquefaction probability is highest in the areas adjacent to San Francisco Bay and the creeks feeding into the bay. This map combines two methods of assessment, which are further described in appendix 1. M_w, moment magnitude.

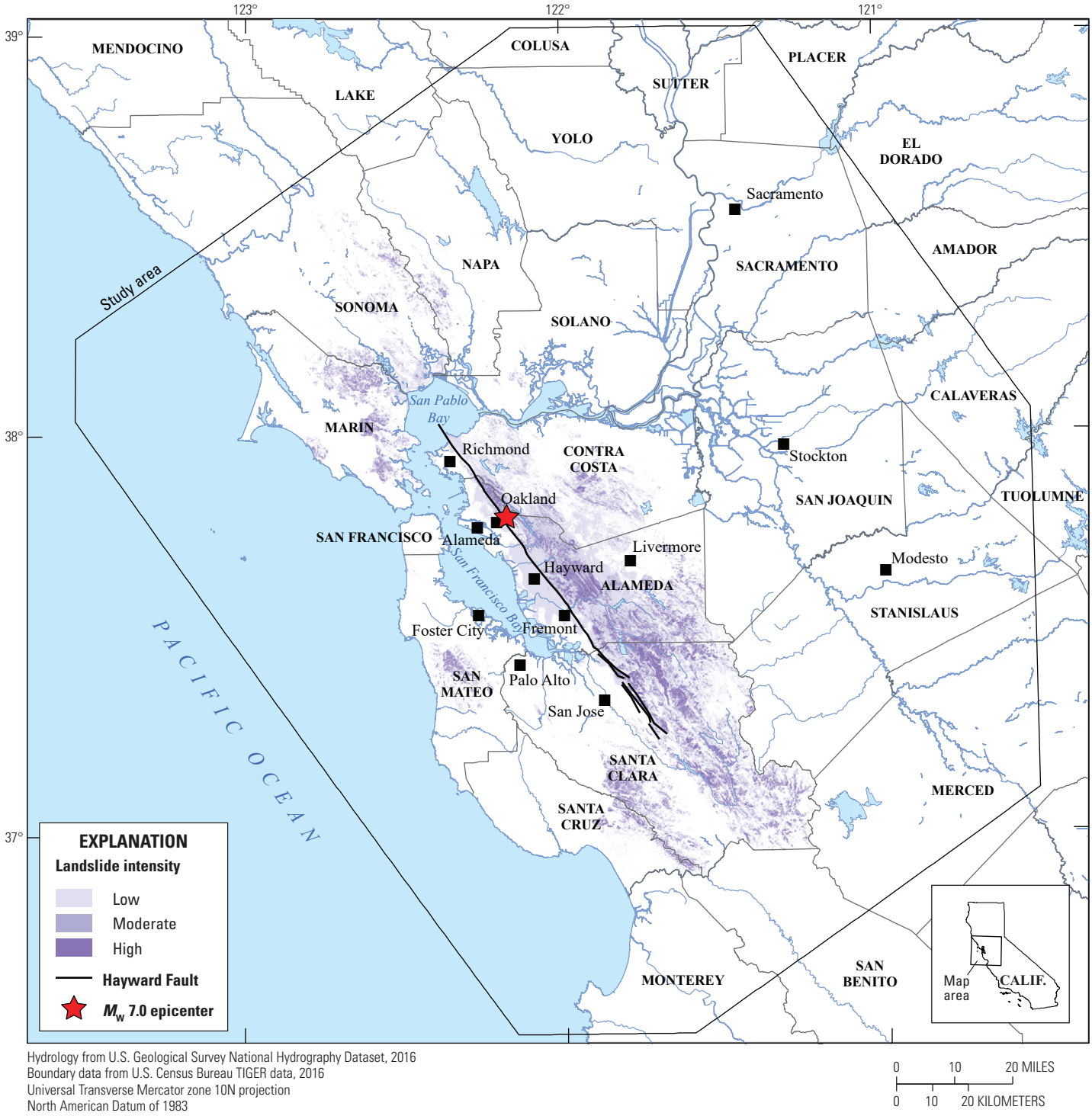


Figure 6. Map of the San Francisco Bay region, California, showing the landslide probability modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. Landslide probability is highest in the areas surrounding the fault rupture as well as on the northwest side of San Francisco Bay and the southwest areas of Santa Cruz County. M_w, moment magnitude.

Scawthorn (2018) simulates a fire following earthquake scenario for the HayWired mainshock to estimate the square footage of building stock burned in a series of Voronoi areas[1] of varying sizes, each served by one fire station. The results are mapped by Voronoi area for the region (Scawthorn, 2019). We convert the burned area to a density of burned buildings, that is, the square footage of burned buildings in each Voronoi area divided by the area containing the buildings (approximated using developed area). The developed area is taken from the 2011 National Land Cover Database (Homer and others, 2015) and includes low-, medium-, and high-intensity developed areas ("intensity" here refers to the amount of impervious surface in a pixel, where a more impervious surface corresponds to a higher intensity). Restricting the analysis to only developed areas refines the geographical distribution of fire affecting buildings. This assumes that burned buildings are in areas classified as developed in the National Land Cover Database. Buildings in very remote areas may be missed, but the biggest concern for fire following an earthquake are conflagrations when the fire spreads faster than it can be contained and blocks of buildings in developed areas of the National Land Cover Database are burned. The final burned-building density extent covers a 1,220 km^2 area.

Fire burns buildings and restricts access in surrounding areas. The fire density calculation is burned-building square footage divided by the area in which the buildings are located for each Voronoi area. The low-, moderate-, and high-intensity threshold classifications were selected by using the GIS to identify natural breaks in the data. The burned building density classifications are detailed in table 6 and mapped in figure 7. In contrast to the liquefaction and landslide data, the fire density breaks are low because the burned-building square footage covers only a small fraction of the total developed land area within a Voronoi area.

Table 6. Fire-following-earthquake hazard intensity classification for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Fire density refers to burned-building square footage (Scawthorn, 2018) relative to the developed area containing the fires for each Voronoi area. Thresholds are designed for classification and discussion purposes only and not intended to provide guidance about potential magnitude of impacts on lifeline infrastructure. km^2, square kilometers]

Intensity classification	Fire density	Estimated geographic extent (km^2)
Low	>0 to <0.0085	994
Moderate	0.0085 to <0.023	159
High	≥0.023	67

Individual Lifeline Exposure to Individual Hazards

Exposure analyses of a single lifeline infrastructure system and a single hazard is a straightforward GIS analysis, given the spatial data for lifeline facilities and conveyances (table 7) and the hazard maps. International air and seaports were examined visually in GIS with hazard data overlain on satellite imagery to estimate exposure to these systems. Key findings for the exposure of each lifeline infrastructure to each HayWired mainshock hazard in the San Francisco Bay region follow. The findings are derived from summary tables of hazard exposure in appendix 2, with one table for numbers of lifeline infrastructure fault crossings and lengths in the fault uncertainty buffer and a series of tables for each lifeline infrastructure category summarizing exposure to the other hazards. Additional detail from these analyses, including exposure for specific subcategories of these lifeline infrastructure types, can be found in Jones (2019).

[1] A Voronoi area is a polygon whose sides are equidistant between the point the Voronoi area is centered around and any neighboring points—a line is drawn between two points, the midpoint of that line is found, a perpendicular line is drawn through that midpoint, and this is repeated for all neighboring points to complete a Voronoi polygon for a specific point.

Table 7. Lifeline infrastructure types in California's San Francisco Bay region, scales of analysis, and data sources.

["All hazards" includes shaking, surface slip, landslide, liquefaction, and fire. HSIP, Homeland Security Infrastructure Program; BART, Bay Area Rapid Transit; Caltrans, California Department of Transportation; HIFLD, Homeland Infrastructure Foundation-Level Data; EPA FRS, U.S. Environmental Protection Agency Facility Registry Service; POL, petroleum, oil, and lubricants; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Infrastructure type	Scale of analysis	Data source	Year	Hazards of importance
Transportation				
Roadways (highway, secondary, surface)	Kilometers	HSIP Gold	2013	Shaking[1], surface slip, landslide, liquefaction
Railways	Kilometers	HSIP Gold	2013	All hazards
BART facilities	Number of stations/yards	HSIP Gold	2013	All hazards
Highway bridges	Number of structures	Caltrans	2015	Shaking, surface slip, landslide, liquefaction
Ports	Number of docks/berths	HSIP Gold	2013	All hazards

Table 7.—Continued

Infrastructure type	Scale of analysis	Data source	Year	Hazards of importance
Water supply and wastewater				
Transmission conveyance systems	Kilometers	Various[2]	2015	Surface slip, landslide, liquefaction
Dams	Number of structures	HSIP Gold	2013	All hazards
Drinking-water sources	Number of sources	HIFLD	2015	All hazards
Drinking-water treatment plants	Number of plants	HIFLD	2015	All hazards
Wastewater treatment plants	Number of plants	EPA FRS	2016	All hazards
Oil and gas				
Pipelines (natural gas, petroleum)	Kilometers	HSIP Gold	2013	Surface slip, landslide, liquefaction
Natural gas compressor stations	Number of stations	HSIP Gold	2013	All hazards
Natural gas processing plants	Number of plants	HSIP Gold	2013	All hazards
Natural gas receipt and delivery points	Number of points	HSIP Gold	2013	All hazards
Natural gas storage facilities	Number of facilities	HSIP Gold	2013	All hazards
POL terminals, storage facilities, and tank farms	Number of facilities	HSIP Gold	2013	All hazards
Oil refineries	Number of facilities	HSIP Gold	2013	All hazards
Electric power				
Transmission lines	Kilometers	HSIP Gold	2013	Surface offset, landslide, liquefaction, fire[3]
Electric power generation plants	Number of facilities	HSIP Gold	2013	All hazards
Energy distribution control facilities	Number of facilities	HSIP Gold	2013	All hazards
Substations	Number of facilities	HSIP Gold	2013	All hazards
Telecommunications				
Fiber routes (long-haul, interoffice)	Kilometers	GeoTel	2018	Surface slip, landslide, liquefaction, fire[3]
Cellular sites (macro and small cells)	Number of units	GeoTel	2018	All hazards
Fiber-lit buildings (data center, central office, point of presence)	Number of buildings	GeoTel	2018	All hazards
Wireless switch offices	Number of offices	GeoTel	2018	All hazards
Internet exchange points	Number of points	HSIP Gold	2013	All hazards
Microwave towers	Number of towers	HSIP Gold	2013	All hazards
AM radio antennas	Number of units	HSIP Gold	2013	All hazards
FM radio antennas	Number of units	HSIP Gold	2013	All hazards
NTSC television transmitters	Number of units	HSIP Gold	2013	All hazards
Digital television transmitters	Number of units	HSIP Gold	2013	All hazards

[1]Shaking is an indirect impact on surface streets owing to the potential for debris to fall on streets.

[2]Water transmission conveyance systems are a combination of named aqueducts, canals, and tunnels in the U.S. Geological Survey National Hydrography Dataset (2013 version) and supplementation from digital maps available from the California Department of Water Resources and the Metropolitan Water District of Southern California. See Jones (2019) for more information.

[3]Fire is a potential issue for aerial lines; available geographic information system data do not specify whether the lines are subterranean or aerial, so we do not distinguish between them here.

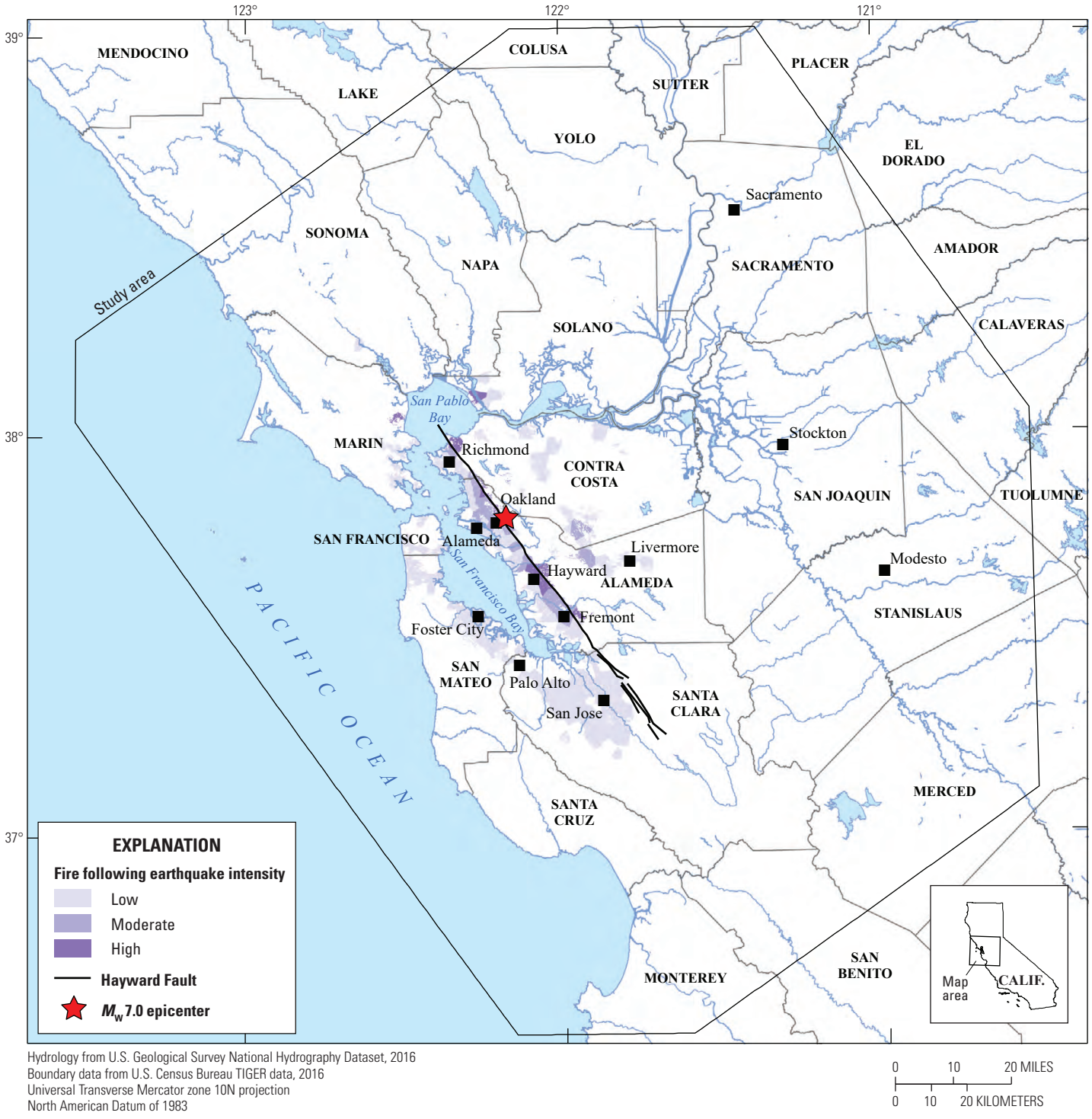


Figure 7. Map of the San Francisco Bay region, California, showing the fire-following-earthquake modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. The scale of analysis is determined by the location of each fire station. Analysis boundaries are drawn based on the closest distance to each fire station. Low, moderate, and high classifications are based on the density of burned-building square footage relative to developed land. Areas considered undeveloped based on the 2011 National Land Cover Database were not considered in this analysis. M_w, moment magnitude.

Transportation Infrastructure

Referring to Applied Technology Council (2016), the transportation system is composed of several types of infrastructure, including roadways (highways, secondary roads, and surface streets), bridges, railways (including local and regional commuter and freight systems), and ports (air and sea based). Whereas some redundancies are built into the highway transportation network (especially in urban areas), damage to highways, major arterials, and bridges (commonly the weakest links in the system) can cause significant impacts to traffic in the region (especially in rural areas where there is less redundancy in the system). The railway network has similar susceptibilities, but fewer redundancies than the highway network, such that a few failures can have major impacts on rail transportation. Airport structures (for example, terminals or control towers) may experience damage as a result of most hazards, whereas runways experience similar damage as other roadways; takeoff and landing safety concerns mean that runways are more difficult to repair than other infrastructure (Applied Technology Council, 2016). Seaports serve various types of vessels that rely on waterfront structures (for example, wharves or piers), cargo handling equipment (for example, cranes), cargo storage facilities (for example, warehouses), control centers, and fuel facilities to run, but damage to one port can cause major delays and economic impacts on the port and its environs. The transportation system is multimodal—if one part of the system is impacted, another part of the system can pick up the slack. However, all parts of the system need to be working correctly for the multimodal component to be optimally efficient (Applied Technology Council, 2016).

Earthquakes have the potential to damage most components of the transportation system, with the exception of air and water vessels not on land and land vehicles on at-grade roadways. Minor earthquakes that generate shaking below system design levels do not generally have extensive impacts on the transportation system—some structures, roadways, and bridges may experience minor damage requiring simple repairs, which are usually completed within days of the earthquake. Major earthquakes produce shaking at or greater than design specifications for the system, however, and may severely damage bridges, seaport facilities, airport facilities, and railways (damaged rail alignment). Damages are not limited to ground shaking: airport runways and seaport structures may be impacted by liquefaction and lateral spread (Applied Technology Council, 2016). High-intensity heat from fire (which may follow earthquakes) may warp railway lines via thermal expansion or ignite any wooden ties. Moreover, flames can extend into roads and railways and flammable trees can fall into transportation corridors (Radke and others, 2018).

For the HayWired scenario, we find:

- Roadways cross the Hayward Fault rupture zone more than any other lifeline infrastructure, with highways crossing 37 times, secondary roads crossing 127 times, and surface streets crossing 424 times. Whereas roadways have the most fault crossings, some of these crossings are points where a single road crosses multiple times (for example, part of Interstate 580 [I–580], which runs parallel and adjacent to the fault). The cities of Fremont and Oakland have the most road segments crossing the fault rupture zone; Fremont roadways could be impacted by afterslip whereas Oakland roadways could be affected by coseismic slip and afterslip.
- Highways crossing the fault with estimated measurable coseismic slip include: Interstate 80 (I–80) through San Pablo, I–580 in Oakland, California Routes 13 and 24 in Oakland, and the Richmond Parkway, which connects I–580 and I–80. Coseismic slip and afterslip could occur multiple times along the California Route 13 freeway, as large lengths of the freeway run parallel and adjacent to the fault rupture, similar to I–580.
- Shaking damage to structures along roads may dump debris on the streets and (or) be closed for safety reasons; around 4,100 km of surface roads are in developed parts of high-intensity shaking areas.
- Owing to the concentration of BART infrastructure in the east bay, 13 percent (6) of BART facilities are exposed to high shaking intensity compared to 8 percent (292) of highway bridges in the region.
- Three to five percent of the region's highways (nearly 180 km; 4 percent), bridges (around 170; 5 percent), and railways (about 90 km; 3 percent) are found in high liquefaction intensity areas. Other roadways and BART facilities are less exposed (percentage-wise) to high liquefaction probability.
- About 325 km of roadways go through high landslide intensity areas and where there is less redundancy (landslides are more common in hilly areas, where road coverage is more sparse) and road repair may be more challenging. About 82 bridges are exposed to moderate-intensity landslide hazards, whereas 20 are exposed to high-intensity landslide hazards.
- Since the HayWired fire following earthquake analysis is focused in urban areas, BART facilities (which service urban areas) are relatively more exposed to fire than other transportation infrastructure.
- The three major San Francisco Bay region airports have terminals, gates, runways, and other structures used for airport operations (for example, hangars) exposed to high liquefaction hazards, particularly at the Oakland International Airport (including the majority of runways there). The San Jose International Airport has some operations structures that are impacted by high ground-shaking intensity. Travis Air Force Base in Solano County is exposed to low-to-moderate shaking from the mainshock but not to

any of the other earthquake hazards. Moffett Federal Airfield in Santa Clara County is exposed to moderate to high shaking from the mainshock (a small part of the northernmost part of the Moffett airstrip has high liquefaction potential) and would be in moderate or high shaking intensity areas for four or five aftershocks of magnitude 5 or greater.

- Most of the Oakland seaport and the southern half of the San Francisco seaport is exposed to high liquefaction. Six percent of seaport docks and (or) berths are in areas with high liquefaction intensity, and three percent of docks and (or) berths are in high shaking intensity areas.

Water Supply and Wastewater Infrastructure

Referring to Applied Technology Council (2016), water infrastructure is a complex series of systems, each comprising several subsystems. Water supply systems include the raw water supply (for example, aqueducts or wells), treatment (for example, plants), transmission (for example, systems that move raw or treated water between treatment plants and either the raw water source or the treated-water distribution plant), and distribution (for example, local water pipelines) systems. Wastewater systems include collection (for example, local sanitation pipelines), conveyance (for example, sewer systems), treatment (for example, plants), and discharge and (or) disposal (for example, bay drainage lines) systems. Stormwater and flood-control systems are a third component, devoted to collection, diversion, storage, and release of storm and flood runoff. Water delivery, if interrupted, adversely affects water and wastewater systems, public health, and firefighting capabilities. Stormwater systems rely on wastewater systems for drainage functionality, whereas wastewater systems can provide an alternative water source for nonpotable purposes (including firefighting) (Applied Technology Council, 2016).

Water system pipelines have no seismic design standard; leaks and breaks occur from shaking and ground failure (Porter, 2018). Dam failures may occur as a result of ground shaking caused by an earthquake, and the resulting flooding may impact numerous people in downstream communities. Water loss immediately after an earthquake (caused by ground shaking, liquefaction, or lateral spreading) can potentially lead to the spread of fires because firefighters may not have access to sufficient water to put out the fires. Sewer systems can also be damaged by liquefaction, which may then lead to contamination of potable water systems. Treatment plants could even be damaged by excess amounts of foreign materials (for example, sand or silt disturbed by liquefaction) introduced into plant filters (Applied Technology Council, 2016).

For the HayWired scenario, we find:

- Two major water-transmission conveyances (the San Pablo Tunnel and the Mokelumne Aqueduct) cross the fault rupture zone in three places where measurable coseismic slip occurs. The San Pablo Tunnel crosses the Hayward Fault at a location where two parallel fault segments are present.
- Ten percent of the dams in the study area are exposed to high shaking intensity.
- Wastewater treatment plants are the most exposed (of all water infrastructure) to high liquefaction intensity (9 percent of plants), followed by dams (5 percent of dams).
- Drinking-water sources and drinking water treatment plants are generally located outside of high-intensity hazard areas. However, around 2 percent of these facilities are in high shaking intensity areas and 1 percent or less of facilities are exposed to high liquefaction, landslide, or fire intensity.

Oil and Gas Infrastructure

Referring to Applied Technology Council (2016), oil and gas infrastructure moves and serves natural gas and liquid fuels. It includes transmission systems (for example, pipelines transporting unrefined products to processing, refining, and storage facilities) and distribution systems (for example, pipelines from distribution terminals that move refined products to households). Facilities like refineries and processing plants serve as nodes within and between the transmission and distribution systems (Applied Technology Council, 2016).

Ground deformation damages gas distribution systems, especially those with vulnerable lines. On the other hand, aboveground facilities and lines are more susceptible to ground shaking and acceleration (E. Hickey and G. Molnar, Pacific Gas and Electric Company, written commun., 2017). Pipelines are commonly buried and insulated but have aboveground appurtenances that are susceptible to exposure (Radke and others, 2018).

For the HayWired scenario, we find:

- Natural gas and petroleum transmission pipelines cross the Hayward Fault in locations with measurable coseismic slip 7 and 8 times, respectively, mostly in Contra Costa County (with one in Alameda County).
- One oil refinery out of five is in an area of high-intensity ground shaking and another is in a high-intensity liquefaction area.
- One third of petroleum, oil, and lubricant (POL) terminals, storage facilities, and tank farms are found in areas with high liquefaction intensity.

- Fifteen percent of natural gas compressor stations are in areas with high shaking intensity, whereas nine percent are in high liquefaction intensity areas.
- No natural gas storage facilities are within high-intensity ground shaking areas and no natural gas processing plants are in the study area.

Electric Power Infrastructure

Referring to Applied Technology Council (2016), the electric power infrastructure system is comprised of three main components. The first is the electric generation system (for example, power plants), the second is the electric transmission system (for example, high-voltage substations, towers, and lines), and the third is the electric distribution system (for example, distribution substations and low-voltage lines). Generation systems can either be self-contained (for example, a coal-fired power plant) or distributed (for example, a wind farm), which affects how a generation source is impacted after a hazard event. Substations work at multiple levels, in addition to serving as nodes in the transmission and distribution system to help reduce energy loss over distance. Some transmission substations reduce high voltages to subtransmission voltages for distribution substations and the distribution substations convert the voltage to full distribution voltages to serve individual customers.

Underground electric power distribution lines may be more susceptible to earthquake-induced ground failure (liquefaction and ground displacement), but aboveground lines are generally not directly at risk of earthquake damage. Instead, aboveground infrastructure is more commonly impacted by earthquake damage to supporting towers (for example, from landslides) or substations (for example, from ground shaking). Earthquake damage to distribution systems most commonly result from poor installation methods, vulnerabilities in surrounding entities (for example, nearby buildings), and aging system components (Applied Technology Council, 2016).

For the HayWired scenario, we find:

- Transmission lines cross the Hayward Fault 8 times in areas with measurable coseismic slip. The majority of these crossings are aboveground (and hence not as likely to be directly damaged); one of these crossings occurs on a subterranean transmission line that transects San Pablo Bay.
- Substations and electric power generation plants are exposed to high-intensity ground shaking (63 and 18, respectively), high liquefaction probability (33 and 12, respectively), and high fire density (7 and 3, respectively). One substation is located in a high landslide probability area.

Telecommunications Infrastructure

Referring to Applied Technology Council (2016), the telecommunications infrastructure system is much more complex than other lifeline infrastructure systems. Whereas other systems tend to run in one major hierarchy (transmission to distribution), telecommunications has a number of subsystems running in parallel. Fiber infrastructure (for example, fiber optic cables and fiber-lit buildings [buildings with large-bandwidth connections to receive fiber optic cables for internet and (or) data service]) can coexist with cellular infrastructure (for example, cellular sites), and cellular infrastructure can be collocated with older telecommunications infrastructure (for example, AM and FM radio transmitters or microwave towers). This provides redundancy in the communications network but may also have cascading impacts if a facility that serves as a node for multiple subsystems (for example, both FM radio and cellular transmission) goes offline. Fiber optic cables may also be used by multiple carriers, so damage to one cable may disrupt service for several different providers simultaneously (Applied Technology Council, 2016).

Earthquake impacts on buried fiber cables are not well known; impacts likely depend on the amount of ground displacement (fault offset, liquefaction, and so on) and design (Wein, Witkowski, and others, this volume). Aged cellular site infrastructure are more vulnerable to earthquakes and could disrupt cellular networks. For more information on the interrelated components of the telecommunications infrastructure system and how they are affected by earthquakes, please refer to Wein, Witkowski, and others (this volume).

For the HayWired scenario, we find:

- 123 fiber optic routes cross the Hayward Fault (second only to the number of surface streets crossing the fault) in locations where measurable coseismic slip occurs. The majority of these crossings (102) are interoffice distribution fiber cables and the remainder (21) are long-haul transmission fiber cables. Similar to roadways, the crossings with measurable coseismic slip occur in the cities of Richmond and San Pablo in Contra Costa County and the cities of Hayward, Oakland, and Berkeley in Alameda County.
- Five cellular sites and eight point of presence fiber-lit buildings are located within the zone of uncertainty with measurable coseismic slip.
- Cellular sites (about 1,100) and fiber-lit buildings (more than 5,200) are the most exposed of all lifeline infrastructure to high shaking intensity (13 percent). Within fiber-lit buildings, data centers have slightly greater exposure to high shaking intensity at 15 percent. In addition, 5 to 6 percent of cellular sites and fiber-lit buildings are exposed to high liquefaction intensity.

- In general, wireless switch offices are not very exposed to high-intensity hazards. Ground shaking is the only high-intensity hazard affecting these facilities (6 percent of facilities).
- The majority of internet exchange points in the San Francisco Bay region are in the southern and peninsular areas of the region, but there are a small number of them. Whereas only three of these facilities are exposed to high shaking intensity, the percentage exposed is 27 percent.
- AM radio antennas are the most exposed facility to high liquefaction probability (14 percent of antennas) and 8 percent are in high shaking intensity areas.
- Microwave towers are exposed to high shaking intensity (8 percent), high liquefaction intensity (6 percent), and high landslide or fire intensity (1 percent or less each).
- Analog and digital television transmitters are not exposed to any high hazard intensities.
- Telecommunications infrastructure lifelines are the most affected by aftershocks, with 10 percent of microwave towers, 11 percent of cellular sites, 17 percent of point of presence fiber-lit buildings, 45 percent of internet exchange points, and 55 percent of data centers exposed to at least moderate shaking. In total, 108 and 226 data centers are exposed to at least moderate shaking during the first three months and between three months and one year after the HayWired scenario mainshock, respectively. This is consistent with the movement of the HayWired scenario aftershock sequence into the south bay—data centers and internet exchange points are located in greater abundance in the south bay than in other parts of the region.

Combinations of Hazards

The next level of detail identifies combinations of mainshock hazards affecting each lifeline conveyance or facility. Aftershocks are not included in the multi-hazard assessment of the mainshock because the exposure is additive over time and shown in the individual hazard exposure analyses in appendix 2. We describe the methods to estimate exposure of lifeline infrastructure to combinations of mainshock hazards, followed by results.

Methods

In GIS, the area for mainshock hazard combinations was calculated using all low, moderate, and high-intensity hazard areas. For each hazard combination, the extent of the area (in km^2) that contained at least one hazard of high-intensity was calculated, as well as the percentage of the area where at least one hazard is high-intensity (table 8). Figure 8 highlights areas where one or more hazards are classified as high-intensity. The GIS dataset is used to assess the exposure of lifeline infrastructure to combinations of hazards.

Table 8. Geographic extent of hazard combinations from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[The entire study region is exposed to ground shaking; therefore, all values in this table assume ground shaking as a hazard included in each value. For example, the geographic extent listed for landslide is the area exposed to landslide and ground shaking hazards. km^2, square kilometers; %, percent]

Hazards in addition to ground shaking	Geographic extent for hazard combination[1] (km^2)	Extent with at least one hazard at high-intensity (km^2)	Percentage of total hazard combination extent with at least one hazard at high-intensity (%)
None	45,449	565	1
Surface slip[2]	<1	<1	100
Landslide	2,461	1,183	48
Liquefaction	2,034	295	14
Fire	245	24	10
Landslide and liquefaction	206	101	49
Liquefaction and fire	726	178	24
Liquefaction and surface slip[2]	<1	<1	100
Landslide and surface slip[2]	<1	<1	100
Fire and surface slip[2]	<1	<1	100
Landslide and fire	70	39	56
Three additional hazards	178	124	69
All four additional hazards	<1	<1	100

[1]Geographic extent for hazard combination includes all intensity levels for each hazard.

[2]Surface slip includes parts of the Hayward Fault that have measurable coseismic slip as well as areas without measurable coseismic slip (which may experience afterslip).

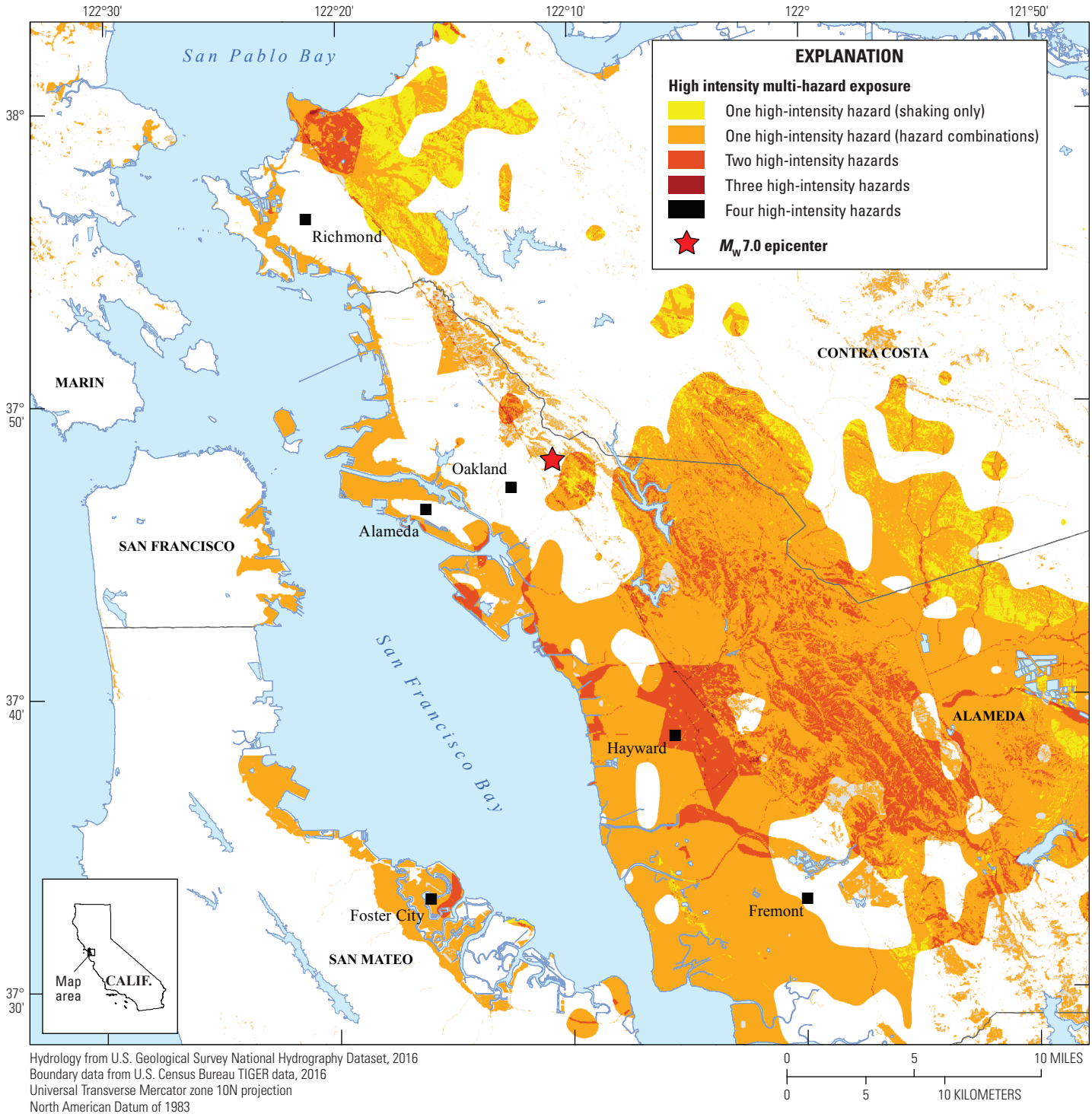


Figure 8. Map of the San Francisco Bay region, California, showing areas exposed to one or more high-intensity HayWired earthquake scenario mainshock hazards. Areas in dark red or black indicate exposure to multiple high-intensity hazards and are mostly found in the Hayward, Richmond, and Oakland urban areas as well as many areas directly surrounding San Francisco Bay (for example, Foster City). M_w, moment magnitude.

Results for Hazard Combinations

Table 8 shows that all of the approximately 50,000 km^2 study area is affected by ground shaking. Much of the area (about 90 percent) is affected by ground shaking hazard alone; of this area, only 1 percent is affected by high-intensity shaking (as defined in table 8). In the rest of the study area, the most common additional hazards are landslides and liquefaction. A high-intensity hazard is most likely to occur in the shaking and landslide hazard combination (in 50 percent of the shaking-plus-landslide area). After ground shaking, slip hazards most commonly occur with landslide hazards because parts of the Hayward Fault run along the base of the east bay foothills, where liquefaction and fire are less common. One hundred percent of the hazards combined with surface slip involve at least one hazard of high-intensity because surface slip is a high-intensity hazard by definition. Aside from ground shaking, fire following earthquake hazards most commonly occur in areas with liquefaction hazards—liquefaction occurs mostly on flat land, as does development, which is where urban fires and liquefaction damage to the water supply (for firefighting) are modeled to coincide. Four hazards cooccur in 178 km^2 of area. There is a small area (0.2 km^2) along the fault trace where all five hazards could coincide.

Results for Lifeline Infrastructure Exposure to Three or More Hazards

Because all the additional ground failure and fire hazards occur with ground shaking, lifeline infrastructure is exposed to a minimum of two mainshock hazards. Lifeline infrastructure exposure to two hazards is detailed in appendix 2 and the findings are captured by the single hazard assessment of ground failure and fire hazards. Table 9 isolates the exposure of lifeline infrastructure to three or more hazards. In this case, we find that lifeline infrastructure is most commonly exposed to the combination of ground shaking, liquefaction, and fire (consistent with the prevalence of this hazard combination in the study area), but many fewer include a high-intensity hazard in this combination. From table 9, infrastructure exposed to ground shaking, liquefaction, and fire includes:

- Thirteen BART facilities (approximately 28 percent of all facilities), but only one facility (2 percent of all facilities) is exposed to at least one high-intensity hazard.
- Eight internet exchange points (about 73 percent of all facilities), but only one facility (9 percent of all facilities) is exposed to at least one high-intensity hazard.
- More than 13,000 fiber-lit buildings (about 32 percent of all facilities), more than 3,000 (8 percent of all facilities) of which are exposed to at least one high-intensity hazard.
- Around 300 data centers (67 percent of all facilities), of which close to 50 (10 percent of all facilities) are exposed to at least one high-intensity hazard.

The prevalent combination of hazards affecting electric power lines and dams is liquefaction, landslide, and ground shaking. Fifty-two percent (approximately 64 km) of electric power transmission lines in areas with liquefaction, landslide, and ground shaking are exposed to at least one high-intensity hazard. For 6 of the 7 dams that are exposed to the combination of ground shaking, landslide, and liquefaction, at least one hazard in the combination is of high-intensity. We note that the Cull Creek dam, a dam that is being managed for seismic instability (Alameda County Flood Control and Water Conservation District, 2017), is exposed to high shaking intensity, high liquefaction probability, as well as moderate landslide probability.

Bridges straddle various multi-hazard combinations. Notably, 357 bridges are exposed to four hazard combinations; 39 percent of these bridges include at least one hazard of high-intensity. Nearly three quarters of cellular sites exposed to four hazard combinations are exposed to at least one hazard of high-intensity (284 of 384), as are about two thirds of fiber-lit buildings that are exposed to four hazards (1,386 of 2,168). Whereas the majority of these facilities are in Alameda County, some are located in Contra Costa and Santa Clara Counties.

All five hazards could affect three bridges in Alameda County and two cellular sites in Contra Costa County. Conveyances running through areas with all five hazards sum to 3 km of fiber optic cables (1 km of long-haul fiber, 2 km of interoffice fiber), less than 2 km each of secondary roads, surface streets, and highways (mostly in Alameda County), and a combined length of less than 1 km of natural gas pipelines, petroleum pipelines, railways, and transmission lines (found in either Alameda or Contra Costa County). Additional detail from this analysis, including exposure for specific subcategories of these lifeline infrastructure types, can be found in Jones (2019).

Exposure of Individual Lifeline Infrastructure to Multi-hazard Intensities

This section collapses the multiple mainshock hazards to one layer of multi-hazard intensities to simplify an analysis of collocated infrastructure in hazardous places for the HayWired scenario. The intermediary results of lifeline infrastructure exposed to multi-hazard intensities are related to the above results for the specific combinations of hazards. We describe GIS methods developed to identify collocated infrastructure. Furthermore, the points of collocated infrastructure among all infrastructure types are spatially aggregated to show larger areas containing a high density of collocated infrastructure. This analysis of lifeline infrastructure and hazards is constructed to frame lifeline infrastructure interaction examples in the next section.

Table 9. Amount of lifeline infrastructure exposed to three, four, or five overlapping hazards resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[In each column, the total is presented in kilometers (km) or number of facilities. The "1+ high" columns indicate the total amount of infrastructure from the corresponding "Total" column that is exposed to at least one hazard with a high-intensity classification. The results in this table are exclusive and can be considered with the numbers in table 2.7 of appendix 2, which summarizes the exposure of lifeline infrastructure to shaking and coincidence with one additional hazard. km, kilometers; BART, Bay Area Rapid Transit; POL, petroleum, oil, and lubricants; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Lifeline	Study area total	Ground shaking + landslide + liquefaction		Ground shaking + liquefaction + fire		Ground shaking + landslide + fire		Ground shaking + surface slip[1] + liquefaction		Ground shaking + surface slip[1] + landslide		Ground shaking + surface slip[1] + fire		Four hazards		Five hazards	
		Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high
Transportation																	
Roadways, highway (km)	4,624	72	37	562	193	63	36	0	0	<1	<1	<1	<1	143	103	1	1
Roadways, secondary (km)	16,353	166	112	2,147	451	130	68	<1	<1	1	1	1	1	558	359	1	1
Roadways, surface (km)	69,899	682	452	7,920	1,779	756	414	<1	<1	4	4	5	5	1,890	1,307	2	2
Railways (km)	2,726	29	18	259	64	18	16	0	0	<1	<1	<1	<1	121	80	<1	<1
BART facilities	47	1	1	13	1	0	0	0	0	0	0	0	0	11	5	0	0
Highway bridges	3,520	162	67	349	108	85	26	0	0	0	0	0	0	357	141	3	3
Ports	696	1	1	7	5	1	0	0	0	0	0	0	0	0	0	0	0
Water supply and wastewater																	
Transmission conveyance systems (km)	879	21	10	41	5	1	<1	0	0	<1	<1	<1	<1	6	2	0	0
Dams	137	7	6	1	0	2	1	0	0	0	0	0	0	0	0	0	0
Drinking water sources	3,648	6	5	173	31	0	0	0	0	0	0	0	0	33	9	0	0
Drinking water treatment plants	1,857	0	0	19	6	5	0	0	0	0	0	0	0	8	5	0	0
Wastewater treatment plants	92	0	0	8	2	0	0	0	0	0	0	0	0	1	1	0	0
Oil and gas																	
Pipelines, natural gas (km)	7,674	50	34	564	112	24	21	0	0	<1	<1	<1	<1	115	92	<1	<1
Pipelines, petroleum (km)	2,336	29	20	216	64	17	14	0	0	<1	<1	<1	<1	27	17	<1	<1
Natural gas compressor stations	34	0	0	4	2	1	1	0	0	0	0	0	0	0	0	0	0

Table 9.—Continued

Lifeline	Study area total	Ground shaking + landslide + liquefaction		Ground shaking + liquefaction + fire		Ground shaking + landslide + fire		Ground shaking + surface slip[1] + liquefaction		Ground shaking + surface slip[1] + landslide		Ground shaking + surface slip[1] + fire		Four hazards		Five hazards	
		Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high
Oil and gas—Continued																	
Natural gas processing plants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas receipt and delivery points	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas storage facilities	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
POL terminals, storage facilities, and tank farms	36	0	0	8	5	0	0	0	0	0	0	0	0	0	0	0	0
Oil refineries	5	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Electric power																	
Transmission lines (km)	13,413	123	64	443	162	17	10	0	0	<1	<1	<1	<1	63	34	<1	<1
Electric power generation plants	258	1	1	36	11	2	1	0	0	0	0	0	0	3	1	0	0
Energy distribution control facilities	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Substations	1,007	4	2	97	33	7	4	0	0	0	0	0	0	11	6	0	0
Telecommunications																	
Fiber routes, long-haul (km)	6,049	123	76	765	255	255	87	0	0	1	1	<1	<1	618	403	1	1
Fiber routes, interoffice (km)	46,793	676	482	6,368	1,540	321	240	0	0	1	1	1	1	1,536	1,077	2	2
Cellular sites	8,311	93	59	1,670	470	52	35	0	0	0	0	0	0	384	284	2	2
Fiber-lit buildings, data centers	428	0	0	286	47	0	0	0	0	0	0	0	0	1	1	0	0
Fiber-lit buildings, central offices	673	1	1	136	9	5	2	0	0	0	0	0	0	33	15	0	0
Fiber-lit buildings, point of presence	40,728	344	266	12,974	3,282	387	198	0	0	0	0	3	3	2,135	1,370	0	0
Wireless switch offices	53	0	0	11	0	0	0	0	0	0	0	0	0	1	1	0	0

Table 9.—Continued

Lifeline	Study area total	Ground shaking + landslide + liquefaction		Ground shaking + liquefaction + fire		Ground shaking + landslide + fire		Ground shaking + surface slip[1] + liquefaction		Ground shaking + surface slip[1] + landslide		Ground shaking + surface slip[1] + fire		Four hazards		Five hazards	
		Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high	Total	1+ high
Telecommunications—Continued																	
Internet exchange points	11	0	0	8	1	0	0	0	0	0	0	0	0	0	0	0	0
Microwave towers	3,807	27	19	799	235	20	11	0	0	0	0	0	0	103	67	0	0
AM radio antennas	78	2	2	9	4	0	0	0	0	0	0	0	0	0	0	0	0
FM radio antennas	326	0	0	4	0	1	1	0	0	0	0	0	0	2	1	0	0
NTSC television transmitters	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Digital television transmitters	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[1]Surface slip includes parts of the Hayward Fault that have measurable coseismic slip as well as areas without measurable coseismic slip (which may experience afterslip).

Multi-hazard Intensity Classification

The single hazard layers are the foundations of the multi-hazard layer. The classifications for the multi-hazard layer range from low to very high and are defined in table 10. For example, at a location, low multi-hazard intensity indicates that all individual hazards are either classified as low intensity or no hazard, whereas a multi-hazard intensity of very high- indicates that at least two of the hazards are classified as high-intensity. The resulting multi-hazard layer provides the basis for a multi-hazard lifeline infrastructure collocation analysis.

The multi-hazard intensity map was created using GIS tools. We combined all of the individual hazard intensity vector polygon datasets iteratively in Esri ArcGIS version 10.5 into a single dataset that contains a hazard intensity class for each hazard. Combining the individual hazard polygon datasets into one allowed us to identify which hazards at each intensity are present at each location across the study area. The criteria in table 10 are used to assign the final multi-hazard intensity (for example, two or more individual high-intensity hazards present in a polygon is classified as very high multi-hazard intensity). Figure 9 illustrates the hazard combination process, showing five individual hazards schematically overlayed and combined into one multiple hazard dataset.

Table 10. Multi-hazard classifications used in this study for hazards resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Classification	Description
Low	All hazards low or nonexistent
Moderate	One hazard moderate, all others low or nonexistent
Moderate-high	One hazard high, all others low or nonexistent, or Two or more hazards moderate, all others low or nonexistent
High	One hazard high, at least one hazard moderate
Very high	Two or more hazards high

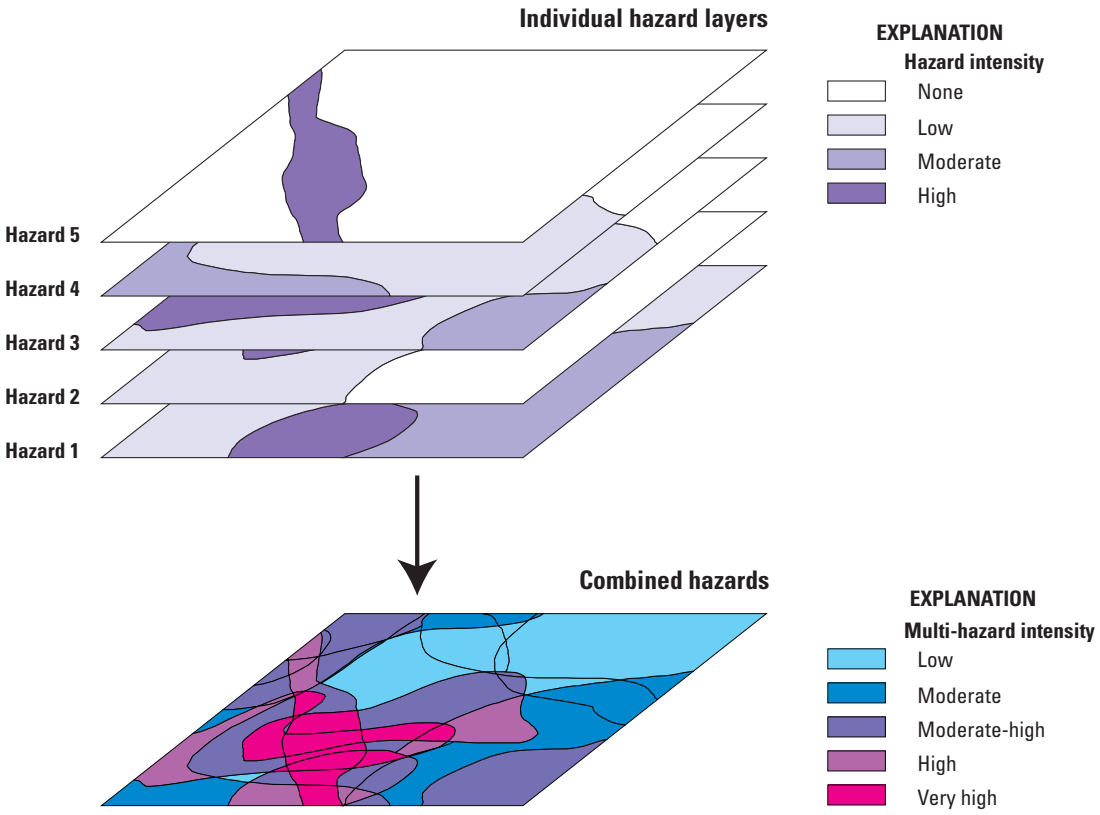


Figure 9. Schematic illustration showing how overlapping hazards are merged into one multiple hazard output. All individual hazards are combined into one dataset; the number and intensity of all overlapping hazards in a specific location are assessed in order to assign final multi-hazard values for each part of each overlapping polygon. For example, a polygon where two hazards are classified moderate and one hazard is classified high is assigned a multi-hazard value of high (see table 10).

Results for Individual Lifeline Infrastructure Exposure to Multi-hazard Intensities

Table 11 shows the exposure of individual lifelines to the reclassified multi-hazard dataset (shown in fig. 10). One can work back from the multi-hazard intensity to find the hazard combinations. Dams have the highest percentage in very high multi-hazard exposure areas (5 percent; 7 dams). We know (from the "Individual Lifeline Exposure to Individual Hazards" section) that dams are subjected to high shaking intensity and high landslide and liquefaction probabilities and (or) fault rupture. POL terminals, storage facilities, and tank farms have the highest percentage (31 percent) exposed to high multi-hazard intensity—all occur in areas with high liquefaction intensity and moderate shaking intensity. One oil refinery (20 percent of these facilities) is exposed to high multi-hazard intensity owing to high liquefaction intensity and moderate shaking intensity. AM radio antennas have 14 percent (11 antennas) exposure to high multi-hazard intensity, owing to high liquefaction probability and moderate shaking. Data centers have the highest percentage of exposure to moderate-high multi-hazard intensity, with 47 percent (202 facilities) in areas with either high or moderate shaking intensity and moderate liquefaction intensity (rarely accompanied by moderate fire intensity). Internet exchange points follow, with 45 percent (4 facilities) exposed to moderate-high multi-hazard intensity; the contributing moderate- and high-intensity hazards are shaking and liquefaction. Point-of-presence fiber-lit buildings are also commonly located in areas of moderate-high exposure—nearly 12,000 buildings (29 percent) fall in this category owing to the same moderate and high-intensity hazards affecting data centers. Additional detail from this multi-hazard analysis, including exposure for specific subcategories of these lifeline infrastructure types, can be found in Jones (2019).

Lifeline exposure patterns across multi-hazard classes emerge. Generally, lifelines have more exposure to moderate multi-hazard exposure than low multi-hazard exposure (for example, water supply transmission conveyance systems and electric substations). Only a few systems have the majority of their multi-hazard exposure in low intensity areas (for example, roadways and transmission lines). Data centers and BART facilities are unique in that the majority of these facilities are exposed to moderate-high multi-hazard intensity. All lifelines have no more than one third of their assets exposed to high or very high multi-hazard intensity classes.

Collocated Lifeline Infrastructure

Whereas the physical proximity and collocation of lifeline infrastructure can provide for enhanced efficiencies, during an earthquake event collocation of infrastructure increases the potential for one to damage another, cascading failures, and complex interactions during restoration (Applied Technology Council, 2016). For example, transportation infrastructure can serve as corridors for buried infrastructure (such as pipes and conduits for water, wastewater, telecommunications, power, and natural gas) (Applied Technology Council, 2016). An earthquake could, for example, damage a bridge and as a result cut off any or all infrastructure routed along it.

This section describes the GIS method to identify and map the density of collocated infrastructure. The numbers of different types of collocated infrastructure are mapped against the multi-hazard layer. Maps show collocated infrastructure for (1) all infrastructure of different types, (2) transmission infrastructure, and (3) potentially critical infrastructure (more or less critical to society). The criticality of infrastructure to society is explained in more detail in this section.

Table 11. Single-lifeline exposure to multi-hazard intensity distribution for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Units are in number of facilities, except where noted to be in kilometers. Owing to rounding, the sum of individual multi-hazard intensity exposure values may not add up to the study area total. km, kilometers; BART, Bay Area Rapid Transit; POL, petroleum, oil, and lubricants; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Lifeline	Study area total	Multi-hazard intensity classification				
		Low	Moderate	Moderate-high	High	Very high
Transportation						
Roadways, highway (km)	4,624	1,883	1,775	572	342	51
Roadways, secondary (km)	16,353	7,394	5,973	1,948	877	162
Roadways, surface (km)	69,899	29,941	27,600	7,791	3,829	739
Railways (km)	2,726	859	1,323	325	178	42
BART facilities	47	7	14	19	5	2
Highway bridges	3,520	1,272	1,360	553	272	63
Ports	696	88	527	34	47	0

Table 11.—Continued

Lifeline	Study area total	Multi-hazard intensity classification				
		Low	Moderate	Moderate-high	High	Very high
Water supply and wastewater						
Transmission conveyance systems (km)	879	295	412	122	40	11
Dams	137	73	39	13	5	7
Drinking water sources	3,648	2,072	1,354	179	39	4
Drinking water treatment plants	1,857	1,173	593	59	26	6
Wastewater treatment plants	92	31	35	18	8	0
Oil and gas						
Pipelines, natural gas (km)	7,674	3,147	3,483	745	247	51
Pipelines, petroleum (km)	2,336	550	1,217	382	158	29
Natural gas compressor stations	34	7	17	6	3	1
Natural gas processing plants	0	0	0	0	0	0
Natural gas receipt and delivery points	2	0	2	0	0	0
Natural gas storage facilities	6	2	4	0	0	0
POL terminals, storage facilities, tank farms	36	2	18	4	11	1
Oil refineries	5	0	3	1	1	0
Electric power						
Transmission lines (km)	13,413	6,309	5,568	1,092	363	81
Electric power generation plants	258	92	108	36	19	3
Energy distribution control facilities	1	0	1	0	0	0
Substations	1,007	391	446	111	49	10
Telecommunications						
Fiber routes, long- haul (km)	6,049	2,008	2,254	902	657	230
Fiber routes, interoffice (km)	46,793	12,245	22,029	7,924	3,603	992
Cellular sites	8,311	2,620	3,126	1,681	729	155
Fiber-lit buildings, data centers	428	16	180	202	30	0
Fiber-lit buildings, central offices	673	195	300	148	23	7
Fiber-lit buildings, point of presence	40,728	8,464	14,947	11,879	4,809	629
Wireless switch offices	53	9	32	11	1	0
Internet exchange points	11	0	6	5	0	0
Microwave towers	3,807	1,254	1,506	661	338	48
AM radio antennas	78	26	35	4	11	2
FM radio antennas	326	218	90	15	1	2
NTSC television transmitters	37	31	6	0	0	0
Digital television transmitters	51	20	31	0	0	0

Method for Identifying Collocated Infrastructure

GIS was used to determine areas of intersecting infrastructure based on the lifeline data in table 7. To identify collocation, we began by creating polygons using a 5 m buffer applied to point and line infrastructure as a standardized distance to account for varying sizes of facilities and conveyances. Using ArcGIS v. 10.5, these lifeline polygons were combined into a single feature of multiple polygons using the merge and feature-to-polygon tools. By creating centroid points inside each polygon and running a spatial join with the lifeline polygons, we were able to determine the number of intersecting lifeline features, as well as which types of infrastructure were collocated. The resulting

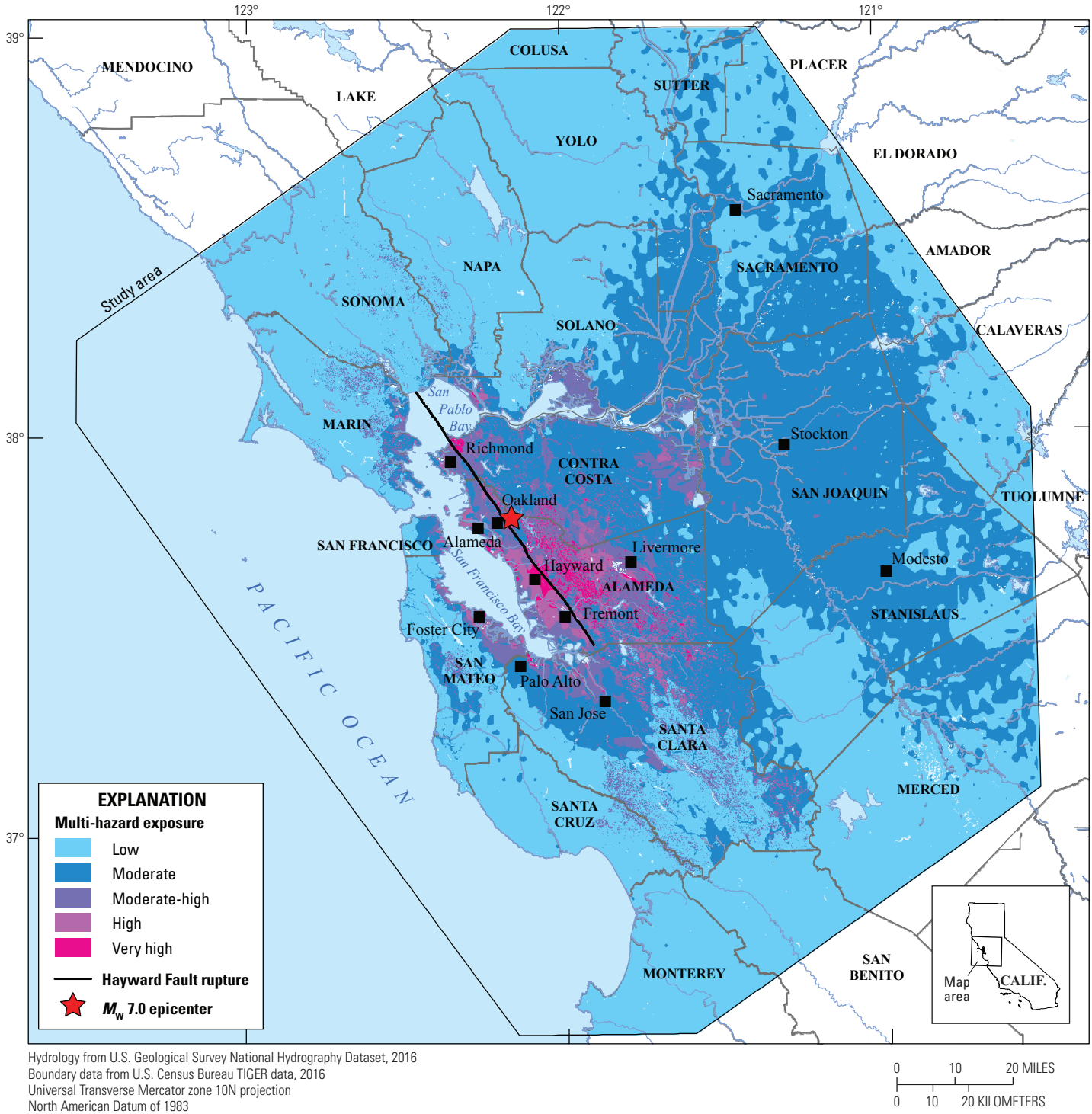


Figure 10. Map of the San Francisco Bay region, California, showing the composite multi-hazard exposure as a result of HayWired scenario mainshock hazards. For classifications of the multi-hazard layer, see table 10. M_w, moment magnitude.

point dataset required the removal of single points with no intersections, as well as further reduction of points where duplicate collocations were indicated. Figure 11 illustrates the collocation identification process: figure 11*A* shows the 5-m buffers for the lifelines, figure 11*B* presents the merged buffer dataset and the original collocation points created from the merged buffer dataset, and figure 11*C* includes the final collocation points (two lifelines or more at the location) and the original lifeline datasets.

Where applicable, multiple intersections along the same infrastructure assets were removed. This was most common for collocations involving surface streets and fiber routes running parallel and adjacent to each other owing to the larger lengths of these infrastructures. Surface streets also represent other distribution infrastructure because many household-level access systems run along or underneath many streets in urban areas. In some cases, multiple fiber routes serve one location (such as a large building). These and similar situations were removed from the analysis as much as possible to identify unique collocations among different infrastructure asset types. This also means that intersections within the same infrastructure network (such as surface street intersections) were not counted. Where more than one type of infrastructure intersected, a collocation point was identified. In the study region, we found more than 208,000 collocation points. The majority of these collocations (more than 132,000) contain two types of infrastructure, nearly 66,000 points had three types, and approximately 9,800 points had four to seven types of collocated infrastructure. In the next section, we show the collocation results for all infrastructure, transmission infrastructure, and potentially societally critical infrastructure with respect to the multi-hazard layer to highlight collocated infrastructure in hazardous places for the HayWired earthquake scenario.

Density of Collocated Infrastructure

To expand the view to concentrations of collocated infrastructure, we set up a 500 square meter (m^2) fishnet grid over the study area using GIS. Each individual point of collocation between two or more lifeline infrastructure assets was aggregated within each grid square. The resulting grid of collocation point counts serves as a density map of collocated infrastructure. The grid resolution is coarser than the hazard mapping, but it is used to find contiguous areas with dense

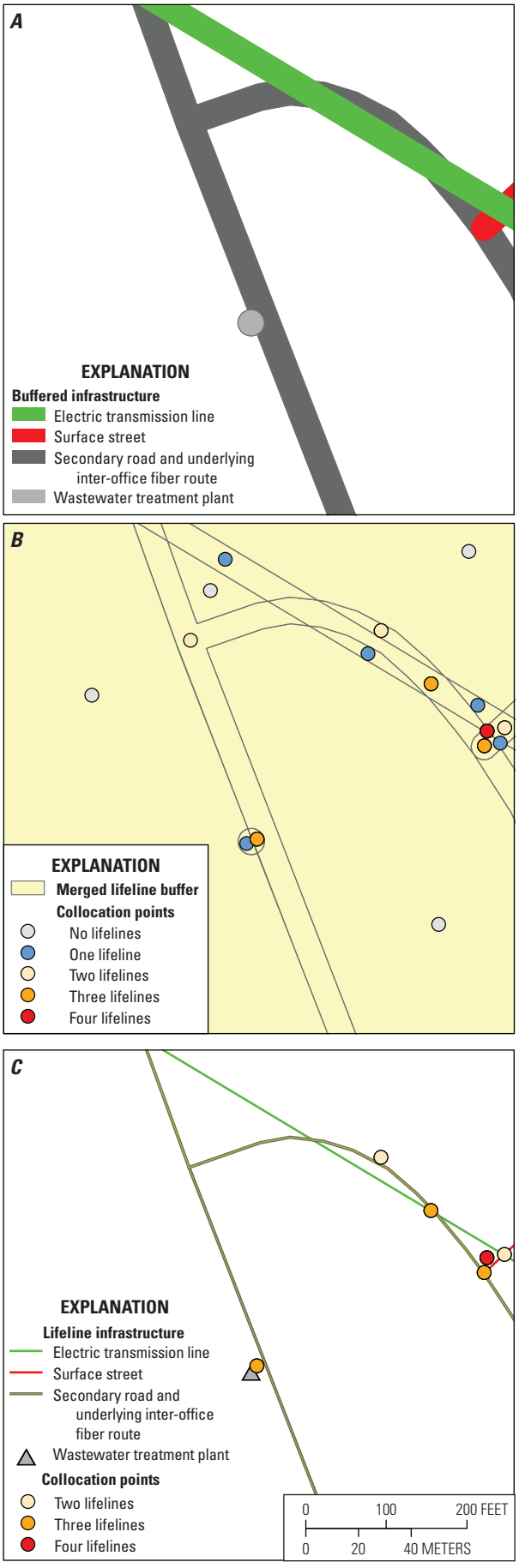


Figure 11. Simplified maps showing the steps of the process used to identify collocated lifeline infrastructure. *A*, Buffers of 5 meter width overlaid on top of each lifeline infrastructure system. *B*, Merged lifeline buffers and resulting polygon centroids used to determine final collocations. Note that some collocation points have been moved from their respective polygon centroids to appear within the bounds of this figure. *C*, Final collocation points (spatially joined to initial lifeline infrastructure buffers) and original infrastructure data.

collocation of infrastructure that would require intense coordination during restoration and recovery.

Figure 12*A* maps the density of collocated infrastructure as the number of points in 500 m² areas: orange represents 26–50 points of collocated infrastructure and red represents greater than 50 points. Predictably, the hot spots are in the larger cities of San Francisco, Sacramento, and Oakland, as well as scattered throughout the south bay in Santa Clara and

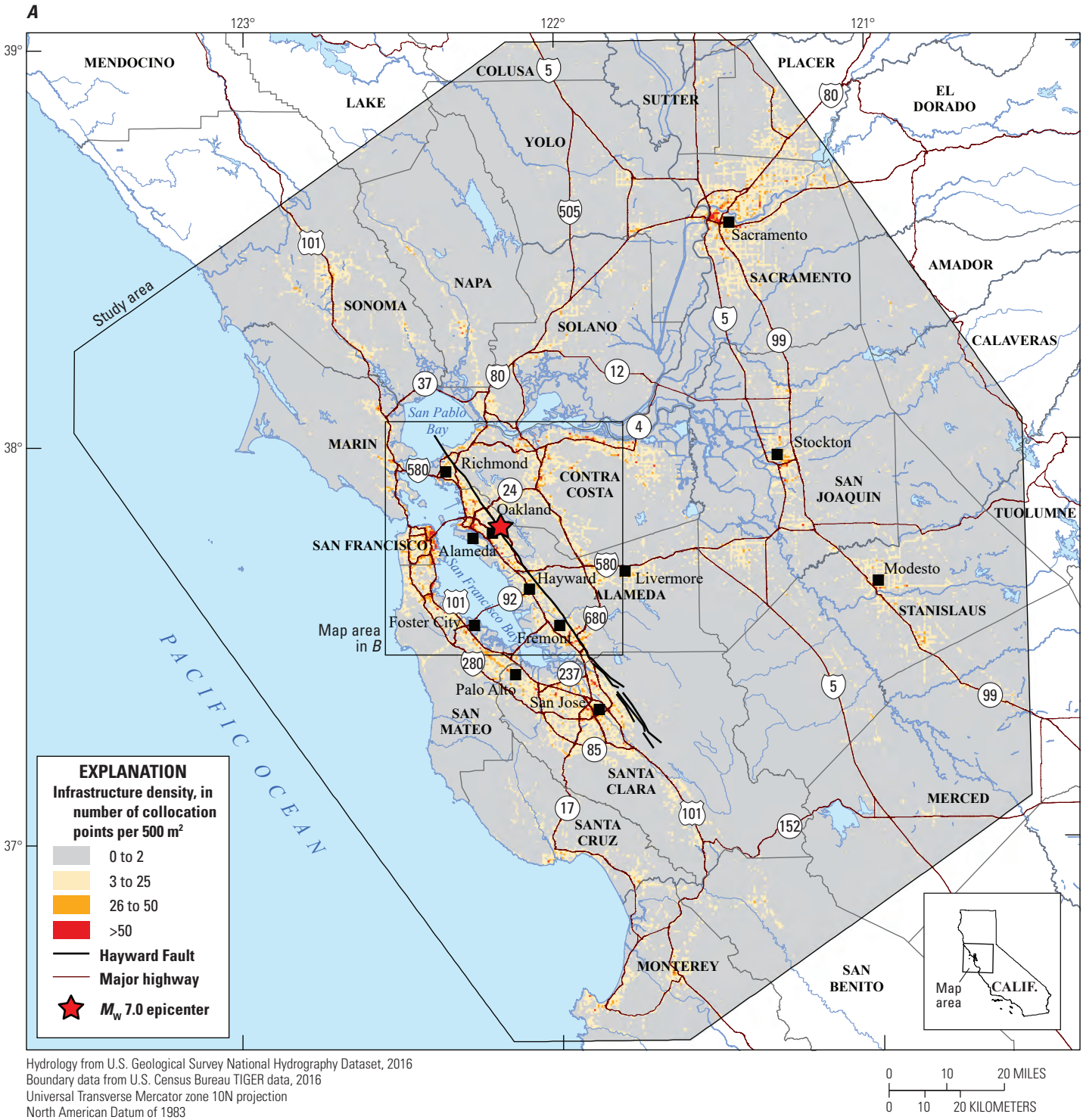


Figure 12 (pages 144–145). Maps of the San Francisco Bay region, California, showing a density assessment of collocated infrastructure per 500 square meters (m²). Red areas highlight exposure exceeding 50 unique collocation points and orange areas show 26–50 unique collocation points. This map is independent of the HayWired earthquake scenario and shows only the density of collocated infrastructure points. *A*, Regional view of the density of unique collocated infrastructure locations throughout the study region. *B*, Zoomed-in view of the density of unique collocated infrastructure locations around the Hayward Fault. M_w, moment magnitude.

San Mateo Counties. They also run along major highway corridors, such as U.S. Route 101 between San Jose and San Francisco and Interstate 580 in Alameda County between Hayward and Livermore. When we zoom in (fig. 12*B*), we see spots of dense infrastructure in smaller cities, including San Rafael in Marin County, Walnut Creek in Contra Costa County, and Redwood City in San Mateo County. These hubs of infrastructure in smaller cities coincide with moderate or moderate-high multi-hazard intensity for the HayWired scenario mainshock.

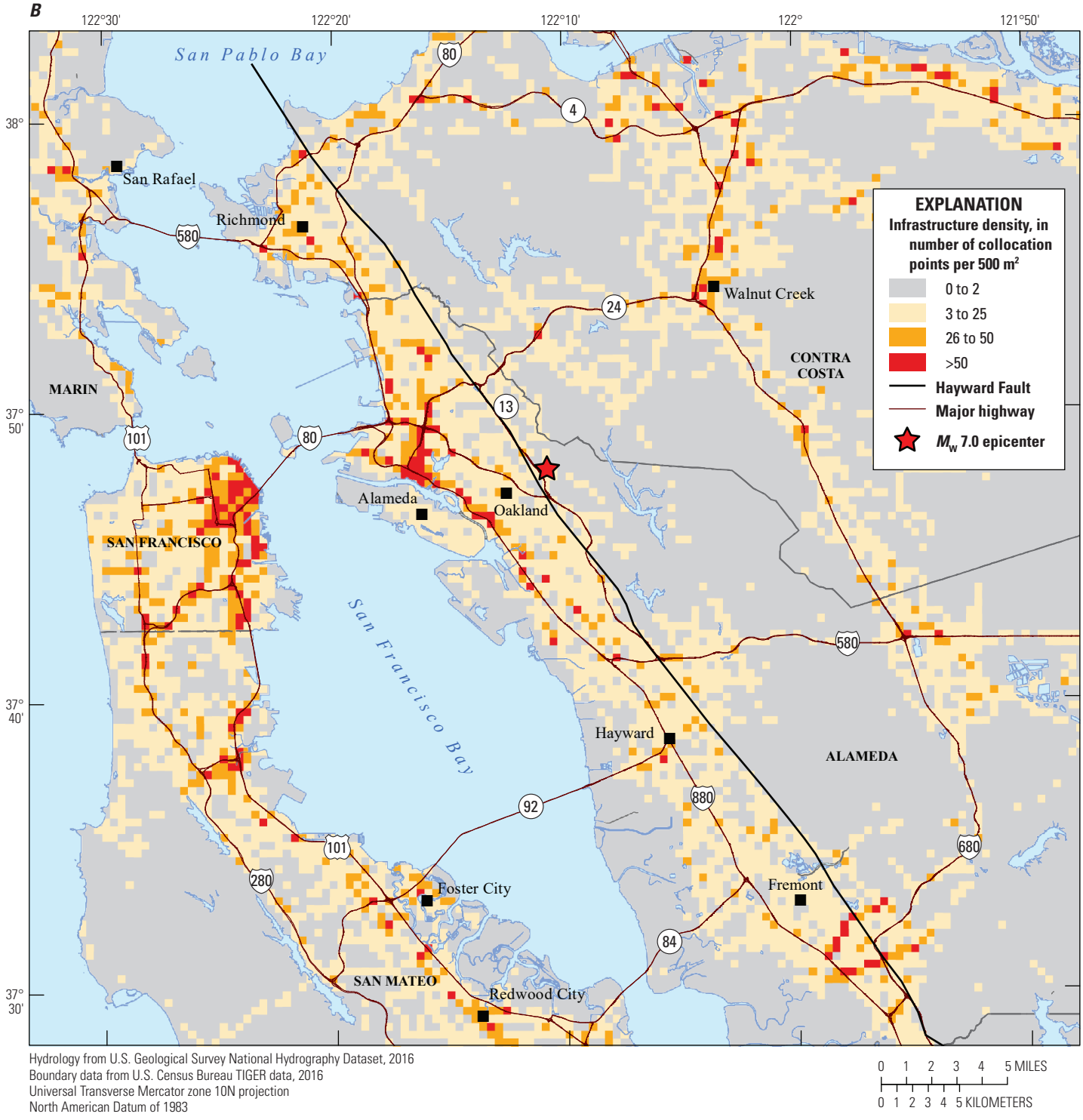


Figure 12 (pages 144–145).—Continued

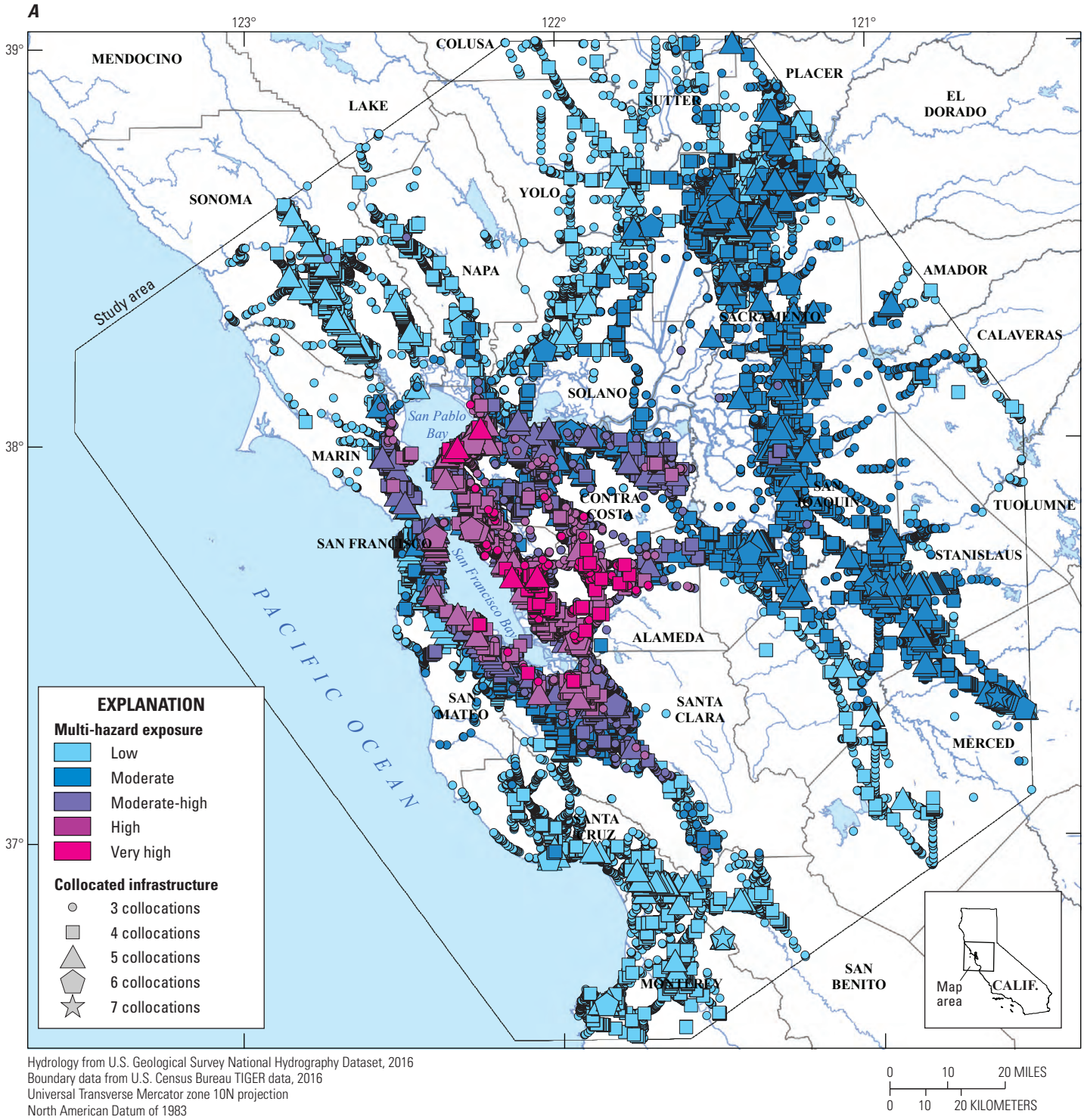
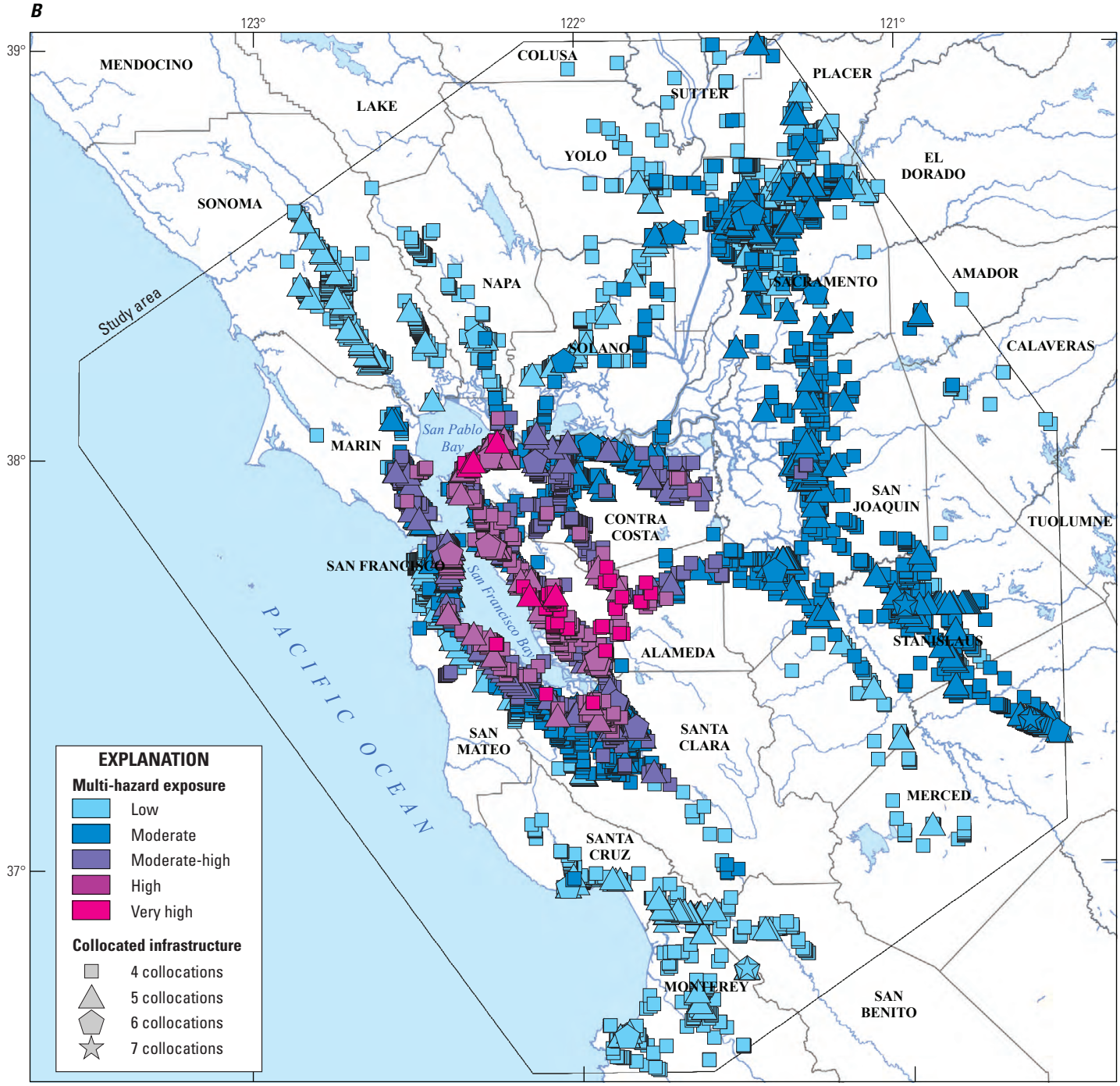


Figure 13 (pages 146–147). Maps of the San Francisco Bay region, California, showing collocated infrastructure points and exposure level to multiple HayWired earthquake scenario mainshock hazards (three or more collocated infrastructure assets only). The symbol shape corresponds to the number of infrastructure assets collocated at each point, ranging from 3 (smallest) to 7 (largest). Colors correspond to level of exposure, ranging from low (cyan) to very high (magenta). *A,* Each unique point with three or more collocated infrastructure assets and corresponding multi-hazard exposure level in the study region. *B,* Each unique point with four or more collocated infrastructure assets and corresponding multi-hazard exposure level in the study region.

Exposure of Collocated Infrastructure to Multiple Hazards

Figure 13 shows infrastructure collocation points and their exposure to multiple hazards in the San Francisco Bay region for the HayWired scenario mainshock. The color indicates the level of exposure to all hazards (cyan is low exposure and magenta indicates very high exposure) and the symbol shape indicates the number of infrastructure assets collocated at each unique point. Because more than half of all collocations are between two lifeline infrastructures, we limit our visualization and discussion to collocations of three or more infrastructure types. This excludes the many collocations where a facility is close to the street (owing to the buffer used). Figure 13*A* displays unique locations where three or more infrastructure types are collocated and figure 13*B* shows only points where four or more collocated infrastructure types occur.

Figure 13 shows that many areas with high numbers of collocated infrastructure systems occur east of the Hayward



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016
Boundary data from U.S. Census Bureau TIGER data, 2016
Universal Transverse Mercator zone 10N projection
North American Datum of 1983

Figure 13 (pages 146–147).—Continued

Fault (concentrated in Contra Costa County, as well as beyond the east bay foothills where multi-hazard exposure is low) and in San Francisco and, thus, have low exposure to multiple hazards caused by the HayWired scenario mainshock. However, collocated infrastructure is exposed to very high multi-hazard intensity along the Hayward Fault rupture and in developed areas of Alameda and western Contra Costa Counties. Collocated infrastructure is also exposed to high multi-hazard intensity in San Francisco, San Mateo, and Santa Clara Counties and along the southeastern edge of the Sacramento-San Joaquin Delta. The majority of these collocations highlight a pattern of conveyances—surface streets, other roadways and railways, pipelines, transmission lines, fiber optic cables, and water supply transmission conveyances.

Underlying this picture of collocated infrastructure in hazardous areas is the unseen collocation of end-user utility distribution systems with surface streets. The exposure of surface streets to multi-hazard intensities is listed in table 12 and as an underlying base dataset for highway bridge damage assessment results in appendix 5. By extracting collocations with surface streets out of the infrastructure collocation analysis (table 12), we found about 115,000 collocation points involving surface streets, about 9,700 of which are in high and very high hazard intensity areas. More than 40 percent of the surface street collocations involve three or four types of infrastructure. The collocation in the high and very high-intensity areas involve other roadways, rails, and (or) fiber optic cables twice as much as pipelines and transmission lines. Additional detail from this analysis, including exposure for specific subcategories of these lifeline infrastructure types, can be found in Jones (2019).

Relative Importance of Lifeline Infrastructure

Within communities, collocation of surface streets and other distribution infrastructure will amount to a large number of repairs that may or may not be coordinated to reduce disruption, but the number overshadows the importance of the infrastructure in two senses: transmission infrastructure and societally critical infrastructure. Identifying transmission infrastructure is straightforward, but the concept of societal criticality of infrastructure is not well established (Theoharidou and others, 2009). We attempt to identify the criticality of infrastructure using attributes in the data. We then map collocated transmission and criticality of infrastructure with respect to the multi-hazard layer.

Classification of Criticality of Lifeline Infrastructure

Theoharidou and others (2009) discuss the criticality of infrastructure and compile various societal impact factors, including economic impact, interdependency with other infrastructure, public confidence, public order, continuity of government, safety, and defense. Impact criteria consider scope, severity, and timing of the factors. Such an assessment is beyond the scope of this analysis and would require in-depth knowledge of infrastructure in the region. At the asset level of infrastructure systems, we identified available attributes in infrastructure data that indicate societal criticality within the transmission systems in terms of potential economic impact inherent in capacity (for example, larger power generation facilities or number of licenses for microwave towers), service area (for example, broadcasting range), and safety (for example, seismic condition of dams or closeness of pipelines to buildings).

Many lifeline infrastructure systems had attributes included, which served as discrete classes with varying levels of societal criticality. For example, the AM and FM radio antenna datasets include a field that defines the station class, which indicates the broadcast reach. By referring to the metadata for the datasets (and filling in missing information from internet searches) we were able to break most of the lifeline data into some set of discrete classes. In the absence of class data for dams, microwave towers, and natural gas and petroleum pipelines, we used other societal impact indicators. Dams are classified into one of five classes, depending on their condition assessment as completed by the California Department of Water Resources Division of Dam Safety (California Department of Water Resources, 2017). Satisfactory and undefined conditions were treated as less societally critical and the remaining classes (unsatisfactory, poor, and fair) were considered more societally critical, owing to their increased likelihood of being damaged by an earthquake. Microwave towers were classified into two categories depending on the number of licensees for the tower; fewer than 10 was considered less societally critical and 10 or more was determined to be more societally critical. For natural gas and petroleum pipelines, we used a variant on the classification provided in Applied Technology Council (2016) to classify pipeline segments. We classified each as class 1, 2, or 3 based on the number of buildings within 220 yards of a 220-yard pipeline segment (class 1 is fewer than 10 buildings, class 2 is between 10 and 45 buildings, and class 3 is more than 45 buildings). We limit our classes to three for pipelines, though a fourth class is also generally used (available GIS data were not sufficient to determine which pipelines were class 4). For this analysis, we generalized the pipeline classes further by assuming that classes 2 and 3 are more societally critical and class 1 is less so. For the lifeline infrastructure systems where discrete capacity data were the only practical attribute for defining criticality, Pareto's principle (also known as the 80-20 rule; refer to Newman [2005] for more information) was used to identify the more societally critical facilities. We ranked each facility's capacity as a proportion of the total capacity in the State from large to small; summing from the largest value down, the facilities whose cumulative proportion added up to the top 80 percent were considered most societally critical and the remainder classified as less so. Some datasets (noted by "N/A" in the "infrastructure class or attribute" column of table 13) did not have an attribute that could help discretize the data, so these were treated as equally important. Table 13 lists the importance assignment for each lifeline.

Table 12. Number of collocations of surface streets with other lifeline infrastructure, organized by exposure to multi-hazard intensity classifications for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Multi-hazard classification	Other transportation		Water supply and wastewater		Oil and gas		Electric power		Telecommunications		Two additional infrastructure assets	Three or more additional infrastructure assets
	Facilities	Roads and rail	Facilities	Transmission conveyances	Facilities	Pipelines	Facilities	Transmission lines	Facilities	Fiber routes		
Low	95	7,987	163	197	0	2,920	1	4,626	454	5,567	14,553	1,952
Moderate	115	9,039	101	457	1	4,075	0	4,676	649	7,431	17,603	2,526
Moderate-high	56	3,730	23	252	1	1,472	0	1,389	330	3,468	8,399	1,234
High	29	1,454	7	64	1	717	0	686	180	1,505	3,145	419
Very high	10	256	2	3	0	163	0	113	30	271	612	64
Total	305	22,466	296	973	3	9,347	1	11,490	1,643	18,242	44,312	6,195

Table 13. Lifeline infrastructure types and assignment of societal criticality by infrastructure class or attribute.

[BART, Bay Area Rapid Transit; N/A, no applicable infrastructure subcategory; Caltrans, California Department of Transportation; POL, petroleum, oil, and lubricants; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Infrastructure type	Infrastructure class or attribute	Criticality		System type	
		More	Less	Transmission	Distribution
	Transportation				
Roadways	Highways	X		X	
	Secondary roads		X	X	
	Surface streets		X		X
Railways	Heavy rail	X		X	
	Light rail		X		X
BART facilities	N/A	X		X	
Highway bridges	N/A	X		X	
Ports	Major ports (named by Caltrans[1])	X		X	
	Other ports (not named by Caltrans[1])		X	X	
	Water supply and wastewater				
Transmission conveyance systems	N/A	X		X	
Dams	Unsatisfactory condition[2]	X		X	
	Poor condition[2]	X		X	
	Fair condition[2]	X		X	
	Satisfactory condition[2]		X	X	
	Unrated condition[2]		X	X	

Table 13.—Continued

Infrastructure type	Infrastructure class or attribute	Criticality		System type	
		More	Less	Transmission	Distribution
	Water supply and wastewater—Continued				
Drinking-water sources	Permanent source	X		X	
	Seasonal source		X	X	
	Emergency source		X	X	
	Other source		X	X	
	Interim source		X	X	
Drinking-water treatment plants	Community water plant	X		X	
	Non-transient noncommunity water plant	X		X	
	Transient noncommunity water plant		X	X	
Wastewater treatment plants	N/A	X		X	
	Oil and gas				
Pipelines (natural gas, petroleum)	Class 3	X		X	
	Class 2	X		X	
	Class 1		X	X	
Natural gas compressor stations	N/A	X		X	
Natural gas processing plants	N/A	X		X	
Natural gas receipt and delivery points	N/A	X		X	
Natural gas storage facilities	Top 80 percent of statewide working capacity	X		X	
	Remaining statewide working capacity		X	X	
POL terminals, storage facilities, tank farms	N/A	X		X	
Oil refineries	Top 80 percent of statewide facility capacity	X		X	
	Remaining statewide facility capacity		X	X	
	Electric power				
Transmission lines	N/A	X		X	
Electric power generation plants	Top 80 percent of statewide operating capacity	X		X	
	Remaining statewide operating capacity		X	X	
Energy distribution control facilities	N/A	X		X	
Substations	N/A	X		X	
	Telecommunications				
Fiber routes	Long-haul	X		X	
	Interoffice		X		X
Cellular sites	Macro cell sites	X		X	

Table 13.—Continued

Infrastructure type	Infrastructure class or attribute	Criticality		System type	
		More	Less	Transmission	Distribution
	Telecommunications—Continued				
	Small cell sites		X		X
Fiber-lit buildings	Data center	X		X	
	Central office	X		X	
	Carrier hotel	X		X	
	Colocation	X		X	
	Point of presence or other		X	X	
Wireless switch offices	N/A	X		X	
Internet exchange points	N/A	X		X	
Microwave towers	10 or more licensees	X		X	
	Fewer than 10 licensees		X	X	
AM radio antennas	Class A	X		X	
	Class B		X	X	
	Class C		X	X	
	Class D		X	X	
FM radio antennas	Class B	X		X	
	Class B1		X	X	
	Class A		X	X	
	Class D		X	X	
	Class L1		X	X	
NTSC television transmitters	CA (analog class A) service class	X		X	
	LD (digital low power[3]) service class		X	X	
	TX (analog auxiliary) service class		X	X	
Digital television transmitters	DT (digital full-power) service class	X		X	
	DC (digital class A) service class		X	X	
	DX (digital auxiliary) service class		X	X	

[1]Ports named by Caltrans include the Ports of Benicia, Oakland, Redwood City, Richmond, San Francisco, Stockton, and West Sacramento.

[2]Dam infrastructure subcategories obtained from California Department of Water Resources (2017) dam condition assessment.

[3]Though LD service class transmitters are primarily digital systems, these transmitters may still transmit analog signals at the time of this analysis (https://www.fcc.gov/consumers/guides/low-power-television-lptv-service). As such, LD transmitters are included in the NTSC system.

Figure 14 shows the different perspectives of infrastructure collocation density (fig. 14*A*), and collocations among all types of infrastructure (transmission and distribution) (fig. 14*B*), transmission infrastructure (fig. 14*C*), and societally critical infrastructure as defined here (fig. 14*D*). The results offer windows into areas for further examination, which we demonstrate in the next section by broadening the consideration of collocation to other types of interactions. Please note that we do not highlight San Francisco or Fremont as examples. In the San Francisco case, there appears to be more potential for system redundancy in the roadways than at the San Francisco International Airport example. In the Fremont case, the area has the same types of collocations as the North Richmond and Hayward examples, so does not offer additional insight.

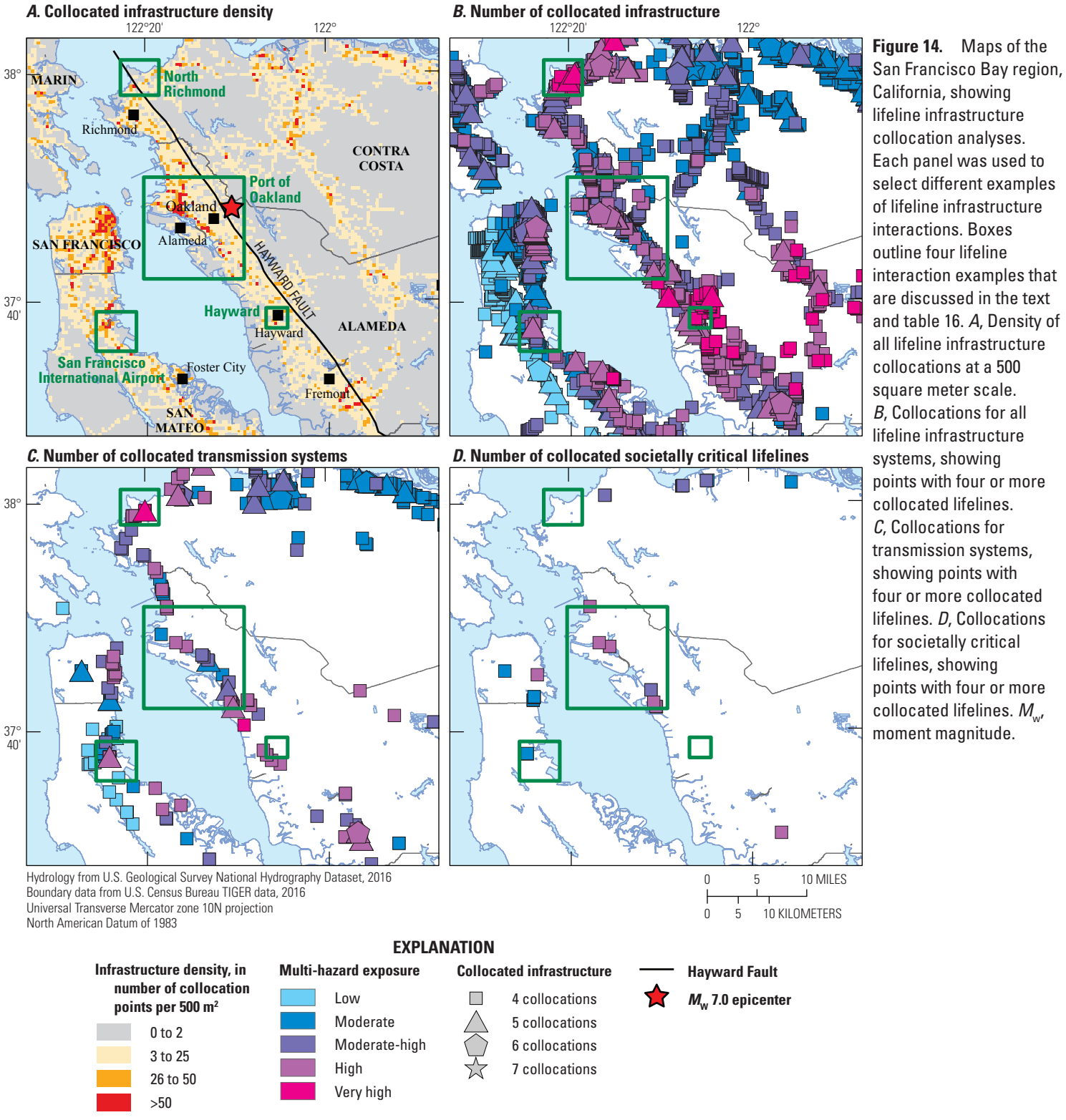


Figure 14. Maps of the San Francisco Bay region, California, showing lifeline infrastructure collocation analyses. Each panel was used to select different examples of lifeline infrastructure interactions. Boxes outline four lifeline interaction examples that are discussed in the text and table 16. *A*, Density of all lifeline infrastructure collocations at a 500 square meter scale. *B*, Collocations for all lifeline infrastructure systems, showing points with four or more collocated lifelines. *C*, Collocations for transmission systems, showing points with four or more collocated lifelines. *D*, Collocations for societally critical lifelines, showing points with four or more collocated lifelines. M_w, moment magnitude.

To get a sense of the nature of collateral damage and (or) coordination involved around collocated lifeline infrastructure in high or very high hazard areas, we calculated the top ten types of collocated infrastructure for the three perspectives (table 14). Interoffice fiber optic cable and surface and secondary roadways are most commonly involved in lifeline collocations in high and very high hazard areas (9,000–10,000 for each infrastructure type, representing 8–9 percent of their total collocations). Narrowing the focus to collocations among transmission infrastructure only in high and very high hazard areas, secondary roadways remain in the top ten (approximately 2,500 collocations), followed by other transportation (highways, bridges, and railways), electric transmission lines, natural gas and petroleum pipelines, and long-haul fiber optic cable. Comparing our societally critical infrastructure collocations with transmission infrastructure collocations, electric substations, water transmission conveyance systems, and macro cellular sites move into the top ten in place of highway bridges and less critical infrastructure (for example, secondary roads). As the importance of the infrastructure increases, the number of times infrastructure (of the same level of importance) is collocated in high and very high hazard areas is reduced from tens of thousands to thousands or hundreds of collocation sites. Societally critical infrastructure collocations with the highest percentage of occurrence in high and very high multi-hazard areas are natural gas and petroleum pipelines (15 and 20 percent, respectively). More broadly, long-haul fiber optic cable and heavy railway collocations also feature commonly in the most hazardous areas, likely reflecting that pipelines and long-haul fiber cables run along heavy railway corridors. Additional detail from these collocation analyses, including exposure for specific subcategories of these lifeline infrastructure types, can be found in Jones (2019).

Table 14. Top ten lifeline infrastructure types collocated in high and very high multi-hazard intensity areas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Collocations range from two to seven collocated lifeline infrastructure types. Top ten items for all lifeline collocations were identified by summing up all occurrences of collocation for each individual lifeline infrastructure type in high or very high multi-hazard intensity areas and selecting the ten infrastructure types with the most occurrences of collocation with other infrastructure. The percentage of high and very high collocations for each lifeline infrastructure type is calculated by dividing the number of high and very high collocations for each infrastructure type by the total number of collocations of the infrastructure type. %, percent; Caltrans, California Department of Transportation]

Lifeline infrastructure type	Number of high or very high hazard collocations	Percentage of high or very high hazard collocations
All lifeline collocations		
Interoffice fiber routes	10,413	9
Surface streets	9,731	8
Secondary roads	9,284	8
Electric transmission lines	2,830	7
Class 1 natural gas pipelines	2,225	8
Highways	2,162	11
Heavy railways	1,745	12
Class 2 or 3 natural gas pipelines	1,456	10
Long-haul fiber routes	1,321	13
Class 1 petroleum pipelines	1,096	12
Transmission collocations		
Secondary roads	2,541	10
Highways	1,354	12
Electric transmission lines	1,186	8
Class 1 natural gas pipelines	1,174	8
Heavy railways	1,026	12
Class 2 or 3 natural gas pipelines	830	11
Long-haul fiber routes	810	12
Class 1 petroleum pipelines	730	12
Class 2 or 3 petroleum pipelines	444	16
Caltrans highway bridges	325	9
Societally critical collocations		
Electric transmission lines	431	9
Highways	420	10
Heavy railways	374	11
Long-haul fiber routes	304	12
Class 2 or 3 natural gas pipelines	214	15
Caltrans highway bridges	165	9
Class 2 or 3 petroleum pipelines	143	20
Electric substations	40	5
Water transmission conveyance systems	38	7
Macro cellular sites	32	7

Lifeline Infrastructure Interactions

Up to this point, we have illustrated the complexity of multiple lifeline infrastructure systems and collocated infrastructure exposed to multiple HayWired scenario mainshock hazards. The challenges are further exacerbated by other interdependencies and interactions within and between lifeline infrastructure systems. Functional interactions occur when performance failures of one type of lifeline infrastructure may disrupt the function of another that depends on it or performs a similar function. For example, electric power and telecommunication infrastructure are prime examples of interconnected infrastructure (Applied Technology Council, 2016): telecommunications depend on a power source, fiber optic cables are strung on power poles, and electric power depends on communications to monitor systems. Also, a performance failure of one infrastructure system may transfer demand to a substitutable infrastructure (for example, roads could substitute for railways or vice versa and more fuel is needed during electric power outages to run generators).

Business-as-usual operations do not force coordination between different lifeline infrastructure agencies in ways that are needed after an earthquake or other disaster. Before an event, lifeline infrastructure emergency planners make assumptions about the function of other lifeline infrastructure systems for their respective response, recovery, and mitigation decisions (for example, Bay Area Urban Areas Security Initiative, 2013; The Lifelines Council, 2014; Applied Technology Council, 2016). After an event, interactions and dependencies require coordination among lifeline infrastructure systems to prioritize the allocation of scarce resources and perform restorations and repairs. For example, after the 2010–11 Christchurch earthquakes, the Stronger Christchurch Infrastructure Repair Team (SCIRT) developed a software tool called the Forward Works Viewer to share restoration information and data among horizontal infrastructure (for example, roads and pipelines) organizations. By this means, SCIRT could identify opportunities for efficient restoration and issues, and notify others (for example, traffic circulation) about disruptions at particular locations (Stronger Christchurch Infrastructure Rebuild Team, 2017). In the San Francisco Bay region, workshops and exercises are currently being used to model a disaster environment and practice before disasters occur, including exercises with the California Earthquake Clearinghouse (http://californiaeqclearinghouse.org/). Tools to securely share information are also under development (for example, Bay Area Center for Regional Disaster Resiliency, n.d.).

A workshop after the M_w 6.0 South Napa earthquake in 2014 concluded that current communication constraints limit understanding beyond first-level interactions and there is a lack of available tools and risk-analysis methods that can aid decision making and planning around interdependent restoration challenges (Scalingi, 2015). Similarly, the Applied Technology Council (2016) highlights data and methodological challenges with visualization of interdependencies. These conclusions provided the impetus to further examine interaction among lifeline infrastructure with respect to the multiple HayWired scenario hazards.

Our approach was to interactively zoom in on areas characterized by collocated and dense infrastructure in high or very high multi-hazard intensity areas and interpret them for possible lifeline infrastructure system interactions. We performed the analyses within The Lifelines Council (2014) framework for different types of interdependencies and interactions. We also expanded on the interaction table in that report, using what we learned from other regional studies including Germeraad and others (2014), HayWired workshops, and other HayWired scenario analyses.

Interaction and Interdependencies Among Lifeline Infrastructure Systems

The San Francisco Bay region is noted for forward-thinking resilience planning and earthquake preparation and mitigation activities, which includes foundational thinking about interactions and interdependencies between lifeline infrastructure systems (for example, The Lifelines Council, 2014). We adopt the five categories of lifeline infrastructure interdependencies identified in The Lifelines Council (2014). What follows are definitions of the categories and comparisons with examples offered in Germeraad and others (2014), during the Bay Area Center for Regional Disaster Resiliency (BACRDR) August 30, 2017, workshop on power and water lifelines (which used the HayWired scenario), conversations with transportation agencies (see appendixes 4 and 5), and HayWired scenario water supply and telecommunications analyses (Porter, 2018; Wein, Witkowski, and others, this volume).

1. *General interaction between components of the same system*.—All systems would have general interaction issues but some are more crucial issues for the system's potential disruption and restoration (The Lifelines Council, 2014). For example:

    - Among water systems, owing to the estimated 8,000 water pipeline breaks or leaks in East Bay Municipal Utility District (EBMUD) and San Jose Water Company (SJWC) utilities in the HayWired scenario (Porter, 2018), there may not be enough materials for repairs. Water utilities are evaluating inventories and would work with the California Office of Emergency Services (Cal OES) to prioritize repairs (BACRDR power and water lifelines workshop, oral commun., 2017).

    - The telecommunication industry expressed less concern about the availability of materials and more concern for shortfalls of trained labor to respond, restore, and repair lifelines after a large San

Francisco Bay region earthquake (Wein, Witkowski, and others, this volume).

- In some instances, refineries rely on one kind of fuel to prepare others. For example, natural gas may be needed to enhance still gas fuel (gas used for power in the refinery) production (Schremp, 2015).

2. *Functional interaction is disaster propagation and cascading interactions from one system to another owing to interdependence* (The Lifelines Council, 2014).—For example:

   - The operation of roads in daily operations requires electric power for traffic signals. The short-term and limited solution of traffic direction by local officials can help to mitigate this type of failure (Jones and others, 2008). Similarly, electric power is needed for lighting and environmental monitoring systems in some tunnels (for example, the Caldecott Tunnel in Oakland) (Diablo Magazine, 2013).

   - BART needs running water for fire safety in tunnels (appendix 4).

   - EBMUD depends on the Pacific Gas and Electric Company (PG&E) for power to pump water up into their gravity-fed systems. Communications between PG&E and EBMUD are ongoing to develop methods for understanding interdependencies and impact assessments between them (BACRDR power and water lifelines workshop, oral commun., 2017).

   - Electric power plants in Santa Clara use recycled water from wastewater treatment plants (that depend on power to operate) (J. Wollbrinck, San Jose Water Company, oral commun., 2018).

   - Water distribution pipeline leaks and breaks and power outages could impact otherwise functional hospitals (J. Wollbrinck, San Jose Water Company, oral commun., 2017).

   - Water leaks near San Jose International Airport could affect the airport, even though it is expected to be the most operational of the three regional international airports immediately after the HayWired scenario (J. Wollbrinck, San Jose Water Company, oral commun., 2017).

   - Telecommunications infrastructure depends strongly on electric power; dependence on water for cooling remains to be assessed for the region (Wein, Witkowski, and others, this volume).

   - Electric power is needed to pump fuel to the airplanes at San Francisco International Airport (BACRDR power and water lifelines workshop, oral commun., 2017).

   - Whereas most refineries in California have cogeneration capability, other outside services are essential to sustain operations (for example, water is needed in the refineries for generating steam used during the oil-refining process) (Schremp, 2015).

3. *Geographic proximity (or collocation) interaction represents physical disaster propagation among lifeline systems* (The Lifelines Council, 2014).—For example:

   - Damage to highway bridges can disrupt the use of underlying surface streets (appendix 5).

   - Damage to highway bridges can cause collateral damage to collocated infrastructure, such as petroleum and natural gas pipelines and fiber optic cables (BACRDR power and water lifelines workshop, oral commun., 2017; Wein, Witkowski, and others, this volume).

   - Water and (or) wastewater pipeline breaks can scour bridge abutments (appendix 5).

   - Water and (or) wastewater pipeline breaks can cause sink holes that are capable of damaging collocated fuel pipelines and fiber optic cables (S. Terentieff, EBMUD, oral commun., 2017).

   - Water and (or) wastewater pipeline breaks can cause collateral damage to collocated buried distribution infrastructure along surface streets (for example, pipelines for natural gas, copper wire, fiber optic cable, and electric power distribution lines) (The Lifelines Council, 2014).

4. *Restoration interaction refers to various hindrances in the restoration and recovery stages*.—For example:

   - For the HayWired analysis of water supply restoration, Porter (2018) factored in dependencies on other infrastructure, such as electric power and resources, including labor, materials, and fuel.

   - EBMUD learned the importance of sharing infrastructure information when the repair of a broken water line took a month because a fuel pipeline had to be repaired first (S. Terentieff, EBMUD, oral commun., 2017).

   - If water intrudes into the Transbay Tube, BART needs electric power to pump water out (appendix 4).

   - Damages and repair of surface streets and (or) collocated distribution infrastructure disrupts traffic circulation (Stronger Christchurch Infrastructure Rebuild Team, 2017; The Lifelines Council, 2014).

   - The newest bore of the Caldecott Tunnel is designated a “lifeline” structure and as such is designed to reopen to emergency responders within 72 hours of an event

such as a major earthquake. Until the tunnel is reopened, however, alternate routes between Oakland and Orinda (in Contra Costa County) must be used (California Department of Transportation, 2013).

- Water supply (quality and quantity) and other resources are needed to accommodate emergency operations centers, responders, and restoration labor for all infrastructure (J. Wollbrinck, San Jose Water Company, oral commun., 2017; Wein, Witkowski, and others, this volume).
- Fire following an earthquake could warp railroad tracks, and flammable materials (for example, trees) could fall into roadways, hindering fuel transportation efforts (Radke and others, 2018).

5. *Substitute interaction occurs when one system's disruption influences dependencies on alternative systems*.—For example:

   - Inoperable BART transit rail stations and lines would cause commuting traffic to be rerouted onto highway and other roadway infrastructure, increasing congestion on roadways (M. Salmon, BART, oral commun., 2016).
   - BART transit disruptions could be counteracted by increasing usage of telecommunications systems, but these systems may also be impacted (Wein, Witkowski, and others, this volume).
   - Within the telecommunication system, traditional landline, voice over Internet protocol (VoIP), and cellular voice are substitute technologies for voice calls. Other means of communication (for example, texting or social media) substitute for voice calls. Similar to transportation systems, loss of one system increases the potential to overload another (Wein, Witkowski, and others, this volume).
   - Fuels transportation, which generally relies on pipelines to move products, could be moved using alternate methods (road, rail, or marine systems) in cases where pipelines are damaged in areas with high demand for fuels (Schremp, 2015). This assumes that alternate methods are themselves undamaged (or repaired) and repurposed quickly.

Cascading failures are a series of lifeline infrastructure interactions. For example:

- Power outages can cause communication outages that reduce the ability to report fires; transportation disruptions can affect fire truck access to fires; and water supply outages can reduce firefighting capability and result in fires following the earthquake to spread into conflagrations (Scawthorn, 2018).
- Electric power outages affect the pumping of water; water is needed by refineries at a time when more fuel is needed owing to power outages (BACRDR power and water lifelines workshop, oral commun., 2017).
- Dam and levee failures from earthquake hazards pose a flood threat to populated areas and can cause further damage to infrastructure (BACRDR power and water lifelines workshop, oral commun., 2017).

Table 15 adapts The Lifelines Council's (2014) interaction table that is constructed to show lifeline interactions within the five categories of general, functional, collocation/geographic, substitution, and restoration interactions. With respect to functional dependencies, the table shows upstream and downstream dependencies (National Protection and Programs Directorate, 2017) by reading the table across by row and down by column, respectively. Our additions to The Lifelines Council (2014) interdependency table represent the above listed examples. These additional interactions pertain mostly to water and telecommunications infrastructure systems.

Illustration of Interactions Among Lifeline Infrastructure Systems in the HayWired Scenario

Our collocation analyses processed hundreds of thousands of infrastructure assets in a 51,000 km^2 geographic area exposed to multiple hazards in the HayWired scenario. We zoomed in on some areas with collocated infrastructure in very high multi-hazard areas and (or) high single hazard areas where infrastructure is most dense. We interactively examined the layers of lifeline infrastructure and hazard data in GIS. We interpreted these areas for possible lifeline interactions within the framework of table 15. Table 16 summarizes four example areas that illustrate lifeline interactions and describes how we found them, what HayWired hazards are present, what infrastructure is present, and what potential interactions are indicated.

Without an understanding of what the service areas and system redundancies in the San Francisco Bay region are, we cannot clearly see potential functional dependencies that extend beyond the immediate environs. In table 16, we note some potential functional interactions where lifelines are in close proximity, such as electric power for fiber-lit buildings in North Richmond and electric power for wastewater in the Port of Oakland area. These functionally dependent facilities and their service providers are affected by the same combination and intensity of hazards.

When describing collocation, we differentiate between parallel (for example, shared right of ways), intersection (for example, one infrastructure crossing another), and hub (where there is a convergence of multiple intersections or infrastructure intersecting with parallel infrastructure). We find

Table 15. Matrix of potential lifeline infrastructure interdependencies for the San Francisco Bay region, California (modified from The Lifelines Council, 2014).

[Colors shown in each cell represent the strength of the lifeline system's interaction and dependency for service delivery and restoration efforts: light blue represents limited interaction and dependency for the lifeline system, medium blue represents moderate interaction and dependency, and dark blue represents significant interaction and dependency. Red text is material added in this study, which is unique to the HayWired scenario and the San Francisco Bay region. The table is designed to be read by row—for each lifeline infrastructure type, reading across a row indicates the dependency (if any) on the lifeline infrastructure type indicated in that column. BART, Bay Area Rapid Transit; SCADA, supervisory control and data acquisition; telecom, telecommunications; SF, San Francisco]

	Regional roads	City streets	Electric power	Natural gas and oil	Telecom	Dams and water	Auxiliary water (SF only)	Wastewater	Transit/rail	Port	Airport	Fuel
Regional roads	General	Restoration, Substitute	Restoration	Restoration	Restoration	Restoration		Restoration	Substitute		Restoration	Restoration
City streets	Collocation (high and med-high bridge damage closes underlying road), Substitute, Restoration	General	Functional (traffic lights), Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Substitute, Restoration	Collocation, Restoration		Restoration
Electric power	Restoration	Collocation, Restoration	General	Collocation, Restoration	Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration		Collocation	Restoration	Restoration
Natural gas and oil	Collocation, Restoration	Functional, Collocation, Restoration	Collocation (with transmission), Substitute	General	Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation	Collocation	Restoration	Restoration
Telecom	Collocation, Restoration	Collocation, Restoration	Collocation (on power poles), Functional, Restoration	Collocation, Restoration	Substitution, General	Functional (cooling), Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation		Restoration	Restoration
Dams and water	Collocation (pipeline break scours bridge foundations), Restoration	Collocation (distribution system), Restoration	Functional (pumps), Restoration	Collocation, Restoration	Functional (for example, SCADA), Restoration	General				Collocation		Restoration
Auxiliary water (SF only)	Restoration	Functional, Restoration	Restoration		Restoration	Functional, Restoration	General			Collocation, Restoration		Restoration
Waste-water	Restoration	Collocation, Restoration	Functional, Restoration		Restoration	Functional, Restoration		General		Collocation, Restoration		Restoration

Table 15.—Continued

	Regional roads	City streets	Electric power	Natural gas and oil	Telecom	Dams and water	Auxiliary water (SF only)	Wastewater	Transit/rail	Port	Airport	Fuel
Transit/rail	Substitute, Restoration	Functional, Substitute, Collocation, Restoration	Functional, Restoration		Restoration	Functional (fire safety in BART tunnels), Collocation, Restoration	Collocation, Restoration	Collocation, Restoration	Collocation, General	Collocation, Restoration		Functional, Restoration
Port	Restoration	Collocation, Restoration	Collocation, Restoration		Collocation, Restoration	Collocation, Restoration	Collocation	Collocation	Collocation	General		Restoration
Airport	Restoration		Functional, Restoration		Restoration	Functional, Restoration		Restoration	Collocation, Restoration		General	Functional, Restoration
Fuel	Restoration	Restoration	Functional, Restoration		Restoration	Restoration				Restoration	Restoration	General

Table 16. Summary of four representative examples of lifeline system interdependencies in the San Francisco Bay region, California.

[The four areas in these examples are outlined in figure 14. BART, Bay Area Rapid Transit; m, meters; I, Interstate; CA, California Route]

Location method	High-intensity hazards	Infrastructure	Interdependencies
North Richmond area, Contra Costa County			
Collocated infrastructure (as many as 3 different types), including transmission in high and very high multi-hazard intensity area	High shaking intensity and high fire density with as much as 2 m surface rupture and potential afterslip	Petroleum and natural gas pipelines, railways, transmission lines, fiber optic cables, and surface streets	Collocation (parallel): (1) railway corridor with petroleum pipeline; (2) railway corridor with fiber optic cable and transmission line. Collocation (intersection): transmission line crossing a natural gas pipeline. Collocation (hub): multiple (4–5) fiber optic cables, 5 petroleum pipelines, and 2 natural gas pipelines. Collocation (hub on fault): surface street crosses parallel fiber optic cable and railway. Collocation (parallel across fault): (1) 3 petroleum pipelines and 2 natural gas pipelines; (2) railway and fiber optic cable. Functional: power substations in the vicinity of a cluster of fiber-lit buildings and some cellular sites connected by fiber optic cables. Restoration: response and restoration complicated and delayed by fire; telecommunications dependencies on electric power service possible if substation is affected by fire and backup power discharges; repair of possibly unknown collocated (parallel and intersecting) lifeline infrastructure will require coordination between systems.

Table 16.—Continued

Location method	High-intensity hazards	Infrastructure	Interdependencies
		Hayward area, Alameda County	
Collocated infrastructure (as many as 4 different types) including transmission infrastructure in very high-intensity multi-hazard area	High shaking intensity, high fire density, moderate liquefaction probability, low landslide probability	Fiber optic cables, surface streets, highways (I–880, CA–92), and transmission lines	Collocation (intersection): fiber optic cable crossing surface streets and distribution infrastructure along these streets. Collocation (parallel): several fiber optic cables and transmission lines. Substitution: limited by hazards affecting substitutes among roadways and possibly among different types of telecommunication (copper and fiber optic) cables. Restoration: response and restoration complicated and delayed by fire; roadway access affected by multiple hazards including high potential impact to bridges and debris on streets; repairs of possibly unknown collocated lifeline infrastructure will require coordination between systems.
		Port of Oakland area, Alameda County	
High density of collocated infrastructure in high-intensity multi-hazard area including transmission and potentially societally critical infrastructure	High liquefaction probability; moderate shaking intensity	Electric power substation, electric power generation plant, and wastewater treatment plant	Functional: Electric power for wastewater treatment plant.
		Railways, roadways, fiber optic cables, and petroleum and natural gas pipelines	General: A hub of fiber optic cable infrastructure. Collocation (intersection): natural gas pipelines crossed by railways, fiber optic cables, and petroleum pipelines; petroleum pipelines with fiber optic cables. Collocated (parallel): railway, petroleum pipelines, fiber optic cables, highways, BART, and natural gas pipelines. Functional: multiple infrastructure systems serving the ports. Substitution: limited by parallel collocation of railway and highway. Restoration: impacts to multiple and substitute transportation routes could restrict access; repairs of possibly unknown collocated lifeline infrastructure will require coordination between systems.
		San Francisco International Airport area, San Mateo County	
High density of collocated transmission infrastructure in high-intensity multi-hazard area, including transmission and potentially societally critical infrastructure	High liquefaction probability, moderate shaking intensity	Roadways, fiber optic cables, transmission lines, and natural gas pipelines	Collocation (parallel and hub): parallel highway and fiber optic cables crossed by natural gas and petroleum pipelines; transmission lines running parallel to and crossing natural gas pipelines. Collocation (parallel): Fiber optic cable running on a bridge. Substitution: less impacted surface streets could substitute for impacted highway. Restoration: repairs of possibly unknown collocated lifeline infrastructure will require coordination between systems.

collocated infrastructure in high shaking and (or) liquefaction hazard intensity areas and on top of the fault rupture. In the event of an earthquake, collocated infrastructure is vulnerable to collateral damages, cascading failures, and restoration repair delays (for example, when one has to be repaired before another). In addition to potential collocation impacts on repairs, the North Richmond and Hayward examples pose the situation of fire delaying response and restoration. Also, the Hayward and Port of Oakland examples highlight potential access issues.

With respect to substitution between infrastructure systems, we find examples where one lifeline may not be able to substitute for another. Whereas BART did serve as a substitute for road-based transportation when the Bay Bridge was damaged by the 1989 Loma Prieta earthquake (Schiff and others, 1990), places where BART and the road network are collocated or exposed to the same hazards may not have a simple solution for substitution. On the other hand, roadways to the west of the San Francisco International Airport could substitute for any transportation disruptions in those areas.

We cannot conclude that any of the examples in table 16 are priority areas. We do not know infrastructure design regarding potential damages or what coordination has already been established between lifeline infrastructure systems. This approach simply offers a window into cross-examining lifeline interactions for a hypothetical earthquake scenario.

Lifeline Infrastructure System Damage and Downtime Assessments

We refer to the lifeline infrastructure damage assessments that were obtained for the HayWired scenario: water supply (Porter, 2018), telecommunications (Wein, Witkowski, and others, this volume), electric power (appendix 3), BART (appendix 4), and the Caltrans Division of Research, Innovation, and System Information for the Division of Maintenance (appendix 5). PG&E shared a written statement about some of their results for electric power and natural gas. To fill the gap in damage assessments, we display them in the multi-hazard exposure map. We also compile the downtime and restoration time estimates for these infrastructure systems for the HayWired scenario. Lacking specific damage and restoration time estimates for fuel infrastructure, refineries, and oil and gas pipelines for the HayWired scenario, we refer to the Bay Area Urban Areas Security Initiative plan (Bay Area Urban Areas Security Initiative, 2014) and the California Energy Commission for relevant information in the wake of a large earthquake in the San Francisco Bay region. We remark on the extent that collocation and restoration dependencies were factored into damage and restoration time assessments.

Damage Impact Assessments

Porter (2018) offers the most comprehensive damage assessment for lifeline infrastructure in his analysis of water distribution pipelines. The analysis factors in all of the HayWired scenario earthquake hazards except fire. Consequently, although the fire following earthquake hazard depends on water supply, the effect of fire on delaying water infrastructure restoration was not considered. Wein, Witkowski, and others (this volume) map out telecommunications infrastructure against all the HayWired mainshock hazards (including fire) and performed (1) a damage analysis for central offices, data centers, and cellular sites and (2) an exposure analysis for fiber optic cables. BART and Caltrans used only ground shaking data in their damage assessments (appendixes 4 and 5). PG&E conducted their own damage assessment of electric power and natural gas systems using the HayWired mainshock ground motions, their own proprietary system damage models and inventories, and their own methods for liquefaction and landslide hazards. The baseline Hazus analysis for electric power completed by the Federal Emergency Management Agency only uses ground shaking data, but estimated the liquefaction hazard and related damages in the process (appendix 3). These are examples of inconsistent damage assessments and illustrate why a multi-hazard exposure analysis can help to create a more complete picture with respect to all hazards. We compare the multi-hazard exposure and damage assessments for BART, electric power, and transportation infrastructure systems.

Comparing BART ground-shaking hazard damage results with exposure to all hazards, we find many of the BART facilities that experience the highest impact from ground shaking (see appendix 4 for details) are also exposed to moderate liquefaction probability, but BART reports that they have investigated these sites for liquefaction potential. There was general alignment between BART-estimated damages and the exposure analysis. Fire following earthquake is the main difference between BART's damage assessment and the multi-hazard exposure. For example, the Fremont station (classified green by BART but in an area of high multi-hazard intensity) is the only exception owing to its exposure to moderate ground shaking intensity, moderate liquefaction probability, and high fire-following-earthquake intensity. Please refer to appendix 4 for more details on the BART damage assessment and how it compares to hazard exposure estimated in this chapter.

The differences between the Caltrans ground-shaking damage assessment and multi-hazard intensity was most commonly high liquefaction hazard intensities, followed by high fire or high landslide hazard intensities (especially for bridges Caltrans identified as having low impact potential). Consequently, the distribution of highway bridges across the multi-hazard intensity landscape spans all Caltrans damage impact classes and hazard intensity classes—no particular hazard explains the differences between exposure and damage

assessments. Please refer to appendix 5 for more details on the Caltrans damage assessment and how it compares to hazard exposure estimated in this chapter.

The Hazus results for electric power roughly correspond with our multi-hazard exposure results, such that a lower percentage of subcomponent damage at substations more commonly occurs in lower multi-hazard intensity areas and a higher percentage of subcomponent damage at substations more commonly occurs in higher multi-hazard intensity areas. After shaking, liquefaction affects the most substations and is the only other hazard to affect more than ten substations with moderate or high-intensity (though the numbers are still relatively low compared to the total number of substations in the area). One substation is modeled to have more than 75 percent subcomponent damage; this substation is also in an area with high-intensity for fire following earthquake. More detailed discussions of substation exposure according to Hazus and the analysis in this study are in appendix 3.

Damage to marine terminals, oil refineries, fuel storage tanks, fuel transmission lines, and fuel dispensaries is likely in a large San Francisco Bay region earthquake (G. Schremp, California Energy Commission, written commun., 2018). As a result, there will likely not be enough transportation fuel supplies available after a large earthquake. This affects fuel pipelines as well as end-users—pipelines require transportation fuel to push liquid through the system (Schremp, 2015). Our multi-hazard exposure analysis shows potential shaking, liquefaction, and (or) fire damage to fuel facilities, as well as all forms of ground failure (liquefaction, landslides, and fault offset) affecting natural gas and petroleum pipelines. It should be noted that, at the Lyttelton Harbour during the Canterbury, New Zealand, earthquake sequence, less damage was observed for fuel storage tanks that were less than half full (A. Tang, L&T Consultant, written commun., 2018), meaning that fuel inventory levels at the time of the earthquake could be a variable to consider in the hazard analysis.

HayWired Lifeline Infrastructure Restoration Times

For the HayWired scenario, Porter (2018) developed a method to factor in the effects of other lifeline services (electric power and transportation), materials, and labor on the restoration times of water supply. Wein, Witkowski, and others (this volume) related the restoration of voice and data services to electric power restoration (owing to the heavy dependence on power) and assumptions about the arrival of trucks carrying fuel and equipment. However, electric power, BART, and Caltrans restoration times (appendixes 3–5) were derived independently of other lifeline infrastructure restoration times.

The restoration of electric power (according to Hazus), voice and data services, water distribution, BART facilities, and Caltrans bridges are compiled and graphed by county (figs. 15–19). The repair times for BART facilities are used to construct a restoration curve for BART facilities (as opposed to passengers served) in figure 18. Bridge functionality (fig. 19) was calculated as a percentage of bridges that are open assuming uniform repair within ranges of repair times. Partly opened bridges (1 lane) were assumed to be operating at 30 percent functionality. As an example, the five restoration curves for Alameda County are combined to illustrate the relative restoration times for those services (fig. 20). The economic impacts of these utility and transportation service outages are investigated by Sue Wing and others (this volume) and Kroll and others (this volume), respectively.

Although no restoration curve for natural gas was obtained, PG&E provided a written statement that their gas transmission model for the HayWired scenario estimates approximately 40 locations in need of repair, whereas their gas distribution model estimates at least 2,000 gas leaks. However, PG&E also noted that actual damage from a similar event will likely be different from what the model estimates (E. Hickey and G. Molnar, PG&E, written commun., 2019). PG&E surmises that the majority of its gas restoration work would be dedicated to leak surveys because the location of a repair or a leak cannot be found without extensive leak surveys or patrols. The amount of time to assess, repair, and restore gas service to customers would be significantly longer than that of electric power restoration. In addition, because there would be preemptive gas shut-offs and subsequent loss of gas service to many PG&E customers, the relight effort would take many months to complete. PG&E estimates that more than 200,000 customers could require relights after the event, not including those who proactively shut off gas to their homes and businesses and the gas safety shut-ins performed by PG&E (E. Hickey and G. Molnar, PG&E, oral commun., 2017). For comparison, 156,355 service relights after the 1989 Loma Prieta earthquake were accomplished within ten days and involved more than 1,000 servicemen, many of whom were from out-of-state utility companies (Eguchi and Seligson, 1994).

Impacts on the fuel supply after a large earthquake in the San Francisco Bay region (not specific to the HayWired scenario) are examined by the Bay Area Urban Areas Security Initiative plan (Bay Area Urban Areas Security Initiative, 2014) and the California Energy Commission. After a large earthquake, refineries will likely go offline immediately and remain offline for at least three days after the event, even given limited damage to the physical plant. The refineries will likely take some time to return to normal operating rates once they are back online. In a recent case, following the passage of Hurricane Harvey through Texas, a refining complex required six weeks to return to normal operating rates after just a brief period of high winds and extraordinary rainfall totals (G. Schremp, California Energy Commission, written commun., 2018). Refinery restart critically depends on natural gas and water supplies, crude oil delivery (that may be inhibited by damaged pipelines or marine terminals),

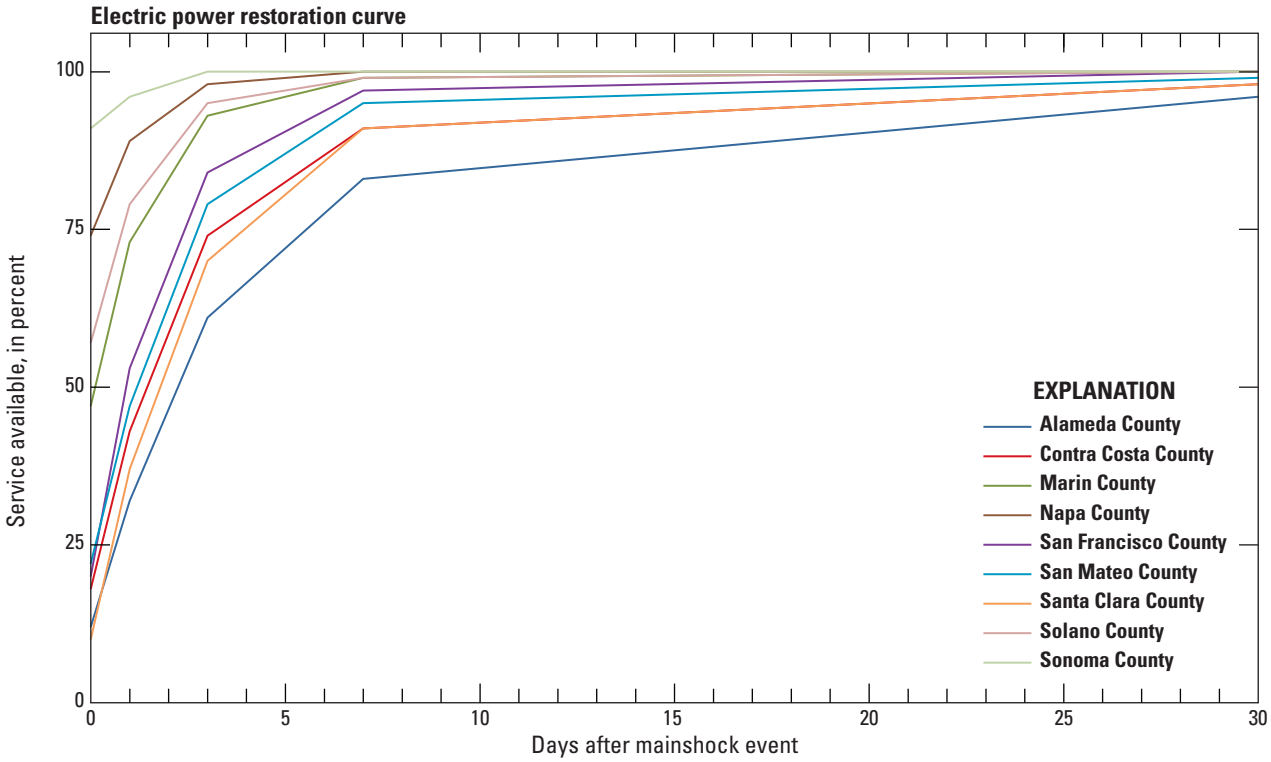


Figure 15. Line graph showing the electric power restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

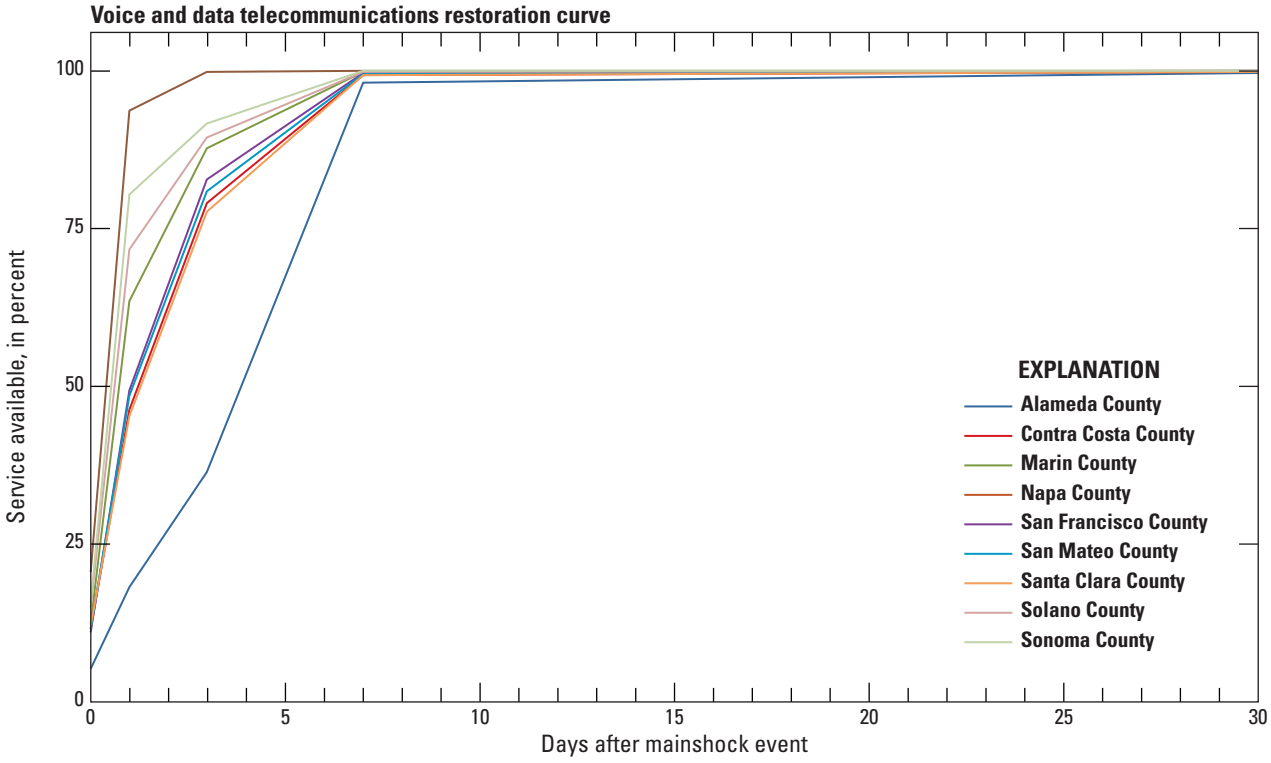


Figure 16. Line graph showing the voice and data telecommunications restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

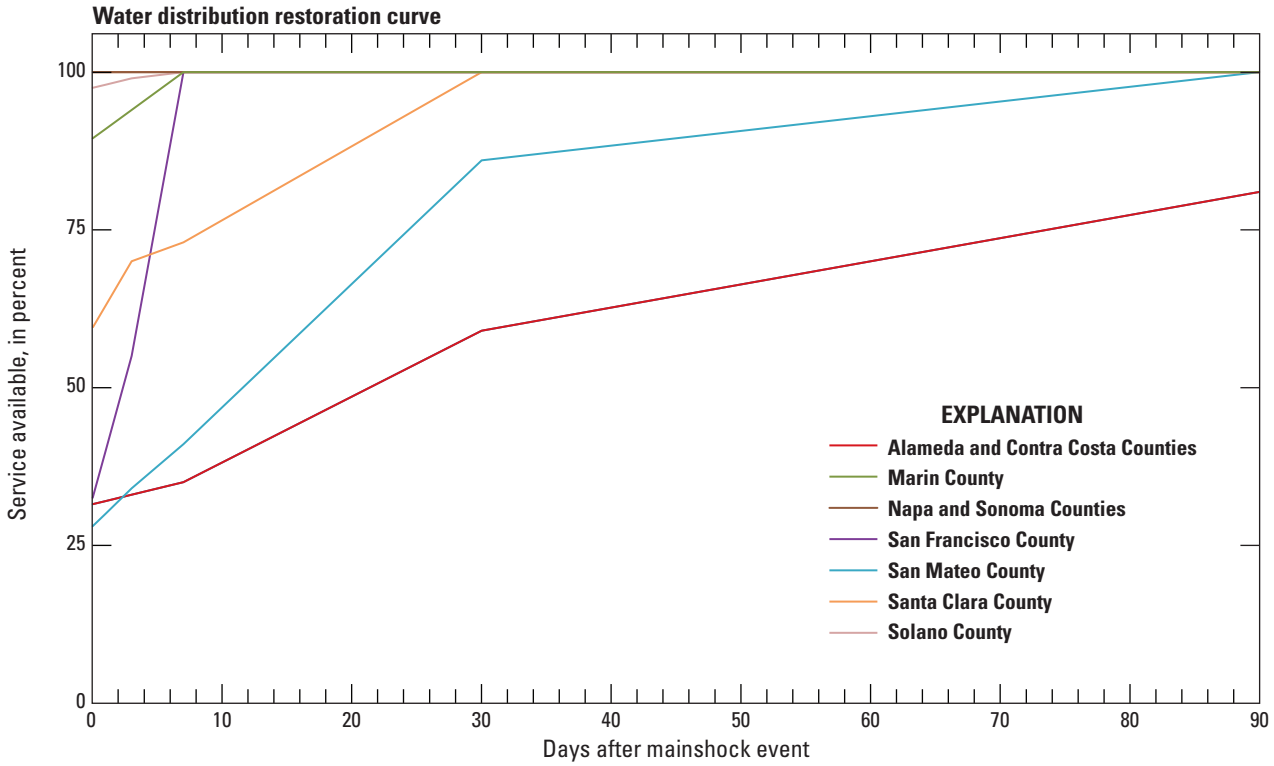


Figure 17. Line graph showing the water distribution restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California. Data originally from Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) and modified for Alameda, Contra Costa, and Santa Clara Counties by Porter (2018).

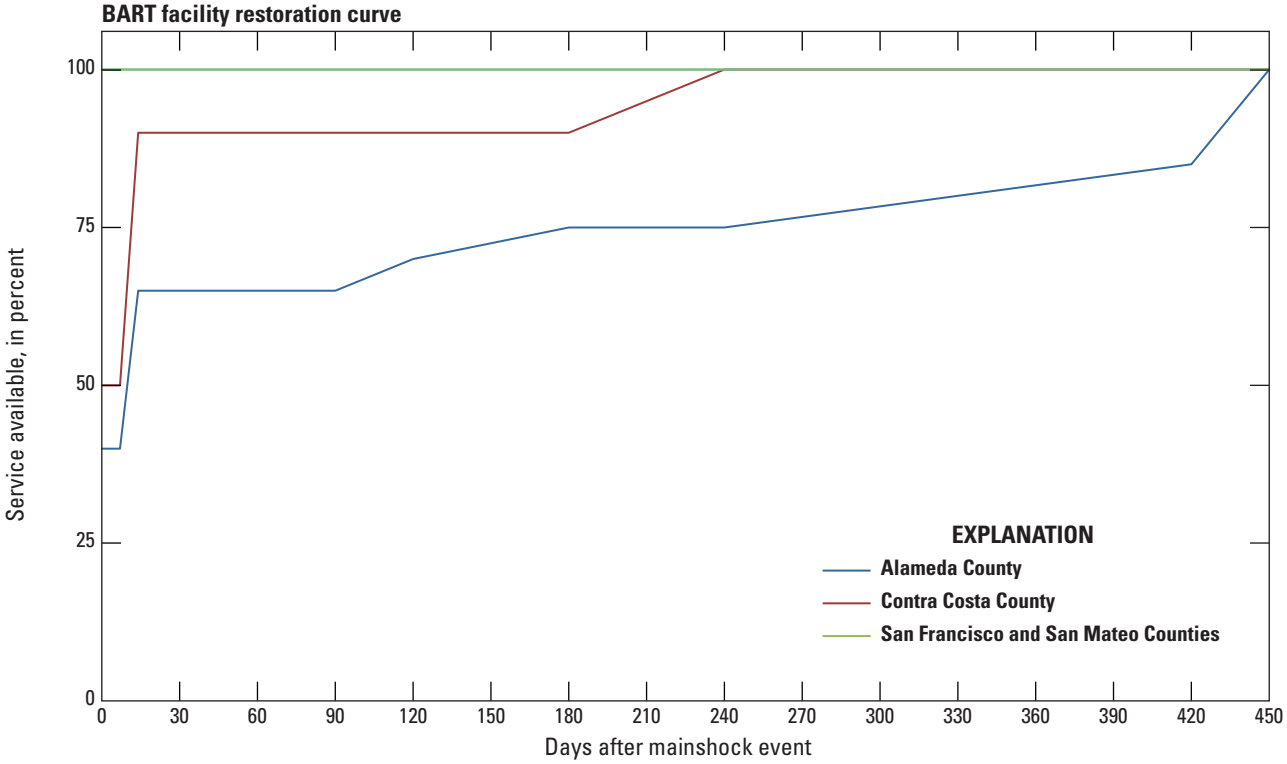


Figure 18. Line graph showing the Bay Area Rapid Transit (BART) facility restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California. Damage estimates only apply to stations in the original BART system (built between 1972 and 1976). The Warm Springs/South Fremont station (opened in 2017), Milpitas station (currently scheduled to open in 2019), and Berryessa station (currently scheduled to open in 2019) are not included in the base number of stations used to estimate station service fraction (stations built between 1996 and 2016 are included in the base number).

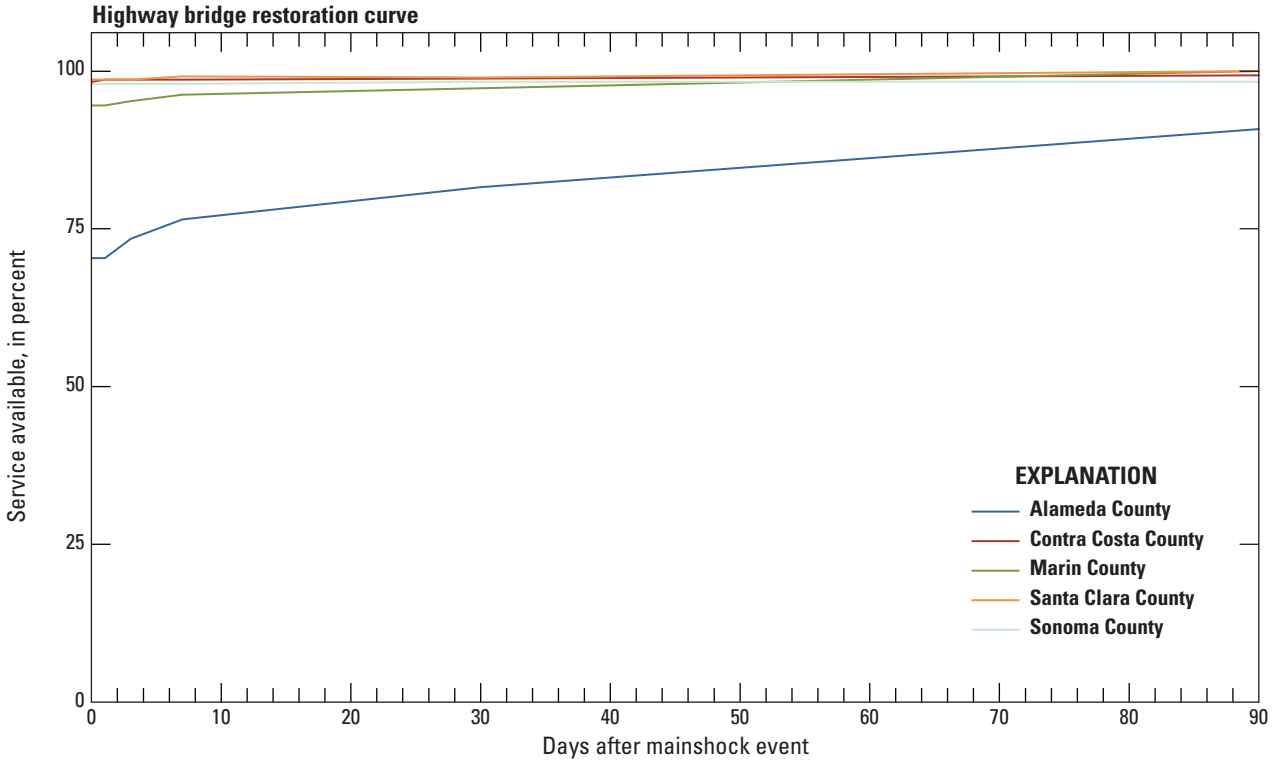


Figure 19. Line graph showing the California Department of Transportation highway bridge restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

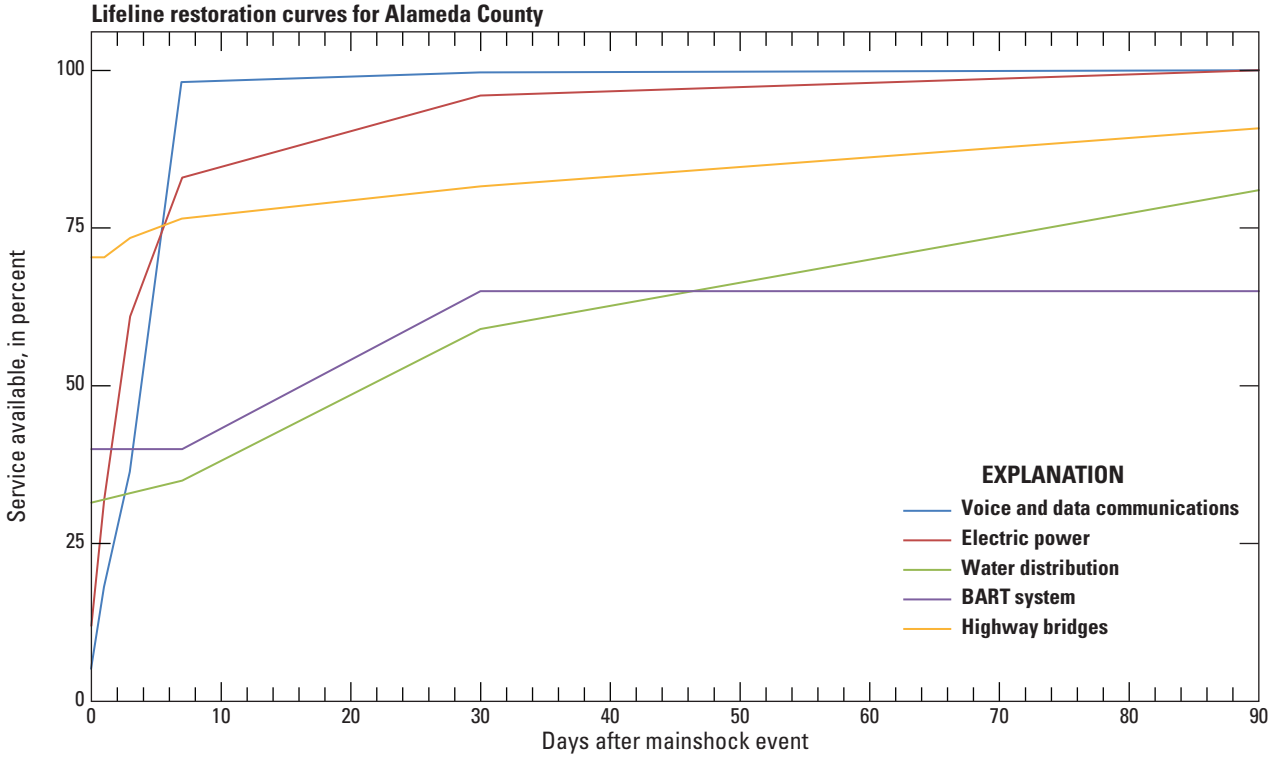


Figure 20. Line graph showing the lifeline restoration curves (electric power, voice and data, water distribution, Bay Area Rapid Transit [BART] service, and California Department of Transportation bridges) for Alameda County for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

and operational petroleum pipelines (G. Schremp, California Energy Commission, written commun., 2018). Refineries rely on "just-in-time" shipments, so fuel supplies for as long as 72 hours may be available.

Furthermore, fuel distribution would be impeded by damages to transportation systems, and power outages would make it difficult to pump gas out of the ground at most gas stations in the region (placing further demands on fuel for generated power). Transporting fuel via rail on land or via tankers or barges on water (with a waiver) are suggested as potential solutions to consider in anticipation of a major earthquake. For example, one train car can transport as much fuel as three tanker trucks, and one full train can transport as much fuel as nearly 300 tanker trucks (Schremp, 2015). In addition, California's unique gasoline blend—intended to help reduce vehicle emissions—prevents the State from bringing in fuel from other States unless a waiver is granted by the State government. Waivers could also be granted to permit use of nontaxable diesel fuel (Schremp, 2015).

The working assumption is that fuel will be limited for the initial response phase, the movement of evacuees and resources, and power generation. The quantity of fuel needed to support all response operations and other critical functions is expected to be inadequate; prioritization and coordination of fuel allocations will be necessary. The California Energy Commission advises locals to plan on being self-sufficient for a minimum of 7 to 10 days (G. Schremp, California Energy Commission, written commun., 2018). An analysis of a *M*7.0 earthquake on the Hayward Fault (with a Berkeley epicenter) by Wilson and others (2015) assumes that all refineries in the San Francisco Bay region would lose power for 3 days and be shut down for 14 days before restarting. They also assume that damage to transmission pipelines crossing the fault would halt transmission to the west side of San Francisco Bay for 28 days. Wilson and others (2015) estimate that in the absence of temporary fuel shipments by other modes, San Francisco (and the rest of the bay region) consumption would be reduced to zero for 3 days and then increased to 20 percent of their normal fuel load until the pipelines are repaired.

Knowledge Gaps and Modeling Limitations

This work advances the lifeline exposure analyses performed for prior scenarios. It extends the purview to all earthquake hazards, fire following an earthquake, and multiple hazards and delves into interactions among lifeline infrastructure. We experiment with spatial tools to find, visualize, and interpret collocated infrastructure, other interactions, and potential cascading failures. A comprehensive hazard exposure analysis complements available damage analyses for some of the hazards. We also compile lifeline infrastructure restoration time estimates. In this section, we acknowledge the shortcomings of our analyses.

Uncertainties and limitations of the specific hazard data for the HayWired scenario hazards are thoroughly covered in the first volume of the HayWired scenario (Detweiler and Wein, 2017) and Scawthorn (2018). The lack of site-specific information for liquefaction mapping also applies to our more detailed liquefaction map. Also, by using only one measurement of shaking in the exposure analysis (in this case, 0.3 second peak spectral acceleration), it is not necessarily the most relevant measure for each infrastructure type. For example, BART and Caltrans damage assessments use 1.0 second peak spectral acceleration. As such, only so much is captured by the standardized exposure analysis.

We integrated the multiple hazard assessments using relative low-, moderate-, or high-intensity classifications to manage the complexity of collocated infrastructure exposed to multiple hazards. The relative hazard intensity thresholds were selected as follows: ground shaking thresholds were informed by expert engineering opinion, the high liquefaction intensity threshold was limited by a 25 percent probability cap (used in Hazus), landslide intensity thresholds were aligned with liquefaction intensity thresholds for consistency, and fire intensity was classified using natural breaks in the data using GIS. The resulting multi-hazard intensity was created from the profile of intensity classifications. Others may choose to set the hazard intensity thresholds and the multi-hazard intensity descriptions differently.

There were issues with the lifeline infrastructure dataset. First, some of the data are misrepresented (such as a pathway through a park attributed as a surface street). Second, though a large amount of lifeline infrastructure was assessed, the available data were incomplete. This is particularly true for "last-mile" distribution infrastructure which generally includes household-level access to water, wastewater, electricity, and other infrastructure. In many cases, these types of infrastructure can be approximated by surface streets, which are included in this analysis. Other lifeline infrastructure data (for example, city gates for natural gas transmission and distribution, booster stations for water transmission and distribution, and mobile telephone switching offices for communications) would be useful inputs but were not publicly available. A third data limitation was duplication, particularly in the telecommunications data. We tried wherever possible to remove data points that were duplicated, but some double-counting of data owing to these duplicates is still possible. A fourth limitation is that many infrastructure collocations are unknown; for example, fiber optic cables are known to be collocated on Caltrans bridges, yet they are not documented (L. Turner, Caltrans, oral commun., 2016), which required us to develop GIS methods to identify potential collocations that would have to be manually verified. Although California utilities use Underground Service Alert to identify other infrastructure that may be present before digging to make repairs, the data are not kept current (Wein, Witkowski, and others, this volume).

Hazard exposure assessments pick up the presence but not performance of lifeline infrastructure. Different types

of facilities (for example, above and belowground) have different responses to the various hazards and have different design standards (Applied Technology Council, 2016). A limitation of lifeline infrastructure data is that it is not attributed with design standards, and fragility functions for different hazards may be approximated or unavailable. In other cases, information about the physical location of the lifeline may be missing (for example, fiber optic cable data do not specify whether the cables are above or belowground). System retrofitting and enhanced design standard information for lifeline infrastructure was not fully accounted for by the transportation agencies and Hazus. Comprehensive fragility information would be required to gain more insight into damages among collocated infrastructure.

A particular challenge in the assessment of collocation and other lifeline infrastructure interactions is the sheer volume of infrastructure data that needs to be processed. We developed GIS methods to paint a regional picture of collocated and dense infrastructure in hazardous areas. The collocation algorithm is not perfect and identified facilities near surface streets as collocated, but not facilities that were set back more than 5 m, which could also be affected by damage to surface streets. This is an area where the spatial methods could be further developed. In addition, we make assumptions about which lifeline infrastructure are more and less societally critical in our collocation analysis. Different agencies would surely have different opinions on what qualifies lifeline infrastructure as more or less critical to society and, as a result, could identify different collocations of interest. For example, Radke and others (2018) used a betweenness centrality measure, which identifies nodes of importance along a network based on the number of routes needing to pass through a particular node, instead of using classifications based on the number of structures within a distance of the pipeline (as was done for this chapter).

Quantitative assessment of interactions among lifeline infrastructure is still a relatively nascent field with limited examples available for anticipating how complex systems interact, particularly during hazardous events. Applied Technology Council (2016) provides a review of gaps in literature and practice. Our approach to lifeline infrastructure interactions is limited because not all interactions within and between systems occur within a confined area. For example, the 2010 gas line explosion in San Bruno, California, began with an error in electrical maintenance work 50 miles away, which resulted in a natural gas pressure surge and explosion of a weak part of pipe in San Bruno (Germeraad and others, 2014). We approached regional lifeline infrastructure systems using the location of physical infrastructure (what is at this spot?) rather than an operational or horizontal approach (what is downstream from this spot?), and, as such, miss the effect of how damage in one place may affect another in the network. A recent infrastructure interdependency assessment regarding Puerto Rico's recovery after Hurricane Maria (U.S. Department of Homeland Security, 2018) demonstrates a comprehensive assessment methodology that combines a top-down approach to system operations and dynamics with a bottom-up approach that extracts characteristics and performance of critical infrastructure and economic activities through structured interviews, facilitated discussions, and standardized dependency-related question sets. We also tackled this analysis from both sides.

Some organizations used their own tools and (or) collaborated with the HayWired scenario team to conduct damage and restoration assessments. Future lifeline infrastructure assessments could attend more closely to assessing (1) damage for multiple earthquake hazards (including fires following an earthquake), (2) additional damage caused by damage to collocated infrastructure, (3) restoration delays owing to collocated infrastructure, and (4) restoration delays from fire following an earthquake. These additions would make damage and restoration assessments more robust and more representative of what could happen during a major disaster, such as the HayWired earthquake scenario.

Summary and Conclusion

This study applied scientific and comprehensive hazard data from the HayWired scenario to anticipate impacts on lifeline infrastructure and illustrate potential interactions (or interdependencies) among them. We created a multi-hazard map to integrate five hazards: surface rupture, mainshock ground shaking, liquefaction, landslides, and fire following the earthquake. We performed standardized hazard and multi-hazard exposure analyses for various lifeline infrastructure systems, including transportation, water supply and wastewater, oil and gas, electric power, and telecommunications. The hazard exposure analyses complement available regional lifeline infrastructure damage assessments. We visualized collocated lifeline infrastructure systems in the San Francisco Bay region and their exposure to multiple hazards. Zooming in on collocated lifeline infrastructure in high or very high hazard areas, we illustrate potential lifeline infrastructure interactions (that are mostly geographical, but also potentially functional, substitutional, and restorative). Finally, we compiled utility and transportation service restoration timeline estimates and noted whether lifeline infrastructure interactions were considered. These analyses can be used by lifeline infrastructure organizations, communities and government officials, businesses, and public safety agencies to develop emergency management exercises and support business continuity planning. They also provide materials for information-sharing tool development and coordinated planning among the various organizations and communities in anticipation of a large earthquake.

The material in this chapter reinforces prior efforts and findings. Applied Technology Council (2016) promotes the assessment of lifeline infrastructure and interactions to improve the ability of lifeline operators to "set priorities and define strategies to reduce risks and improve lifeline resilience."

Within the San Francisco Bay region, The Lifelines Council (2014) undertook a collaborative and qualitative effort to offer recommendations to improve the performance of lifeline infrastructure and interactions in the event of a large earthquake in San Francisco on the San Andreas Fault. The study considered port, electricity, transportation, water, wastewater, telecommunications, and fuel infrastructure systems. Perkins and Hutchings (2010) laid out numerous strategies and funding statuses for lifeline infrastructure and interactions for the San Francisco Bay region. Subsequently, Germeraad and others (2014) used publicly available data to investigate potential vulnerabilities in transportation and utility systems in the region. The HayWired analysis builds on these studies by expanding the extent of the San Francisco study to the entire San Francisco Bay region, broadening the infrastructure included (for example, adding telecommunications infrastructure), extending analyses to identify collocated and interacting lifeline infrastructure, and placing these analyses in a comprehensive multi-hazard (and non-San Andreas-specific) environment.

Hazard exposures vary by lifeline infrastructure. Shaking is the most widespread hazard and affects all lifeline infrastructure, but, in general, less than 15 percent of facilities and conveyances in each lifeline infrastructure system are subjected to high-intensity shaking (as defined for this study); cellular sites and fiber-lit building are at the upper end of this exposure range. Internet exchange points and oil refineries exceed the range with 27 and 20 percent, respectively, in high-intensity shaking areas, but the total number of exposed facilities in the study area is quite small (11 and 5, respectively).

Building of structures in the fault zone is constrained by the Alquist-Priolo Act of 1972 (Perkins and Hutchings, 2010; California Department of Conservation, 2017): only 1 microwave tower, 6 bridges, 6 cellular sites, and 8 fiber-lit buildings are in the fault zone. In contrast, there are no limitations on conveyances in the fault zone: hundreds of roadways and fiber optic cables and a few pipelines and water conveyances cross the surface rupture and (or) are further exposed to afterslip. We know that the East Bay Municipal Utility District (EBMUD) has built for and planned for damages resulting from offset on the Hayward Fault for the few water transmission crossings it manages.

In two places along the fault, surface rupture coincides with landslide and fire hazards and, in both cases, surface streets are the most exposed infrastructure, in agreement with the urban nature of the fires modeled. There is infrastructure in the fault zone that is exposed to all five hazards at the same site, including 3 bridges, around 4 km of roadways, 3 km of fiber optic cable (1 km of long-haul fiber and 2 km of interoffice fiber), less than 1 km of natural gas and petroleum pipelines, and 2 cellular sites. Zooming in, we found a few instances of collocated infrastructure on the fault: parallel natural gas and petroleum pipelines, and a parallel railway and fiber optic cable that are crossed by a surface street (and presumably other distribution infrastructure).

We generated a more expansive liquefaction probability map than provided (by Jones and others, 2017) using liquefaction susceptibility data in conjunction with multiple Hazus runs (areas outside of the modeled part of Santa Clara and Alameda Counties) to improve the resolution within census tracts to better match the spatial scale of lifeline infrastructure data. Liquefaction is the primary hazard at the three international airports and seaports in terms of affected area and severity during the HayWired scenario mainshock (and likely for some nearby aftershocks). Prior recognition of liquefaction as a problem has resulted in some mitigation (Germeraad and others, 2014). Wastewater treatment plants are also located in flat areas around and near the bay and are mostly exposed to liquefaction hazards. We also found nearby power plants and substations serving wastewater treatment plants simultaneously exposed to the liquefaction hazard.

We show the potential for ground failure (liquefaction and landslides) to impact roadways, railways, and fiber optic cables. Where respective facilities (bridges, stations, and fiber-lit buildings) are impacted by heavy shaking, the impact on the system is likely dominated by restoration of facilities rather than conveyances. Therefore, the impact of ground failure on these systems could extend recovery times where shaking is less intense and facility shaking damage is minor. Considering the potential bridge damages and exposure of roads to landslide hazards, safe egress from the east bay (especially away from ensuing fires) might well be west across the trans-bay bridges rather than to the east.

Bay area refineries are generally out of the way of the largest impacts of the HayWired scenario earthquake hazards, except for one exposed to high liquefaction hazard intensity. PG&E confirmed that ground failure resulting from the HayWired scenario mainshock would likely cause more damage to gas pipelines than shaking (E. Hickey and G. Molnar, PG&E, written commun., 2017). We found oil and gas pipelines collocated on the fault. Also, we found pipelines running parallel to and crossing various transportation infrastructure and fiber optic cables in areas that have high liquefaction hazard intensity. Therefore, collateral damage and restoration interactions could arise. The proximity and potential impacts of hazards on gas and liquid fuel pipeline facilities in urban areas is accounted for in current construction codes, but is an important consideration in the context of larger scale, infrequent events that may exceed normal circumstances (Applied Technology Council, 2016).

Fire was not considered in any of the HayWired scenario lifeline infrastructure damage assessments or restoration estimates. Owing to the urban nature of fire following an earthquake in the HayWired scenario, Bay Area Rapid Transit (BART) facilities are relatively more exposed to higher fire density areas than other infrastructure. Aerial power lines and fiber optic cable would be vulnerable to fire, but the data did not always distinguish between aerial and buried systems.

Compounding hazards can be problematic for lifeline infrastructure, even if one or more of the hazards poses relatively minor damage potential—damage from one hazard could increase the fragility of infrastructure to a second or third hazard, making a facility unsafe. Considering lifeline infrastructure exposure to three or more hazards at the same site, we found that the most likely combination is shaking,

liquefaction, and fire hazards. This is not surprising given that (1) liquefaction affects the largest area after shaking, and (2) damage to vulnerable water distribution pipelines from liquefaction and shaking hazards could inhibit firefighting. For this hazard combination, in the majority of cases, at least one of the hazards affecting a lifeline is of high-intensity. We find 14 percent of terminals, storage facilities, and tank farms for petroleum, oil, and lubricants; 9 percent of internet exchange points; 8 percent of fiber-lit buildings; 6 percent of cellular sites, natural gas compressor stations, and microwave towers; 5 percent of AM radio antennas; and 3–4 percent of roadways, electric power generation plants, substations, petroleum pipelines, and fiber optic cables (both long-haul and interoffice fiber) exposed to the combination of shaking, liquefaction, and fire hazards.

Surface streets (and unaccounted collocated distribution ["last-mile"] lifeline infrastructure) are involved in infrastructure collocations and most commonly collocated with other transportation infrastructure (roadways or railways) and (or) fiber optic cables, but also with oil and gas pipelines and electric transmission lines. More than 40 percent of the 9,700 surface street collocations in high and very high-intensity areas involved three or four types of infrastructure. Although fewer in number, interactions from collocated transmission or potentially more societally critical infrastructure would have a greater impact (for example, the Port of Oakland and San Francisco International Airport).

Interactions with data around collocated infrastructure in hazardous areas identify potentially complex situations that could arise from a large earthquake in the San Francisco Bay region. Such an approach could help multiple lifeline infrastructure systems, communities, government officials, and emergency managers locate and discuss interactions that may be otherwise unknown (for example, collocated water and gas pipelines, as discussed by EBMUD).

Our hazard exposure findings precede damage assessment. We find that exposure analyses complement damage assessments that are limited to a subset of the hazards (most commonly, shaking only) and draw attention to ground failure and fire hazards. Consideration of fire following an earthquake is the main difference between BART's damage assessment and the multi-hazard exposure assessment presented here. No one hazard explained the differences between highway system exposure and California Department of Transportation's damage assessments.

Service restoration times were derived from damage analyses conducted for water distribution (Porter, 2018), electric power (appendix 3), BART facilities (appendix 4), and highway bridges (appendix 5). Also, Wein, Witkowski, and others (this volume) posited restoration curves for voice and data services. In general, the indications are that BART stations and train yards will take longer (years) than highway bridges (months) to restore in the most heavily impacted areas, and water supply restoration times (months) extend beyond power (weeks to a month) and telecommunications (days to weeks) restoration times. The water supply analyses assumed road access, but showed that other lifeline infrastructure interactions have a greater effect on extending restoration times of less impacted systems. Although telecommunications infrastructure performance depends heavily on electric power, back-up power and portable equipment can help to decouple that dependence at the cost of increasing dependence on fuel sources and transportation of fuel. Future lifeline infrastructure assessments could more closely assess (1) damages from multiple earthquake hazards (including fire following the earthquake), (2) additional damages caused by damages to collocated infrastructure, (3) restoration delays due to collocated infrastructure and other types of interactions, and (4) restoration delays from fire following the earthquake.

We presented results in maps of hazards, infrastructure systems, and collocation; counts of facilities and collocations; lengths of conveyances; percentages of system assets exposed to hazards; and estimations of restoration times. Counts and lengths are a basic step to understanding the cost and effort required to restore a system and percentages provide a relative measure of potential impact to a system. As we developed material in parallel with emergency managers for exercises, they responded to combining the hazards into a multi-hazard landscape as an indicator of problem areas as well as the focused examples of complex situations that could arise. This is consistent with the need to anticipate, plan, and prepare for less predictable and less visible, potentially disastrous, lifeline infrastructure system interactions. According to Grain (2014), there is great value in well-designed, informative exercises that can test the efficacy of contingencies and preparedness plans; more sophisticated and challenging scenario-based training will be vital in validating and revising these plans.

When lifeline infrastructure information is not available or shared among lifeline infrastructure operators, it is difficult to anticipate and plan for any interactions or coordinate system restoration. At the most fundamental level, data collection across multiple systems can improve communication across lifeline service providers and support analyses of geographically collocated infrastructure, which are currently largely unknown (Applied Technology Council, 2016; Scalingi, 2015). To our knowledge, our analysis is the first attempt to process vast quantities of data that may or may not be known between infrastructure asset owners and managers, map collocation across a region, and visualize collocation within a multi-hazard landscape. Utilities and transportation agencies could interact with lifeline infrastructure layers from the Department of Homeland Security (P. Beilin, City of Walnut Creek, oral commun., 2017) and dive deeper into potential interactions pertaining to mitigating damage and planning for response and recovery.

The San Francisco Bay region has been receptive to earthquake information and has proactively reduced risk of damage and disruption in lifeline infrastructure. Since the 1989 Loma Prieta earthquake, Brocher and others (2018) document seismic retrofits of $20 billion spent on transportation, about $8 billion on water supply and sewers, $3 billion on electric power, and $1 billion on telecommunications. As in this study,

information is lacking on energy infrastructure. Looking ahead, the Loma Prieta 25th Anniversary Symposium (LP25) policy partners and the Association of Bay Area Governments Executive Board recommended the establishment of a Regional Lifelines Council (modeled on the San Francisco Lifelines Council) to address vulnerabilities in the San Francisco Bay region's infrastructure systems. Our analyses align with the proposed goals of the Regional Lifeline Council: sharing risk assessments, understanding lifeline infrastructure interactions, communicating restoration times, and correcting for serious risks, such as those inherent in cascading failures (Association of Bay Area Governments, 2015).

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Appendixes 1–5

Appendix 1. HayWired Scenario Liquefaction Modeling Expansion Methodology

By Jamie L. Jones,[1] Anne M. Wein,[1] and Hope A. Seligson[2]

The liquefaction probability estimation for the HayWired mainshock uses two methods to cover the San Francisco Bay region. First, a detailed estimate of liquefaction probability was performed in most of Alameda and Santa Clara Counties for the HayWired scenario mainshock by Jones and others (2017). Using methods originally developed by Holzer and others (2008, 2010), they estimate liquefaction probabilities at a spatial resolution of 50 meters (m) ranging from zero to as high as 78 percent (fig. 1.1). Second, for the rest of the bay area, the Hazus-MH 2.1 (hereafter referred to as Hazus) census-tract-scale liquefaction analysis (shown in Jones and others, 2017) was refined to make a map that better aligns the liquefaction risk with the location of lifeline infrastructure. This was accomplished using San Francisco Bay region liquefaction susceptibility data (Knudsen and others, 2000) and running Hazus liquefaction probability estimation multiple times, once for each susceptibility class within census tracts. This revised analysis, though limited to a maximum liquefaction probability of 25 percent by Hazus methodology, provides sub-census-tract level liquefaction probability results for a much wider area than originally modeled by Jones and others (2017) (fig. 1.2).

Specifically, the liquefaction probability estimation was conducted by running the Hazus earthquake module with HayWired mainshock ground motions for five liquefaction susceptibility classes (very low, low, moderate, high, and very high), as defined by Knudsen and others (2000). For each of the five Hazus runs, census tracts were assigned the same susceptibility class. For example, the first run forced all census tract centroids to have the same very low liquefaction susceptibility class. Each run yielded liquefaction probability results for the liquefaction susceptibility class in the census tract. These results were mapped on to the liquefaction susceptibility polygons in the geographic information system (GIS) data from Knudsen and others (2000). The census tract map used on top of the liquefaction susceptibility map was of 2000 vintage because the version of Hazus used for the HayWired scenario was compatible with 2000 census data and not 2010 census data. We then mapped liquefaction probability within a census tract by assigning the susceptibility class specific probabilities for the tract to the corresponding area of the tract. For example, the liquefaction probability from the high liquefaction susceptibility class Hazus run for a census tract was mapped on to the high-liquefaction susceptibility area within the census tract. Figure 1.3 illustrates the above steps for census tract 6051 in the City of Burlingame in San Mateo County.

In Alameda and Santa Clara Counties, where liquefaction probability data from Jones and others (2017) were available, the results from the Hazus runs were replaced, creating a final composite liquefaction probability map using Jones and others (2017), where available, and application of Hazus data elsewhere in the region (fig. 1.4).

[1] U.S. Geological Survey.

[2] Seligson Consulting.

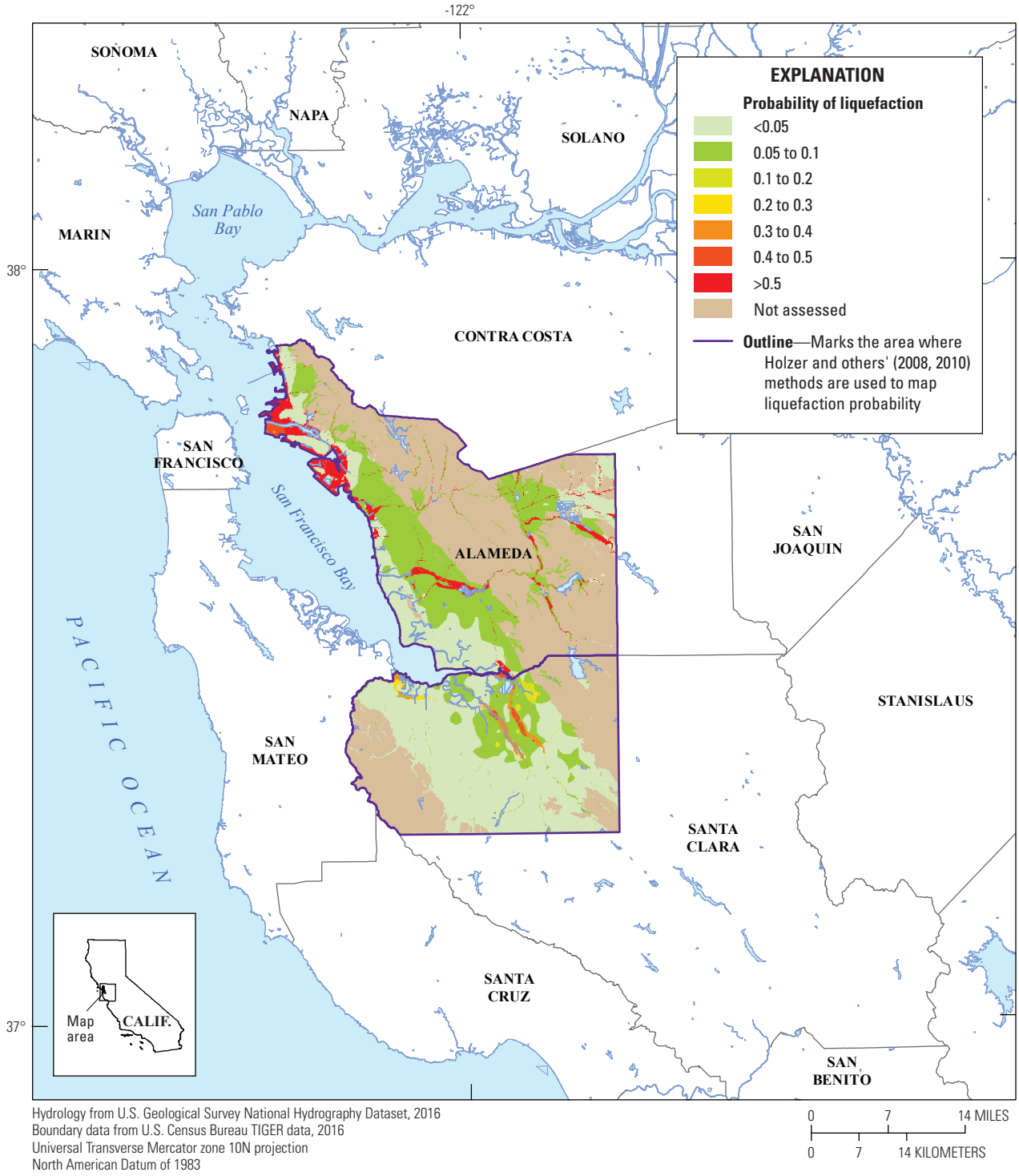


Figure 1.1. Map of the San Francisco Bay region, California, showing liquefaction probability results modeled by Jones and others (2017).

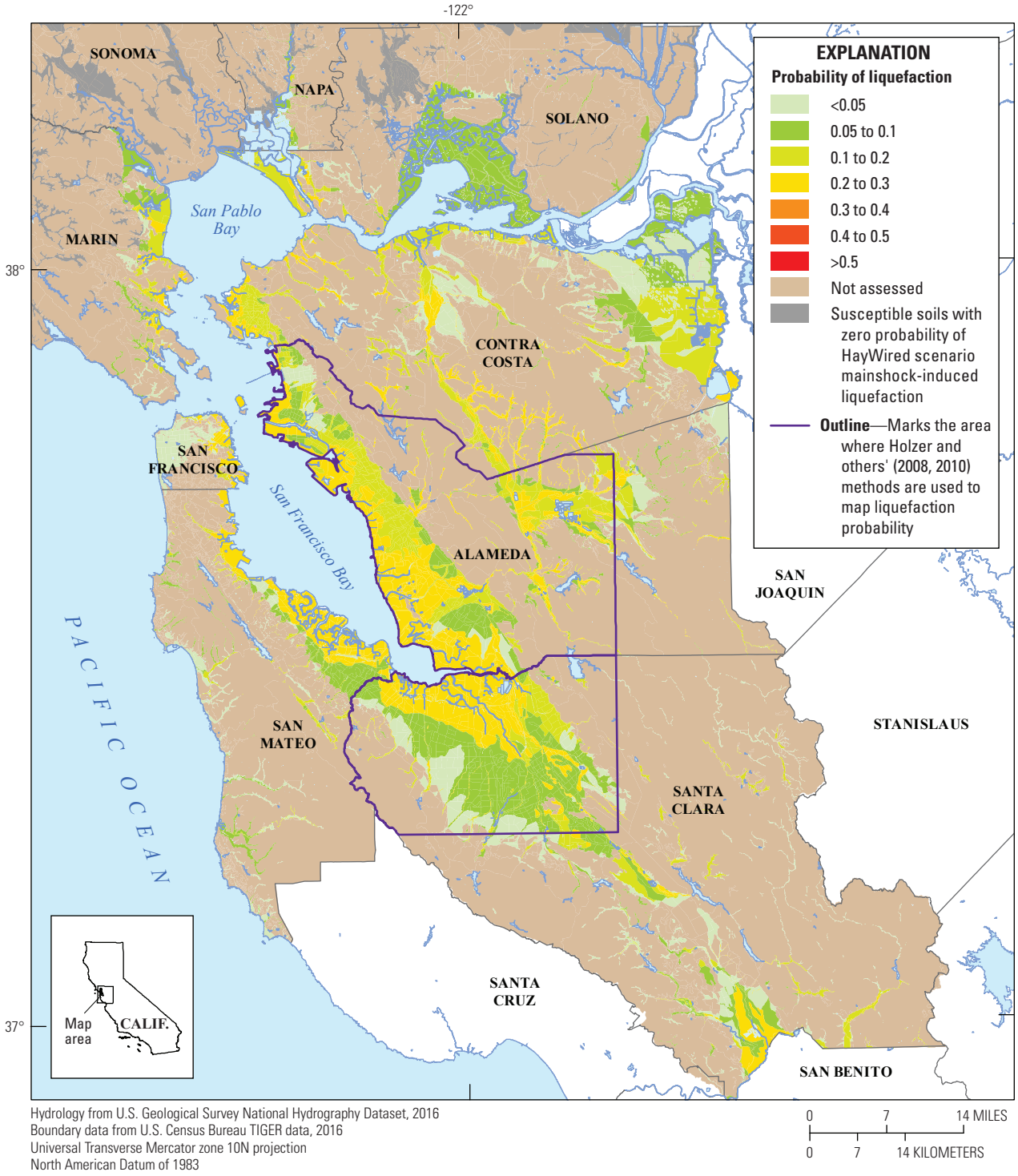


Figure 1.2. Map of the San Francisco Bay region, California, showing liquefaction probability results modeled using Hazus-MH 2.1 (Federal Emergency Management Agency, 2012); modified using methods described in this appendix.

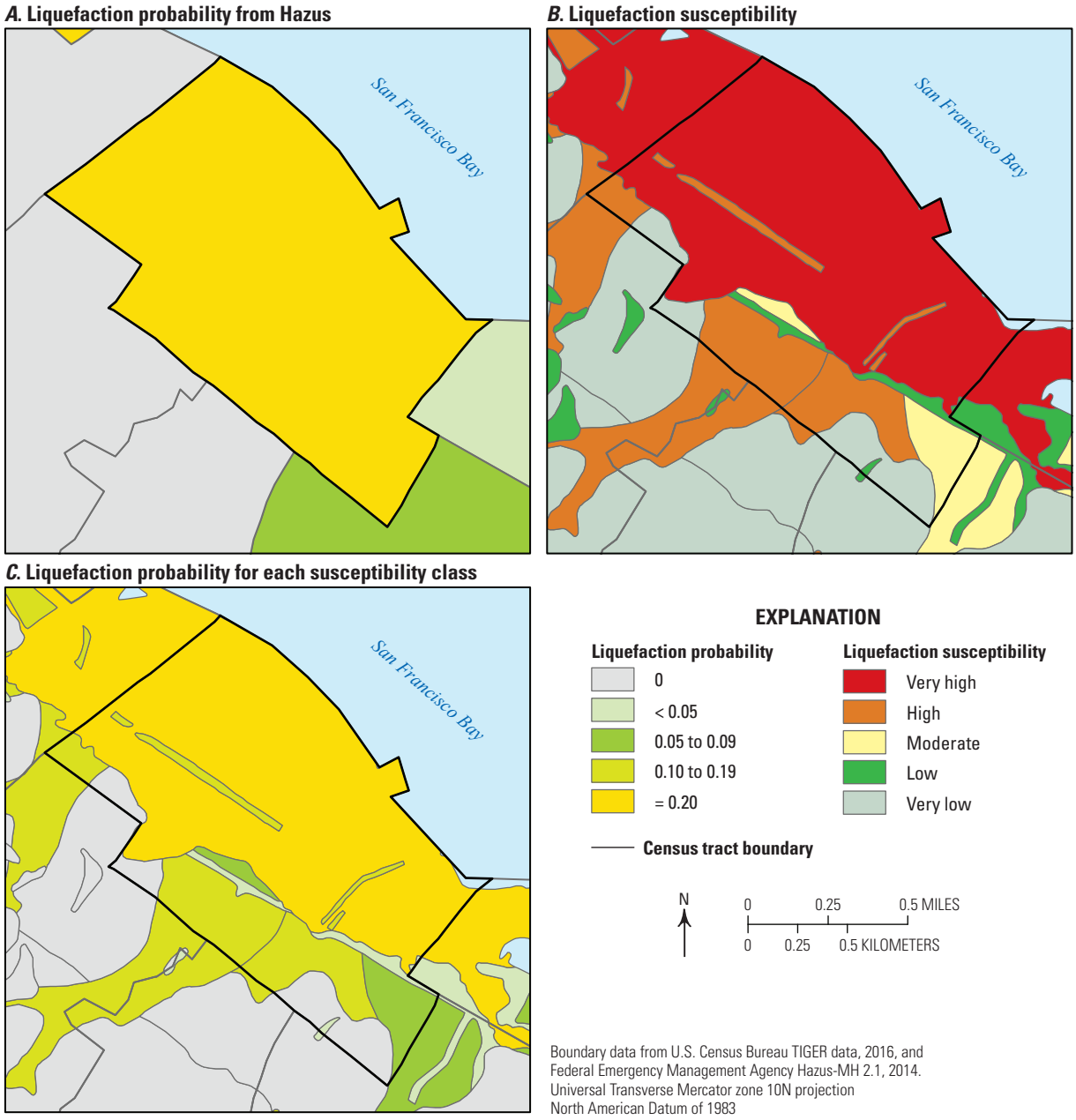


Figure 1.3. Series of simplified maps showing how census tract-level liquefaction probability data (from Hazus-MH 2.1 [Federal Emergency Management Agency, 2012]) were downscaled to sub-census-tract level susceptibility class areas within a single census tract. *A*, Original census-tract liquefaction probability from Hazus. *B*, Liquefaction susceptibility classes from Knudsen and others (2000) for the census tract and surrounding area. *C*, Final census-tract liquefaction probabilities from Hazus runs for each susceptibility class.

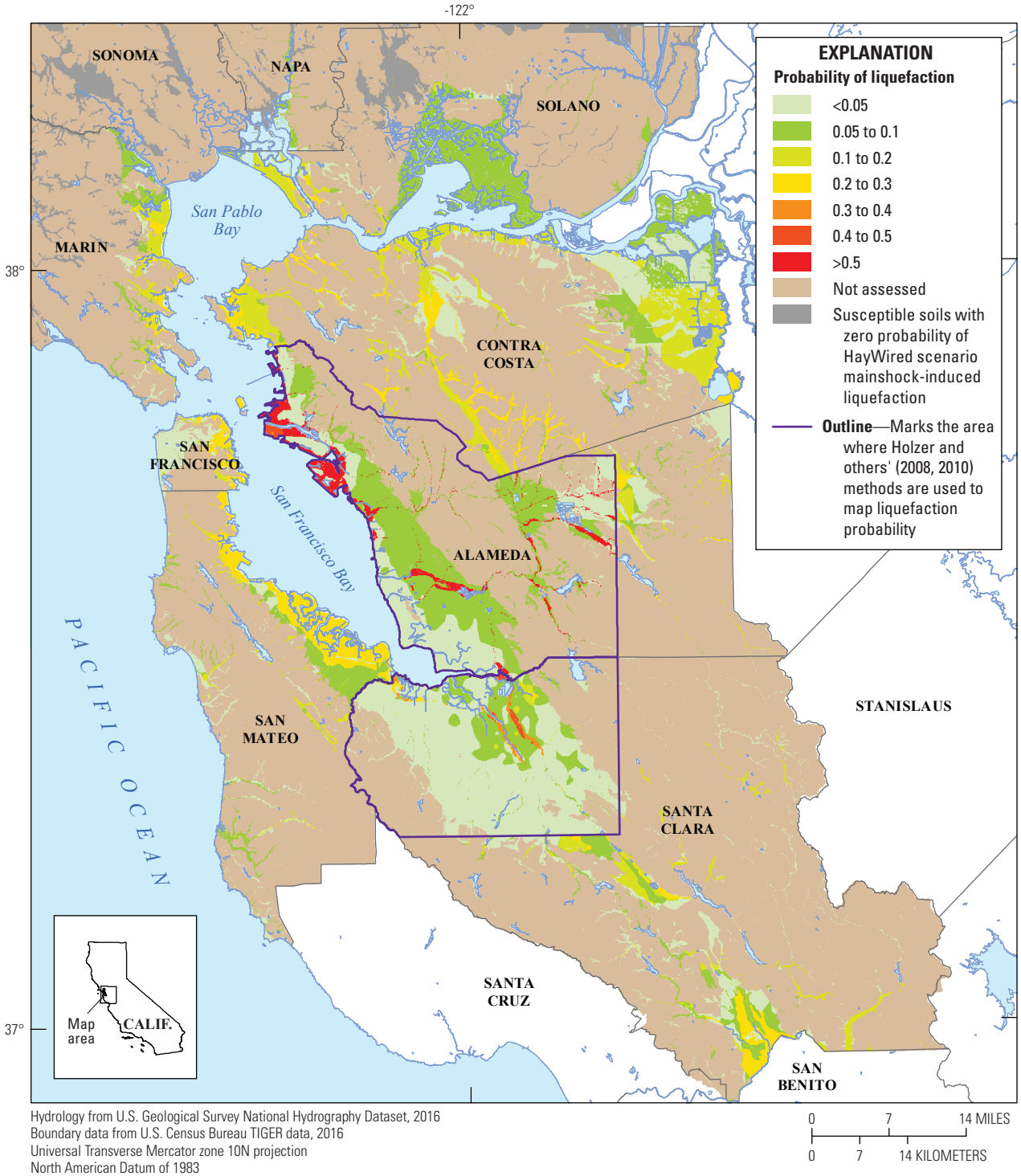


Figure 1.4. Map of the San Francisco Bay region, California, showing the final liquefaction probability data used for the lifeline exposure analysis.

Appendix 2. Individual Lifeline Exposure to Individual HayWired Scenario Hazards

By Jamie L. Jones,[1] Laurel R. Ballanti,[1] Amy E. Schweikert,[1] and Anne M. Wein[1]

Each lifeline infrastructure system (transportation, water supply and wastewater, oil and gas, electric power, and telecommunications infrastructure) was analyzed for exposure to a series of hazards caused by the HayWired earthquake scenario (surface rupture, mainshock and aftershock shaking, liquefaction probability, landslide probability, and fire following earthquake). The descriptions for each hazard intensity class are described in the HayWired hazard descriptions and classifications section of this chapter. Table 2.1 summarizes lifeline crossings with measurable coseismic slip and potential total slip (owing to afterslip), as well as coseismic slip ranges. Figure 2.1 provides a visual summary of infrastructure intersections with the Hayward Fault, aggregating infrastructure crossings at 250-meter intervals. Tables 2.2–2.6 show the amounts and percentages of lifeline infrastructure exposed to each remaining individual hazard by hazard intensity class in the study area. Finally, table 2.7 shows the amount of lifeline infrastructure exposed to two different hazards in the study area (including the amount where at least one of the two hazards is high-intensity).

[1] U.S. Geological Survey.

Table 2.1. Surficial coseismic slip and afterslip effects on lifeline infrastructure as a result of the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Afterslip includes all segments of the Hayward Fault within the HayWired scenario, including those where surface coseismic slip is zero. "Exposure in zone of uncertainty" column presents results in kilometers (km) or number of facilities. m, meters; km, kilometers; BART, Bay Area Rapid Transit; POL, petroleum, oil, and lubricants; AM amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Lifelines	Coseismic slip			Afterslip	
	Surface slip range (m)	Fault trace crossings	Exposure in zone of uncertainty	Fault trace crossings	Exposure in zone of uncertainty
Transportation					
Roadways, highway (km)	0.00–2.0	27	3.49	37	5.19
Roadways, secondary (km)	0.00–2.1	80	10.14	127	13.20
Roadways, surface (km)	0.00–2.1	270	30.09	424	37.41
Railways (km)	0.00–1.6	4	0.34	8	0.66
BART facilities	0	0	0	0	0
Highway bridges	0.00–1.0	0	3	0	6
Ports	0	0	0	0	0
Water supply and wastewater					
Transmission conveyance systems (km)	0.00–0.9	3	0.18	13	0.82
Dams	0	0	0	0	0
Drinking-water sources	0	0	0	0	0
Drinking-water treatment plants	0	0	0	0	0
Wastewater treatment plants	0	0	0	0	0
Oil and gas					
Pipelines, natural gas (km)	0.00–1.9	7	0.50	14	0.93
Pipelines, petroleum (km)	0.00–2.1	8	0.74	11	0.90
Natural gas compressor stations	0	0	0	0	0
Natural gas processing plants	0	0	0	0	0
Natural gas receipt and delivery points	0	0	0	0	0

Table 2.1.—Continued

Lifelines	Coseismic slip			Afterslip	
	Surface slip range (m)	Fault trace crossings	Exposure in zone of uncertainty	Fault trace crossings	Exposure in zone of uncertainty
Oil and gas—Continued					
Natural gas storage facilities	0	0	0	0	0
POL terminals, storage facilities, tank farms	0	0	0	0	0
Oil refineries	0	0	0	0	0
Electric power					
Transmission lines (km)	0.00–1.7	8	0.65	37	1.69
Electric power generation plants	0	0	0	0	0
Energy distribution control facilities	0	0	0	0	0
Substations	0	0	0	0	0
Telecommunications					
Fiber routes, long-haul (km)	0.00–1.6	21	1.69	36	3.50
Fiber routes, interoffice (km)	0.00–2.1	102	8.46	191	16.90
Cellular sites	0.00–1.9	0	5	0	6
Fiber-lit buildings, data centers	0	0	0	0	0
Fiber-lit buildings, central offices	0	0	0	0	0
Fiber-lit buildings, point of presence	0.15–1.0	0	8	0	8
Wireless switch offices	0	0	0	0	0
Internet exchange points	0	0	0	0	0
Microwave towers	1.0–1.0	0	1	0	1
AM radio antennas	0	0	0	0	0
FM radio antennas	0	0	0	0	0
NTSC television transmitters	0	0	0	0	0
Digital television transmitters	0	0	0	0	0

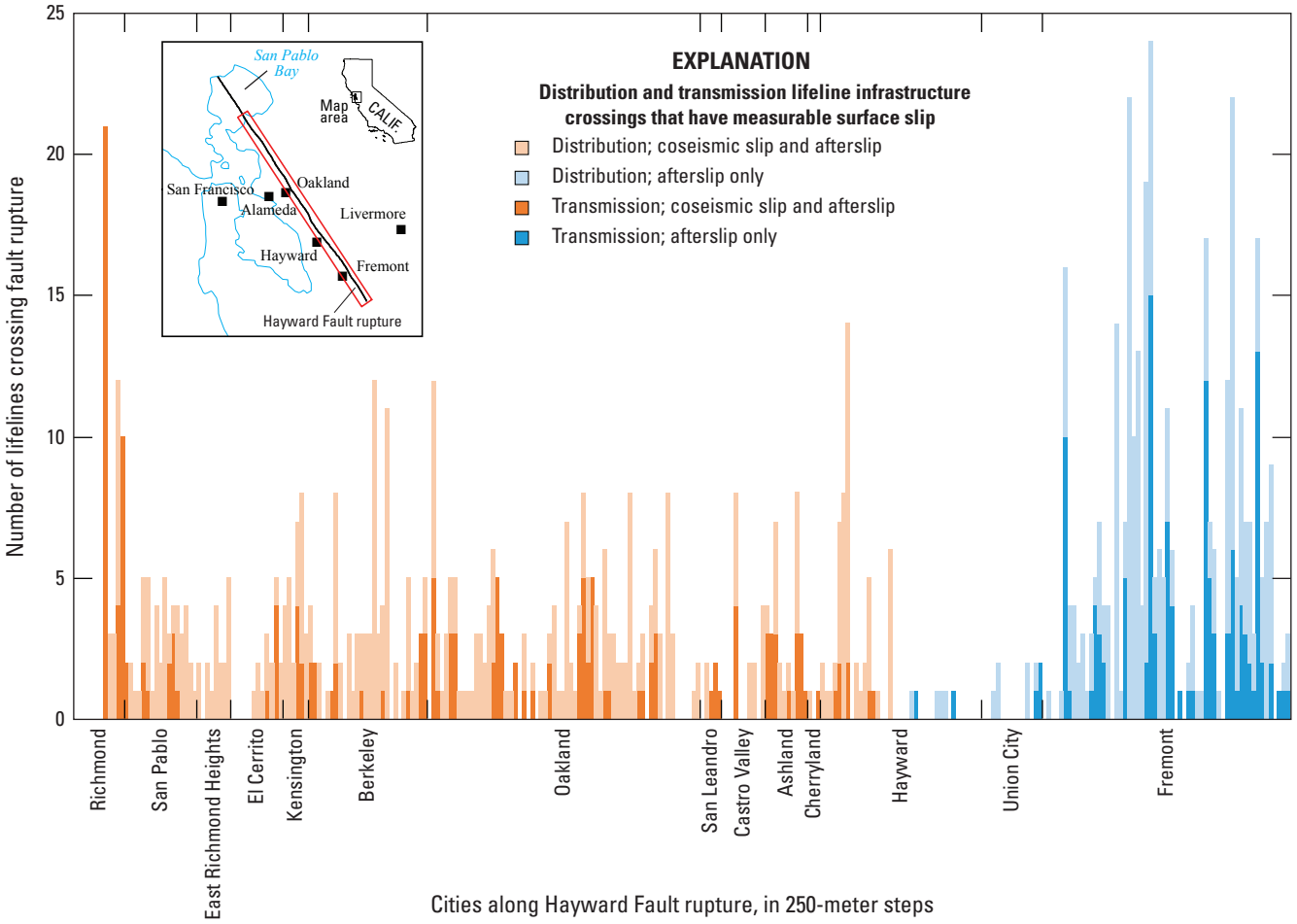


Figure 2.1. Schematic illustration showing the number of lifelines that cross the ruptured length of the Hayward Fault within the HayWired scenario in the San Francisco Bay region, California. Lifelines are shown in 250-meter segments. The chart reads from San Pablo Bay at the northwestern edge of the fault rupture (left) to Fremont at the southeastern edge of the fault rupture (right). Segments colored blue are potentially only affected by surface slip as a result of afterslip in the days, weeks, and months following the HayWired scenario mainshock; segments colored orange are affected by surface slip as a result of coseismic slip as well as afterslip.

Table 2.2. Exposure of transportation infrastructure to HayWired earthquake scenario hazards in the San Francisco Bay region, California.

[Exposure is detailed by amount (kilometers or number of facilities) and percentage (relative to the entire study region) of affected infrastructure. Owing to rounding, amounts and percentages within exposure classes for an individual hazard may not add up to the total exposed. BART, Bay Area Rapid Transit; km, kilometers; %, percent]

Total in study area	Roadways, highway (km)	Roadways, secondary (km)	Roadways, surface (km)	Railways (km)	BART facilities	Highway bridges	Ports
Mainshock ground shaking							
Low exposure	1,989	7,595	30,699	916	8	1,361	90
Percentage exposed	43%	46%	44%	34%	17%	39%	13%
Moderate exposure	2,267	7,621	34,233	1,607	33	1,867	586
Percentage exposed	49%	47%	49%	59%	70%	53%	84%
High exposure	368	1,138	4,967	203	6	292	20
Percentage exposed	8%	7%	7%	7%	13%	8%	3%
Total exposure	4,624	16,353	69,899	2,726	47	3,520	696
Percentage exposed	100%	100%	100%	100%	100%	100%	100%
Liquefaction							
Low exposure	522	2,095	8,189	291	12	549	10
Percentage exposed	11%	13%	12%	11%	26%	16%	1%
Moderate exposure	633	2,102	7,836	400	21	550	14
Percentage exposed	14%	13%	11%	15%	45%	16%	2%
High exposure	179	314	1,523	90	1	171	45
Percentage exposed	4%	2%	2%	3%	2%	5%	6%
Total exposure	1,334	4,511	17,548	781	34	1,270	69
Percentage exposed	29%	28%	25%	29%	72%	36%	10%
Landslide							
Low exposure	306	1,022	4,418	180	12	558	2
Percentage exposed	7%	6%	6%	7%	26%	16%	<1%
Moderate exposure	14	54	233	8	0	82	0
Percentage exposed	<1%	<1%	<1%	<1%	0%	2%	0%
High exposure	7	42	276	5	0	20	1
Percentage exposed	<1%	<1%	<1%	<1%	0%	1%	<1%
Total exposure	327	1,118	4,927	193	12	660	3
Percentage exposed	7%	7%	7%	7%	26%	19%	<1%
Fire following earthquake							
Percentage developed[1]	78%	67%	65%	56%	100%	87%	17%
Low exposure	737	2,747	10,847	328	14	712	5
Percentage exposed	16%	17%	16%	12%	30%	20%	1%
Moderate exposure	144	541	1,883	82	12	194	3
Percentage exposed	3%	3%	3%	3%	26%	6%	<1%
High exposure	47	151	777	40	3	31	2
Percentage exposed	1%	1%	1%	1%	6%	1%	<1%
Total exposure	928	3,439	13,507	450	29	937	10
Percentage exposed	20%	21%	19%	17%	62%	27%	1%

Table 2.2.—Continued

Total in study area	Roadways, highway (km)	Roadways, secondary (km)	Roadways, surface (km)	Railways (km)	BART facilities	Highway bridges	Ports
Aftershocks							
3 months[2]	150	405	2,097	54	0	104	3
1 year[3]	392	1,271	4,966	150	0	362	2
Total exposed[4]	303	1,025	4,363	105	0	294	3
Percentage exposed	7%	6%	6%	4%	0%	8%	<1%

[1]Percentage developed refers to the percentage of an individual lifeline infrastructure system found in areas classified as low-, moderate-, or high-intensity developed land by the 2011 National Land Cover Database.

[2]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks of magnitude (*M*) 5 or greater during the first three months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a *M*5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a *M*5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a *M*5.3 event with a hypocenter in Palo Alto on July 1, 2018, at 11:19 a.m.

[3]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks *M*5 or greater between 3 and 12 months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a *M*6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a *M*5.4 event with a hypocenter in Sunnyvale on October 1, 2018, at 2:24 a.m.

[4]Total exposed to aftershocks is the count of exposed lifeline infrastructure length or facilities affected by at least moderate shaking from one or more aftershocks (regardless of the number of aftershocks to which the lifeline infrastructure are exposed).

Table 2.3. Exposure of water supply and wastewater infrastructure to HayWired earthquake scenario hazards in the San Francisco Bay region, California.

[Exposure is detailed by amount (kilometers or number of facilities) and percentage (relative to the entire study region) of affected infrastructure. Owing to rounding, amounts and percentages within exposure classes for an individual hazard may not add up to the total exposed. km, kilometers; %, percent]

Total in study area	Transmission conveyance systems (km)	Dams	Drinking-water sources	Drinking-water treatment plants	Wastewater treatment plants
Mainshock ground shaking					
Low exposure	305	75	2,115	1,205	33
Percentage exposed	35%	55%	58%	65%	36%
Moderate exposure	488	48	1,459	608	54
Percentage exposed	56%	35%	40%	33%	59%
High exposure	85	14	74	44	5
Percentage exposed	10%	10%	2%	2%	5%
Total exposure	879	137	3,648	1,857	92
Percentage exposed	100%	100%	100%	100%	100%
Liquefaction					
Low exposure	78	9	242	65	9
Percentage exposed	9%	7%	7%	4%	10%
Moderate exposure	87	2	203	43	15
Percentage exposed	10%	1%	6%	2%	16%
High exposure	8	7	8	0	8
Percentage exposed	1%	5%	<1%	0%	9%
Total exposure	173	18	453	108	32
Percentage exposed	20%	13%	12%	6%	35%

Table 2.3.—Continued

Total in study area	Transmission conveyance systems (km)	Dams	Drinking-water sources	Drinking-water treatment plants	Wastewater treatment plants
			Landslide		
Low exposure	76	12	57	36	2
Percentage exposed	9%	9%	2%	2%	2%
Moderate exposure	13	5	4	15	0
Percentage exposed	1%	4%	<1%	1%	0%
High exposure	21	2	7	26	0
Percentage exposed	2%	1%	<1%	1%	0%
Total exposure	110	19	68	77	2
Percentage exposed	13%	14%	2%	4%	2%
			Fire following earthquake		
Percentage developed[1]	28%	40%	54%	40%	76%
Low exposure	63	8	195	44	19
Percentage exposed	7%	6%	5%	2%	21%
Moderate exposure	3	4	19	11	1
Percentage exposed	<1%	3%	1%	1%	1%
High exposure	2	3	1	0	0
Percentage exposed	<1%	2%	<1%	0%	0%
Total exposure	68	15	215	55	20
Percentage exposed	8%	11%	6%	3%	22%
			Aftershocks		
3 months[2]	44	1	37	17	4
1 year[3]	54	2	160	42	5
Total exposed[4]	39	3	140	32	2
Percentage exposed	4%	2%	4%	2%	2%

[1]Percentage developed refers to the percentage of an individual lifeline infrastructure system found in areas classified as low-, moderate-, or high-intensity developed land by the 2011 National Land Cover Database.

[2]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks of magnitude (*M*) 5 or greater during the first three months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a *M*5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a *M*5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a *M*5.3 event with a hypocenter in Palo Alto on July 1, 2018, at 11:19 a.m.

[3]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks *M*5 or greater between 3 and 12 months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a *M*6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a *M*5.4 event with a hypocenter in Sunnyvale on October 1, 2018, at 2:24 a.m.

[4]Total exposed to aftershocks is the count of exposed lifeline infrastructure length or facilities affected by at least moderate shaking from one or more aftershocks (regardless of the number of aftershocks to which the lifeline infrastructure are exposed).

Table 2.4. Exposure of oil and gas infrastructure to HayWired earthquake scenario hazards in the San Francisco Bay region, California.

[Exposure is detailed by amount (kilometers or number of facilities) and percentage (relative to the entire study region) of affected infrastructure. Owing to rounding, amounts and percentages within exposure classes for an individual hazard may not add up to the total exposed. km, kilometers; POL, petroleum, oil, and lubricants; %, percent]

Total in study area	Pipelines, natural gas (km)	Pipelines, petroleum (km)	Natural gas compressor stations	Natural gas processing plants	Natural gas receipt and delivery points	Natural gas storage facilities	POL terminals, storage facilities, tank farms	Oil refineries
Mainshock ground shaking								
Low exposure	3,237	598	7	0	0	2	3	0
Percentage exposed	42%	26%	21%	0%	0%	33%	8%	0%
Moderate exposure	4,021	1,532	22	0	2	4	32	4
Percentage exposed	52%	66%	65%	0%	100%	67%	89%	80%
High exposure	416	205	5	0	0	0	1	1
Percentage exposed	5%	9%	15%	0%	0%	0%	3%	20%
Total exposure	7,674	2,336	34	0	2	6	36	5
Percentage exposed	100%	100%	100%	100%	100%	100%	100%	100%
Liquefaction								
Low exposure	685	137	3	0	0	0	1	0
Percentage exposed	9%	6%	9%	0%	0%	0%	3%	0%
Moderate exposure	781	398	2	0	0	0	5	0
Percentage exposed	10%	17%	6%	0%	0%	0%	14%	0%
High exposure	92	81	3	0	0	0	12	1
Percentage exposed	1%	3%	9%	0%	0%	0%	33%	20%
Total exposure	1,558	616	8	0	0	0	18	1
Percentage exposed	20%	26%	24%	0%	0%	0%	50%	20%
Landslide								
Low exposure	263	118	1	0	0	0	0	0
Percentage exposed	3%	5%	3%	0%	0%	0%	0%	0%
Moderate exposure	14	8	0	0	0	0	0	0
Percentage exposed	<1%	<1%	0%	0%	0%	0%	0%	0%
High exposure	16	8	0	0	0	0	0	0
Percentage exposed	<1%	<1%	0%	0%	0%	0%	0%	0%
Total exposure	293	134	1	0	0	0	0	0
Percentage exposed	4%	6%	3%	0%	0%	0%	0%	0%

Table 2.4.—Continued

Total in study area	Pipelines, natural gas (km)	Pipelines, petroleum (km)	Natural gas compressor stations	Natural gas processing plants	Natural gas receipt and delivery points	Natural gas storage facilities	POL terminals, storage facilities, tank farms	Oil refineries
Fire following earthquake								
Percentage developed[1]	42%	46%	74%	0%	100%	33%	94%	100%
Low exposure	753	313	6	0	0	0	9	2
Percentage exposed	10%	13%	18%	0%	0%	0%	25%	40%
Moderate exposure	75	27	0	0	0	0	0	0
Percentage exposed	1%	1%	0%	0%	0%	0%	0%	0%
High exposure	30	22	1	0	0	0	0	0
Percentage exposed	<1%	1%	3%	0%	0%	0%	0%	0%
Total exposure	858	362	7	0	0	0	9	2
Percentage exposed	11%	15%	21%	0%	0%	0%	25%	40%
Aftershocks								
3 months[2]	145	0	0	0	0	0	0	0
1 year[3]	331	0	0	0	0	0	1	0
Total exposed[4]	244	0	0	0	0	0	1	0
Percentage exposed	3%	0%	0%	0%	0%	0%	3%	0%

[1]Percentage developed refers to the percentage of an individual lifeline infrastructure system found in areas classified as low-, moderate-, or high-intensity developed land by the 2011 National Land Cover Database.

[2]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks of magnitude (*M*) 5 or greater during the first three months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a *M*5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a *M*5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a *M*5.3 event with a hypocenter in Palo Alto on July 1, 2018, at 11:19 a.m.

[3]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks *M*5 or greater between 3 and 12 months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a *M*6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a *M*5.4 event with a hypocenter in Sunnyvale on October 1, 2018, at 2:24 a.m.

[4]Total exposed to aftershocks is the count of exposed lifeline infrastructure length or facilities affected by at least moderate shaking from one or more aftershocks (regardless of the number of aftershocks to which the lifeline infrastructure are exposed).

Table 2.5. Exposure of electric power infrastructure to HayWired earthquake scenario hazards in the San Francisco Bay region, California.

[Exposure is detailed by amount (kilometers or number of facilities) and percentage (relative to the entire study region) of affected infrastructure. Owing to rounding, amounts and percentages within exposure classes for an individual hazard may not add up to the total exposed. km, kilometers; %, percent]

Total in study area	Transmission lines (km)	Electric power generation plants	Energy distribution control facilities	Substations
Mainshock ground shaking				
Low exposure	6,474	99	0	407
Percentage exposed	48%	38%	0%	40%
Moderate exposure	6,169	141	1	537
Percentage exposed	46%	55%	100%	53%
High exposure	769	18	0	63
Percentage exposed	6%	7%	0%	6%
Total exposure	13,413	258	1	1,007
Percentage exposed	100%	100%	100%	100%
Liquefaction				
Low exposure	671	25	0	100
Percentage exposed	5%	10%	0%	10%
Moderate exposure	783	42	0	107
Percentage exposed	6%	16%	0%	11%
High exposure	144	12	0	33
Percentage exposed	1%	5%	0%	3%
Total exposure	1,598	79	0	240
Percentage exposed	12%	31%	0%	24%
Landslide				
Low exposure	611	6	0	25
Percentage exposed	5%	2%	0%	2%
Moderate exposure	91	0	0	0
Percentage exposed	1%	0%	0%	0%
High exposure	123	0	0	1
Percentage exposed	1%	0%	0%	<1%
Total exposure	825	6	0	26
Percentage exposed	6%	2%	0%	3%
Fire following earthquake				
Percentage developed[1]	24%	70%	0%	73%
Low exposure	601	44	0	132
Percentage exposed	4%	17%	0%	13%
Moderate exposure	28	2	0	10
Percentage exposed	<1%	1%	0%	1%
High exposure	23	3	0	7
Percentage exposed	<1%	1%	0%	1%
Total exposure	652	49	0	149
Percentage exposed	5%	19%	0%	15%

Table 2.5.—Continued

Total in study area	Transmission lines (km)	Electric power generation plants	Energy distribution control facilities	Substations
		Aftershocks		
3 months[2]	200	12	0	39
1 year[3]	502	19	0	76
Total exposed[4]	358	18	0	59
Percentage exposed	3%	7%	0%	6%

[1]Percentage developed refers to the percentage of an individual lifeline infrastructure system found in areas classified as low-, moderate-, or high-intensity developed land by the 2011 National Land Cover Database.

[2]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks of magnitude (*M*) 5 or greater during the first three months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a *M*5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a *M*5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a *M*5.3 event with a hypocenter in Palo Alto on July 1, 2018, at 11:19 a.m.

[3]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks *M*5 or greater between 3 and 12 months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a *M*6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a *M*5.4 event with a hypocenter in Sunnyvale on October 1, 2018, at 2:24 a.m.

[4]Total exposed to aftershocks is the count of exposed lifeline infrastructure length or facilities affected by at least moderate shaking from one or more aftershocks (regardless of the number of aftershocks to which the lifeline infrastructure are exposed).

Table 2.6. Exposure of telecommunications infrastructure to HayWired earthquake scenario hazards in the San Francisco Bay region, California.

[Exposure is detailed by amount (kilometers or number of facilities) and percentage (relative to the entire study region) of affected infrastructure. Owing to rounding, amounts and percentages within exposure classes for an individual hazard may not add up to the total exposed. km, kilometers; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Total in study area	Fiber routes, long-haul (km)	Fiber routes, interoffice (km)	Cellular sites	Fiber-lit buildings, data centers	Fiber-lit buildings, central offices	Fiber-lit buildings, point of presence	Wireless switch offices	Internet exchange points	Microwave towers	AM radio antennas	FM radio antennas	NTSC television transmitters	Digital television transmitters
Mainshock ground shaking													
Low exposure	2,270	12,649	2,744	17	204	8,902	11	0	1,297	27	218	31	20
Percentage exposed	38%	27%	33%	4%	30%	22%	21%	0%	34%	35%	67%	84%	39%
Moderate exposure	3,025	27,943	4,471	345	436	26,677	39	8	2,192	45	96	6	31
Percentage exposed	50%	60%	54%	81%	65%	66%	74%	73%	58%	58%	29%	16%	61%
High exposure	754	6,200	1,096	66	33	5,149	3	3	318	6	12	0	0
Percentage exposed	12%	13%	13%	15%	5%	13%	6%	27%	8%	8%	4%	0%	0%
Total exposure	6,049	46,793	8,311	428	673	40,728	53	11	3,807	78	326	37	51
Percentage exposed	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Liquefaction													
Low exposure	680	5,934	1,392	205	135	10,144	9	9	612	11	2	0	0
Percentage exposed	11%	13%	17%	48%	20%	25%	17%	82%	16%	14%	1%	0%	0%
Moderate exposure	1,495	7,134	1,581	173	151	12,064	11	2	609	5	6	0	0
Percentage exposed	25%	15%	19%	40%	22%	30%	21%	18%	16%	6%	2%	0%	0%
High exposure	260	1,064	389	11	5	2,516	0	0	220	11	0	0	0
Percentage exposed	4%	2%	5%	3%	1%	6%	0%	0%	6%	14%	0%	0%	0%
Total exposure	2,435	14,132	3,362	389	291	24,724	20	11	1,441	27	8	0	0
Percentage exposed	40%	30%	40%	91%	43%	61%	38%	100%	38%	35%	2%	0%	0%

Table 2.6.—Continued

Total in study area	Fiber routes, long-haul (km)	Fiber routes, interoffice (km)	Cellular sites	Fiber-lit buildings, data centers	Fiber-lit buildings, central offices	Fiber-lit buildings, point of presence	Wireless switch offices	Internet exchange points	Microwave towers	AM radio antennas	FM radio antennas	NTSC television transmitters	Digital television transmitters
Landslide													
Low exposure	889	5,356	690	1	41	3,078	1	0	261	2	17	2	3
Percentage exposed	15%	11%	8%	<1%	6%	8%	2%	0%	7%	3%	5%	5%	6%
Moderate exposure	22	549	33	0	0	37	0	0	21	0	2	0	0
Percentage exposed	<1%	1%	<1%	0%	0%	<1%	0%	0%	1%	0%	1%	0%	0%
High exposure	14	816	13	0	0	32	0	0	18	0	0	0	0
Percentage exposed	<1%	2%	<1%	0%	0%	<1%	0%	0%	<1%	0%	0%	0%	0%
Total exposure	925	6,721	736	1	41	3,147	1	0	300	2	19	2	3
Percentage exposed	15%	14%	9%	<1%	6%	8%	2%	0%	8%	3%	6%	5%	6%
Fire following earthquake													
Percentage developed[1]	63%	60%	73%	98%	95%	95%	96%	100%	66%	22%	18%	11%	27%
Low exposure	1,029	7,882	2,054	287	158	14,650	11	8	905	9	7	0	0
Percentage exposed	17%	17%	25%	67%	23%	36%	21%	73%	24%	12%	2%	0%	0%
Moderate exposure	287	1,284	251	3	38	2,264	1	0	111	0	2	0	0
Percentage exposed	5%	2%	3%	1%	6%	6%	2%	0%	3%	0%	1%	0%	0%
High exposure	254	409	119	0	9	540	0	0	40	0	2	0	0
Percentage exposed	4%	1%	1%	0%	1%	1%	0%	0%	1%	0%	1%	0%	0%
Total exposure	1,570	9,575	2,424	290	205	17,454	12	8	1,056	9	11	0	0
Percentage exposed	26%	20%	29%	68%	30%	43%	23%	73%	28%	12%	3%	0%	0%

Table 2.6.—Continued

Total in study area	Fiber routes, long-haul (km)	Fiber routes, interoffice (km)	Cellular sites	Fiber-lit buildings, data centers	Fiber-lit buildings, central offices	Fiber-lit buildings, point of presence	Wireless switch offices	Internet exchange points	Microwave towers	AM radio antennas	FM radio antennas	NTSC television transmitters	Digital television transmitters
						Aftershocks							
3 months[2]	92	1,866	461	108	27	3,785	1	4	203	3	2	0	0
1 year[3]	221	4,353	1,322	226	71	10,363	7	8	596	2	5	0	0
Total exposed[4]	144	3,108	917	236	59	7,000	5	5	439	1	6	0	0
Percentage exposed	2%	7%	11%	55%	9%	17%	9%	45%	12%	1%	2%	0%	0%

[1]Percentage developed refers to the percentage of an individual lifeline infrastructure system found in areas classified as low-, moderate-, or high-intensity developed land by the 2011 National Land Cover Database.

[2]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks of magnitude (*M*) 5 or greater during the first three months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a *M*5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a *M*5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a *M*5.3 event with a hypocenter in Palo Alto on July 1, 2018, at 11:19 a.m.

[3]This count includes the lifeline infrastructure length or facility count exposed to all aftershocks *M*5 or greater between 3 and 12 months after the HayWired scenario mainshock. If a lifeline is exposed to multiple aftershocks, it is counted each time it is exposed. Aftershocks included in this category are a *M*6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a *M*6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a *M*5.4 event with a hypocenter in Sunnyvale on October 1, 2018, at 2:24 a.m.

[4]Total exposed to aftershocks is the count of exposed lifeline infrastructure length or facilities affected by at least moderate shaking from one or more aftershocks (regardless of the number of aftershocks to which the lifeline infrastructure are exposed).

Table 2.7. Amount of lifeline infrastructure exposed to only two hazards for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[In all areas of the study region, ground shaking is present, therefore all results include some level of ground shaking. In each column, the total number of kilometers (km) or facilities is shown. The "1+ high" column indicates the total amount of infrastructure from the "Total" column exposed to at least one hazard with a high classification. The results in this table are exclusive and can be considered with the numbers in table 9 of the main text, which summarizes the exposure of lifeline infrastructure to shaking and coincidence with two or more additional hazards. km, kilometers; BART, Bay Area Rapid Transit; POL, petroleum, oil, and lubricants; AM, amplitude modulation; FM, frequency modulation; NTSC, National Television System Committee]

Lifeline	Study area total	Ground shaking and landslide		Ground shaking and liquefaction		Ground shaking and fire	
		Total	1+ high	Total	1+ high	Total	1+ high
Transportation							
Roadways, highway (km)	4,624	47	19	557	105	158	19
Roadways, secondary (km)	16,353	262	120	1,645	253	602	42
Roadways, surface (km)	69,899	1,594	767	7,066	1,250	2,936	289
Railways (km)	2,726	25	12	372	84	51	6
BART facilities	47	0	0	9	1	5	0
Highway bridges	3,520	53	25	399	65	143	5
Ports	696	1	0	61	41	2	1
Water supply and wastewater							
Transmission conveyance systems (km)	879	82	46	104	24	20	0
Dams	137	10	6	10	2	12	2
Drinking-water sources	3,648	29	10	241	21	9	0
Drinking-water treatment plants	1,857	64	45	81	7	23	0
Wastewater treatment plants	92	1	0	23	8	11	1
Oil and gas							
Pipelines, natural gas (km)	7,674	103	58	828	108	154	10
Pipelines, petroleum (km)	2,336	61	33	345	75	102	8
Natural gas compressor stations	34	0	0	4	3	2	0
Natural gas processing plants	0	0	0	0	0	0	0
Natural gas receipt and delivery points	2	0	0	0	0	0	0
Natural gas storage facilities	6	0	0	0	0	0	0
POL terminals, storage facilities, tank farms	36	0	0	10	7	1	0
Oil refineries	5	0	0	0	0	1	0
Electric power							
Transmission lines (km)	13,413	623	339	970	223	130	14
Electric power generation plants	258	0	0	39	10	8	2
Energy distribution control facilities	1	0	0	0	0	0	0
Substations	1,007	4	4	128	30	34	7

Table 2.7.—Continued

Lifeline	Study area total	Ground shaking and landslide		Ground shaking and liquefaction		Ground shaking and fire	
		Total	1+ high	Total	1+ high	Total	1+ high
Telecommunications							
Fiber routes, long-haul (km)	6,049	96	33	929	168	100	11
Fiber routes, interoffice (km)	46,793	4,186	2,260	5,554	1,379	1,347	98
Cellular sites	8,311	205	124	1,216	402	316	24
Fiber-lit buildings, data centers	428	0	0	0	102	1	27
Fiber-lit buildings, central offices	673	2	0	0	121	19	11
Fiber-lit buildings, point of presence	40,728	281	10	156	9,276	474	2,101
Wireless switch offices	53	0	0	8	2	0	0
Internet exchange points	11	0	0	3	2	0	0
Microwave towers	3,807	150	66	513	119	134	8
AM radio antennas	78	0	0	16	8	0	0
FM radio antennas	326	16	7	2	0	4	0
NTSC television transmitters	37	2	0	0	0	0	0
Digital television transmitters	51	3	0	0	0	0	0

Appendix 3. Electric Power Assessment using Hazus-MH

By Jamie L. Jones,[1] Anne M. Wein,[1] and David T. Witkowski[2]

Loss of electrical power can be caused by failure of central generation facilities, like substations, and by physical failure of transmission lines and service delivery lines (through toppling, shear breaks in conduits, stretch breaks in conduits or aerial lines, or physical impacts to aerial lines from trees or other objects). Electrical power in California is primarily generated by burning natural gas (49.9 percent) and from renewables (27.9 percent: biomass, geothermal, small hydroelectric [local hydroelectric systems that generally produce less than 30 megawatts of power], solar, and wind) and the remainder is from nuclear, coal, and hydroelectric sources (California Energy Commission, 2017). These sources are subject to failure either through direct damage or from impacts to the fuel delivery systems. Power is distributed from generation sources via aerial transmission lines to substations, which monitor, route, and control the flow of electricity to voltage transformers (either pole-mounted or located in underground vaults), and ultimately to homes and businesses. Loss of electrical power in distribution can be caused by direct damage to substations, toppling of poles, flooding of underground vaults, breakage of distribution lines, or disconnection at the customer site. For example, during the 2014 South Napa earthquake in California, damage to buildings cut off mainline power to a telephone central office building, requiring the facility to utilize backup generators and batteries to stay online (Noyes, 2014).

Conservatively, no individual electric power generation facility in the San Francisco Bay region produces more than 10 percent of the overall energy use share (M. Germeraad, Metropolitan Transportation Commission and Association of Bay Area Governments, written commun., 2018). However, the northern waterfront in Contra Costa County has a high density of larger power generation facilities.

Ground failure (liquefaction, landslide, and so on) affecting buried systems, rather than shaking damage to aerial poles, is the most likely cause of damage to electric transmission lines. Overhead electric power systems are easier to access and repair than belowground systems; whereas power outages may be more extensive, the time necessary to restore service is typically shorter (Applied Technology Council, 2016). Pacific Gas and Electric Company (PG&E) shared that, for the HayWired scenario as run through their electric distribution damage model, they estimate the work to be evenly distributed between overhead, underground, and services.

Facilities associated with the electric system, however, are susceptible to all earthquake hazards. In addition, facilities using nonrenewable energy sources are more likely to have stronger functional interactions with infrastructure that supplies fuels (for example, natural gas pipelines that feed a natural gas power plant) (M. Germeraad, Metropolitan Transportation Commission and Association of Bay Area Governments, written commun., 2018). Overall, PG&E reported that, in the distribution system, slightly less than half of the damage will result from shaking, followed by damage resulting from ground deformation. Electric power interruption, especially in areas with little to no extensive building damage, has historically been caused by damage to substations (M. Germeraad, Metropolitan Transportation Commission and Association of Bay Area Governments, written commun., 2018).

In terms of restoration, PG&E identified the limitations owing, in part, to access issues and transportation challenges that will occur after the earthquake. In addition, as with all major or catastrophic incidents, restoration timing is driven by resources, materials, and equipment with varying lead times, ability to secure external assistance, and weather impacts. Any restoration estimates provided would likely be affected by any number of factors that are outside of PG&E's control (E. Hickey and G. Molnar, PG&E, written commun., 2019). Aftershocks would be a major concern for employees involved in the restoration effort, and whereas most of the damage would be created by the mainshock scenario, PG&E expects aftershocks and repeated damage assessments would also impact the restoration effort. The overall restoration and assessment would likely be completed within the peripheral areas, as the effort converges towards the most heavily damaged areas (E. Hickey and G. Molnar, PG&E, written commun., 2019).

Service restoration would also be dictated by priorities that were determined by the affected counties to be critical and essential to the local communities. Even though emphasis would be placed on restoring service to the majority of customers as quickly as possible, PG&E would focus its efforts on providing power to critical facilities such as hospitals, water treatment and pumping plants, fire stations, and others. This prioritization would minimize further impact to the affected areas and enable a foundation for first responders to attend to the needs of its affected citizens (E. Hickey and G. Molnar, PG&E, written commun., 2019).

[1] U.S. Geological Survey.

[2] Joint Venture Silicon Valley.

To evaluate interdependencies, substation damage and power outages were estimated by the Federal Emergency Management Agency using its Hazus-MH 2.1 (hereafter referred to as Hazus) loss-estimation application (Federal Emergency Management Agency, 2012). The Hazus results estimate damages to substations resulting from ground shaking and Hazus assessment of the liquefaction hazard (using Knudsen and others, 2000). County power restoration estimates were also estimated using Hazus. Some notes on these results from PG&E are included for comparison to the Hazus analysis.

Results

Hazus results for shaking and liquefaction damages to electric power substations are expressed as the percentage of electric subcomponent failures (table 3.1). Of nearly 1,800 substations analyzed by Hazus, 44 were estimated to have higher than 50 percent subcomponent failure. Most of these substations are located in Alameda and Contra Costa Counties within 5 kilometers of the Hayward Fault, though a small number of substations on one trunk line near the City of Livermore in Alameda County (running north into Contra Costa County) also have estimated subcomponent failure percentages above 50 percent.

Table 3.1. Electric substation analysis groupings and exposure determined using Hazus-MH 2.1.

[Functionality percentages are only estimated for 6 time steps in Hazus: 1-day, 3-day, 7-day, 14-day, 30-day, and 90-day]

Damage class	Description	Number of substations in class	Repair duration, in months[1]
<25 percent	Likely damage restricted to less than 25 percent of substation subcomponents	1,402[2]	0–1.5
25–50 percent	Likely damage between 25 and 50 percent of substation subcomponents	190	0.5–??[3]
50–75 percent	Likely damage between 50 and 75 percent of substation subcomponents	43	1.5–??[3]
>75 percent	Likely damage affects at least 75 percent of substation subcomponents	1	1.5

[1]Repair durations are estimated by referring to the estimated percentage of functionality restored to a substation calculated by Hazus. If the functionality percentage was 99 or higher, the substation was considered repaired.

[2]The number of substations listed here only include those within the hazard extent used for the analyses completed in the body of the lifelines chapter. The total including substations outside this hazard extent is 1,773.

[3]If the estimated functionality percentage was not 99 at the 90-day mark, then no further assumptions could be made about the repair duration and the high range value was listed as "??". This affects 37 substations in the 25–50 percent class (19 percent) and 5 substations in the 50–75 percent class (12 percent).

Table 3.1 also provides an estimate of the repair duration for ranges of subcomponent failure. Functionality percentages are estimated at 6 time steps for each facility: 1 day, 3 days, 7 days, 14 days, 30 days, and 90 days. In addition, Hazus does not assign a full functionality percentage of 100 to any facility. In order to assign repair durations to the substations, the time step at which the substation reached 99 or greater was selected as the duration. For a small number of substations, the functionality percentage was still less than 99 at 90 days (the percentage was between 96 and 98 for all substations in this situation). The unknown restoration times are reflected in table 3.1 using the notation "??". All substations where less than 25 percent of subcomponents were estimated to be damaged would likely be repaired within 90 days of the HayWired scenario mainshock, as would around 80 percent of substations that have between 25 and 50 percent of subcomponents damaged, and around 90 percent of substations that have between 50 and 75 percent of subcomponents damaged. Interestingly, the one substation with greater than 75 percent subcomponent damage is estimated to be repaired within 90 days, whereas some substations with lower subcomponent damage are estimated to take longer than 90 days to be repaired. Though the exact reason for this in the Hazus model is not investigated, it does reflect the fact that different facilities built at different times to different standards would likely fare differently in a major earthquake event.

Table 3.2 shows estimates for the restoration of electric power service to households by county for five time steps: after 1 day, 3 days, 1 week, 1 month, and 3 months. After day 1, Hazus estimates that 1.4 million households (2000 census data) will lose power. According to Hazus, the largest numbers (350,000–360,000) and percentages (25–26 percent) of households are without power on the first day in Alameda and Santa Clara County. Alameda County takes the longest to restore power to 90 percent of its households, with 16.7 percent of households (around 87,400 households) still without power after one week (followed by Santa Clara County at 8.7 percent, or 49,230 households). Santa Clara County has the highest proportion of power restored to households in the first three days, at 33.5 percent (189,564 households). The largest improvements in household power restoration occur in the first three days, but three counties (Alameda, Contra Costa, and Santa Clara) have power restoration percentages between 17 and 23 percent between day 3 and day 7. By the end of the first week after the HayWired scenario mainshock, only 6 percent of households are without power, and by the end of the first month less than 2 percent of households are without power. However, 0.1 percent of households (3,393 households) will potentially still be without power after three months.

Note that the electric power restoration estimates from Hazus are calculated at the census-tract level based on the tract's total population and each substation's power outage probability. Power service outages are assumed to be dependent

Table 3.2. Electric power restoration estimated using Hazus-MH 2.1 for 15 counties for select time steps after the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Numbers in this table represent the percentage of households with power restored for a county]

County	Total number of households	Time since HayWired mainshock				
		1 day	3 days	1 week	1 month	3 months
Alameda	523,366	32	61	83	96	100
Contra Costa	344,129	43	74	91	98	100
Marin	100,650	73	93	99	100	100
Merced	63,815	89	98	100	100	100
Monterey	121,236	94	99	100	100	100
Napa	45,402	89	98	100	100	100
Sacramento	453,602	98	100	100	100	100
San Benito	15,885	63	89	98	100	100
San Francisco	329,700	53	84	97	100	100
San Joaquin	181,629	78	96	100	100	100
San Mateo	254,103	47	79	95	99	100
Santa Clara	565,863	37	70	91	98	100
Santa Cruz	91,139	83	97	100	100	100
Solano	130,403	79	95	99	100	100
Sonoma	172,403	96	100	100	100	100
Stanislaus	145,146	86	98	100	100	100
Yolo	59,375	94	99	100	100	100
Region total	3,597,846	62	83	95	99	100

on the functionality (or lack thereof) of the region's substations. Hazus uses a weighted combination to determine the estimated power restoration/outage for each substation using the probability of subcomponent restoration at each Hazus damage state. The average for each county is established based on the outage percentages for each substation relative to each substation's service area (Federal Emergency Management Agency, 2012). The combination of methods here leads to the possibility that power could be essentially completely restored even though not all substations have been completely restored to full functionality.

Unrelated to the provided Hazus results, PG&E (using their proprietary model) estimate independently that around 700,000 customers would lose power across their customer base as a result of the HayWired scenario mainshock. PG&E's estimates for overall restoration times are consistent with the estimates provided by Hazus, but prior restoration events within PG&E service territories suggest that the majority of restoration effort would come from distribution system damage instead of substation damage. So, despite the fact that substations may be restored in significantly less time than what was stipulated by Hazus, the damage within the distribution system would prevent customers from receiving service until available distribution crews have sufficient time to assess and restore service. It should also be noted that PG&E has 959 substations in its service territory, but Hazus includes substations from other utilities (for example, those owned by local water utility and energy companies) that would also be impacted by the HayWired scenario mainshock (E. Hickey and G. Molnar, PG&E, written commun., 2019).

Comparing Hazus Electric Power Assessment with Chapter Exposure Results

Hazus does not factor in the potential damages resulting from landslide and fire hazards. Figure 3.1 maps Hazus-estimated electric substation subcomponent failure in relation to the ground failure hazard datasets generated in this chapter. Figures 3.2 and 3.3 map estimated substation failure and substation repair time relative to multi-hazard exposure. Around one quarter of the substations analyzed by Hazus are also potentially impacted by landslide or fire following earthquake (refer to table 3.3 for specifics) in addition to shaking and liquefaction. In the HayWired scenario analysis, fire in urban areas is more of a concern than landslides. Fire can affect substations by causing equipment shorts as a result of ash and soot deposition on bushings and buses; however, the standoff distance from the perimeter fence is generally sufficient for protecting substations from radiant heat (C. Scawthorn, SPA Risk LLC, written commun., 2018). Several substations in Berkeley (between 25 and 50 percent subcomponent damage) and Richmond (more than 50 percent subcomponent damage) are also exposed to high fire-following-earthquake intensity. One substation (between 50 and 75 percent subcomponent damage) on the Oakland-Orinda border is exposed to high landslide intensity.

Less than 15 percent of substations that are assigned less than 25 percent subcomponent damage may be affected by hazards other than ground shaking, with liquefaction being the most expansive (approximately 11 percent), followed by fire following earthquake (approximately 5 percent). Over

90 percent of substations that are assigned between 25 and 50 percent subcomponent damage and between 50 and 75 percent subcomponent damage are affected by liquefaction, landslide, or fire following earthquake, with the damages following a similar pattern of hazard exposure as the group with less than 25 percent estimated subcomponent damage. The substation that is assigned more than 75 percent subcomponent damage may potentially be affected by landslides and fire following earthquake.

In general, the pattern of substation damages is consistent with the multi-hazard dataset (see table 3.4 for details). The lowest damage class (substations with less than 25 percent subcomponent damage) has the greatest amount of exposure to low and moderate multi-hazard intensity, and the highest damage class is also in the very high hazard intensity class. The 25 to 50 percent class and the 50 to 75 percent class are mostly exposed to moderate-high or high multi-hazard intensity, where the 25 to 50 percent

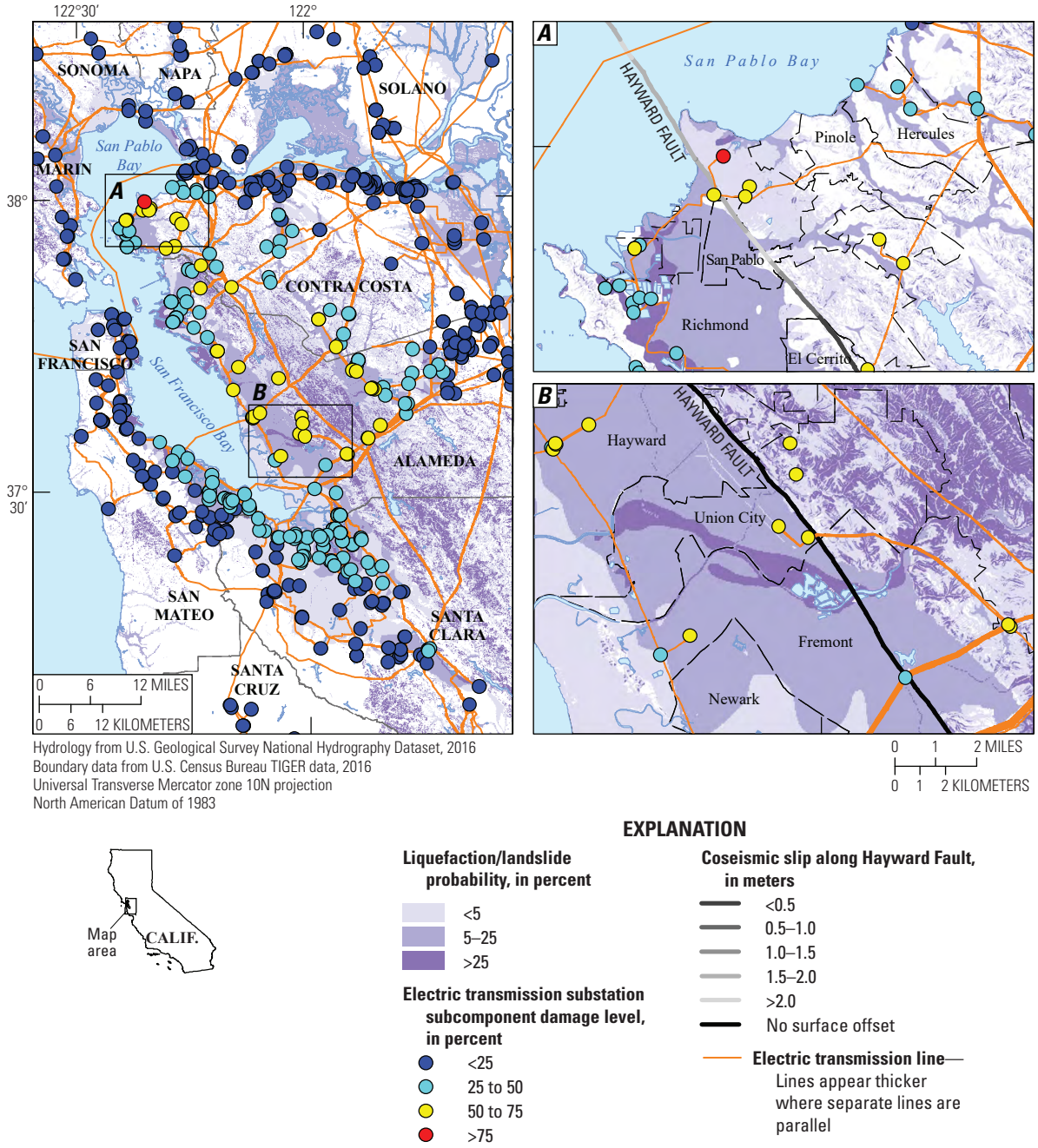


Figure 3.1. Map of the San Francisco Bay region, California, showing the ground failure (coseismic slip, landslide, and liquefaction) exposure of the electric transmission system (electric transmission lines and substations) relative to the electric transmission substation subcomponent damage level estimated by Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) for the HayWired earthquake scenario.

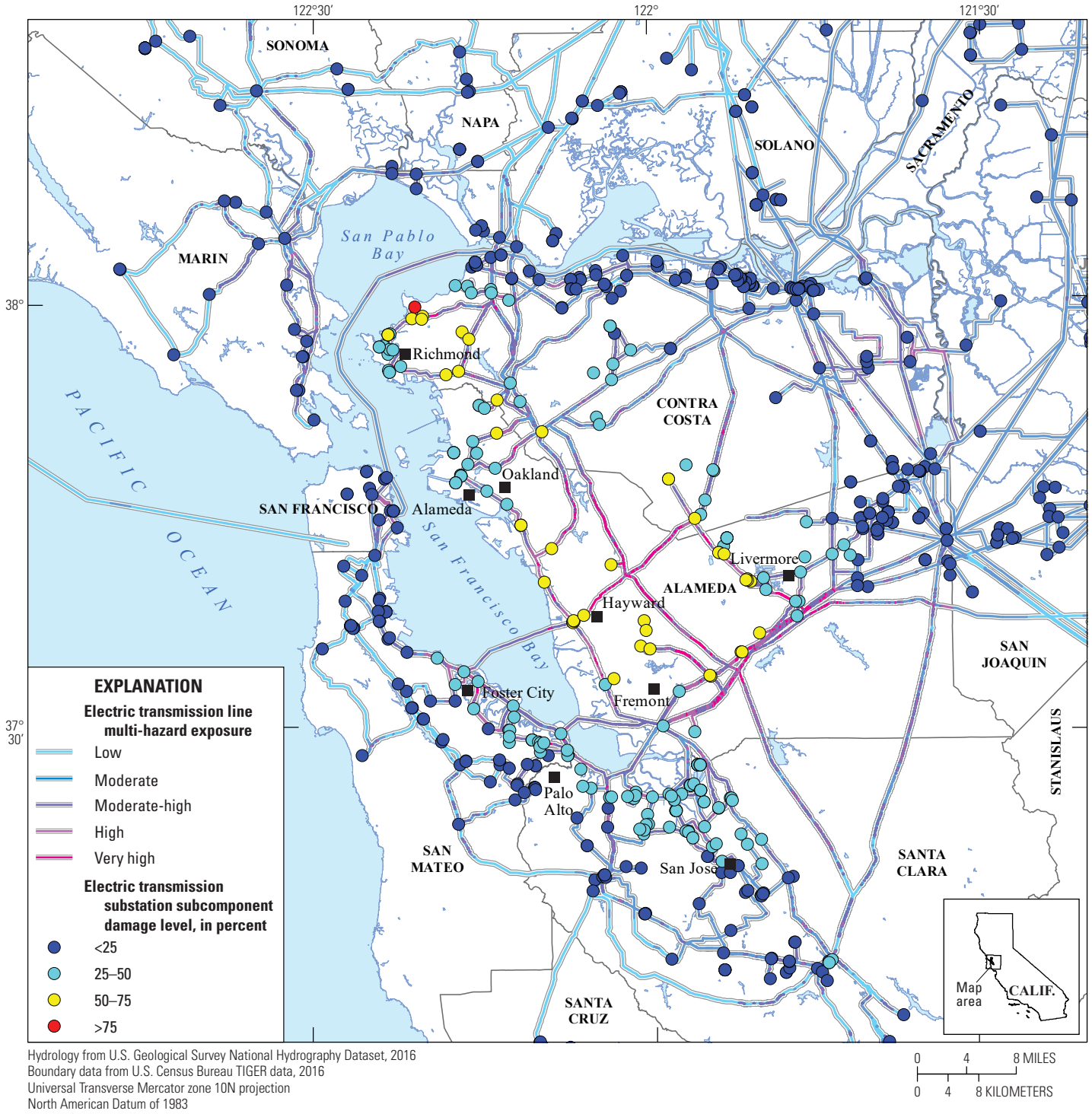


Figure 3.2. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the electric transmission system (electric transmission lines and substations) relative to the electric transmission substation subcomponent damage level estimated by Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) for the HayWired earthquake scenario.

class is proportionally more exposed to the moderate-high multi-hazard class and the 50 to 75 percent class is proportionally more exposed to the high multi-hazard class. A few substations do not fit this pattern, however. More than 5 substations estimated to experience between 25 and 50 percent subcomponent damage are in areas with very high multi-hazard intensity resulting from high shaking and high liquefaction intensity—several of these are in the cities of Menlo Park and Palo Alto in San Mateo and Santa Clara Counties, respectively, and others are in the cities of Hercules

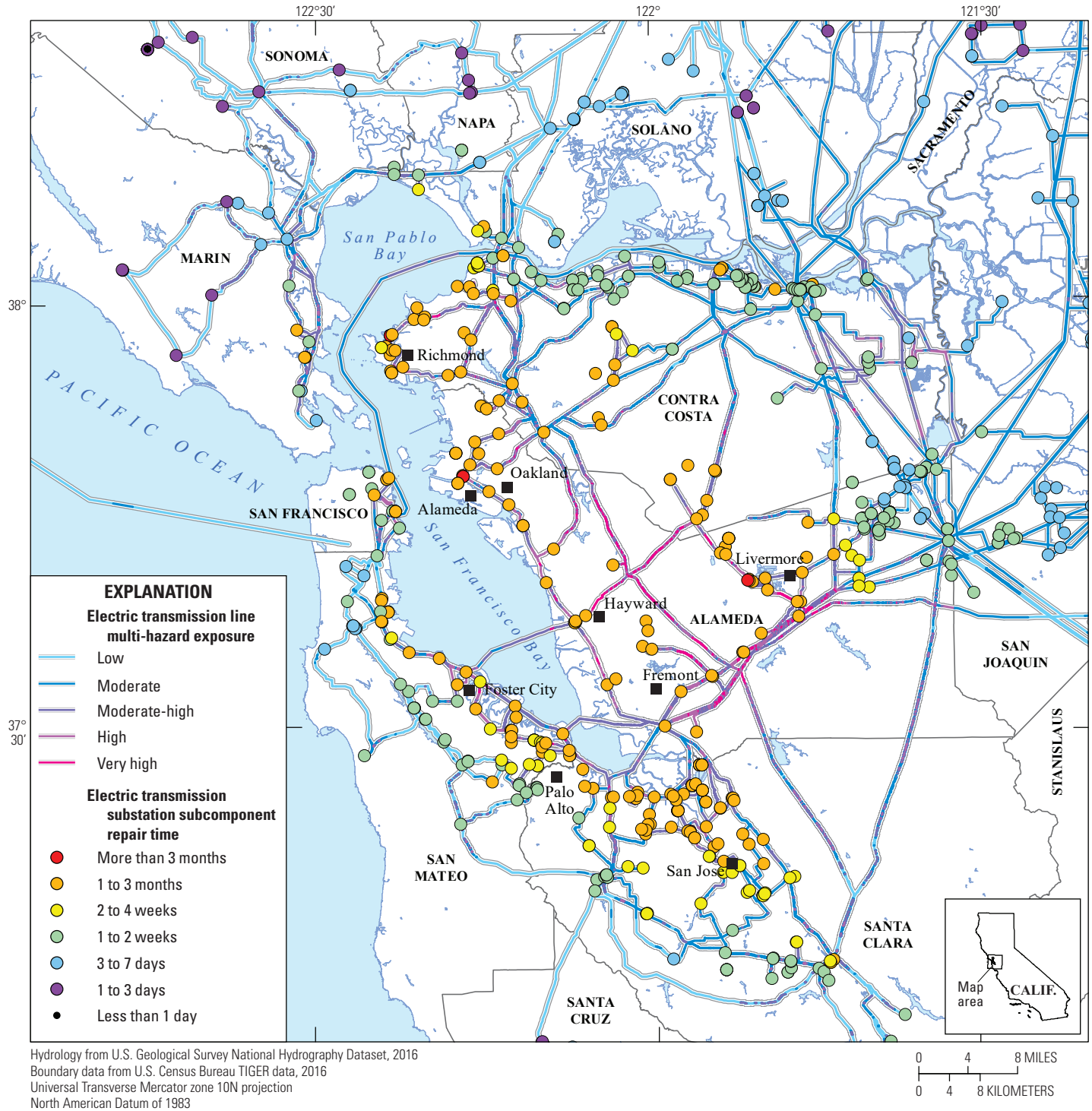


Figure 3.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the electric transmission system (electric transmission lines and substations) relative to the transmission substation repair time estimated by Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) for the HayWired earthquake scenario.

Table 3.3. Summary of electric substation shaking damages estimated using Hazus-MH 2.1 relative to exposure of ground-movement and fire-following-earthquake hazards for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Liquefaction exposure is included because the analysis in this chapter uses an improved liquefaction probability dataset rather than the default Hazus liquefaction analysis, which is reliant on liquefaction susceptibility and tract centroid locations]

Damage class	Description	Coseismic slip	Landslide intensity			Liquefaction intensity			Fire following earthquake intensity		
			Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
<25 percent	Likely damage restricted to less than 25 percent of substation subcomponents	0	4	0	0	75	64	12	76	0	0
25–50 percent	Likely damage between 25 and 50 percent of substation subcomponents	0	18	0	0	41	80	37	80	5	3
50–75 percent	Likely damage between 50 and 75 percent of substation subcomponents	0	21	1	1	3	21	1	16	3	3
>75 percent	Likely damage affects at least 75 percent of substation subcomponents	0	1	0	0	0	0	0	0	0	1
	Total	0	44	1	1	119	165	50	172	8	7

and Richmond in Contra Costa County. A couple of substations with estimated subcomponent damages between 50 and 75 percent are also located in areas with very high multi-hazard intensity, one caused by high shaking and high fire hazards and the other caused by high shaking and high liquefaction hazards; these substations are located in or near the cities of Richmond and Hayward.

Electric Power Interdependencies

PG&E notes dependencies on equipment and material issues, continued aftershocks, and safety concerns. According to Yao and others (2004), several potential additional interdependencies could affect electric power systems. For example, lost power can cause transportation delays and impact fuel and materials distribution, leading to increased difficulty for electric utility repair vehicles to get themselves and their equipment to locations that need restoration. Karagiannis and others (2017) point out that most critical infrastructure rely on electric power to operate, but, in a disaster, some of these infrastructure systems may also be supporting electric power system repairs. As such, electric power recovery is adversely affected by other systems lacking electric power. For example, electric utilities may rely on two-way radios or cellular phones to communicate during a disaster; these telecommunication systems may be significantly less effective when a large-scale power outage occurs, making communication between electric utility workers more difficult (Karagiannis and others, 2017).

Table 3.4. Summary of electric substation shaking damages estimated using Hazus-MH 2.1 relative to multi-hazard exposure intensity classes for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Damage class	Description	Multi-hazard intensity				
		Low	Moderate	Moderate-high	High	Very high
<25 percent	Likely damage restricted to less than 25 percent of substation subcomponents	664	667	60	11	0
25–50 percent	Likely damage between 25 and 50 percent of substation subcomponents	1	45	91	46	7
50–75 percent	Likely damage between 50 and 75 percent of substation subcomponents	0	1	27	12	3
>75 percent	Likely damage affects at least 75 percent of substation subcomponents	0	0	0	0	1
	Total	665	713	178	69	11

Appendix 4. Bay Area Rapid Transit Damage Assessment to HayWired Scenario Ground Shaking

By Mark Salmon,[1] Jamie L. Jones,[2] Anne M. Wein,[2] Laurel R. Ballanti,[2] and Thomas Horton[1]

The Bay Area Rapid Transit (BART) system in the San Francisco Bay region is a major commuter rail system that services areas throughout the east bay and the peninsula, with future expansions planned in the south bay. With annual ridership of around 130 million people in 2016 (Bay Area Rapid Transit, 2017a), BART is a popular transit method for commuters who work on one side of the bay area and live on the other side (for example, live in Oakland and work in San Francisco).

BART ran HayWired ground shaking data through ShakeCast for the original BART system (built between 1966 and 1976), incorporating the seismic retrofits constructed since 2008 as developed by the BART Earthquake Safety Program to enhance the seismic performance of BART. BART extensions (stations and tracks) built in the 1990s or later have been built to a higher seismic design standard (Bay Area Rapid Transit, 2017b), and were thus not included in the BART Earthquake Safety Program. Therefore, analytical fragilities were not developed to analyze facilities in the BART extensions. The ShakeCast results provided damage estimates for 34 stations and 4 train yards run by BART (nine stations were built after 1996 and are not counted in the BART analysis; the new Warm Springs station is not included in this list, nor are the Milpitas and Berryessa stations currently scheduled to open in 2019), as well as the interconnecting tunnels and aerial guideways. The BART results classified the 34 stations, 4 train yards, tunnels, and aerial guideways into one of five damage states: green, yellow, orange, hi-orange, and red (descriptions of the damage states are in table 4.1). Though BART developed a custom analytical fragility curve for each of the stations analyzed, the fragilities for the buildings and facilities at the train yards were based on the default fragility curves from Hazus-MH 2.1 (Federal Emergency Management Agency, 2012).

Table 4.1. Damage state definitions and exposure as determined by Bay Area Rapid Transit's ShakeCast analysis in the San Francisco Bay region, California.

[BART, Bay Area Rapid Transit]

Damage class	Description	Number of stations/yards in class	Repair duration, in months[1]
Green	Likely minor or no damage	20	0
Yellow	Likely operable after short term repairs	10	0.5–6[3]
Orange	Likely not operable, but likely safe	2	3–9
Hi-orange[2]	Likely not operable, but likely safe	5	9–18
Red	Likely unsafe or collapsed	1	24–36[4]

[1]Repair durations in this table are for the stations and yards only. In many cases the interconnecting guideways have longer repair durations, as shown in table 4.3.

[2]Hi-orange is distinguished from orange to help BART prioritize response and repair and indicates a greater degree of damage than orange.

[3]The Rockridge station has a repair time of 3–6 months owing to some parts of the station receiving orange-class damage. The majority of the station is classified as yellow, however, so the station as a whole was classified yellow.

[4]The estimated sequential repair time for the buildings at the Hayward train yard is 42 months, but BART states that all repairs would be completed after no more than 36 months. If repairs are estimated to take longer, multiple contracts would be awarded in order to speed up repairs to within the 36-month time frame.

[1] Bay Area Rapid Transit.

[2] U.S. Geological Survey.

One item to note regarding damage here is that the BART Earthquake Safety Program design objective for most of the original BART system (excluding the "core BART system") is for safety rather than operability, where either the safety design basis earthquake is a probabilistic 500-year return period ground motion (or 10 percent probability of ground motion in 50 years) or the deterministic median ground motion plus one-half standard deviation, whichever is greater. For the core BART system, from Daly City to Rockridge Station and Downtown Berkeley, the BART Earthquake Safety Program design objective also includes operability after short-term repairs, where the operability design-basis earthquake is typically the deterministic median ground motion (except for the Transbay Tube, which is designed for higher ground motions). BART identifies the deterministic ground motion for the core BART system by using estimates of maximum ground motions owing to earthquakes principally on three different faults (Concord, Hayward, and San Andreas Faults).

Results

Twenty BART facilities (stations or train yards; 53 percent) are modeled to experience only minor damage as a result of the HayWired scenario mainshock shaking. Another 10 facilities (26 percent) may experience damage that leaves the facilities operable or almost operable. Seven facilities (18 percent) are modeled to experience severe enough damage to shut the facility down but not be severely enough damaged to be considered unsafe (5 facilities are more severely impacted than the remaining 2 facilities). Only one facility (the Hayward train yard) is expected to experience damage severe enough to require a complete rebuild of some of the buildings at the facility. A summary of the damage states, along with the number of stations and train yards and the range of repair times for each class, can be found in table 4.1.

While performing the ShakeCast analysis of the BART facilities for the HayWired scenario ground motions, BART observed that, in some local areas, the HayWired ground motions were considerably stronger than the BART Earthquake Safety Program design earthquakes, such as near the Hayward train yard, potentially explaining why some of the retrofitted facilities at this yard indicate red damage potential. Likewise, some stations indicate greater damage from the HayWired scenario than would be expected from their design earthquakes, owing to locally higher motions provided by the HayWired scenario.

Facilities classified as green impact potential would be repaired during operation of the facility, whereas facilities classified as yellow impact potential would take only a few weeks to reopen (with the exception of one station with a couple of supports classified as higher damage, which would take around 6 months to reopen). Several stations in Alameda County that run near the Hayward Fault could take as long as 3 years to repair; the more extensive repairs to these stations would potentially cut off one BART line (the BART extension through Castro Valley into Pleasanton) and seriously truncate another (the Fremont line, which now extends into the Warm Springs neighborhood in Fremont and is currently scheduled to extend into Santa Clara County in 2019). Tracks run through the same structure as the stations, so it is possible that tracks could be repaired a bit earlier and the impaired station could be bypassed. System-level damages and repair durations by damage state can be found in table 4.1; station level damages are provided in table 4.2 and station-level repair durations are in table 4.3.

Two of the largest aftershocks in the HayWired scenario earthquake sequence were also run through ShakeCast for the BART system. BART did not have adjusted fragility curves for damaged stations or train yards. Assuming facilities were undamaged, BART found that the potential damages resulting from the two closest aftershocks—in Union City on the same day as the mainshock and in Oakland 33 days after the mainshock—are lower than the mainshock, with the highest damage potential being orange. The majority of potential damages would be along the A-line, which, among other stations, includes the Fruitvale, Coliseum/Oakland Airport, San Leandro, Bay Fair, and Hayward stations (which were classified to have hi-orange mainshock damage) and the Hayward train yard (the only facility with some of its buildings classified red). BART assumes a maximum repair duration of 3 years, with contractors available for mobilization within 50 days. Since these two aftershocks occur within about one month of the mainshock, any resulting damages would not interrupt repairs and any additional damage to stations could be incorporated into initial contracts.

Table 4.2. Results by damage state for Bay Area Rapid Transit stations impacted by ground shaking from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Line code	Station name	Number of principal structural supports or subdivisions by damage state					
		Green	Yellow	Orange	Hi-orange	Red	Total[1]
A-line North	Lake Merritt	1					1
	Fruitvale			2	9		11
	Coliseum		2	2	7		11
	San Leandro				11		11
	Bay Fair			1	10		11
A-line South	Hayward				7		7
	South Hayward			1			1
	Union City		1				1
	Fremont	1					1
C-line	Rockridge		8	2			10
	Orinda		2	4			6
	Lafayette	1					1
	Walnut Creek	1	10				11
	Pleasant Hill/Contra Costa Centre	7	17				24
	Concord	4					4
R-line North	El Cerrito Plaza		10				10
	El Cerrito del Norte	9					9
	Richmond		1				1
R-line South	Ashby		1				1
	Downtown Berkeley		1				1
	North Berkeley	1					1
N. Oak	12th Street/Oakland City Center	1					1
	19th Street/Oakland	1					1
	MacArthur		1				1
W. Oak	West Oakland		11				11
M-Line	Embarcadero	1					1
	Montgomery Street	1					1
	Powell Street	1					1
	Civic Center/UN Plaza	1					1
	16th Street Mission	1					1
	24th Street Mission	1					1
	Glen Park	1					1
	Balboa Park	1					1
	Daly City	9					9

[1]At-grade or underground stations were typically considered as a single unit, whereas aerial stations were subdivided into the number of principal structural supports at each station.

Table 4.3. Repair duration for Bay Area Rapid Transit stations as a result of ground shaking from the HayWired earthquake scenario mainshock in the San Francisco Bay region.

Line code	Station name	Approximate repair duration, in months			
		Yellow to green[1]	Orange and hi-orange to green	Number of repair contracts	Total line segment repair time[2]
A-line North	Lake Merritt			2	24–36
	Fruitvale		12–18		
	Coliseum		12–18		
	San Leandro		12–18		
	Bay Fair		12–18		
	Interconnecting guideways		24–36	3	
A-line South	Hayward		9–12	1	24–36
	South Hayward		3–6		
	Union City	0.5			
	Fremont				
	Interconnecting guideways		24–36	1	
C-line	Rockridge		3–6	1	9–15
	Orinda		6–9		
	Lafayette				
	Walnut Creek	0.5			
	Pleasant Hill/Contra Costa Centre	0.5			
	Concord				
	Interconnecting guideways		9–12	1	
R-line North	El Cerrito Plaza	0.5			6–12
	El Cerrito del Norte				
	Richmond	0.5			
	Interconnecting guideways		6–12	1	
R-line South	Ashby	0.5			0.5–1
	Downtown Berkeley	0.5			
	North Berkeley				
	Interconnecting guideways		0.5–1	1	
N. Oak	12th Street/Oakland City Center				1–2
	19th Street/Oakland				
	MacArthur	0.5			
	Interconnecting guideways		1–2	1	
W. Oak	West Oakland	0.5			0.5–1
	Interconnecting guideways		0.5–1	1	
M-line	Embarcadero				0.5–1
	Montgomery Street				
	Powell Street				
	Civic Center/UN Plaza				
	16th Street Mission				
	24th Street Mission				
	Glen Park				
	Balboa Park				
	Daly City				
	Interconnecting guideways	0.5			

[1]Minor repairs, such as inspections and shoring.

[2]Assumes multiple concurrent repair contracts are issued such that the maximum repair duration is 3 years, and contractors are available for mobilization within 50 days. Some of the repairs involve temporary shoring sufficient to restore operations; permanent repairs or reconstruction may take longer.

Comparing BART Assessment with Chapter Exposure Results

The multi-hazard assessment of all shaking, liquefaction, landslide, slip, and fire following earthquake hazards is described in the body of this chapter. Figure 4.1 shows the BART system shaking damage results relative to ground failure hazards (coseismic slip, landslide, and liquefaction); figure 4.2 presents the multi-hazard intensity for the BART rail system with the damage state for each BART facility on top for comparison; and figure 4.3 couples the multi-hazard intensity with estimates of downtime for repairs. Tables 4.4 and 4.5 compare BART shaking damage states to the single-hazard and multi-hazard intensity classes used in this chapter. BART facilities classified as green generally are not located in areas where other hazards that result from

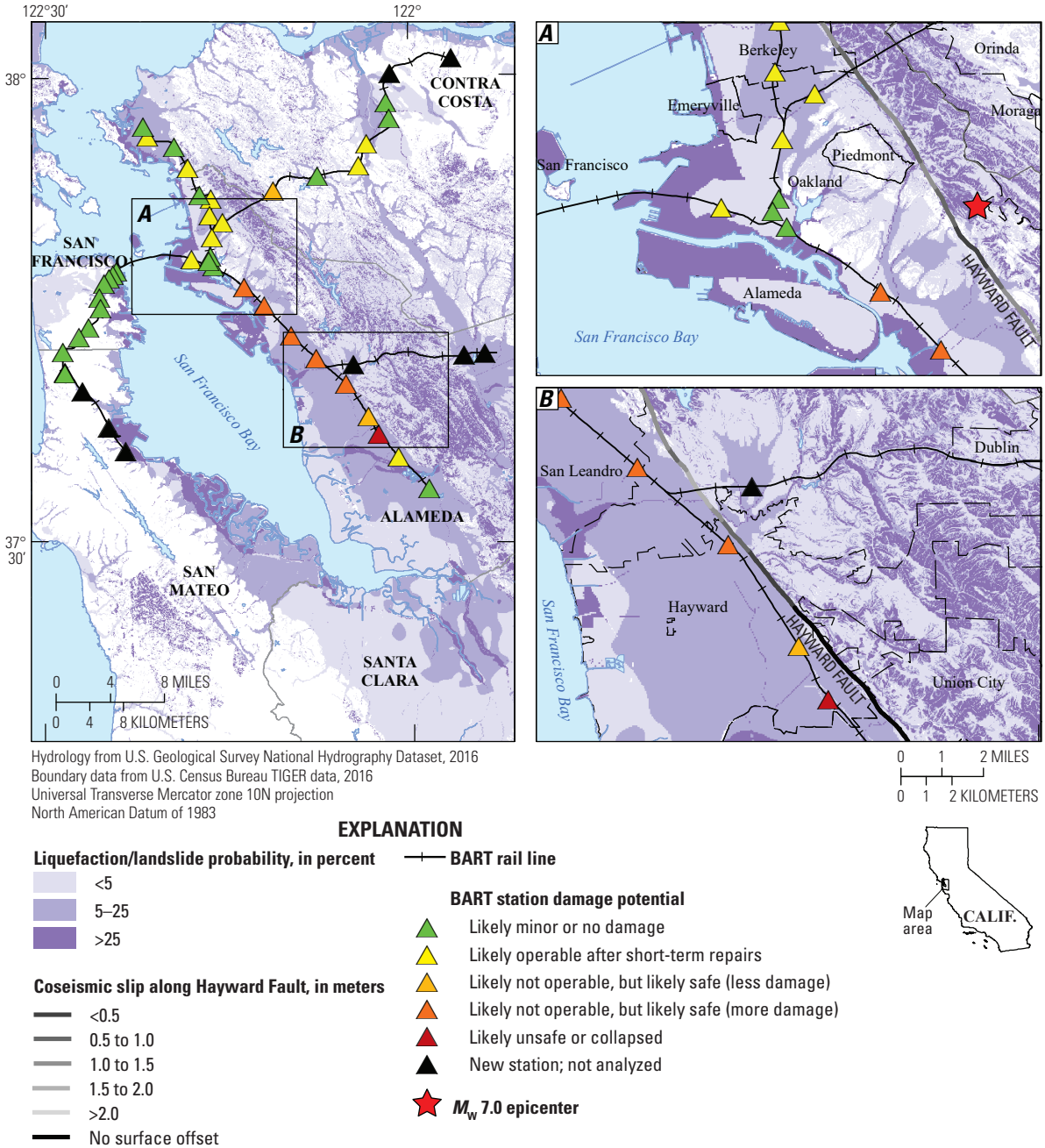


Figure 4.1. Map of the San Francisco Bay region, California, showing the ground failure (coseismic slip, landslide, and liquefaction) exposure of the Bay Area Rapid Transit (BART) system relative to the BART estimated shaking damage potential for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 extensions to Milpitas and Berryessa.

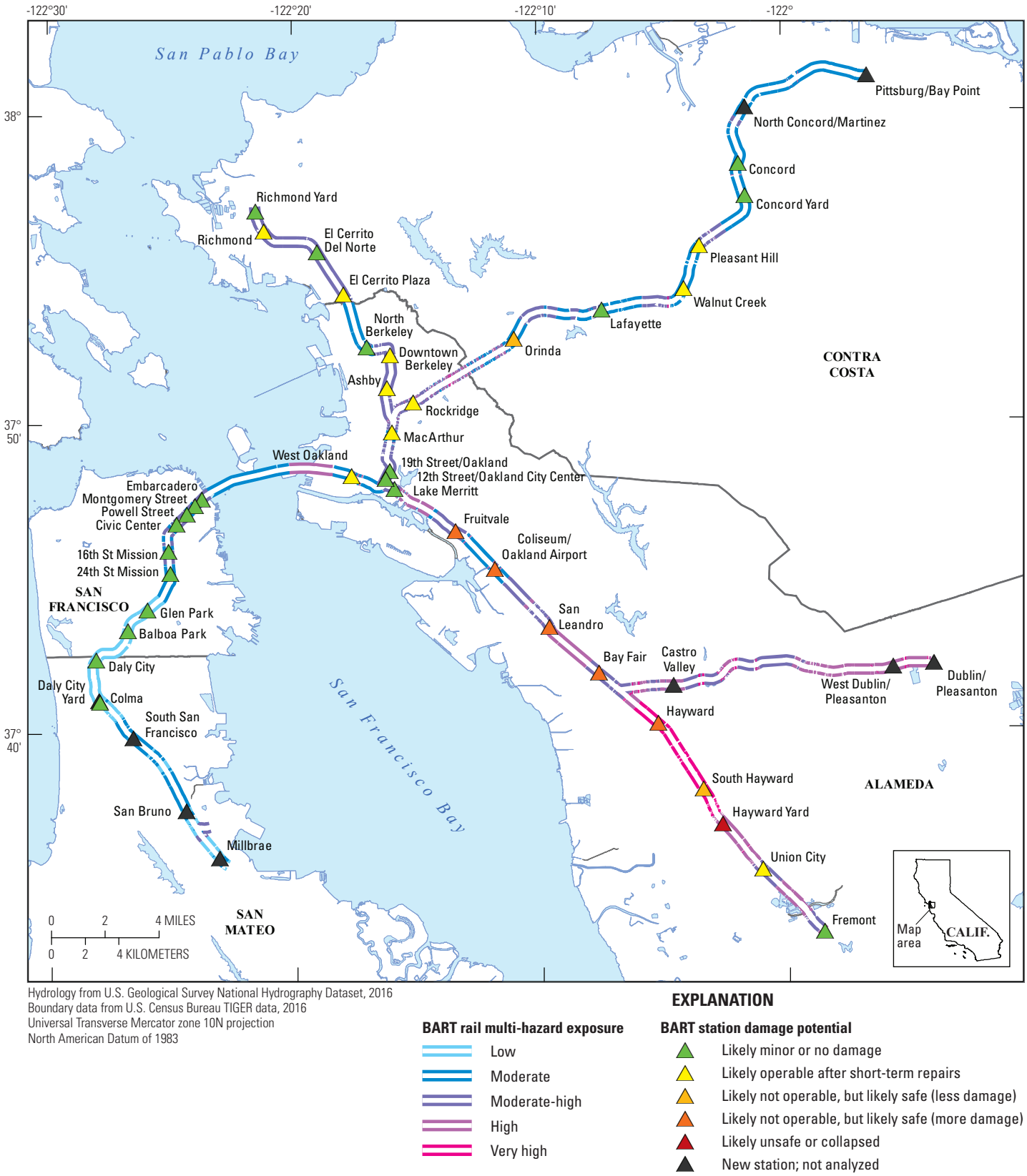


Figure 4.2. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the Bay Area Rapid Transit (BART) system relative to the BART-estimated shaking damage potential for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 extensions to Milpitas and Berryessa.

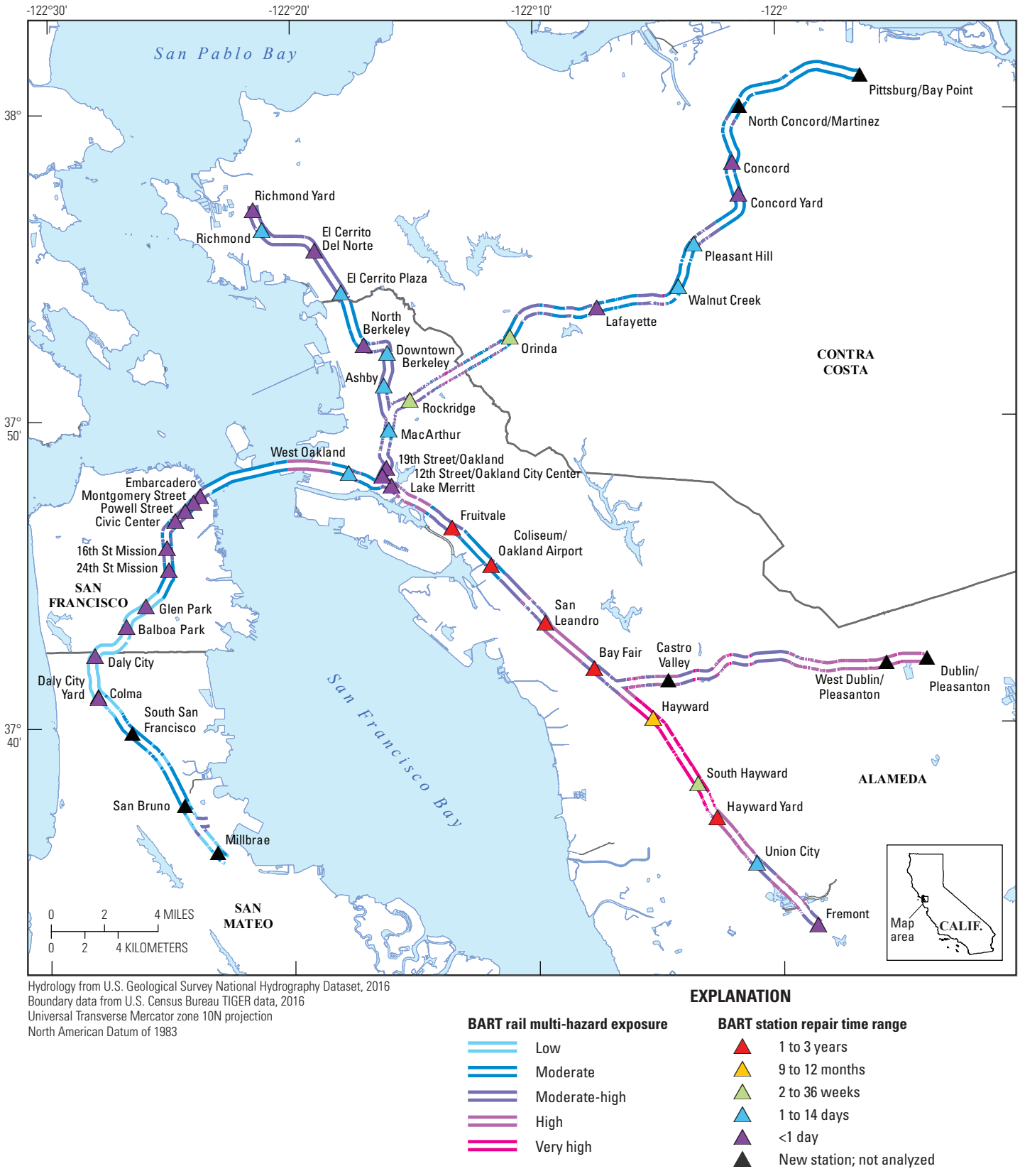


Figure 4.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the Bay Area Rapid Transit (BART) system relative to BART-estimated facility repair duration for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 extensions to Milpitas and Berryessa.

Table 4.4. Summary of Bay Area Rapid Transit shaking damages to facilities relative to exposure to ground movement and fire following earthquake hazards for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Damage class	Description	Coseismic slip	Landslide intensity			Liquefaction intensity			Fire following earthquake intensity		
			Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
None	New station; not analyzed	0	2	0	0	1	3	0	3	1	0
Green	Likely minor or no damage	0	1	0	0	7	7	0	6	3	1
Yellow	Likely operable after short-term repairs	0	4	0	0	3	6	0	4	4	0
Orange	Likely not operable, but likely safe	0	1	0	0	0	1	0	0	0	1
Hi-orange	Likely not operable, but likely safe	0	3	0	0	1	3	1	1	3	1
Red	Likely unsafe or collapsed	0	1	0	0	0	1	0	0	1	0
	Total	0	12	0	0	12	21	1	14	12	3

Table 4.5. Summary of Bay Area Rapid Transit shaking damages to facilities relative to multi-hazard exposure intensity classes for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

Damage class	Description	Multi-hazard intensity				
		Low	Moderate	Moderate-high	High	Very high
None	New station; not analyzed	3	3	1	2	0
Green	Likely minor or no damage	4	6	9	1	0
Yellow	Likely operable after short-term repairs	0	4	6	0	0
Orange	Likely not operable, but likely safe	0	1	0	0	1
Hi-orange	Likely not operable, but likely safe	0	0	3	1	1
Red	Likely unsafe or collapsed	0	0	0	1	0
	Total	7	14	19	5	2

the HayWired scenario mainshock are high-intensity. The Fremont station illustrates an exception owing to high fire following earthquake intensity (for the HayWired scenario), which was not considered in BART's ShakeCast analysis. The Fremont station is also in an area of moderate liquefaction and moderate ground shaking intensity, so the station is classified as being in a high multi-hazard intensity area. Yellow stations also tend to be in areas with only moderate multi-hazard intensity, with no single hazard identified as high-intensity. The stations that have very high multi-hazard intensity are classified as orange and hi-orange (both are considered potentially operable, but hi-orange has longer associated repair times) in BART's ShakeCast analysis. Two of these stations, the Hayward and South Hayward stations, demonstrate the potential for high ground-shaking intensity and high fire following earthquake intensity, along with moderate liquefaction intensity. This demonstrates the possibility of multiple hazards exacerbating the shaking damages such that the potentially inoperable (orange and hi-orange) stations may have longer repair times or even become unsafe (red). In the HayWired scenario, fire is the most likely cause of high-intensity damage beyond shaking to BART facilities owing to the urban nature of the fire-following-earthquake model. Moderate liquefaction (5–25 percent probability) is near more than half of the facilities. It should be noted that BART performed site-specific liquefaction vulnerability analysis for each facility and found that, in general, the facilities are not vulnerable to seismically induced liquefaction, either because liquefaction does not actually occur at the facility site (based on local geotechnical site investigation data) or the structures were found to be essentially undamaged by liquefaction effects.

Please note that the discussion above focuses on core BART system facilities rather than rail lines. BART estimates that the most impacted rail line would take about 6 months to be repaired (T. Horton, BART, written commun., 2018). BART assumes that stations will take longer to repair than lines, so they focused their more extensive hazard impact analysis on the facilities. In 2014, a seismic retrofit feasibility study was completed for the Berkeley Hills tunnels between the Rockridge and Orinda stations. The study considered three different levels of fault offset (not including postseismic creep) resulting from the maximum magnitude (*M*) earthquake (*M*7.25 in this instance): 3.9 feet (ft) for a

lower level design-basis earthquake (median displacement), 7.8 ft for a design-basis earthquake (median plus one sigma displacement), and 12.4 ft for an upper level design basis earthquake (median plus two-sigma displacement). In the HayWired scenario, the Berkeley Hills tunnels would be exposed to around 0.9 meters, or 2.9 ft, of offset. This is lower than the lowest level of fault offset considered by the Berkeley Hills tunnels feasibility study (Jacobs Associates and G&E Engineering Systems, 2014). The study looks at repair times for several different fault offset amounts; the two closest scenarios have 1.0 and 5.1 ft of offset, respectively, resulting in potential repair times of 3.5 to 7.4 months for restoring one tunnel to half speed and 13.5 to 25.5 months to restore both tunnels to full speed. A BART estimate puts the completion time for repairs to the Caldecott Tunnel at about 2 years (T. Horton, BART, written commun., 2018)—within the range established from the seismic feasibility study.

BART Interdependencies

Some interactions between BART and other lifelines include water and power. Tunnel sections of the BART system require the availability of running water in case of fire while trains are operating through the tunnels. In the event of a major earthquake, the San Francisco Fire Marshal may limit the number of trains running if the water system is compromised. The Transbay Tube is a good example of where lifeline interdependencies are important. In addition to the above-mentioned water dependency, electric power is necessary in the Transbay Tube—in the event of water leakage into the tunnel, power will be needed to pump out the intruding water. If the tube were to become filled with water, the restoration time for the tube would be much longer than if water intrusion had not occurred. Currently, the Transbay Tube has high-priority power from the Pacific Gas and Electric Company (PG&E), but that is dependent on the overall power situation in the region. BART is also planning to install a large emergency generator to provide pumping and lighting power for the Transbay Tube as part of retrofits to reduce reliance on PG&E; however, this is dependent on adequate fuel supplies in storage tanks. Retrofits are scheduled to be completed for the Transbay Tube in 2023. Structural repairs in the Berkeley Hills tunnels (for a scenario that has between 1.0 and 5.1 ft of fault offset) would potentially require removing existing utilities along a 250 ft section of one tunnel during initial repairs (to restore one track to half speed) and along a 400 ft section of both tunnels during the remainder of the repairs (to restore both tracks to full speed) (Jacobs Associates and G&E Engineering Systems, 2014). While plans are being made to complete repairs owing to fault creep damage to the Berkeley Hills tunnels, there are not any current plans to retrofit the tunnels (Bay Area Rapid Transit, 2017c). Finally, BART would be able to implement bus bridges to transport commuters to operational stations during repairs to damaged stations, but this would be contingent on the road network being restored to functionality and the availability of fuel for buses also.

Appendix 5. California Department of Transportation Bridge Damage Assessment to HayWired Scenario Ground Shaking

By Loren Turner,[1] Jamie L. Jones,[2] Anne M. Wein,[2] and Amy E. Schweikert[2]

Mainshock ground shaking in the HayWired scenario was used by the California Department of Transportation (Caltrans) in ShakeCast (https://earthquake.usgs.gov/research/software/shakecast.php) to identify the potential effect on highway bridge inventory in the study region. The Caltrans ShakeCast analysis uses a 1.0 second peak spectral acceleration (PSA) measure of ground shaking to indicate bridge fragility—the likelihood of impact to each bridge. There are other possible impacts to bridges owing to ground failure (for example, landslides, liquefaction, and fault crossings). However, those hazards are not considered in the ShakeCast analysis. Bridge fragility is determined by a range of asset-specific details including year of construction (or retrofit), length of span(s), column heights, material types, and number of spans. The output is a potential impact rating based on a statistical assessment of the operational state probability for each bridge. Figure 5.1 illustrates an example of how potential impact is determined for a bridge: each bridge has multiple potential damage levels but the one with the highest likelihood of exceeding the limit of an impact state is reported (Division of Research, Innovation, and System Information for the Division of Maintenance, California Governor's Office of Emergency Management, 2014). Please note that Caltrans uses the term "potential impact class" in lieu of "damage state" (this term is used in table 5.1 and in Hazus-MH 2.1 [hereafter referred to as Hazus]) so that ShakeCast results are not incorrectly interpreted as reports of actual damage.

[1] California Department of Transportation.

[2] U.S. Geological Survey.

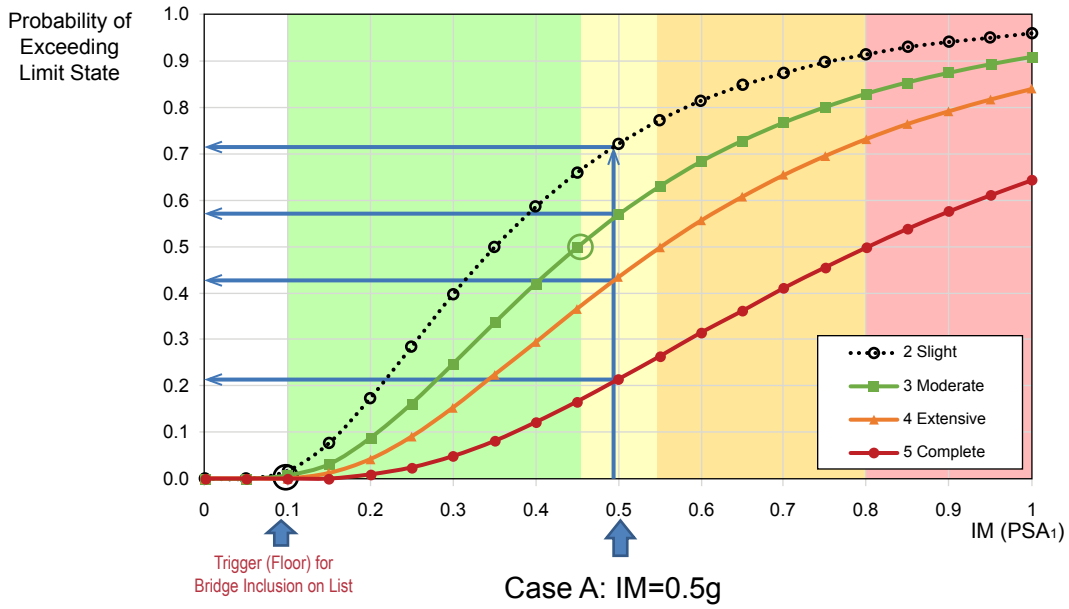


Figure 5.1. Chart showing an example of one set of potential impact curves for a highway bridge in the San Francisco Bay region, California (reproduced here with slight modification from Division of Research, Innovation, and System Information for the Division of Maintenance, California Governor's Office of Emergency Management, 2014). This graph shows the probability that the bridge will see a given impact class (slight, moderate, extensive, or complete) based upon the level of ground shaking experienced (in 1.0-second peak spectral acceleration [PSA_1]) and the bridge fragility of the asset. As shown, the designated potential impact is based upon the largest (greater than 50 percent) likelihood of impact; likelihood of impact is shown on the x-axis and the colored areas highlight ranges of likelihoods (white the lowest and red the highest). In this example, a PSA_1 of 0.5*g* (0.5 times gravitational acceleration, *g*) results in a 72 percent chance of a "low" classification (corresponding to "slight" damage), a 57 percent chance of a "medium" classification (corresponding to "moderate" damage), a 44 percent chance of a "medium-high" classification (corresponding to "extensive" damage), and a 22 percent chance of a "high" classification (corresponding to "complete" damage). As a result, the PSA_1 value here would be assigned a "medium" classification because this is the highest impact class that is greater than 50 percent.

Table 5.1. Default traffic states for bridges damaged by ground shaking (modified slightly from Werner and others, 2000).

[N/A, not applicable; Caltrans, California Department of Transportation]

Damage state	Caltrans equivalent	Repair procedure		Traffic state	
		Description	Duration	Bridge	Underpass
None	N/A	None	None	Fully open	Fully open
Slight	Low	Epoxy injection of cracks	2–3 weeks	Fully open	Fully open
Moderate (repairable structural damage)	Medium	1. Close bridge for inspections and shoring 2. Repair columns, that is, remove damaged concrete, design/implement repair (for example, increase lap splice, add transverse steel, grouting, and jacketing) 3. Repair abutments, bearings, and so on.	1–3 days 3-span bridge: 2–3 weeks 4-span bridge: 2.5–5 weeks 5-span bridge: 4–6 weeks	Closed Partly open to reduced traffic during duration of repairs	Partly closed (one lane each direction) during cleaning, shoring, and column repair operations (2–3 weeks). Open to emergency vehicles.
Extensive (severe damage to structural elements but no overall collapse mechanism)	Medium-high	1. Close bridge for inspections and shoring 2. Repair or replace columns, that is, remove damaged concrete, design/implement repair (for example, increase lap splice, add transverse steel, grouting, and jacketing) 3. Repair abutments, repair or replace bearings, and so on.	1 week 3-span bridge: 4–8 weeks 4-span bridge: 5–10 weeks 5-span bridge: 6–12 weeks	Closed Partly open to reduced traffic during duration of repairs	Partly closed (one lane each direction) during cleaning, shoring, and column repair operations (3–4 weeks). Open to emergency vehicles.
Collapse (severe structural damage leading to overall collapse mechanism, or unseating of deck leading to collapse of deck)	High	Replace bridge for case of severe structural damage. See table 12 of Werner and others (2000) for breakdown of repair procedure.	3-span bridge: 3–6 months 4-span bridge: 4–8 months 5-span bridge: 5–10 months	Closed during bridge reconstruction	Fully closed during demolition and cleaning (3–6 days) Partly closed (one lane each direction) during cleaning, shoring, and column repair operations (4–8 weeks)
		Replace fallen deck span, replace bearings, and repair or replace damaged substructure.	3–6 months	Closed during bridge repair and replacement.	

The bridge fragility used in ShakeCast is derived from existing engineering research and follows the Hazus methodology described by Federal Emergency Management Agency (2012). In many cases, the default system data used in Hazus is based on studies of bridges on the east coast of the United States and are intended to model typical highway bridges, likely not accurately capturing the damage potential for bridges that are more complex, longer, or otherwise outside normal design parameters (for example, bridges that have been seismically retrofitted). The ShakeCast software assessment also does not account for multiple hazards including liquefaction, landslide, coseismic slip, or fire.

Results

In total, 4,216 bridges were assessed by Caltrans using ShakeCast for the HayWired scenario. Of these, 2,734 (65 percent) were at locations where ground shaking was determined to exceed 10 percent of gravitational acceleration, *g*, the minimum value observed for damages to bridges in past earthquakes. The analysis showed that, of the bridges where shaking exceeded 10 percent of *g*, 51 bridges (2 percent) had high potential impact, 60 bridges (2 percent) had medium-high potential impact, 59 (2 percent) had medium potential impact, and 2,564 (96 percent) had low potential impact.

Using information from Werner and others (2000), we applied the range of repair times for each bridge based on the potential impact estimated by ShakeCast and the number of bridge spans included in the bridge geographic information system (GIS) dataset (California Department of Transportation, 2015). Table 5.1 summarizes the repair procedures and durations for three-, four-, and five-span bridges. The repair time is based upon select shaking hazard exposure measures (1.0 second PSA and moment magnitude intensity [MMI]) as well as a number of bridge-specific attributes. However, many bridges in the GIS dataset had listed bridge span counts outside of the range used in table 5.1. For bridges with fewer than three spans listed, we assigned the same time range as a three-span bridge, and for bridges with more than five spans, we assigned the same time range as a five-span bridge. Bridges with low potential impact have estimated repair times under one month and no associated road closures; some of the bridges with high potential impact could take as long as ten months to be fully repaired and require closing roads that pass under the bridges.

Table 5.2 provides descriptions of the potential impact classes and summarizes the number of bridges and repair duration ranges for each class. The ShakeCast analysis was also run for five aftershocks, assuming that all bridges were in their initial condition (before mainshock impacts). None of the aftershocks identified any bridges with medium, medium-high or high impact likelihood. Figure 5.2 shows the location of each bridge analyzed using ShakeCast and the resulting potential impact relative to the ground failure hazards (coseismic slip, landslides, and liquefaction) for the HayWired scenario.

In figure 5.2, many bridges on Interstate 880 (I–880) between Fremont and Oakland are identified as high potential impact, taking at least four months and as many as ten months to be repaired. With several bridges also classified

Table 5.2. Potential impact class definitions and exposure of highway bridges in California Department of Transportation's ShakeCast analysis in the San Francisco Bay region, California.

[PSA, peak spectral acceleration; *g*, gravitational acceleration; in., inches]

Potential impact class	Description	Number of bridges in class	Repair duration, in months
None	1.0-second PSA at location is less than 0.1 *g*	1,482	0
Low[1]	Minor cracking and spalling to the abutment; cracks in shear keys at abutments; minor spalling and cracks at hinges; minor spalling at the column (damage requires no more than cosmetic repair) or minor cracking to the deck	2,564	0.5–0.75
Medium	Any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound); moderate movement of the abutment (<2 in.); extensive cracking and spalling of shear keys; any connection having cracked shear keys or bent bolts; keeper bar failure without unseating; rocker bearing failure or moderate settlement of the approach	59	0.5–1.25
Medium-high	Any column degrading without collapse owing to shear failure (column structurally unsafe); significant residual movement at connections; major settlement approach; vertical offset of the abutment; differential settlement at connections; shear key failure at abutments	60	1–3
High	Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse; tilting of substructure owing to foundation failure	51	3–10

[1]Direct calculations were not completed to define this class—1.0 second PSA less than 0.1 *g* is used as lower limit, so any points not classified in the higher impact classes or below the lower threshold are classified as low.

as high potential impact on I–680 between Fremont and Pleasanton, getting through Alameda County will potentially be difficult. Bridge impacts on I–580 between Oakland and Pleasanton would also disrupt travel from the east into the San Francisco Bay area. Contra Costa County could also have some connectivity issues owing to bridge impacts, especially around the intersection of California Routes (CA) 13 and 24. With several major highways that have four or more months of repair time in the San Francisco Bay region, emergency response, evacuation, and debris removal would be hampered and recovery after the HayWired scenario mainshock could take longer than anticipated. A small number of bridges in Marin and Sonoma Counties also have high potential impact. Figures 5.2*A* and *B* highlight areas affected by ground failure and landslides, which may further exacerbate potential impacts to bridges.

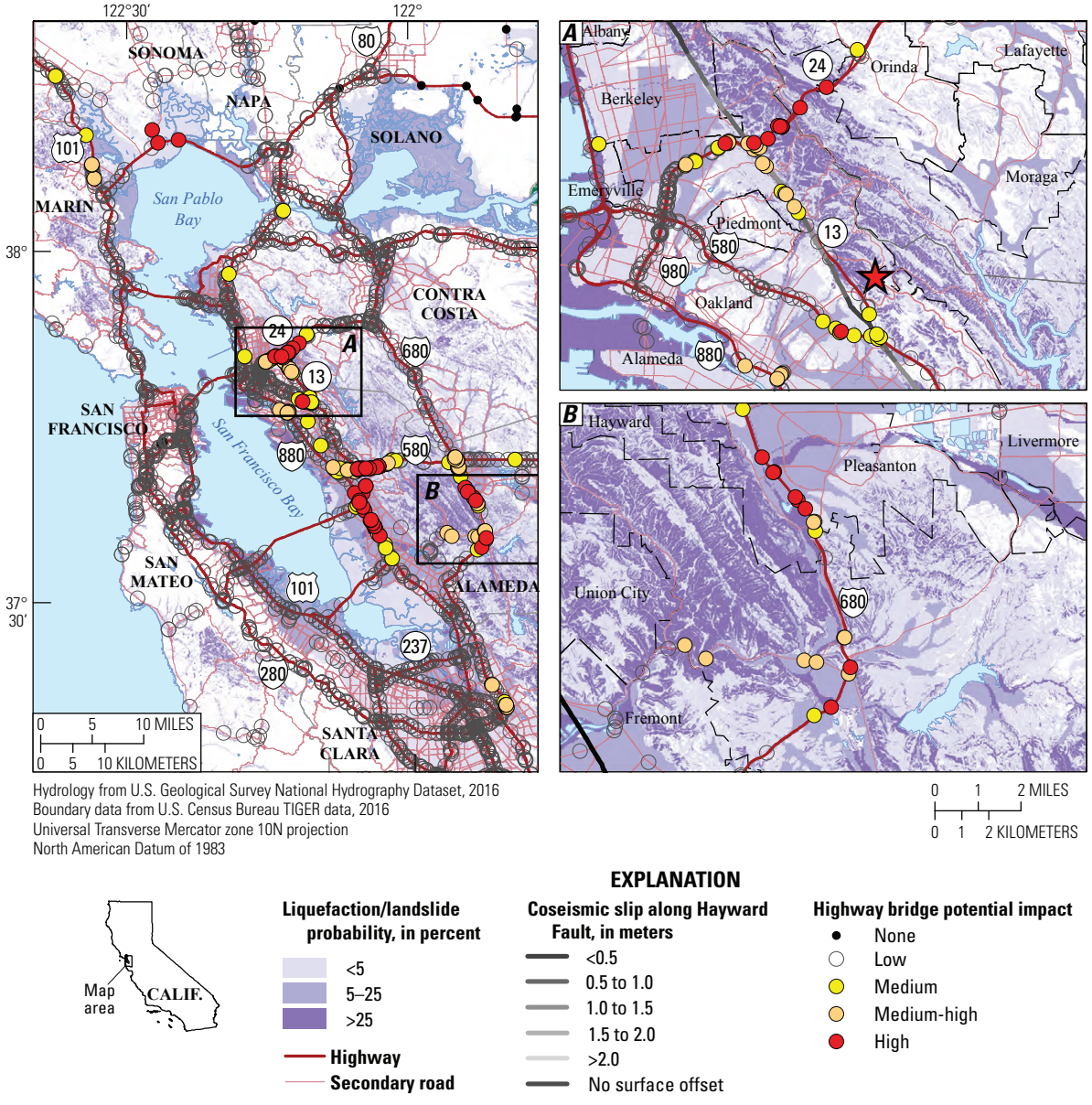


Figure 5.2. Map of the San Francisco Bay region, California, showing highway bridge potential impacts generated by California Department of Transportation's ShakeCast assessment relative to the HayWired scenario mainshock ground-failure hazards (coseismic slip, landslides, and liquefaction). Most bridges of high potential impact are located in Berkeley (*A*) and Hayward (*B*); a few bridges east of Hayward near Livermore and Fremont have high and medium-high potential impacts.

Comparing Caltrans Assessment with Chapter Exposure Results

The multi-hazard assessment of all shaking, liquefaction, landslide, slip, and fire following earthquake hazards is described in the body of this chapter. Figure 5.3 compares the potential impacts to bridges against the HayWired mainshock multi-hazard analysis for transportation lifelines. Table 5.3 summarizes the exposure of Caltrans potential impact bridges (from shaking) relative to landslide, liquefaction, fire following earthquake, and slip. Table 5.4 summarizes Caltrans potential impact bridges relative to the multi-hazard intensity. Some specific examples from this comparison follow.

Overall, the results for landslide and liquefaction hazards, in particular, suggest that using a shaking only assessment may underestimate damages to bridges that are assessed as low potential impact by ShakeCast for the HayWired scenario. A set of bridges in Castro Valley along I–580 have low potential impact from ground shaking but high landslide intensity. More than 150 low potential impact bridges are located in areas of high liquefaction: these are located along U.S. Route 101 in the south bay and along the peninsula and along I–580, I–880, and I–80 in the east bay. A few low potential impact bridges along I–80 in Richmond are located in areas that have high fire-following-earthquake intensity, as does one on I–880 in Hayward and one on I–680 between Fremont and Sunol.

Medium, medium-high, and high potential impact bridges (from shaking) are also exposed to high-intensity landslides and liquefaction. For example, along I–580 in Castro Valley there are several medium, medium-high, and high potential impact bridges that also have high landslide hazard intensity; one of the high potential impact bridges in this area is also affected by overlapping high liquefaction hazard intensity. A medium potential impact bridge on CA–13 in Oakland is in an area with high landslide and high fire following earthquake hazard intensity, and a medium-high potential impact bridge along the same road is also situated in a high landslide hazard intensity area. Several medium-high potential impact bridges in the Dublin-Pleasanton area along I–680 and I–580, along with several high potential impact bridges along I–580 in Castro Valley, are located in high liquefaction hazard intensity locations. In addition, one medium-high potential impact

Table 5.3. Summary of California Department of Transportation's ShakeCast assessment of potential shaking impacts to highway bridges relative to single-hazard exposure intensity classes for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Values are number of bridges]

Potential impact class	Coseismic slip	Landslide intensity			Liquefaction intensity			Fire following earthquake intensity		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
None	0	0	0	0	3	6	0	2	0	0
Low	0	459	37	8	531	459	154	686	133	12
Medium	0	30	15	4	3	35	2	12	25	2
Medium-high	3	41	11	5	10	28	9	9	30	6
High	0	28	19	3	2	22	6	3	6	11
Total	3	558	82	20	549	550	171	712	194	31

Table 5.4. Summary of California Department of Transportation's ShakeCast assessment of potential shaking impacts to highway bridges relative to multi-hazard exposure intensity classes for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Values are number of bridges]

Potential impact class	Multi-hazard intensity				
	Low	Moderate	Moderate-high	High	Very high
None	507	332	2	0	0
Low	762	1,010	498	217	22
Medium	2	4	20	28	5
Medium-high	0	10	18	15	17
High	1	4	15	12	19
Total	1,272	1,360	553	272	63

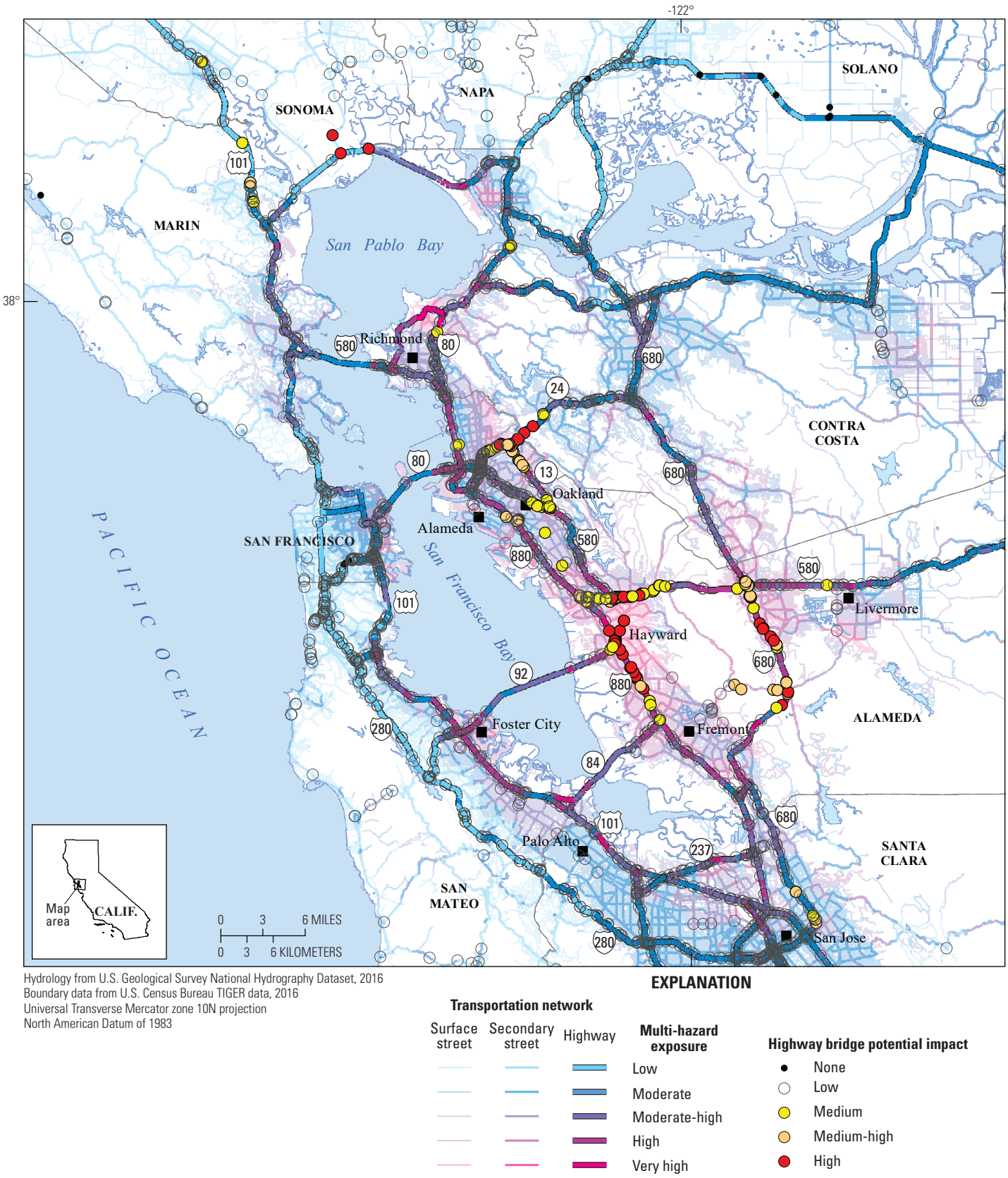


Figure 5.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of roadways and potential impacts to California Department of Transportation highway bridges in the HayWired earthquake scenario.

bridge in Hayward is in an area with high fire-following-earthquake hazard intensity.

These findings suggest that whereas many of the low potential impact bridges are not likely to be exposed to additive damages from other HayWired scenario hazards, the larger liquefaction extent may have an effect on a number of bridges otherwise classified as low impact potential. There is a higher chance of affecting traffic on underlying roads for bridges in medium, medium-high, and high potential impact classes because many of the bridges in these classes cross over other roads. In general, estimated repair times may end up being longer for some of the bridges in order to complete repairs not accounted for in the ShakeCast analysis. Caltrans bridge repair times in relation to our multi-hazard analysis are shown in figure 5.4.

Caltrans Interdependencies

Bridges in the Caltrans system have varying levels of importance, and when a major incident occurs, bridges are repaired in order of importance (L. Turner, Caltrans, oral commun., 2014). Any additional lifelines located on bridges may be subject to this order as well. For example, if a bridge is low on the priority list, then lifelines on the bridge may be delayed in finalizing repairs while they wait for the bridge to be repaired. Pipes can be temporarily repaired independently of a bridge, but the final repairs cannot be completed until bridge repairs are done. Fiber optic cables commonly run along bridges, so damages to bridges could have an impact on telecommunications as well. In some cases, utilities have retrofitted or removed their systems from the bridges, but no information is available on where this may have been completed.

With regard to the differential motion between superstructure spans and abutment-superstructure, the Caltrans design approach since 1990 has provided for protection of utilities (for example, water lines) that are carried on their structures (California Department of Transportation, 1994). We do not know what details were used prior to 1990 (for example, if retrofits have been carried out on older bridges carrying utilities or even which bridges in the study region carry utilities).

Damage to other lifelines near a bridge could also potentially delay repairs to the bridge—for example, if a water pipe breaks near an abutment, the water leaking out of the pipe could scour the abutment (L. Turner, Caltrans, oral commun., 2014) and weaken it more than it would have been affected without the water damage.

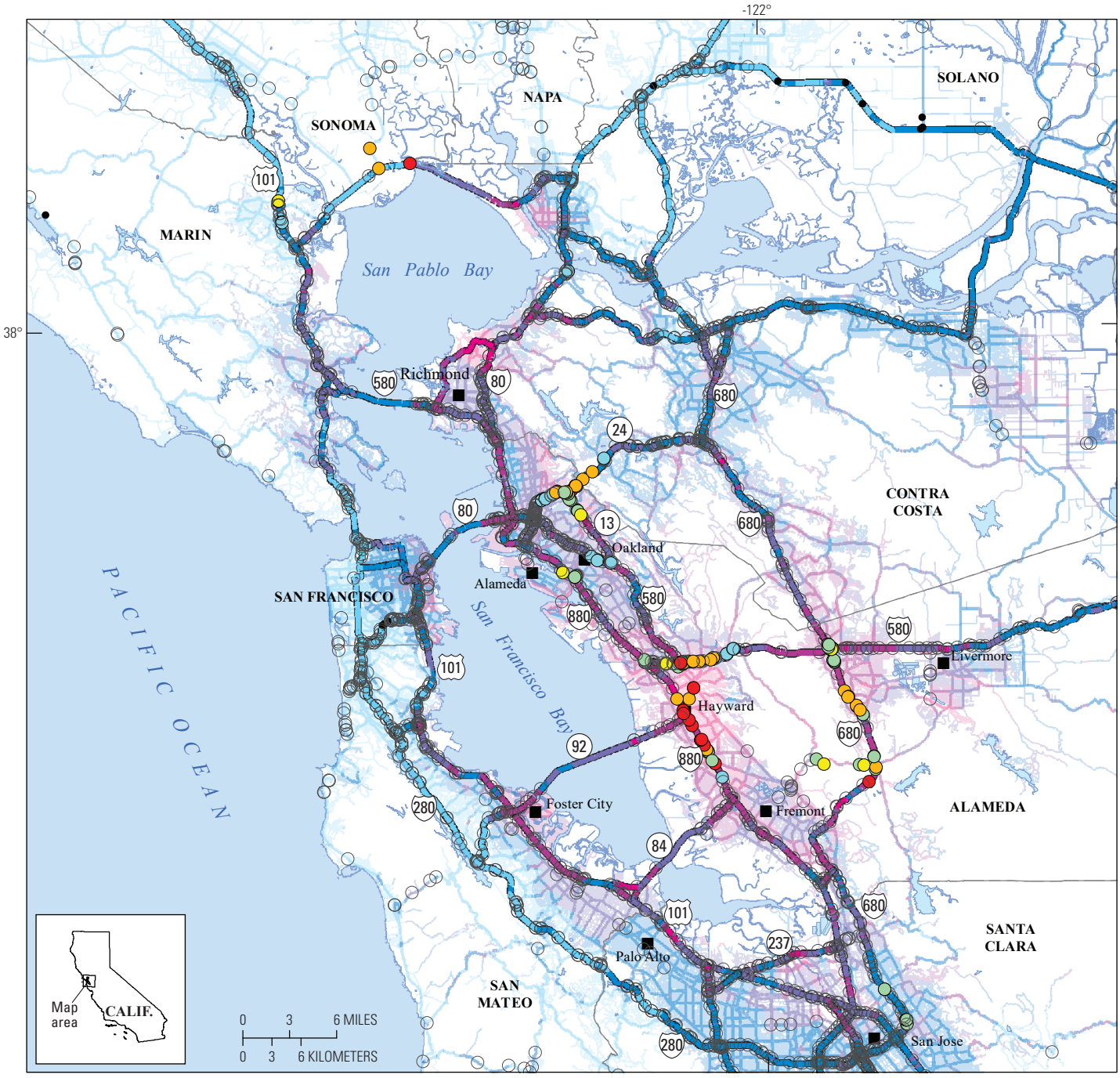


Figure 5.4. Map of the San Francisco Bay region, California, showing repair times for highway bridges as determined by the California Department of Transportation relative to multi-hazard exposure in the HayWired earthquake scenario.

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Chapter U

Analysis of Communities at Risk in the HayWired Scenario—Overview and Policy Implications

By Laurie A. Johnson,[1] Jamie L. Jones,[2] Anne M. Wein,[2] and Jeff A. Peters[2]

Abstract

This chapter adds a social dimension and long-term perspective to the rich details of the hazard and immediate impacts of the HayWired scenario for the nearly 7.7 million residents of the San Francisco Bay region, California, and their many communities. "Communities at risk" are places where normal community functions will be severely impaired or cease to exist for months, even years, after a disaster and where residents may be forcibly displaced because of direct damage to their homes and neighborhoods, or voluntarily relocate because they cannot obtain services or otherwise recover. The analysis of communities at risk for the HayWired scenario is developed in three detailed sections that follow and which are summarized in this overview—integrated building damage and areas of concentrated damage; population movements and vulnerabilities; and long-term community recovery challenges. These analyses inform the development of seven policy implications for improving community resilience in the San Francisco Bay region ahead of such a potentially unprecedented and catastrophic earthquake disaster, and which are offered at the end of this overview.

A methodology to integrate the Hazus analysis of property damage (buildings and contents) caused by ground shaking, liquefaction, and landslides with the analysis of building damage caused by fires following the moment magnitude 7.0 mainshock of the HayWired scenario results in an estimated $74 billion in cumulative property damage, with damage to 1 million residential (containing 1.37 million housing units) and nearly 39,000 nonresidential buildings. Concentrated-damage areas are defined by census tracts with extensive and complete building damages affecting 20 percent or more of the building square footage. A geographic analysis reveals a consistent pattern of building damage for residential and nonresidential occupancies in the urbanized parts of Alameda County and western Contra Costa County, the Novato area of Marin County, and the Vallejo area of Solano County. Concentrations of older, seismically vulnerable buildings and the locations of post-earthquake fire spread are major determinants of concentrated-damage patterns. Development of this integrated view of property damage and areas of concentrated damage are foundational steps in understanding which people and places are most vulnerable to long-term community recovery challenges in the HayWired scenario.

The integrated residential building damage as well as extended outages from damaged water distribution systems and other infrastructure in the HayWired scenario could result in forced or voluntary displacement of 268,000 households or 720,000 people (around 10 percent of the total population for the nine-county San Francisco Bay region). Furthermore, more than 1.45 million people (or nearly 20 percent of the nine-county population) live in areas with concentrated multifamily residential building damage, which past disasters have shown to be especially vulnerable to delays in housing recovery, blight, and degraded neighborhood conditions. Nearly 350,000 people reside in areas of concentrated damage that also have high levels of socially and economically vulnerable population groups. Households with children and disabled persons, homeless persons, and young and mobile households are also known to contribute to population displacement after disasters, and these population groups are also analyzed against the integrated damage and socioeconomic vulnerability data.

All of these estimates provide different views of the potential size and composition of people at risk of displacement in the HayWired scenario. Available shelters in the central nine-county region may quickly reach capacity, especially in heavily impacted areas, such as Alameda and Contra Costa Counties. Regional response plans identify potential host areas in surrounding counties that are less likely to sustain heavy damage. If the immediate sheltering needs exceed the 16-county regional sheltering capacity, some people may need to relocate to other parts of California or adjoining States. An already constrained housing market, combined with a limited supply of interim housing options, may impact the timing and ability of people to return.

These analyses of people and places point to three long-term community recovery challenges that the San Francisco Bay region is likely to face after a major earthquake like that in the HayWired scenario: (1) with limited insurance

[1]Laurie Johnson Consulting | Research.

[2]U.S. Geological Survey.

availability, it will take considerable time and effort to assemble the financial resources necessary for the region's recovery and rebuilding; (2) the repair and replacement of 1.37 million damaged housing units will require considerable funds and create significant workforce and resource demands; and (3) some areas will require substantial governmental intervention and replanning in order to recover. Each of these challenges is further analyzed and a typology of areas that may require governmental interventions and replanning is developed. A series of maps also integrate all elements of this analysis by highlighting the areas with potentially intensive long-term recovery challenges that could be caused by ground failure, heavily concentrated building damage, and extended utility and transportation outages and where these areas intersect with vulnerable populations.

All these areas could also face additional damage from aftershocks (or afterslip in areas along the fault rupture) and increased vulnerability to other hazard events such as storm-related flooding and slope failures, which may generate uncertainty about the feasibility and affordability of repairs and other long-term ripple effects, such as mortgage defaults and a loss of property tax revenues for local and State governments. The governmental interventions and replanning actions that may be necessary to address these post-earthquake conditions will take money, community engagement, and time and the demands will likely come at a time when populations are displaced and local government budgets are very constrained because of a reduced tax base and the additional costs of publicly owned facilities and infrastructure repairs.

Seven policy implications for improving community resilience in the San Francisco Bay region ahead of such a potentially unprecedented and catastrophic earthquake disaster are identified. They are potential opportunities to: (1) accelerate the seismic mitigation of homes; (2) strengthen or replace infrastructure; (3) build more new housing for all income groups; (4) promote seismic resilience in land use and development policies across the region; (5) address population movements and long-term displacement in local, regional, and State preparedness, response, and recovery plans; (6) plan for the management of long-term recovery at all levels of government; and (7) develop a recovery financing strategy.

Introduction

Communities are self-organizing systems that consist of many interdependent and interacting parts—physical, social, political, economic, and institutional. When subjected to an extreme event like a major earthquake, communities will experience direct and indirect consequences that can ripple outward across the community and even affect other places (Alesch and others, 2009).

Disaster recovery happens as communities reconstitute themselves as self-organizing systems and are able to function in the new context in which they find themselves (Alesch and others, 2009). The ability of communities to recover from a disaster is a function of the extent of damage to the community, the preexisting qualities and inequalities that enable them to contain the cascading consequences of a disaster, and the postdisaster policies and actions that also affect the recovery trajectories of communities, their businesses, and their residents (Haas and others, 1977; Comerio, 1998; Olshansky and others, 2006; Bolin, 2007; Smith and Wenger, 2007; Groen and Polivka, 2010; Esnard and Sapat, 2014; Peacock and others, 2014; Fothergill and Peek, 2015; Johnson and Olshansky, 2017; Kroll-Smith, 2018).

In this chapter, we consider how a moment magnitude (M_w) 7.0 earthquake on the Hayward Fault and subsequent aftershocks could affect the recovery of people, housing, and communities in the San Francisco Bay region. Like most major metropolitan areas, the San Francisco Bay region is composed of a vast number of communities and every resident belongs to more than one. There are 101 municipalities and countless neighborhoods in the nine counties that abut San Francisco Bay. The 2016 total estimated population of the nine-county region[3] is 7,684,011—an estimated increase of 533,272 (7.5 percent) since 2010 (U.S. Census Bureau, 2018). The region's population is generally older than the rest of California and the nation and is the second most diverse because it has one of the largest shares of immigrant populations nationwide (Association of Bay Area Governments [ABAG], 2015a; PolicyLink and University of Southern California Program for Environmental and Regional Equity [PERE], 2017).

One's sense of place and community is also commonly defined in large part by one's home and job. Housing composes more than 75 percent of the building square footage in California and at least 55 percent of the urbanized land use in the nine-county region (Aksel Olsen, Association of Bay Area Governments, written commun., 2018). In 2010, there were nearly 2.79 million homes in the nine-county region, of which 56 percent were owner occupied and 44 percent were renter occupied. Although nearly 3 million homes is a substantial figure, the region's housing construction has not kept pace with population and job growth, which has led to the region's persistent housing availability and affordability crisis (San Francisco Bay Area Planning and Urban Research Association [SPUR], 2017). Complicating matters, income inequality has also sharply increased in the region—as the region's highest paid workers have seen their wages increase significantly over the last decades, wages for the lowest paid workers have declined (PolicyLink and PERE, 2017). Yet, the San Francisco Bay region continues to have one of the strongest regional economies in the Nation and the world with a 2016 Gross Domestic Product of $729 billion for the San Francisco and San Jose metropolitan areas combined (U.S. Department of Commerce, 2018).

[3]As used here, the nine-county San Francisco Bay region refers to Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties.

Specifically, this analysis of communities at risk considers (1) the cumulative damage effects of the HayWired scenario—from ground shaking, landslide, and liquefaction damages integrated with fire-related damages—on the nine-county region's people and housing, (2) how their preexisting vulnerabilities and exposure to this scenario may create forced and voluntary population movements over time, and (3) what some of the long-term community recovery challenges are likely to be from such a regionwide earthquake disaster. This is what we mean by "communities at risk." Figure 1 highlights the major estimates and themes emerging from the analysis of communities at risk and how they are likely to unfold over time.

This overview of the communities-at-risk analysis consolidates and elaborates on three more detailed sections that describe analytical methods in more depth and provide further details: section A is on integrated building damage and areas of concentrated damage, section B is on population movements and vulnerabilities, and section C is on long-term community recovery challenges. Policy implications for improving community resilience are included in this overview, as are research needs emerging from this analysis. Wein, Belzer, and others (this volume) present a companion analysis from the perspective of industrial sectors, jobs, and the home-workplace relation. The potential long-term economic consequences are considered in greater depth in chapters V1–V5 (this volume) of the HayWired scenario.

Caution must be exercised in considering these results, as this is only one scenario of many potential major earthquakes that could occur on the Hayward Fault or other major fault systems in the San Francisco Bay region. For every scenario, the damage concentrations and distributions and most impacted communities and populations groups will be different. Nonetheless, this analysis considers the preexisting physical and social conditions of communities and utilizes best-available data and analytical methods to identify the people and places most potentially vulnerable to long-term community recovery challenges after a major earthquake.

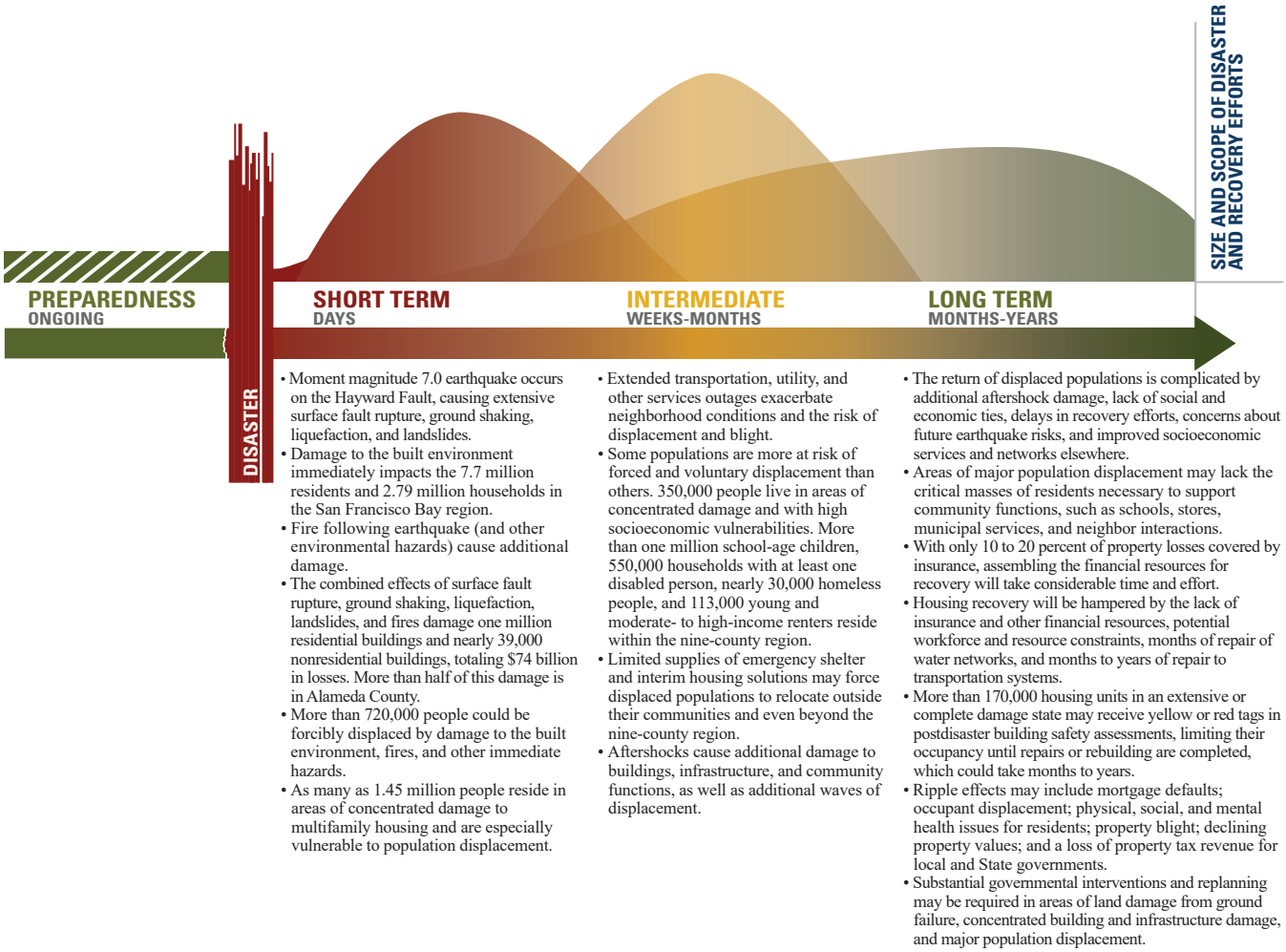


Figure 1. Schematic diagram showing major themes and estimates emerging from the analysis of communities at risk in the HayWired scenario in the San Francisco Bay region, California, with respect to the "disaster recovery continuum" timeline developed by the Federal Emergency Management Agency (2016).

Integrated Building Damage, Property Losses, and Areas of Concentrated Damages

Section A of the communities-at-risk analysis highlights the results of methodologies developed to first combine the building damage caused by the effects of the mainshock earthquake hazards and fires and then to identify geographic areas where concentrated building damage are likely. Property losses estimated for the integrated damage are explained in section C. This integrated view of property damage, losses, and concentrations is a foundational step in understanding which people and places are most vulnerable to long-term community recovery challenges in the HayWired scenario.

Integration of Building Damage Caused by Ground Shaking, Liquefaction, Landslide, and Fire

In volume 2 of the HayWired scenario, building damage caused by the earthquake hazards of ground shaking, landslide, and liquefaction for the M_w 7.0 mainshock and aftershock sequence are analyzed by Seligson and others (2018) using the Hazus-MH 2.1 loss-estimation software (Federal Emergency Management Agency [FEMA], 2012) and customized analyses; we refer to this collective work as the Hazus analysis. In a separate analysis in volume 2, Scawthorn (2018) estimates the damage to buildings from post-earthquake fires.

A methodology was developed to combine the damage data resulting from the Hazus analysis (Seligson and Jones, 2019) and the fire-following-earthquake analysis (Scawthorn, 2019) into an integrated view of building damage (methods in section A; data in Jones and others, 2020). The results are aggregated by occupancies: residential occupancy groupings are single-family/duplex dwellings, multifamily dwellings, and group-living uses; nonresidential occupancy groupings are household-serving, retail and commercial, offices, industrial and warehouse, and agricultural uses. These groupings are defined in section A.

The property (building and content) losses caused by ground shaking, landslide, liquefaction, and fires from the M_w 7.0 mainshock of the HayWired scenario (discussed in section C; data in Jones and others, 2020) are estimated by adding together the Hazus property loss estimates with additional losses generated by fire (using the difference between integrated and Hazus building damages). The property losses total $74 billion in 2016 U.S. dollars (excluding additional living expenses and business interruption losses). One million residential buildings (34 percent of all residential building square footage) containing 1.37 million housing units sustain $48 billion of the losses. There is an additional $26 billion in losses from nearly 39,000 nonresidential buildings (42 percent of all nonresidential building square footage).

Table 1 provides a summary of the integrated building damage, both in terms of building counts and percentage of total building square footage, and total property losses for all five Hazus damage states for each of the residential and nonresidential building occupancy groupings. The results in table 1 are summed for the nine-county region; see table 2 for results by county. Figure 2 shows the distribution of building counts by damage state for residential (fig. 2*A*) and nonresidential (fig. 2*B*) occupancy classes for the nine-county region.

Of the total buildings exposed to the HayWired scenario, approximately 11 percent of the residential and 15 percent of the nonresidential building square footage sustain extensive and complete damage that may impair its use for many months to years until repairs or rebuilding are completed. The extensively and completely damaged building stock is composed of 90,000 single-family/duplex dwellings, 7,300 multifamily and group-living buildings (containing about 78,500 multifamily housing

Table 1. Damages to residential and nonresidential occupancy groupings and total property losses caused by ground shaking, landslide, liquefaction, and fires from the moment magnitude 7.0 mainshock of the HayWired scenario in the San Francisco Bay region, California.

[Total property (building and content) losses are in thousands of 2016 U.S. dollars]

Occupancy grouping	Total building square footage	Estimated building counts and percentage of building square footage by Hazus damage state										Property loss[1] ($1,000)
		None		Slight		Moderate		Extensive		Complete		
		Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	
Residential occupancy groupings												
Single-family/duplex	4,634,481,745	1,946,425	68	608,387	21	230,929	8	50,225	2	39,587	1	$33,217,899
Multifamily	769,783,442	55,845	58	20,529	22	10,448	12	2,931	3	4,406	5	$13,269,370
Group living	120,618,262	3,327	69	820	17	429	9	124	3	125	3	$1,507,371
Subtotal, residential	**5,524,883,449**	**2,005,597**	**66**	**629,736**	**21**	**241,806**	**9**	**53,279**	**2**	**44,118**	**2**	**$47,994,640**
Nonresidential occupancy groupings												
Retail/commercial	739,636,465	31,049	62	10,891	21	6,157	12	1,863	3	1,164	2	$7,972,832
Offices	472,023,992	3,332	56	1,436	24	806	14	211	4	115	2	$5,844,926
Industrial/warehouse	608,072,797	10,263	53	4,513	23	2,975	15	939	5	626	3	$7,746,568
Household-serving	248,803,733	11,217	63	3,708	20	2,040	11	569	3	408	3	$4,369,166
Agricultural uses	34,949,651	916	79	159	14	65	6	16	1	9	1	$107,583
Subtotal, nonresidential	**2,103,486,638**	**56,777**	**58**	**20,707**	**22**	**12,044**	**13**	**3,598**	**4**	**2,321**	**3**	**$26,041,075**

[1]Property losses are calculated using Hazus building and content replacement costs (see section C of this chapter). It does not include damage to time element coverages (for example, additional living expenses and business interruptions).

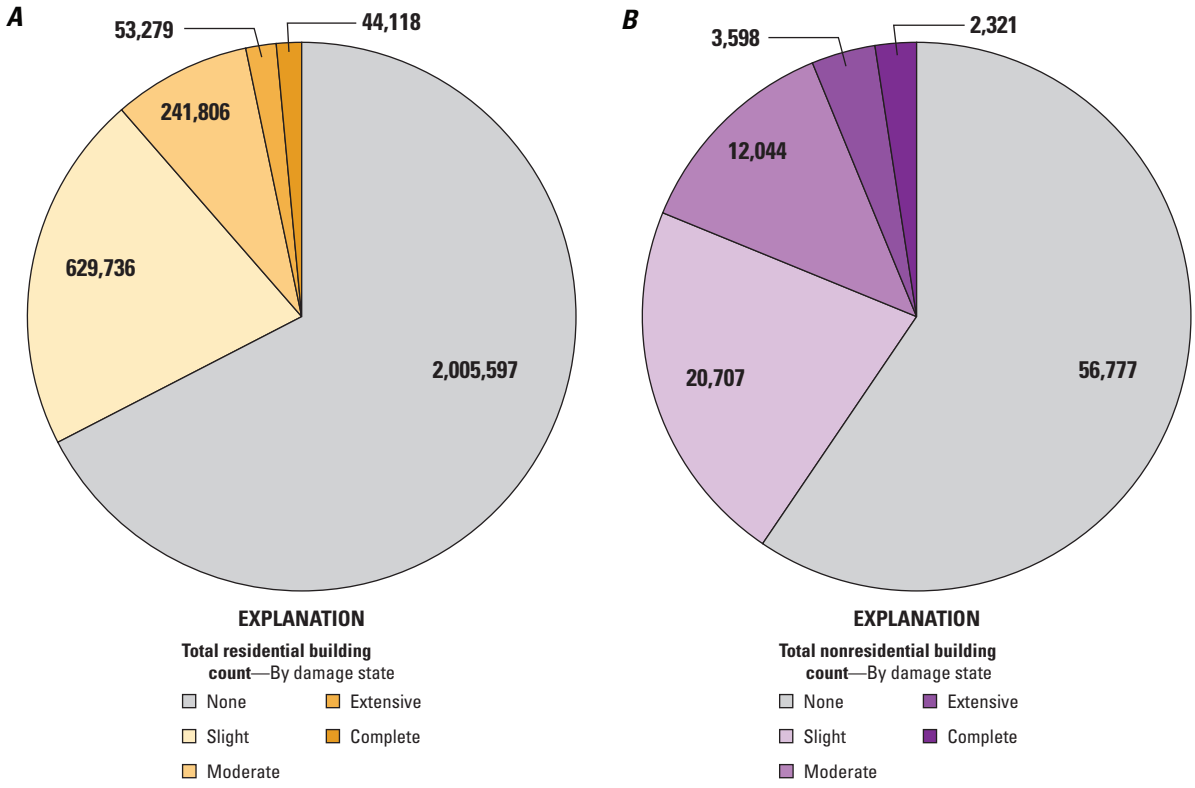


Figure 2. Plots showing the distribution of building counts by damage state for the HayWired earthquake scenario mainshock for the nine-county San Francisco Bay region, California. *A*, Residential occupancy groupings. *B*, Nonresidential occupancy groupings.

units), and nearly 6,000 nonresidential buildings. Of the 44,000 residential buildings in a complete damage state, 29,600 contain about 53,600 housing units that are in a complete damage state owing to fire. Multifamily dwellings and group-living uses sustain proportionally higher damage levels than single-family/duplex dwellings.

Table 2 provides county-level details on the integrated property damages and losses for residential and nonresidential occupancies. Figure 3 shows the distribution by county of $74 billion in residential and nonresidential property losses. Nearly all the property damage, property losses, and buildings with extensive and complete damage are concentrated in the nine

Table 2. County-level damage to residential and nonresidential occupancy groupings and total property losses caused by ground shaking, landslide, liquefaction, and fire following the moment magnitude 7.0 mainshock of the HayWired scenario in the San Francisco Bay region, California.

[Property losses (building and content) are in 2016 U.S. dollars]

County	Residential building damage			Nonresidential building damage		
	Total building count[1]	Number of extensively or completely damaged buildings	Total property loss ($1,000)	Total building count[1]	Number of extensively or completely damaged buildings	Total property loss ($1,000)
Alameda	327,744	62,140	$26,616,206	13,145	4,022	$14,857,771
Contra Costa	180,036	15,913	$7,908,158	4,998	894	$3,600,011
Marin	19,340	1,553	$904,378	886	56	$391,471
Napa	2,677	15	$26,233	136	1	$26,685
San Francisco	59,405	1,295	$1,673,638	5,285	188	$1,491,069
San Mateo	86,675	4,369	$2,667,790	3,235	185	$1,259,630
Santa Clara	229,126	10,282	$6,796,923	8,971	531	$3,911,303
Solano	18,082	1,645	$979,139	462	34	$231,338
Sonoma	3,167	65	$42,516	145	1	$27,122
Eight outlying counties[2]	42,688	122	$379,657	1,408	8	$244,676
Regional total[3]	**968,940**	**97,397**	**$47,994,640**	**38,671**	**5,920**	**$26,041,075**

[1]Total damaged building counts include all structures with slight, moderate, extensive, or complete damage according to Hazus.

[2]The eight outlying counties included in this group are Merced, Monterey, Sacramento, San Benito, San Joaquin, Santa Cruz, Stanislaus, and Yolo Counties.

[3]Because of rounding, regional totals may not add up to the sum of the values shown in the table.

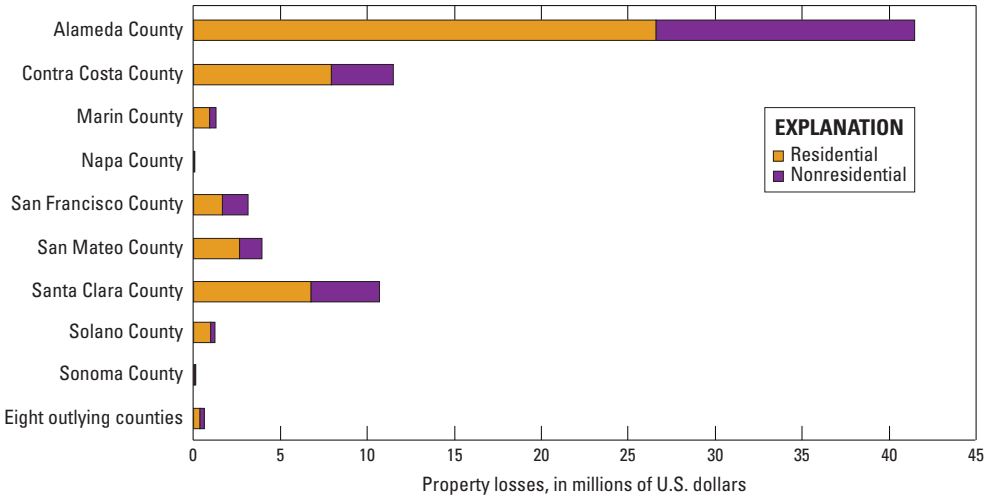


Figure 3. Graph showing county-level distribution of property losses for residential and nonresidential occupancy groupings as a result of the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. Property losses are calculated using Hazus building and content replacement costs and do not include losses from time element coverages (for example, additional living expenses and building interruption costs). The eight outlying counties included in this group are Merced, Monterey, Sacramento, San Benito, San Joaquin, Santa Cruz, Stanislaus, and Yolo.

counties adjacent to San Francisco Bay. These are Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties. More than half of the total property damage and losses for both residential and nonresidential occupancies occur in Alameda County. Santa Clara and Contra Costa Counties also sustain high levels of damage and losses.

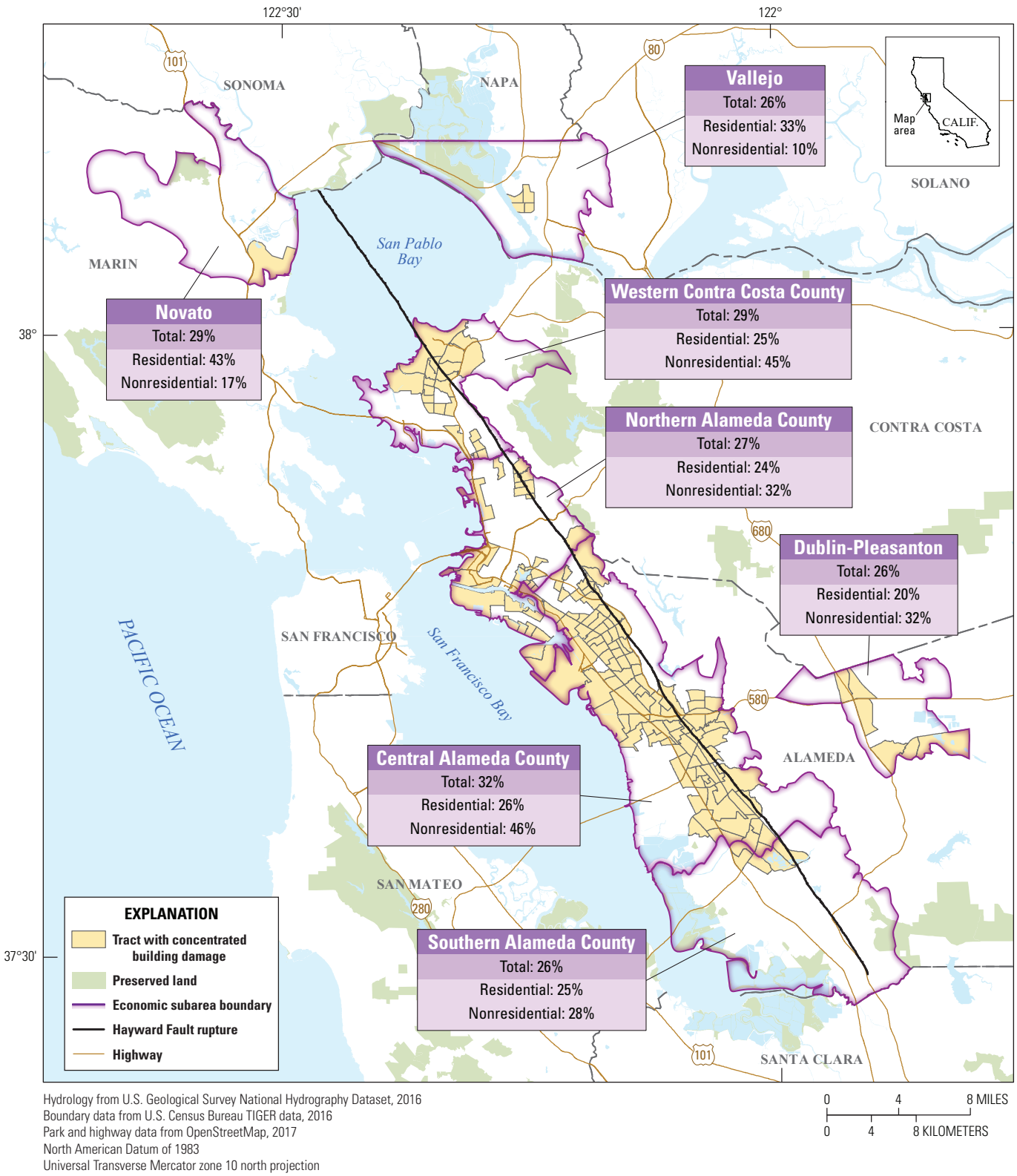
Areas of Concentrated Damage

Past disasters have shown that areas of geographically concentrated building damage are likely to experience more extended and complicated recovery trajectories with cascading effects on more residents than those directly impacted (Olshansky and others, 2006; Alesch and others, 2009; Peacock and others, 2014). A methodology was developed to identify the areas of concentrated building damage in census tracts with 20 percent or more of the building square footage in an extensive or complete damage state. Limited quantitative research (Groen and Polivka, 2010), supplemented with recovery expert opinion (Mary Comerio, University of California at Berkeley, written commun., 2015; Ann-Margaret Esnard, Georgia State University, written commun., 2015), indicated that 20 percent was an appropriate tipping point at which spatial concentrations of housing and building damage can lead to systemic and cascading consequences to more residents than those directly impacted. This is what happened in neighborhoods across Los Angeles after the 1994 Northridge earthquake (see sidebar 2 of section C). Neighborhoods with concentrations of damaged multifamily housing became blighted as more and more residents left.

The census tracts with concentrated building damage were identified for the eight different occupancy groupings (single-family/duplex dwellings, multifamily dwellings; group living; household-serving; retail and commercial; offices; industrial and warehouse; and agricultural uses) and all occupancies. Maps of concentrated damage for each building occupancy grouping are shown in section A. Figure 4 shows a summary of the census tracts with concentrated damage for all building occupancies (for integrated earthquake- and fire-related damages). Consistently across all the occupancy groupings, there are spatial concentrations of building damage in the urbanized parts of Alameda County, as well as western Contra Costa County, the San Ramon Valley and inland valleys, and flat lands surrounding San Francisco Bay, notably the Novato area of Marin County and the Vallejo area of Solano County. The areas of concentrated damage in Marin and Solano Counties are mostly caused by fire rather than earthquake-related hazards. Some areas, such as central Hayward, sustain very high concentrations of damage across multiple occupancy groupings in the HayWired scenario.

The area of concentrated damage for all building occupancies contains approximately 203,000 residential buildings, of which 46,000 sustain extensive or complete damage. This means that nearly 50 percent of the region's residential buildings with extensive or complete damage in the HayWired scenario are located in areas of concentrated building damage, yet this area contains less than 8 percent of the census tracts in the nine-county region. Thus, these areas are likely to have substantially longer recovery trajectories and more significant long-term community recovery challenges than other parts of the region. In any area of concentrated damage there will be smaller variations both higher and lower than the average census tract estimates. There are also areas outside these boundaries that sustain notable damage concentrations below the 20 percent threshold of extensive and complete damage concentration used for this analysis that are also likely to face population displacement and long-term community recovery challenges.

Figure 4 also shows the boundaries of seven economic subareas that are defined by Wein, Belzer, and others (this volume) and encompass nearly all of the areas of concentrated damage. For each economic subarea, the percentage of residential, nonresidential, and total building square footage in an extensive or complete damage state from integrated damages caused by shaking, landslide, liquefaction, and fire following the M_w 7.0 HayWired earthquake scenario mainshock are also provided. The



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016
Boundary data from U.S. Census Bureau TIGER data, 2016
Park and highway data from OpenStreetMap, 2017
North American Datum of 1983
Universal Transverse Mercator zone 10 north projection

Figure 4. Map of the San Francisco Bay region, California, showing areas of concentrated damage in economic subareas as a result of hazards caused by the HayWired earthquake scenario mainshock. Areas of concentrated damage are defined as census tracts with 20 percent or more of the total building square footage in extensive or complete damage from ground shaking, liquefaction, landslide, and fire damages. For each economic subarea, the percentage of residential, nonresidential, and total building square footage in an extensive or complete damage state from the integrated damages are also provided. Data from Wein, Belzer, and others (this volume).

concentrated damage areas in the Novato and Vallejo economic subareas have more than 30 percent of residential occupancies in an extensive or complete damage state. The northern and central Alameda County, Dublin-Pleasanton, and western Contra Costa County economic subareas have concentrated damage areas with more than 30 percent of nonresidential occupancies in an extensive or complete damage state. Table 3 provides additional geographic and housing vulnerability descriptions for each economic subarea. Windshield survey field investigations were conducted in each economic subarea to develop these descriptions.

Population Movements and Vulnerabilities

In large-scale disasters, individuals and communities can face an ongoing exposure to hazards and adverse consequences that can unfold over an extended period of time and cascade through communities (Abramson and others, 2015, p. 3). If the uncertainty and risks associated with these exposures are high, individuals and disaster managers may engage in voluntary or forced movements of individuals and communities away from an endangered area.

The term "evacuation" is most commonly used to describe the movement of people in advance of a threat or hazard incident and in response to the primary or secondary effects soon after an incident occurs. The term "displacement" is increasingly used to describe the more long-term and potentially permanent dislocation, relocation, migration, and resettlement of people—forced or voluntary—in response to physical, economic, or environmental danger or harm (Oliver-Smith, 2009). Predisaster social vulnerability and inequality can increase the likelihood of forced evacuations and permanent displacement for some people; disaster-related damage and disruptions in social and economic services and networks, postdisaster policies, and postdisaster governance processes can also exacerbate these outcomes (Esnard and Sapat, 2014; Fothergill and Peek, 2015; Johnson and Olshansky, 2017; Kroll-Smith, 2018).

Hurricane Katrina, in particular, exposed the issues of large-scale and lengthy postdisaster population displacement in the United States and the disproportionate effects on physically and socioeconomically vulnerable populations and communities (see sidebar 1 of section B). In the San Francisco Bay region, major population displacement and shifts were documented after the 1906 earthquake and fire (Kroll-Smith, 2018; The Virtual Museum of the City of San Francisco, 2018) (see fig. 5) and the 1989 M_w 6.9 Loma Prieta earthquake (Comerio, 1998; Johnson, 1999; SPUR, 2012). For example, displacement from San Francisco after the 1906 earthquake and fire is credited with shaping communities in the east bay, like Oakland and Berkeley, and on the San Francisco Peninsula.

This part of the analysis of communities at risk, which is further detailed in section B, analyzes the potential population at risk of displacement from building damage and extended lifeline outages; specific population groups vulnerable to displacement; how emergency sheltering and interim housing influences population movements; and considerations for anticipating population return.



Figure 5. Photograph of residents evacuating San Francisco, California, after the 1906 earthquake and fire. Photograph by George Williford Boyce Haley, 1925; available from the U.S. National Archives and Records Administration at https://catalog.archives.gov/id/522958.

Population at Risk of Displacement from Building Damage and Lifeline Outages

In volume 2 of the HayWired scenario, Seligson and others (2018) used Hazus software to estimate the number of households displaced because of building damage and the number of people requiring publicly provided short-term shelter for both the M_w 7.0 mainshock and the aftershock sequence of the HayWired scenario. Seligson and others (2018) used both the Hazus default values and a set of customized weighting factors that were developed for the magnitude 7.8 South San Andreas earthquake "ShakeOut" scenario study (Jones and others, 2008), and are derived from population survey data from the 1994 Northridge and 1989 Loma Prieta earthquakes.

Using the customized population displacement rates for moderate, extensive, or complete residential building damage, Seligson and others (2018) estimate 152,881 households (of which 152,438 households are in the nine-county region) displaced because of damage caused by ground shaking and liquefaction; their displacement estimates for aftershocks are substantially lower, with the largest displacement of 2,053 households resulting from the aftershocks occurring on September 30 and October 1, 2018 (about six months after the mainshock). The potential population displacement and sheltering needs caused by damage from landslides, fires, lifeline infrastructure damage and outages, or environmental threats are not included in these estimates and could increase the population displacement and sheltering needs substantially.

Studies of the 1994 Northridge and 1989 Loma Prieta earthquakes in California found that between 20 and 50 percent of residents without power and (or) water services were displaced from their homes (Seligson and others, 2018). In their appendix, Seligson and others (2018) propose increasing the Hazus estimates for population displacement and sheltering needs by 20 percent

Table 3. Geographic and housing vulnerability descriptions for each economic subarea identified for the HayWired earthquake scenario, San Francisco Bay region, California.

[Windshield survey field investigations were conducted in each economic subarea to develop these descriptions]

Economic subarea	Key locations in areas of concentrated damage[1]	Housing characteristics[2]		Hazard impacts					Notes
		Age	Height (stories)	Shaking	Liquefaction	Landslide[3]	Fire[4]	Surface fault rupture[5]	
Northern Alameda County	Parts of the cities of Albany and Berkeley south to Oakland and Alameda	Early 1900s to present	1–3	X	X	X	X	X	Older masonry and concrete residential structures are located in and around the university and downtown business district. Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors.
Central Alameda County	Parts of the city of Oakland south to Union City, as well as San Leandro, Castro Valley, and Hayward	Late 1800s to present	1–4	X	X	X	X	X	Older masonry and concrete residential structures are located in and around several business districts. Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors.
Southern Alameda County	Parts of the cities of Newark and Fremont	1960s to present	1–2	X	X		X		Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors.
Dublin–Pleasanton	Parts of the cities of Dublin and Pleasanton	1960s to present	1–5	X	X		X		Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors.
Western Contra Costa County	Parts of the cities of Pinole and El Sobrante south to Richmond and El Cerrito, as well as the Kensington and North Richmond neighborhoods	1940s to present	1–2	X	X	X	X	X	Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors. In addition, a few older masonry and concrete structures are located in and around the downtown business districts.
Novato	Parts of the city of Novato, as well as the Bel Marin Keys and Hamilton neighborhoods	1950s to present	1–3	X	X	X	X		Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors.
Vallejo	Parts of the city of Vallejo, particularly in and around the downtown business district	1950s to present	1–3	X	X	X	X		Many "soft-story" structures in the area lack adequate seismic bracing on the bottom floors. In addition, older masonry and concrete structures are located in and around the downtown business district.

[1]Areas of concentrated damage have 20 percent or more of the building square footage in an extensive or complete damage state.

[2]Housing characteristics common across all economic subareas include predominantly wood-frame structures serving as single-family or multifamily housing.

[3]Landslides occur most commonly in areas with moderate or steep slopes.

[4]Post-earthquake fires pose high risk in areas of densely spaced wood-frame structures. Areas with high fire risk may include newly constructed buildings.

[5]Surface fault rupture may present as either coseismic slip (which occurs during an earthquake) or afterslip (which occurs in the days, weeks, months, and perhaps years after an earthquake). Surface fault rupture is not explicitly included in the Hazus damage estimates developed by Seligson and others (2018).

to account for utility outages. The multi-month water outages estimated for much of Alameda and Contra Costa Counties in volume 2 of the HayWired scenario (Porter, 2018a) suggest that an additional 20 percent increase in displacement estimation is a reasonable adjustment for this displacement analysis.

Table 4 compares the customized Hazus analysis estimates for displaced households developed by Seligson and others (2018) with four other estimates of households and population at risk of displacement that have been developed by estimating populations in the areas of concentrated damage. The first row is the customized Hazus estimate of displaced households from ground shaking and liquefaction associated with the HayWired scenario mainshock. The second row adds a 20 percent increase onto the customized Hazus analysis estimate to account for utility outages. The third row applies the customized displacement parameters, used by Seligson and others (2018), to the integrated (shaking, liquefaction, landslide, and fire) damage data for residential occupancies (specifically single-family/duplex and multifamily dwellings) along with a 20 percent increase to account for utility outages. The fourth to sixth rows look at the household and population counts in the areas of concentrated damage for three occupancy groupings.

These analyses of the combined effects of potential residential building damage and lifeline utility outages results in a range of 60,994 to 520,210 households and 170,206 to 1,451,838 people at risk of displacement from the M_w 7.0 mainshock, or 2 to 20 percent of the nine-county region totals. Across these perspectives, the percentage of people at risk of displacement in Alameda County ranges from 10 percent (in areas of concentrated damage to single-family/duplex occupancies) to 54 percent (in areas of concentrated damage to multifamily occupancies), with 16 percent displaced in the customized Hazus estimate and 27 percent of the population in the areas of concentrated damage (all occupancies) (see table B4 of section B). For comparison, a study of the spatial economic demand shifts in Louisiana, Mississippi, and Alabama found that one year after Hurricane Katrina the counties and parishes that encompass the core disaster area lost an average of 23.1 percent of their population (Xiao and Nilawar, 2013).

Specific Population Groups Vulnerable to Displacement

In their 2015 study "Stronger Housing, Safer Communities," the Association of Bay Area Governments (ABAG), San Francisco Bay Conservation and Development Commission (BCDC), and partners used the "communities of concern" methodology developed by the San Francisco Bay region Metropolitan Transportation Commission (MTC) to identify census block groups in the San Francisco Bay region that have higher than average concentrations of 10 socioeconomic characteristics known to affect the abilities of individuals and households to prepare for, respond to, and recover from a disaster (ABAG and BCDC, 2015; Brechwald and others, 2015; BCDC, 2016). This analysis was updated by BCDC for their "Adapting to Rising Tides" project in 2016 (BCDC, 2016). Table 5 lists the ABAG/BCDC community vulnerability indicators (CVI), the way in which they are measured, and the threshold percentage per census block group that must be met for a block group to receive a CVI score.

The ABAG/BCDC CVIs were used to evaluate the social and economic vulnerabilities of residents in the areas of concentrated damages for all building occupancies. The prevalence of vulnerability indicators for residents in areas of concentrated building damage varies by CVI score (see section B). Transportation cost burden dominates in the less-vulnerable block

Table 4. Estimates of potential populations at risk of displacement after the moment magnitude 7.0 mainshock of the HayWired scenario, San Francisco Bay region, California.

Displacement analysis method	Displaced households[1]	Displaced people[2]	Percentage of the nine-county regional total
Regionwide analysis of residential building damages			
Customized Hazus analysis	152,438	412,954	6
Customized Hazus analysis plus 20-percent increase for lifeline outages	182,926	495,545	7
Integrated building damage data analysis plus 20-percent increase for lifeline outages[3]	210,995–266,028	574,240–723,206	8–10
Areas of concentrated damage[4]			
All occupancy classes	172,484–267,631	487,698–765,402	7–10
Single-family/duplex occupancy class	60,994–128,543	170,206–363,215	2–5
Multifamily occupancy class	361,948–520,210	1,024,266–1,451,838	14–20

[1]Uses 2000 U.S. Census data.

[2]County-level average household size from the 2010 U.S. Census was used to calculate displaced population estimates for the mainshock.

[3]A range of estimates is provided to account for the variations in housing units possible in each of the multifamily residential occupancy classes.

[4]The lower bound for ranges in this section are total households or people in areas of concentrated damage caused by earthquake hazards (ground shaking, landslides, and liquefaction) and the upper bound for ranges are total households or people in areas of concentrated damage caused by earthquake hazards and fire. It is not likely that all households or people in areas of concentrated damage would be displaced, but neighborhood-serving infrastructure and services and heavy levels of surrounding building damage could lead to higher rates of displacement than less damaged areas.

Table 5. Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) community vulnerability indicators and measures.

[Data from ABAG and BCDC (2015) and Brechwald and others (2015); updated by BCDC (2016). Thresholds for defining the presence of indicators were determined by calculating the regional mean for each indicator and adding one-half the standard deviation to the regional mean]

Indicators	Measure	Percentage per census block group	Score
Housing cost burden	Percentage of household monthly spending on housing is >50 percent of gross monthly income	≥35 (renters) and (or) ≥19 (owners)	1
Transportation cost burden	Percentage of gross monthly income used for transportation costs	≥18	1
Home ownership	Percentage of housing not owner occupied	≥55	1
Household income	Percentage of households with income <50 percent of the region's median income	≥33	1
Education	Percentage of persons ≥25 years of age without a high school diploma	≥19	1
Racial/cultural composition	Percentage of non-white races or ethnicities	≥68	1
Transit dependence	Percentage of households without a vehicle	≥15	1
Non-English speakers	Percentage of households where no one ≥15 years of age speaks English well	≥14	1
Age—Young children	Percentage of young children <5 years of age	≥8	1
Age—Elderly	Percentage of elderly people ≥75 years of age	≥9	1
Total possible community vulnerability indicator (CVI) score			**10**

groups (for example, with CVI scores of 3 or less). The racial and cultural composition indicator dominates the middle range of CVI scores of 4 to 7. The elderly indicator contributes the least overall to the CVI scores, especially higher CVI scores. In areas with CVI scores of 5 or more, there is a greater prevalence of housing- and income-related indicators (for example, lack of home ownership, high housing cost burden, lower household incomes) and literacy indicators (for example, lower levels of education and more non-English speakers).

In areas of concentrated damage, around 350,000 people reside in block groups with CVI scores of 5 or greater. Of those, a large portion—nearly 285,000 people—reside in Alameda County (or 18 percent of the county population), approximately 55,000 people reside in Contra Costa County (or 5 percent of the county population), and more than 9,000 people reside in Solano County (or 2 percent of the county population). In the parts of the economic subareas with areas of concentrated damage, the greatest concentrations of people residing in block groups with CVI scores of 5 or greater are in central Alameda County (40 percent of the subarea population), western Contra Costa County (26 percent of the subarea population), and Vallejo (8 percent of the subarea population). Figure 6 shows the census block groups with populations that have CVI scores of 5 or more in the areas of concentrated damage.

Past disasters have also shown that families with school-age (kindergarten through 12th grade) children, persons with disabilities, and homeless populations are also vulnerable to or less tolerant of postdisaster displacement (Bolin, 2007; Fussell and others, 2010; Esnard and others, 2011; Plyer and Ortiz, 2011; Weber and Peek, 2012; Fothergill and Peek, 2015; Kroll-Smith, 2018); however, these groups were not well represented by the ABAG/BCDC CVIs. Additional analyses were performed on these population groups, using the more current 2012–16 American Community Survey 5-year estimates (U.S. Census Bureau, 2018) and the most recent homeless point-in-time survey data for the nine-county region (County of San Mateo Human Services, 2017; Applied Survey Research, 2018; Contra Costa Health Services, 2018; County of Napa, 2018). Table 6 provides a summary of these analyses.

Young and moderate- to high-income renters may represent a cohort of the population with the means, mobility, a lack of social ties, or tolerance for staying in the region after a major earthquake like that in the HayWired scenario. This population group is also not identified by the ABAG/BCDC CVIs. A major regional disruption to housing, jobs, and transit, could be the tipping point for many people to voluntarily relocate to another city or region, and this population group may be especially likely to do so if they can continue working for the same company, if their employer sustains significant damage or disruption, or if their employer chooses to relocate for some other reason. After the 1994 Northridge earthquake, a few of the more affluent neighborhoods of Sherman Oaks, California, that suffered heavy damage to multifamily rental units and condominiums experienced voluntary outmigration by residents, even from undamaged properties (Olshansky and others, 2005) (see sidebar 2 of section C).

The 2012–16 American Community Survey 5-year estimates offer data on a number of household attributes that could help target potential mobile households that are young, affluent, and

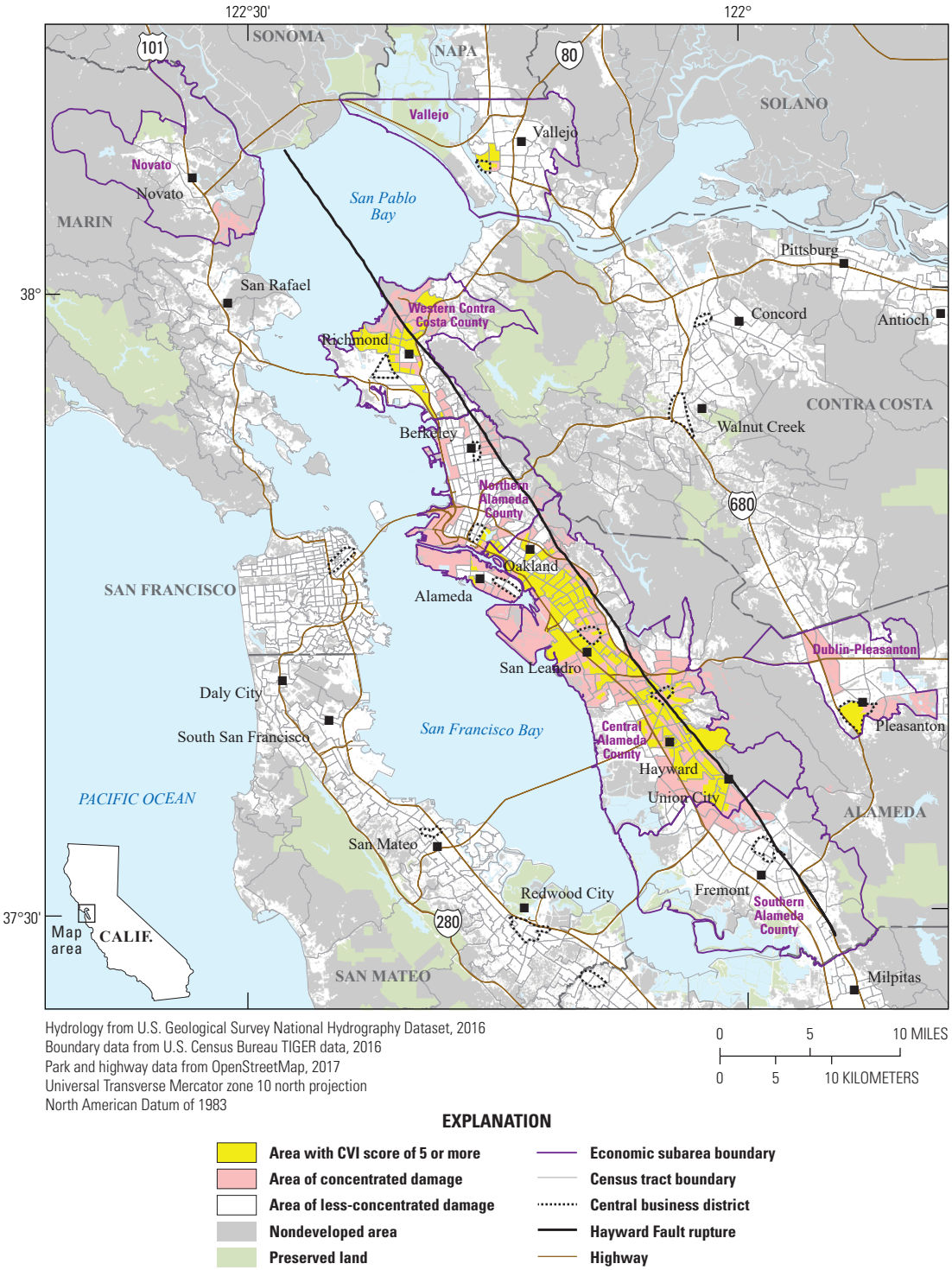


Figure 6. Map of the San Francisco Bay region, California, showing census block groups with populations that have Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) community vulnerability indicator (CVI) scores of 5 or more in the areas of concentrated damage resulting from the HayWired earthquake scenario mainshock. Data from ABAG and BCDC (2016).

Table 6. Summary of additional population groups considered in this analysis that could be vulnerable to postdisaster displacement resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[ABAG, Association of Bay Area Governments; BCDC, San Francisco Bay Conservation and Development Commission; CVI, community vulnerability indicator; n/a, not applicable]

Population group	Total population in nine-county region	Total population in areas of concentrated damage for all occupancies	Key economic subareas and concentrations
School-age children (kindergarten through 12th grade)[1]	1,168,694	130,455	85,067 school-age children in areas of concentrated damage in central Alameda County 64,300 school-age children in areas of concentrated damage with higher concentrations of school age children than other areas[2] Overlapping areas of concentrations of school-age children and areas with ABAG/BCDC CVI scores of 5 or greater are in the central Alameda County, western Contra Costa County, and Vallejo economic subareas
Households with at least one disabled resident[1]	550,901	63,408	39,031 households have at least one disabled resident in areas of concentrated damage in central Alameda County 31,993 households have at least one disabled resident in areas of concentrated damage with higher concentrations of disabled resident households than other areas[2] Overlapping areas of concentrations of disabled resident households and areas with ABAG/BCDC CVI scores of 5 or greater are in the western Contra Costa County and central and northern Alameda County economic subareas
Sheltered and unsheltered homeless populations[3]	28,213	n/a	Counties that have the highest homeless populations are: San Francisco (population of 7,499 or 27 percent of the nine-county regional total), Santa Clara (population of 7,394 or 26 percent of the nine-county regional total), and Alameda County (population of 5,629 or 20 percent of the nine-county regional total) Homeless populations in cities that have one or more census tracts located in areas of concentrated damage are: Oakland (population of 2,761 or 49 percent of the Alameda County total), Berkeley (population of 972 or 17 percent of the Alameda County total), Richmond (population of 270 or 18 percent of the Contra Costa County total), Novato (population of 350 or 31 percent of the Marin County total), and Vallejo (population of 402 or 37 percent of the Solano County total)

[1]Sourced from the American Community Survey 2012–16 5-year estimate and U.S. Census Bureau (2018).

[2]Areas with higher concentrations of the population of interest have concentrations above the regional mean plus one-half standard deviation (calculated at the block-group level) for the total population in the nine-county region.

[3]Sourced from the homeless survey counts by Applied Survey Research (2018) and reports by the County of San Mateo Human Services (2017), Contra Costa Health Services (2018), and County of Napa (2018).

lack family ties and obligations to the region. They are: renter householders between the ages of 25 and 34, householders under age 45 that earn incomes greater than the county median, households with rental costs that are higher than the county median, and nonfamily households without children.

Across the nine-county region, there are 321,507 renter householders between the ages of 25 and 34, approximately two-thirds of which reside in block groups where the concentration of young renter householders is greater than the regional mean plus one-half standard deviation. Of these, approximately 168,663 (or 79 percent) young renter householders reside in block groups that also have at least one other mobile-household attribute with concentrations higher than the defined threshold values, indicating that there are neighborhoods with high concentrations of potentially young and mobile populations.

In the areas of concentrated damage (caused by integrated earthquake- and fire-related damage for all occupancies), there are 24,243 renter householders between the ages of 25 and 34 in block groups where the concentration of young renter householders is greater than the regional mean plus one-half standard deviation. Of these, 14,110 young renter householders (or 58 percent) reside in block groups that also have at least one other mobile-household attribute with concentrations higher than the defined threshold values.

Figure 7 shows the 2010 census block groups that have high concentrations of renter householders between the ages of 25 and 34 in the areas of concentrated damage as well as those block groups with concentrations of young renter householders that also have at least one other mobile-household attribute in concentrations higher than the defined threshold values. The block groups in the areas of concentrated damage that have an ABAG/BCDC CVI score of 5 or more are also shown. There are a few overlapping areas of high concentrations of potentially young and mobile populations and populations with an ABAG/BCDC CVI score of 5 or more in the Vallejo and northern and central Alameda County subareas. This provides some indication of areas where young and mobile populations might choose to voluntarily relocate from in the HayWired

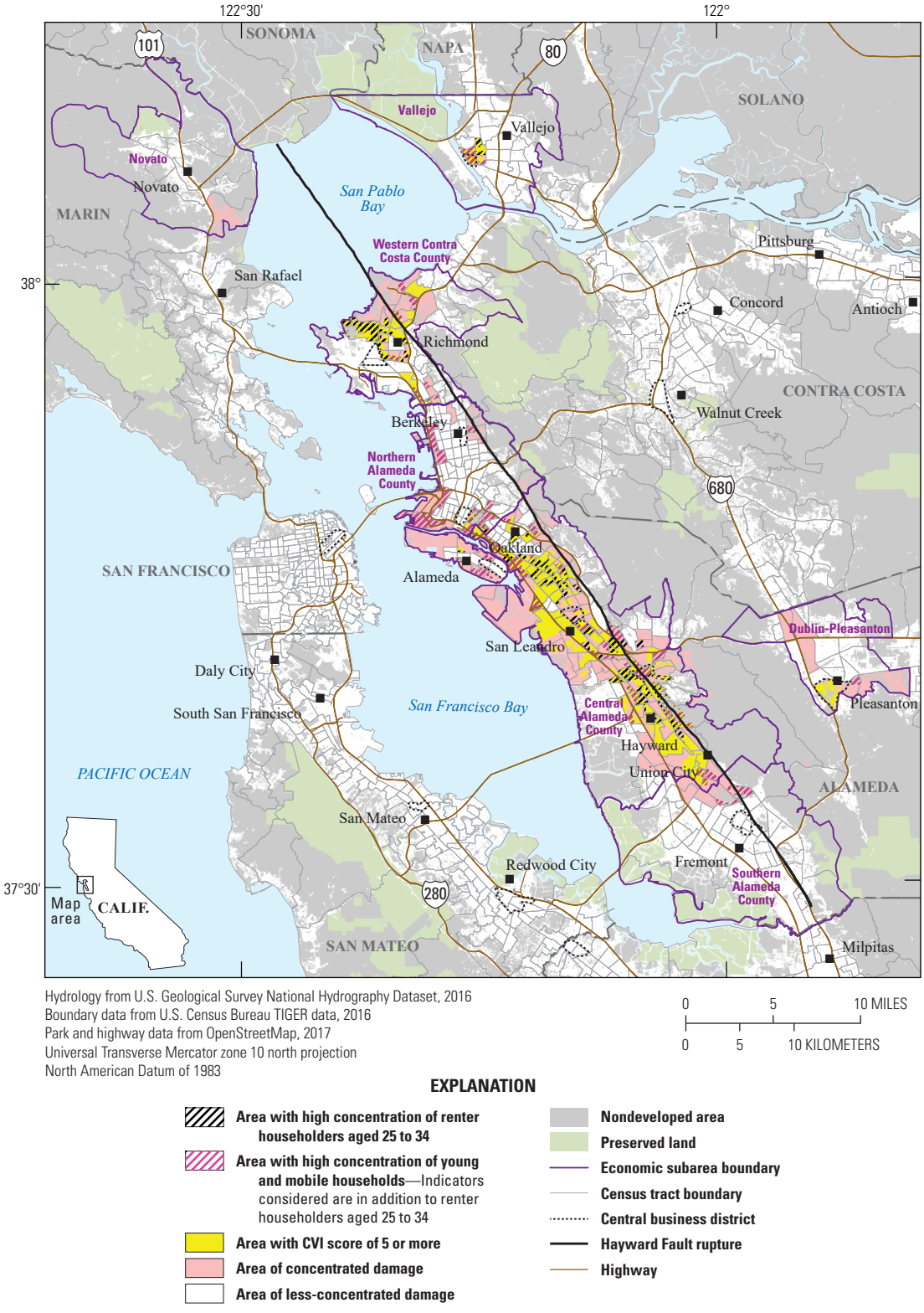


Figure 7. Map of the San Francisco Bay region, California, showing the census block groups in areas of concentrated damage (all building occupancies) resulting from the HayWired earthquake scenario mainshock where the percentage of renter householders aged 25 to 34 is greater than the regional mean plus one-half standard deviation and those areas that also have one additional young and mobile indicator that exceeds the regional mean plus one-half standard deviation. The block groups in the areas of concentrated damage that have a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are also shown. Data from ABAG and BCDC (2016) and U.S. Census Bureau (2018).

scenario, because of the high levels of damage and disruption in these neighborhoods and potential displacement of more socioeconomically disadvantaged neighbors.

Emergency Sheltering and Interim Housing Influences on Population Movements

It is now established practice for Federal, State, and local emergency management plans and policies to address emergency shelter and mass care needs, including for large-scale, urban disasters like that in the HayWired scenario (FEMA, 2008; California Emergency Management Agency, 2009; Bay Area Urban Area Security Initiative [Bay Area UASI], 2011; California Governor's Office of Emergency Services [Cal OES], U.S. Department of Homeland Security [DHS], and FEMA, 2016). However, the long-term, forced or voluntary, displacements of people and the interim and permanent housing needs resulting from building damage, fire, lifeline infrastructure damage and outages, and environmental health threats after a major earthquake are not as well addressed. Planning and policy development for interim and permanent housing is much newer—stimulated to a great extent by Congress's mandate, after Hurricane Katrina, to Federal agencies to develop a national disaster housing strategy (FEMA, 2009).

The "Bay Area Earthquake Plan" estimates that approximately 330,000 individuals would immediately seek sheltering support after a major earthquake on the San Andreas or Hayward Faults (Cal OES, DHS, and FEMA, 2016), and the Bay Area UASI "Regional Catastrophic Earthquake Interim Housing Plan" estimates 400,000 displaced households, of which 160,000 households will still need shelter one year, after a M_w 7.9 earthquake on the San Andreas Fault (Bay Area UASI, 2011). Neither of these plans consider the possibility of widespread fires and extensive lifeline utility disruptions. Thus, the customized Hazus analysis estimates by Seligson and others (2018) of nearly 153,000 displaced households (or 6 percent of the nine-county households) and 48,050 people seeking public shelters (less than 1 percent of the nine-county population) might be considered lower bounds on the region's likely needs in the HayWired scenario. Other estimates provided by the analyses in table 4 may be more appropriate and the larger estimates challenge current planning assumptions for displaced households.

The "Bay Area Earthquake Plan" estimates that there are roughly 2,000 shelters in the 16-county region[4] that, as of January 2014, could accommodate about 800,000 people in evacuation shelters (typically for 24 hours or less) and 280,000 individuals who require temporary shelter (for multiple days) (Cal OES, DHS, and FEMA, 2016). Although the evacuation shelter capacity could cover most of the potential population displacement estimates provided in this analysis, damage to potential shelter sites and personnel shortages, including a shortage of building inspectors to assess safe entry to these sites, may substantially reduce the available sheltering capacity. Supposing that the most vulnerable populations would need temporary shelter, then the approximately 350,000 people with ABAG/BCDC CVI scores of 5 or greater in the areas of concentrated damage approaches the total temporary shelter capacity, which again may be substantially reduced by the same factors affecting the evacuation shelters. Both types of shelters also need to be accessible to persons with disabilities and other access and functional needs.

In the HayWired scenario, available shelters in the central nine-county region may quickly reach capacity, especially in heavily impacted areas, such as Alameda and Contra Costa Counties. In this case, the "Bay Area Earthquake Plan" identifies potential host areas in surrounding counties, such as Mendocino, Sacramento, Yolo, San Joaquin, San Benito, Monterey, and Santa Cruz Counties, that are less likely to sustain heavy damage. If the immediate sheltering needs exceed the 16-county regional sheltering capacity, some people may need to relocate to other parts of California or adjoining States. The "Bay Area Earthquake Plan" estimates that there is additional shelter capacity for millions elsewhere in California and the adjoining States of Oregon, Nevada, and Arizona. As revealed after Hurricane Katrina, people who are displaced farther away from their home communities are more likely to have difficulty returning, especially socioeconomically vulnerable populations (Weber and Peek, 2012; Esnard and Sapat, 2014) (see sidebar 1 of section B).

In the days and weeks after the M_w 7.0 mainshock of the HayWired scenario, many displaced residents may be able to return to their neighborhoods and homes as access controls are lifted, lifeline utility services are restored, and structures are deemed safe to reoccupy. The occupants of damaged housing units will most likely need alternative, or interim, housing while repairs and rebuilding take place, or until other permanent housing is available. There are an estimated 140,000 to 170,000 housing units in an extensive or complete damage state caused by earthquake hazards and fire in the HayWired scenario (see table B3 of section B). These damage conditions mean that they are likely to receive a "red" unsafe or "yellow" restricted entry evaluation from a postdisaster building safety assessment. Units in a complete damage state because of fire are likely to be total losses. Past earthquakes have shown that housing in an extensive or complete damage state are likely to have repair times in excess of three months and as long as three years (FEMA, 2012). Interim housing needs could also increase significantly where the recovery times for critical sewer, water, energy, transportation, education, and health services are extensive.

Federal, State, and local disaster plans prioritize the use of existing housing resources, such as vacant rental properties, hotels, and motels, to the extent that they are available ahead of temporary housing installations, such as manufactured homes or other forms of interim housing that have to be constructed (FEMA, 2009; Bay Area UASI, 2011; Cal OES, DHS, and FEMA, 2016). However, with near-zero housing vacancy rates and housing affordability issues for both for-sale and rental housing at all income levels for several years across the San Francisco Bay region (Pacific Union, 2016; Metcalf, 2017), the available housing supply will likely be depleted quickly, resulting in housing price increases, perhaps dramatically in the central nine-county region. Hotels

[4]This includes the nine-county region abutting San Francisco Bay plus adjoining counties of Mendocino to the north; San Joaquin, Yolo, and Sacramento to the east; and Santa Cruz, San Benito, and Monterey to the south.

and motels in or near affected communities may initially be provided to first responders and recovery contractors, which may further exacerbate the housing shortage for displaced households (Bay Area UASI, 2011). Services like Airbnb's Open Homes program that provide free, temporary housing to those impacted by disasters will also be available. Nonetheless, a large supply of temporary housing units may need to be constructed or brought into the region, but this can take months to implement (Bay Area UASI, 2011).

In a major earthquake, like that in the HayWired scenario, widespread housing damage and preexisting housing market constraints in the San Francisco Bay region will make it extremely challenging to provide quick and affordable interim housing resources and keep people near their home communities, especially in areas of concentrated damage. Socially and economically vulnerable populations may have a much harder time finding alternative housing near their home communities (Peacock and others, 2014; Fussell, 2015). As a result, tens of thousands of households may be required to leave their home communities to find available housing. More distant and more permanent relocations may also result from the lack of interim housing resources.

The "Bay Area Earthquake Plan," "Regional Catastrophic Earthquake Interim Housing Plan," and "National Disaster Housing Strategy" do not offer much guidance on the potential "receiving communities" for residents displaced from their home communities by a major earthquake (FEMA, 2009; Bay Area UASI, 2011; Cal OES, DHS, and FEMA, 2016). However, past disaster experiences have shown that emergency sheltering and interim housing decisions and actions taken early on in a major disaster by local, State, and Federal response personnel may greatly influence the geographic pattern of population displacement and locations of potential receiving communities (Mueller and others, 2011; Esnard and Sapat, 2014). Studies of the spatial economic demand shift in Louisiana, Mississippi, and Alabama after Hurricane Katrina showed that people migrated to places at the edge of the disaster area with minimal to no damage and, in some instances, stayed there for several years (Xiao and Nilawar, 2013).

Given these insights and constraints, it is likely that communities with the capacity to become major receiving communities will be outside the central urbanized core and in less-damaged edge communities of the nine-county region as well as in the seven surrounding counties—Mendocino, Sacramento, Yolo, San Joaquin, San Benito, Monterey, and Santa Cruz Counties—and particularly larger cities within these counties, such as the cities of Sacramento, Stockton, Modesto, and Salinas. However, the combination of damaged regional highways and the Bay Area Rapid Transit (BART) system could severely impede commuter transport. Regional emergency transportation plans to provide added capacity to the region's ferry and public transportation network after a major disaster (Cal OES, DHS, and FEMA, 2016; San Francisco Bay Area Water Emergency Transportation Authority, 2016) would need to be enhanced to extend planned services further afield and over a longer period of time to improve the viability and desirability of interim housing options in some of these areas. Others may relocate to other parts of California, the adjoining States of Oregon, Nevada, and Arizona, or even further afield.

All displaced households will require much more than housing and there will be simultaneous increased demands on community services and infrastructure, such as health care, employment assistance, childcare, and access to schools in receiving communities. It is important that receiving communities plan for and have support for these services, and that the services be offered simultaneously or sequenced in a way that helps settle residents and enhance their recovery (Tobin-Gurley and others, 2010).

Anticipating Population Return

There are factors internal and external to disaster-impacted areas that can influence the duration of displacement and rate of population return (Fraser and others, 2003; Greer, 2015; Husby and Koks, 2017). The restoration of damaged housing or construction of new housing are major factors. Past disasters have shown that it takes at least two years to replace a significant portion of housing; multifamily and affordable housing is much more difficult and slower to replace than single-family, market-rate housing (SPUR, 2012). Aftershocks and an array of postdisaster conditions, including additional damage; lack of schools, health care, and other services; lack of social ties; delays in the recovery efforts; and concerns about future earthquake risks, could also delay population return and increase the potential outmigration from the region. Furthermore, if displaced residents find better schools, more affordable housing, and new jobs in other places, they may delay returning or choose not to return to their home communities, no matter how fast or effective the rebuild.

Past disasters have also shown that population recovery in some communities does not necessarily equate to a return of predisaster residents (Johnson and Olshansky, 2017). Postdisaster changes in the demographic composition of impacted communities is common, with new people, notably recovery workers and the reconstruction labor force, moving in, sometimes permanently. For example, there is a larger population of young adults and Latinos in the recovered City of New Orleans than before Hurricane Katrina (The Data Center, 2019).

Long-Term Community Recovery Challenges

The analyses of areas and population at risk of displacement reveal some significant long-term recovery challenges that residents, businesses, and communities in the San Francisco Bay region are likely to face after a major earthquake like that in the HayWired scenario. Three long-term recovery challenges are explored in greater detail: assembling the financial resources for recovery, repairing and replacing the substantial amount of damaged housing, and, addressing areas that may require governmental interventions and replanning to recover.

Assembling the Financing Resources for Recovery

Money fuels disaster recovery and its availability largely determines the pace and scope of community recovery (Johnson and Olshansky, 2017). In a major earthquake sequence like that in the HayWired scenario, it will be difficult for residents, businesses, and governmental and nongovernmental agencies to quickly assemble the substantial resources necessary to fund repairs and rebuilding.

Total direct economic losses are determined in section C. In summary, the estimated building and content damages and income losses for the mainshock (ground shaking, landslide, liquefaction, and fire) and aftershock (shaking) for the HayWired scenario is about $102 billion (in 2016 U.S. dollars). Of this, about 43.5 percent are residential losses and 56.5 percent are nonresidential losses.

An analysis by CoreLogic, Inc. (2018) estimates $167.3 billion (2016 U.S. dollars) in potential damage to commercial and residential property as well as automobiles and direct business interruption losses caused by the mainshock (ground shaking, landslide, liquefaction, and fire) and aftershock sequence. Approximately 40 percent of these losses occur in Alameda County. A prior analysis by Grossi and Zoback (2013) estimated losses between $172.5 and $186.5 billion (2013 U.S. dollars; between $177.7 and $192.1 billion in 2016 U.S. dollars) for a suite of M_w 7.0 earthquakes on the Hayward Fault; they considered earthquake hazards, fire, and insurance-related postdisaster cost inflation, but not aftershocks. None of these estimates account for damage to the region's utility and transportation infrastructure, contingent business interruption losses, and other direct, indirect, and induced economic impacts of building capital losses and utility disruption.

Though there are some significant discrepancies between these loss estimates, the important point to consider is the scale of loss—a loss that does not yet account for the indirect losses caused by social and economic disruption. These estimates vastly surpass any modern disaster experience in the San Francisco Bay region. For perspective, the M_w 6.9 Loma Prieta earthquake of 1989 caused about $10 billion in economic losses at the time (approximately double in 2016 U.S. dollars) and the M_w 6.0 South Napa earthquake of 2014 caused more than $700 million in economic losses (Insurance Information Institute, 2018).

In most areas of the United States, insurance is a foundational element of a community's disaster recovery. According to national surveys, about 95 percent of homeowners have basic residential insurance coverage (Wilkinson, 2016). In California, however, earthquake insurance is generally offered as a separate policy from the general property insurance; only about 10 percent of general residential property insurance holders in the nine-county region have an earthquake insurance policy (California Department of Insurance, 2017). Most of the commercial earthquake insurance in the State covers large commercial buildings (California Department of Insurance, 2012).

Given the low levels of earthquake insurance coverage in the region, CoreLogic, Inc. (2018) estimates $30.2 billion in insured losses, or only about 18 percent of their total damage estimate for the HayWired scenario is covered by insurance. More specifically, about 20 percent of commercial losses and 9 percent of residential losses are covered by insurance. About $21.2 billion in insured losses are from earthquake-hazard-related damages (for example, ground shaking, landslide, and liquefaction) for the M_w 7.0 mainshock of the HayWired scenario. In the CoreLogic, Inc. (2018) estimation, insured losses for fire and sprinkler damage adds $4 billion to the mainshock estimate and the cumulative insured losses for the aftershock sequence totals $5 billion.

Figure 8 illustrates the portions of the CoreLogic total damage estimates for both residential and nonresidential occupancy groupings that are covered by insurance for the mainshock, aftershocks, and the entire HayWired scenario earthquake sequence.

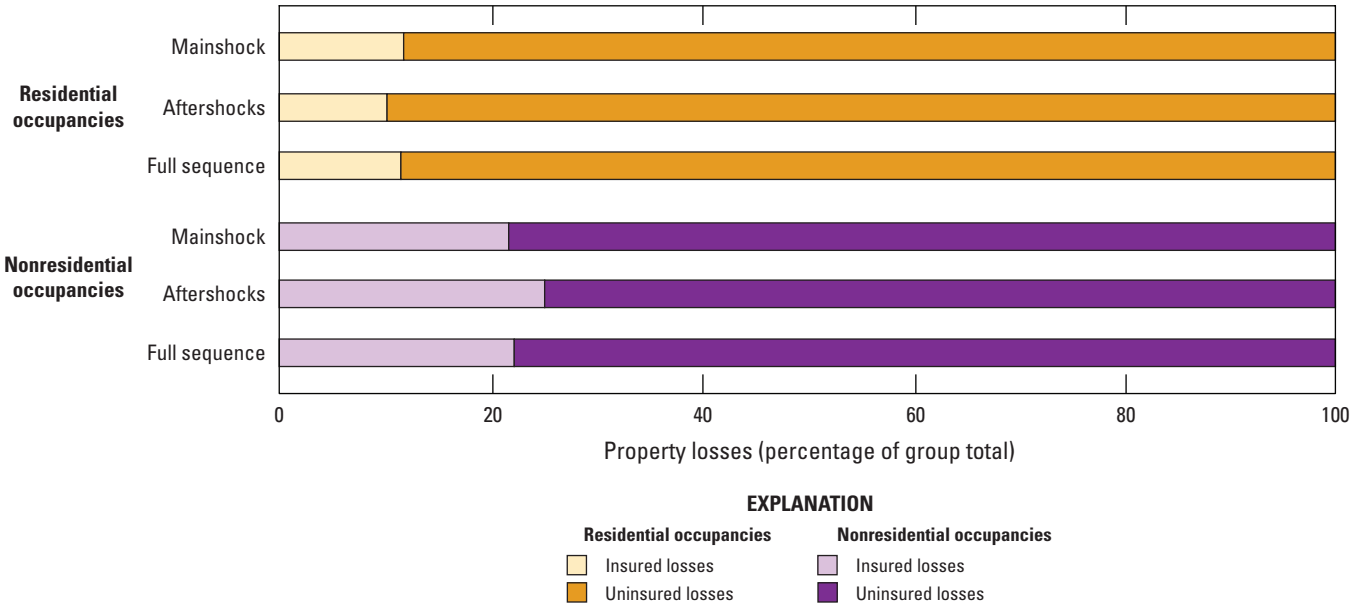


Figure 8. Bar graph showing the percentage of CoreLogic, Inc. (2018) estimated insured and uninsured losses for residential and nonresidential occupancy groupings for the HayWired scenario mainshock, aftershocks, and the entire earthquake sequence in the San Francisco Bay region, California.

These estimates do not include the insured losses for damage to the region's infrastructure; workers compensation exposures; government exposures that are not part of the commercial, residential, and automobile lines of business; and long-term indirect economic impacts of such a major disaster. Most counties, as well as many cities and municipal districts, in the San Francisco Bay region belong to insurance risk pools that provide workers compensation and property insurance coverages and, thus, would be providing additional insurance resources for the recovery.

It is difficult to draw direct comparisons between the insurance estimates for this scenario and the insured losses from the 1989 Loma Prieta and 1994 Northridge earthquakes because the insurance market has changed so much over time. Nonetheless, for the 1989 Loma Prieta earthquake, there was an insured loss of $960 million, or nearly 10 percent of the $10 billion in total losses, and, for the 1994 Northridge earthquake, insurance losses were $15.3 billion, or 35 percent of the $44 billion in total losses (in original values) (Munich RE, 2015).

CoreLogic, Inc. (2018) estimates $2 billion in fire-related insured losses in the HayWired scenario. Scawthorn (2018) estimates that there could be close to $30 billion in replacement value for properties damaged by fires in the HayWired scenario. Removing the potential for double-counting of the losses for both earthquake hazards and fire and using the more conservative Hazus valuation of additional fire damage, the loss is about $20 billion (in 2016 dollars). In either case, a significant portion of that damage would likely be covered by general property insurance. For comparison, in the 1991 fire in the east bay hills, 3,500 homes were destroyed, resulting in about $1 billion in insured losses (1992 U.S. dollars; $1.72 billion in 2016 U.S. dollars) (Scawthorn, 2018), and the 2017 California wildfires resulted in more than $11 billion in insured losses from damage to more than 21,000 homes and 2,800 businesses (Verma, 2017; Aon Benfield, 2018).

Though the CoreLogic, Inc. (2018) and Scawthorn (2018) fire damage differences are not reconciled, an insurance industry loss of more than $30 billion would be comparable in size to the insured property losses after Hurricane Sandy in 2012 (Munich RE, 2015), but less than the expected $135 billion insured losses from the 2017 hurricane season (Kim, 2017; Munich RE, 2018). Nonetheless, as this analysis has shown, a considerable portion of the total losses from a major earthquake, like that in the HayWired scenario, would not be covered by insurance payouts, making it significantly different from other large urban disasters that we have faced recently in the United States, such as major hurricanes in 2005, 2012, and 2017.

A major earthquake like the M_w 7.0 mainshock of the HayWired scenario would almost certainly trigger State and Federal disaster declarations and the provision of disaster assistance programs and activities defined by the California Disaster Assistance Act (California Government Code 8680-8692), the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Public Law 93-288, as amended), as well as other State and Federal disaster assistance programs and activities. Congress can also appropriate supplemental funding to programs like the U.S. Department of Housing and Urban Development's Community Development Block Grant Disaster Recovery (CDBG-DR) to help rebuild areas affected by federally declared disasters. CDBG-DR funding has been a crucial resource for State and local governments and homeowners in addressing unmet disaster recovery needs in many recent disasters (Johnson and Olshansky, 2017); however, the unmet needs from a major earthquake, like that in the HayWired scenario, would far exceed the CDBG-DR allocations made to States and cities impacted by 2005 Hurricane Katrina, 2012 Hurricane Sandy, and the 2017 hurricane and wildfire seasons. It can also take considerable time for Congress to make the allocations, for receiving States and communities to design and implement funding programs, and, thus, for recipients to actually receive the funds. Also, after major disasters, Congress or the President may authorize tax credits and other forms of temporary relief or incentives to help stimulate rebuilding.

Studies from past disasters have shown, however, that race, ethnicity, gender, income, language fluency, and cultural differences can differentially influence the accessibility and distribution of formal disaster assistance, especially from government sources (Bolin, 2007; Enarson and others, 2007; Aldrich, 2011). For the HayWired scenario, some of the hardest hit communities also have high ABAG/BCDC CVI scores and, thus, many individuals, households, and business owners in these areas may have difficulty obtaining formal disaster assistance. Language and education limitations, fear of authorities, complicated forms, and limited internet access to services are just a few of the barriers that socioeconomically disadvantaged groups face (Bolin and Stanford, 1998; Tobin-Gurley and others, 2010; Abramson and others, 2015).

Even with insurance payouts and disaster funding from both the Federal and State government, a considerable amount of private investment would also be required to finance a recovery effort of this magnitude, depleting individual savings and business reserves and with socioeconomic ripple effects to follow for many years. Philanthropic and nonprofit funding would be especially crucial for those with few resources or who have difficulty accessing public postdisaster resources.

Repairing and Replacing Damaged Housing

Reestablishing permanent housing is crucial to both household and community-scale disaster recovery (Peacock and others, 2007; Xiao and Van Zandt, 2011). If housing recovery is impaired, then other dimensions of community recovery are also delayed.

Damage to 1 million residential buildings is valued at $42.4 billion (in 2016 U.S. dollars) using the Hazus methodology. However, these estimates are based on replacement costs of $140 to $150 per square foot (in 2005 U.S. dollars) that are then inflated to $170 to $180 per square foot in 2016 U.S. dollars, which is slightly above the average Hazus replacement cost of $168 per square foot across all occupancies in the San Francisco Bay region. In 2017, construction costs averaged $330 per square foot in San Francisco—the highest in the Nation (Sawyer, 2017)—and temporary postdisaster increases in construction costs, known as demand surge, are common because of workforce and resource

constraints. In the year after the 2017 wildfires, homeowners in Sonoma County reported construction estimates more than doubled to $500 to $600 per square foot (Newberry, 2018). Thus, the actual postdisaster costs to repair and replace damaged housing after a major earthquake in the San Francisco Bay region could be much higher and financing will be a major challenge for some building owners, especially those without insurance.

For most of the nearly 900,000 residential buildings with slight to moderate damage in the HayWired scenario, likely loss levels could be within the range of financing available with Small Business Administration (SBA) disaster loans and Individual Assistance grants from the Federal Emergency Management Agency (FEMA). For the small portion of these building owners who have earthquake insurance, the structural loss levels may not exceed their deductibles and owners may need to seek conventional loans or rely on their individual savings to fund repairs.

Owners of the approximately 90,000 single-family or duplex buildings and 7,600 multifamily buildings with extensive or complete damage may only be able to partly finance their rebuilding costs with SBA disaster loans of as much as $200,000 and FEMA Individual Assistance grants of as much as $34,900 (for Federal disasters declared after October 1, 2018) for qualifying applicants. Insurance is likely to cover a large portion of the fire-related losses as well as the losses incurred by the small portion of owners who have earthquake insurance coverage. All insureds would still need to fund the deductible amounts and there may be policy limitations and instances of underinsurance—where the insurance limits do not sufficiently cover the costs of rebuilding. Multifamily building owners also tend to have greater difficulty assembling the necessary resources to finance repairs and rebuilding than single-family building owners; condominium owners have the added burden of assembling agreement and financing among all the unit owners (Comerio, 1998; Olshansky and others, 2005; Peacock and others, 2014).

Though all residential building owners are likely to have significant recovery financing challenges, owners with lower income levels may face greater difficulties qualifying for SBA loans, face difficulties obtaining conventional financing, and lack the necessary savings to fund repairs or rebuilding. Mortgage defaults and replacing affordable housing could present added difficulties for housing recovery in some neighborhoods (Olshansky and others, 2005). Significant uninsured housing repair costs will likely require some level of governmental intervention and support. Several large government-led housing repair programs have been created to address housing recovery financing gaps after Hurricanes Katrina and Sandy in the United States, the 2010–11 Canterbury earthquakes in New Zealand, as well as other major disasters, and, in a few cases, also helped to control the widespread and simultaneous construction demands and postdisaster cost increases (Johnson and Olshansky, 2017).

Household-level decisions to stay and rebuild depend on more than just housing damage and access to recovery resources. Other important factors include: the speed, strength, and certainty of economic recovery; availability of jobs and businesses; speed with which utilities, critical community services, and nearby business are restored; and regulatory changes to inspections, planning, construction, or zoning (Comerio, 2006; Groen and Polivka, 2010; Xiao and Van Zandt, 2011; Xiao and Nilawar, 2013; Elliott, 2014; Greer, 2015). Delays in the restoration of neighborhood-serving businesses and important community facilities and services, including schools, hospitals, doctor's offices, general health care services, fire and police stations, city and county administration buildings, and social services, can impede housing recovery.

As discussed by Porter (2018a) and Jones and others (this volume), the M_w 7.0 mainshock and aftershocks of the HayWired scenario will cause infrastructure disruptions and damage, particularly to transportation and water distribution systems, that could impede housing recovery. In general, for a housing unit to be deemed habitable, it must have access to water, sewer, and electricity. It is possible that occupants of habitable housing units in areas that have extensive water system damage may be displaced for an extended period of time because of water service outages. There may also be instances where the owners of damaged single-family and multifamily buildings may delay or decide against repairs and rebuilding until utility services are restored. The many aftershocks in the HayWired scenario could also cause additional housing damage and essentially "reset the clock" for many housing recovery efforts. Hard-hit communities, in particular, could be overwhelmed by the planning and permitting needs resulting from a major earthquake and aftershock sequence.

The combination of damaged regional roadways and highways and the BART system in the HayWired scenario (see Jones and others, this volume) could essentially sever north-south transport through central Alameda County and hamper housing recovery throughout the east bay corridor. The jobs-housing commute analysis by Wein, Belzer and others (this volume) informs the commute analysis by Kroll and others (this volume), which considers the effects of potential disruption to commutes from roadway and highway damages and extended repair times on economic recovery.

Areas Requiring Substantial Governmental Intervention and Replanning

A major earthquake like the M_w 7.0 mainshock of the HayWired scenario could also damage some parts of the San Francisco Bay region so extensively that market forces alone cannot facilitate recovery, and governmental interventions and replanning will be required. Determining which areas can successfully recover according to existing plans and policies and which would need to be replanned is a difficult task that largely falls to local governments to address. This analysis identifies potential areas that may require governmental interventions and replanning after a major earthquake in the San Francisco Bay region.

Table 7 defines a typology of these potential areas and provides examples from past disasters; general descriptions of potential communities at risk in the HayWired scenario; potential damage, hazard, and risk considerations; and potential governmental interventions and replanning actions that might be taken.

Table 7. Potential areas that may require governmental interventions and replanning to facilitate recovery in the HayWired scenario, San Francisco Bay region, California.

[km, kilometers; km^2, square kilometers; MMI, Modified Mercalli Intensity; M_w, moment magnitude; BART, Bay Area Rapid Transit]

Area	Past earthquake example(s) and key references	Potential communities at risk in the HayWired scenario	Potential damage, hazard, and risk considerations	Potential government interventions and replanning actions
Areas with substantial land, building, and infrastructure damage caused by liquefaction	Christchurch, New Zealand, 2010–11 earthquakes (van Ballegooy and others, 2014; Rogers and others, 2014; Johnson and Olshansky, 2017)	Neighborhoods along San Francisco, Richmond Marina, and San Pablo Bays, especially those built on bay muds or artificial fill and along major inland drainage ways; see Jones and others (2017) and Seligson and others (2018). Areas of potentially concentrated building damage caused by liquefaction are in Richmond, San Pablo, unincorporated North Richmond, Albany, Berkeley, Emeryville, Oakland, City of Alameda, San Leandro, Hayward, Union City, and Fremont. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.	Damage to building foundations and structural integrity Damage to roads and buried infrastructure Additional damage from aftershocks (such as repeated liquefaction, slope failures, fault rupture, or building and infrastructure damage) Increased vulnerability to flooding (current and future) in liquefaction areas Increased vulnerability to slope failures in landslide areas Uncertainty about the feasibility and affordability of land remediation for liquefaction, landslide, and other ground failure damage Uncertainty about the feasibility and affordability of repairs to existing buildings and infrastructure Building owner mortgage loan defaults Occupant displacement and (or) voluntary relocation Property blight Decline in property values Loss of property tax revenues	Access control Emergency structural and land stabilization measures Potential zones of required investigation, in accordance with the California Seismic Hazards Mapping Act and Alquist-Priolo Earthquake Fault Zoning Act Areawide (not site-specific) geologic hazard investigation to assess future risks Multi-hazard considerations, including current and future flood risks for liquefaction areas and winter storm and wildfire hazards for landslide areas Regional and local planning considerations, such as priority development areas and priority conservations areas in the "Plan Bay Area 2040" Community engagement in hazard evaluations, planning, and rebuilding decisions Psychological and social service support Temporary building moratorium until investigations and planning are completed Areawide remediation approaches Site development and building code changes Land use and zoning changes Voluntary buyout program or land acquisition for replanning areas Funding for access control, emergency measures, hazard investigation, planning and community engagement, areawide remediation, property buyouts, and building, road, and infrastructure repairs and replacement
Areas with substantial land, building, and infrastructure damage caused by landslides	Santa Cruz Mountains, 1989 Loma Prieta earthquake (Tyler, 1995) Anchorage, Alaska, 1964 earthquake (Pruess, 1995; Tyler and others, 2002) Niigata, Japan, 2004 earthquake (Iuchi, 2014)	Neighborhoods on steep to very steep slopes and on existing landslides in the east bay hills near the hypothetical rupture zone of the Hayward Fault and other parts of the region, especially those areas of strong ground shaking (greater than 20 centimeters per second), poor geologic-material strength, and steep slope gradient; see McCrink and Perez (2017). Areas of potentially concentrated building damage from landslide are just to the east of the Hayward Fault trace in parts of Oakland, Berkeley, and unincorporated Kensington. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		
Areas with surface fault rupture, including afterslip	Napa, 2014 earthquake (Hudnut and others, 2014) San Fernando, 1971 earthquake (William Spangle and Associates, 1980)	Neighborhoods along the 63-km stretch of the Hayward Fault that ruptures on land from Point Pinole in the north to the Warm Springs area of Fremont in the south, with as much as 2 meters of coseismic slip as well as 0.5–1.5 meters of afterslip; see Aagaard, Schwartz, and others (2017). The Hayward Fault runs through a highly developed area and most structures and infrastructure are not specifically designed to withstand displacement associated with coseismic slip or afterslip. There are 577 structures—including 535 residential buildings—in the areas of measurable offset from coseismic slip and afterslip along the Hayward Fault for the mainshock of the HayWired scenario. There are 2,654 structures—including 2,515 residential buildings—in the zone of uncertainty along either side of the fault rupture zone in the HayWired scenario. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		

Table 7.—Continued

Area	Past earthquake example(s) and key references	Potential communities at risk in the HayWired scenario	Potential damage, hazard, and risk considerations	Potential government interventions and replanning actions
Areas with concentrated building damage caused by ground shaking and fire	Downtown Santa Cruz, 1989 Loma Prieta earthquake (Mader and Tyler, 1991; Tyler and others, 2002) Los Angeles "ghost towns," 1994 Northridge earthquake (Comerio, 1998; Olshansky and others, 2005, 2006) Kobe, Japan, 1995 earthquake (Olshansky and others, 2005, 2006; City of Kobe, 2010; Edgington, 2010)	Areas subjected to shaking levels of MMI VIII or above are most vulnerable to building damage; see Aagaard, Boatwright, and others (2017). Those areas that also have high-density wood construction and population densities greater than 3,000 people per km^2 are most vulnerable to post-earthquake fires; see Scawthorn (2018). Areas of concentrated building damage caused by ground shaking and fires in the economic subareas[1] of western Contra Costa County; northern, central, and southern Alameda County; Dublin-Pleasanton; Novato; and Vallejo. Areas with concentrations of multifamily housing and (or) low-income renters in north Richmond, Pinole, east Oakland, Hayward, and Union City. Older neighborhood-serving retail districts in Pinole, Richmond, Kensington, Albany, Berkeley, Oakland, Piedmont, San Leandro, Alameda, Castro Valley, and Hayward. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.	Damage to building foundations and structural integrity Damage to roads, bridges, and other lifeline infrastructure facilities Additional building and infrastructure damage from aftershocks Uncertainty about the feasibility and affordability of repairs to existing buildings and infrastructure Building owner mortgage loan defaults Occupant displacement and (or) voluntary relocation Property blight Decline in property values Loss of property tax revenues	Access control Emergency structural and infrastructure stabilization measures Temporary transportation and infrastructure service provision Regional and local planning considerations, such as priority development areas and priority conservations areas in the "Plan Bay Area 2040" Community engagement in planning and rebuilding decisions Psychological and social service support Temporary building moratorium until planning is completed Site development and building code changes Land use and zoning changes Voluntary buyout program or land acquisition for replanning areas Funding for access control, emergency measures, planning and community engagement, property buyouts, and building, road, and infrastructure repairs and replacement.
Areas with substantial transportation and infrastructure damage	Embarcadero Waterfront, San Francisco, 1989 Loma Prieta earthquake (King, 2004a) Hayes Valley, San Francisco, 1989 Loma Prieta earthquake (King, 2004b) West Oakland, 1989 Loma Prieta earthquake (Jackson, 1998)	Jones and others (this volume) investigated the exposure of five lifeline infrastructure systems (water, electric power, oil and gas, transportation, and telecommunications) to all the different hazards from the M_w 7.0 mainshock of the HayWired scenario (ground shaking, surface fault rupture, liquefaction, landslide, and fire) and identified an area of 178 km^2 that had four overlapping mainshock hazards as well as a small 0.2 km^2 area along the Hayward Fault trace where all five mainshock hazards overlap; see Jones and others (this volume). Areas where substantial damage patterns of both buildings and infrastructure offer opportunities for realignment, removal, or substantial reconfiguration and redesign of transportation, infrastructure, and the surrounding neighborhoods. Areas surrounding highway bridges and BART facilities with extended repair times. Areas surrounding San Francisco Bay with seaport, airport, wastewater treatment, and oil and gas processing facilities that may sustain substantial damage. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		

[1]Economic subareas are defined by Wein, Belzer, and others (this volume).

Figures 9–13 integrate all elements of this analysis of communities at risk by highlighting some areas that may face intensive long-term recovery challenges. Specifically, these are areas of:

- Substantial land and building damage caused by liquefaction (fig. 9). These high-liquefaction-hazard areas in the areas of concentrated damage are located primarily in the flat lands along the eastern shores of San Francisco and San Pablo Bays.
- Substantial land and building damage caused by landslides (fig. 10). These high-landslide-hazard areas in the areas of concentrated damage are mostly located on the east side of the Hayward Fault in the east bay hills.
- Potential surface fault rupture, including afterslip (fig. 11). Census block groups in the areas of concentrated damage within one-quarter of a mile of the Hayward Fault are shown.
- Concentrated building damage caused by ground shaking and fire (fig. 12). Census tracts that have 60 percent or more of the building square footage in an extensive or complete damage state for all residential occupancies, the household-serving occupancy grouping, and all other nonresidential occupancies are shown.
- Substantial transportation (BART and highway bridges) and infrastructure (electric power and water supply) damage (fig. 13). We define "substantial" damage as follows: for electric power, an electric substation is estimated to have less than 90 percent restored functionality within 30 days by Hazus; for BART, a station is estimated to need more than 30 days to complete repairs; for highway bridges, a bridge is estimated to need more than 30 days to complete repairs; and for water supply, areas estimated to have more than eight pipeline breaks in a 1-square-kilometer area are identified as needing more than 30 days for repairs to be completed (assuming that areas with high concentrations of pipeline breaks would take longer for repairs to be completed than if fewer breaks occurred).

In all these areas, those neighborhoods that also have populations vulnerable to displacement, may lack recovery resources, or an ability to return may especially need governmental interventions and replanning to facilitate recovery. The areas with ABAG/BCDC CVI scores of 5 or more are shown in all the figures.

All the areas highlighted in figures 9–13 could also face additional damage from aftershocks (or afterslip in areas along the fault rupture) and an increased vulnerability to other hazards, such as flooding and slope failures. This may generate uncertainty about the feasibility and affordability of repairs and ripple effects that may include mortgage defaults by building and property owners, occupant displacement and (or) voluntary relocation, property blight, declining property values, and a loss of property tax revenues for local and State governments. An array of governmental interventions and replanning actions may be necessary to address these post-earthquake conditions, all of which require money, community engagement, and time, and the demands will likely come at a point when populations are displaced and local government budgets may be very constrained because of a reduced tax base and the additional costs of repairing publicly owned facilities and infrastructure.

Policy Implications for Improving Community Resilience

Community resilience is defined as the preparedness of people, entities, and systems to withstand acute shocks, like earthquakes, as well as chronic stresses while still maintaining essential functions to recover more quickly and effectively, and sometimes even emerge stronger (Rockefeller Foundation and Arup International Development, 2014). Work on community seismic resilience has been underway in California and the San Francisco Bay region for many years, but the 1989 Loma Prieta earthquake spotlighted the large-scale vulnerabilities that the region could face from a future, more centrally located earthquake. It also helped to instigate and galvanize a great many efforts in emergency preparedness, hazard mitigation, and response and recovery planning by a multitude of institutions, individuals, and businesses for the next few decades. Brocher and others (2018) estimate that since 1989, as much as $80 billion of investment across the region has been directed to critical infrastructure upgrades as well as extensive retrofitting of seismically vulnerable residential, commercial, and public buildings.

Nonetheless, as this analysis has revealed, substantial housing, infrastructure, social, and financial vulnerabilities to a major earthquake remain across the San Francisco Bay region. Furthermore, some of these vulnerabilities are only likely to continue to grow, unless there are some fundamental shifts in the scale of attention and investment given to reducing the region's seismic risk.

Seven policy implications for improving community seismic resilience in the San Francisco Bay region stem directly from insights gained in this analysis of communities at risk. The first three policy topics focus on ways in which regionwide community resilience can benefit from improving the physical resilience of the region's housing and lifeline infrastructure so that the risks of widespread and prolonged population displacement and long-term recovery challenges after a major earthquake could be significantly reduced. Four additional policy topics address policy and planning initiatives that could also enhance the region's resilience and readiness for a major earthquake. Other chapters of the HayWired scenario (Porter, 2018a; Porter, 2018b; Jones and others, this volume; Sue Wing and others, this volume; Kroll and others, this volume; Wein, Haveman, and others, this volume; Wein,

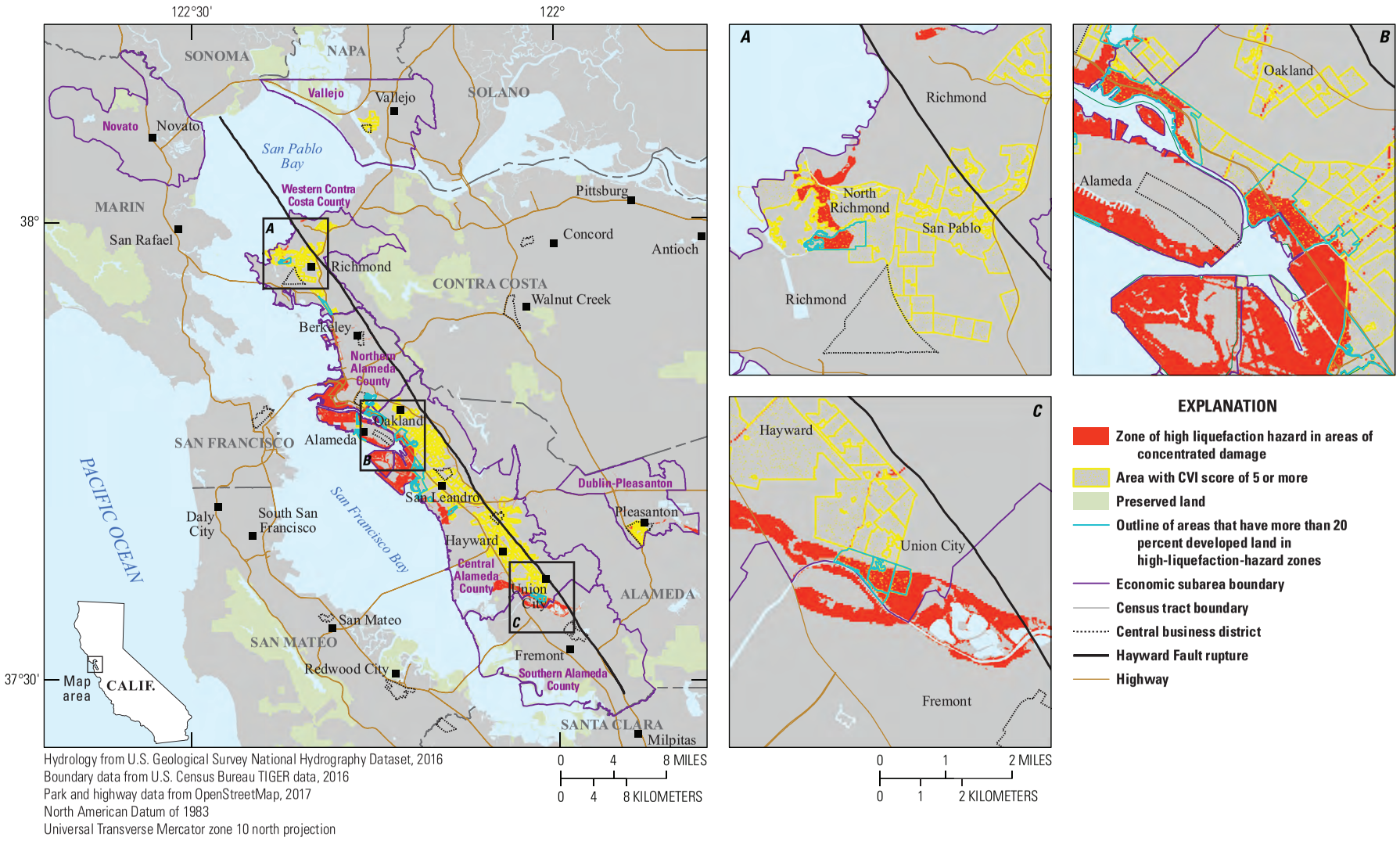


Figure 9. Maps of the San Francisco Bay region, California, showing potential areas of substantial land and building damage caused by liquefaction from the HayWired earthquake scenario mainshock. The hazard areas with high liquefaction probability (25 percent or greater) in the areas of concentrated damage (for all occupancies) are shown in red and those census block groups that have more than 20 percent of developed land in the high-liquefaction-hazard zones are outlined in turquoise. Areas with a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are shown with yellow outline and stippling. *A*, Inset map showing Richmond, North Richmond, and San Pablo in Contra Costa County. *B*, Inset map showing Oakland and Alameda in Alameda County. *C*, Inset map showing Union City, Hayward, and Fremont in Alameda County. Data from ABAG and BCDC (2016), Jones and others (this volume), and Jones and others (2020).

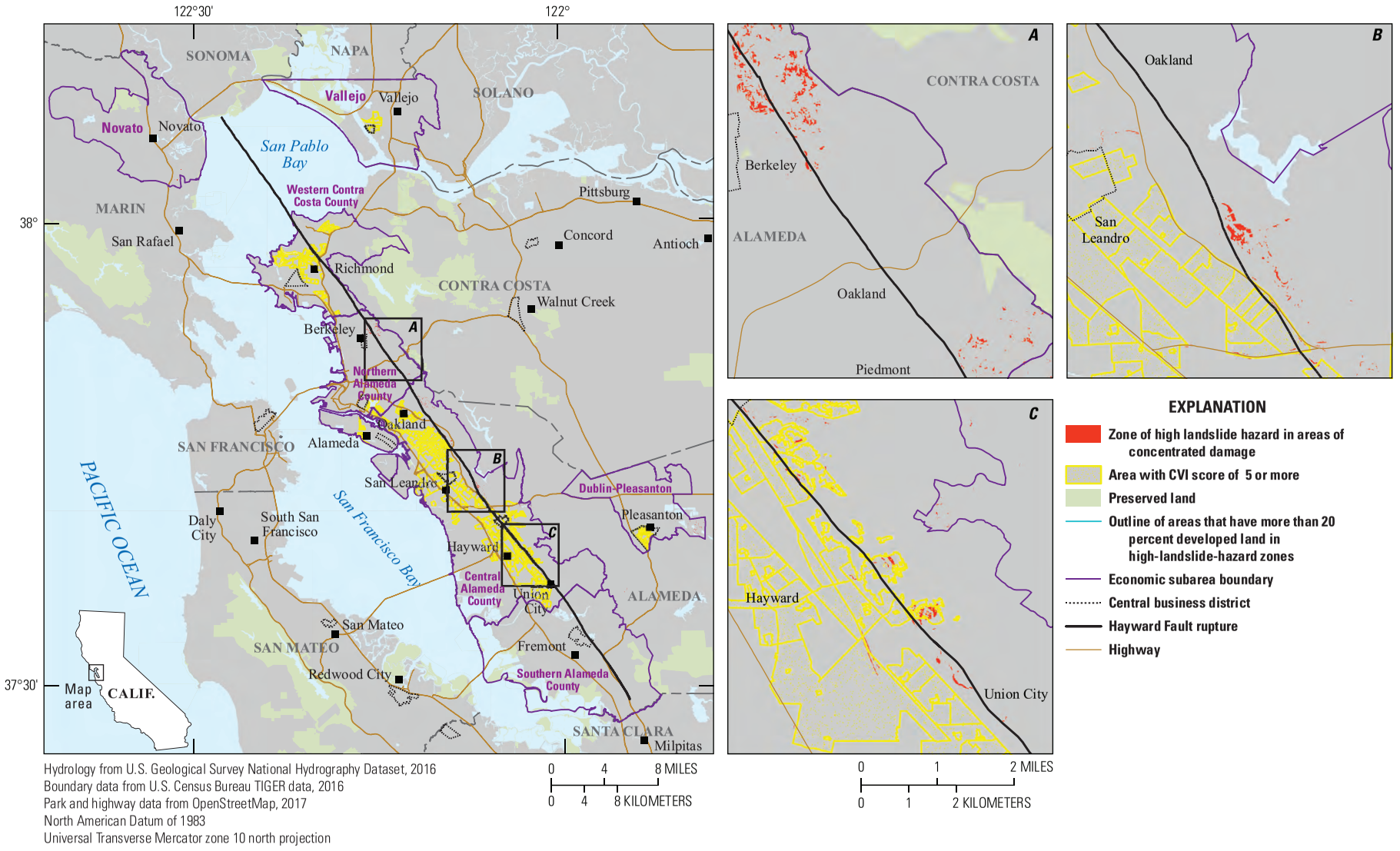


Figure 10. Maps of the San Francisco Bay region, California, showing potential areas of substantial land and building damage caused by landslides from the HayWired earthquake scenario mainshock. The hazard areas with high landslide probability (25 percent or greater) in the areas of concentrated damage (for all occupancies) are shown in red and those census block groups that have more than 20 percent of developed land in the high-landslide-hazard zones are outlined in turquoise (in this case, no census block groups meet this criterion). Areas with a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are shown with yellow outline and stippling. *A*, Inset map showing Oakland, Berkeley, and Piedmont in Alameda County. *B*, Inset map showing the east bay foothills to the east of San Leandro in Alameda County. *C*, Inset map showing Hayward, Union City, and surrounding unincorporated areas in Alameda County. Data from ABAG and BCDC (2016), McCrink and Perez (2017), and Jones and others (2020).

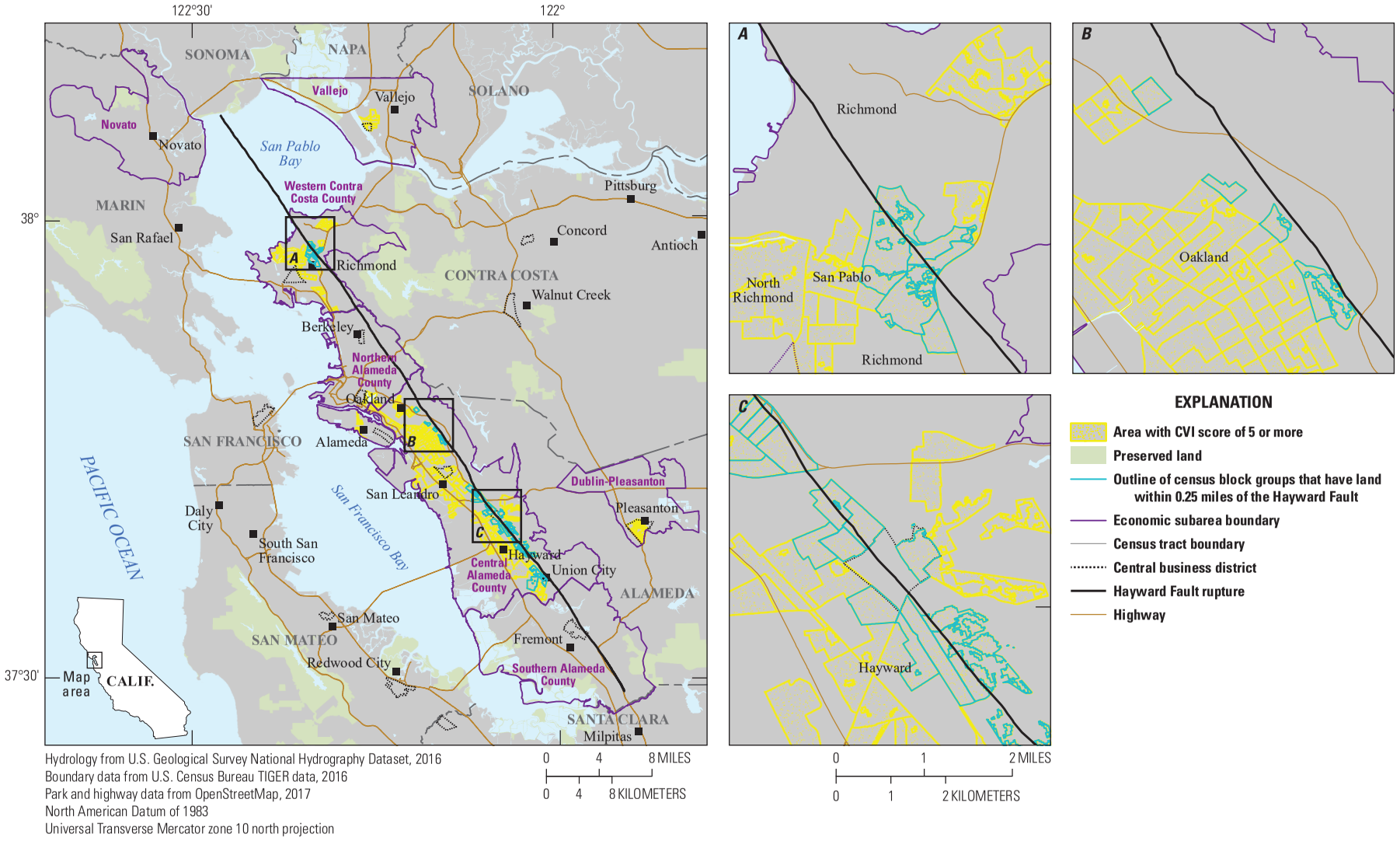


Figure 11. Maps of the San Francisco Bay region, California, showing potential areas of surface fault rupture, including afterslip, in the HayWired earthquake scenario. Census block groups in the areas of concentrated damage that have land within one-quarter of a mile of the Hayward Fault are outlined in turquoise. Areas with a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are shown with yellow outline and stippling. *A*, Inset map showing San Pablo, North Richmond, and Richmond in Contra Costa County. *B*, Inset map showing part of Oakland along the Hayward Fault in Alameda County. *C*, Inset map showing Hayward and the surrounding unincorporated areas in Alameda County. Data from ABAG and BCDC (2016), Jones and others (this volume), and Jones and others (2020).

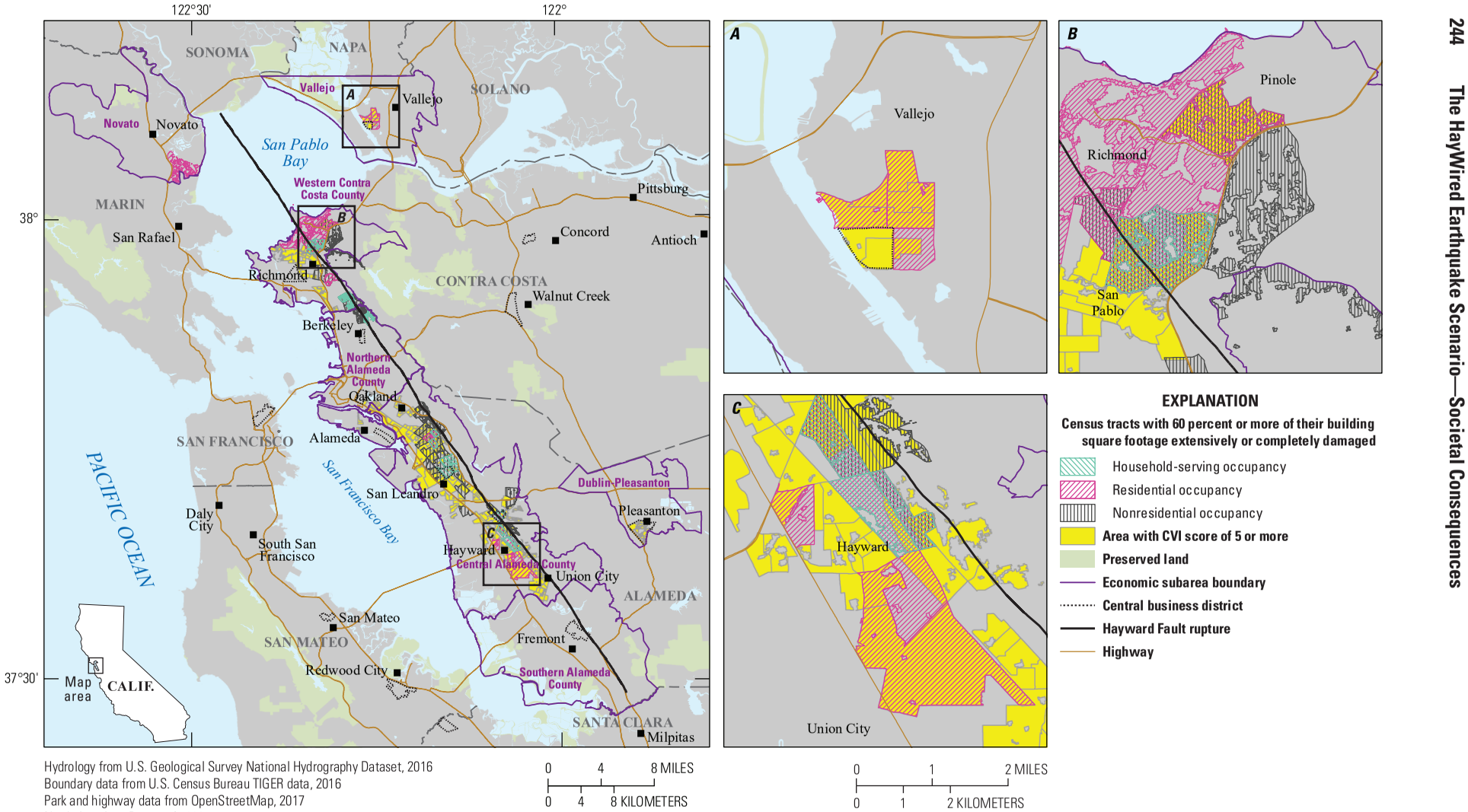


Figure 12. Maps of the San Francisco Bay region, California, showing potential areas of concentrated building damage caused by earthquake hazards and fires following the HayWired scenario mainshock. Census tracts with 60 percent or more of their building square footage in an extensive or complete damage state for residential occupancies, household-serving occupancies, and all other nonresidential occupancies are shown by magenta, turquoise, and dark grey hatching, respectively. Areas with a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are shown in yellow. *A*, Inset map showing Vallejo in Solano County. *B*, Inset map showing parts of Richmond, Pinole, and San Pablo in Contra Costa County. *C*, Inset map showing part of Hayward in Alameda County. Data from ABAG and BCDC (2016) and Jones and others (2020).

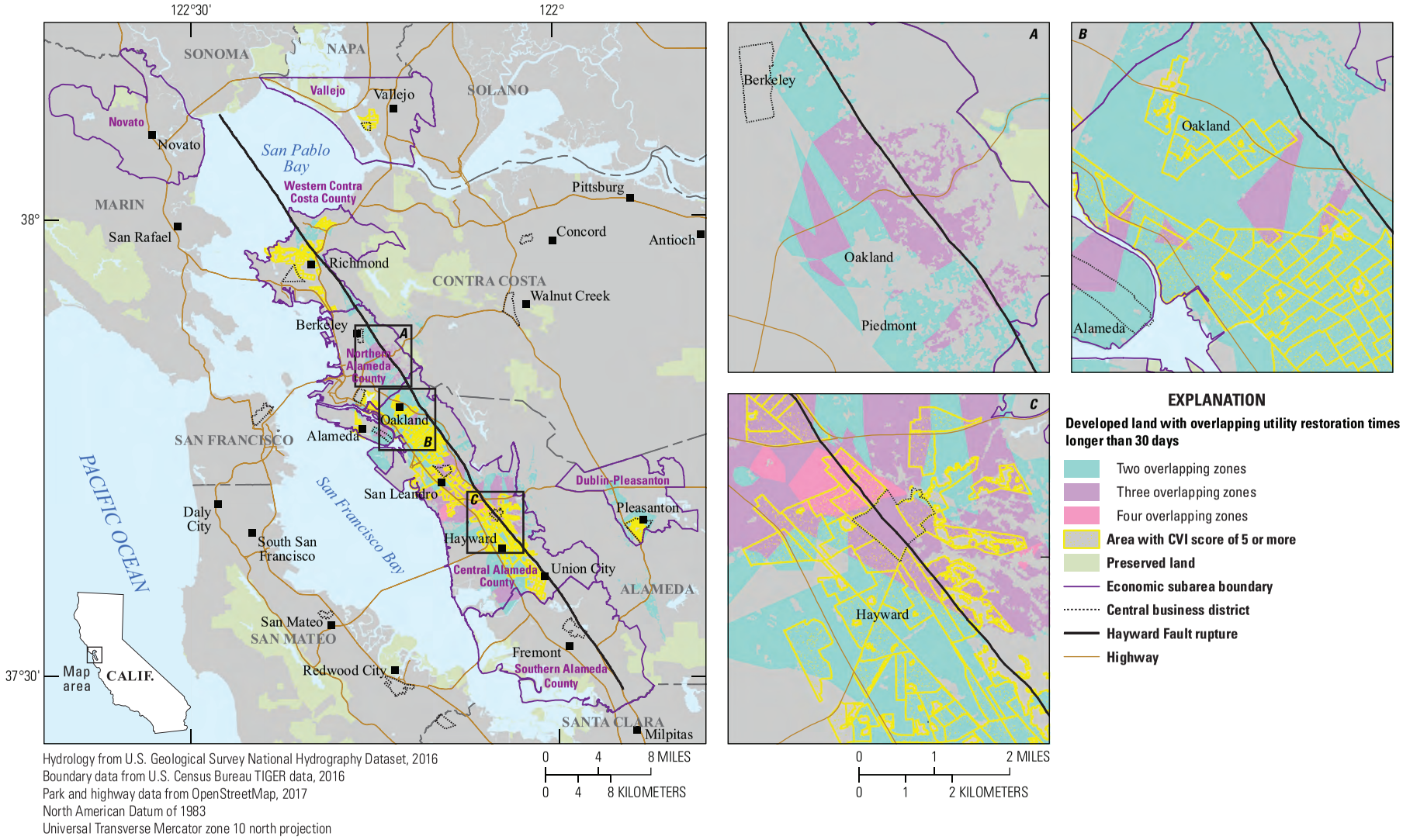


Figure 13. Maps of the San Francisco Bay region, California, showing potential areas of substantial transportation and infrastructure damage from the HayWired scenario mainshock. Developed areas with two or more overlapping utilities with lengthy restoration times (longer than 30 days) that could impede neighborhood recovery are shown. The four systems considered are water, electric power, Bay Area Rapid Transit, and highway bridges. Areas with a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are shown with yellow outline and stippling. *A*, Inset map showing part of Oakland, Piedmont, and Berkeley in Alameda County. *B*, Inset map showing of Oakland in Alameda County. *C*, Inset map showing Hayward and the surrounding unincorporated areas in Alameda County. Data from ABAG and BCDC (2016), Porter (2018a), Jones and others (this volume), and Jones and others (2020).

Belzer, and others, this volume) identify mitigation and resilience opportunities and readers are encouraged to look at these chapters for additional suggestions.

1. Accelerate the Seismic Mitigation of Homes

This analysis shows that catastrophic levels of concentrated housing damage can occur across the San Francisco Bay region and that densely developed neighborhoods with 1970s and older, single-family and multifamily wood-frame residential buildings are also vulnerable to post-earthquake fires and widespread neighborhood impacts.

Retrofit measures for the region's most common type of residential buildings—low-rise wood-frame structures—have been demonstrated to be cost effective, with higher quality measures estimated to save thousands of dollars in potential losses per residential unit (Porter and others, 2006). However, with only a few exceptions, the upgrade of seismically vulnerable housing in the San Francisco Bay region communities is largely a voluntary action undertaken by individual building owners, which has meant that some retrofits are incomplete or not based on uniform, best-practice building codes (Janiele Maffei, California Earthquake Authority, written commun., 2017), and the benefits of the retrofit efforts can rarely be realized on a community scale.

Some cities in the region, including Alameda, Albany, Berkeley, Campbell, Fremont, Hayward, Oakland, Palo Alto, San Leandro, and San Francisco, have developed inventories of seismically vulnerable housing types (1906 Earthquake Centennial Alliance, 2006; ABAG, 2015b), but even fewer have implemented mandatory retrofit programs. The Earthquake Safety Implementation Program evolving out of the Community Action Plan for Seismic Safety and resulting in a suite of mandatory retrofit ordinances adopted by the City and County of San Francisco is a model for both vulnerability assessments and implementation efforts (City and County of San Francisco, 2018). ABAG estimates that there are 140,000 housing units in 17,000 seismically vulnerable, "soft-story" buildings across the nine-county region and is advocating for the enactment of statewide guidelines for the identification, evaluation, and retrofit of seismically unsafe housing as well as the development of the technical and financial resources and incentives to encourage local governments and building owners in the region to take action (ABAG, 2015b).

Also, legislation adopted in California in 2016 makes it easier for single-family homeowners to build an "accessory dwelling unit" on their property or to legalize an existing illegal unit (Pender, 2016). The construction of accessory dwelling units in seismically vulnerable housing is a concern, and seismic upgrades of the entire structure ought to be encouraged as part of any accessory dwelling unit construction.

A systematic, neighborhood-centric, but regionwide approach to the retrofit or replacement of seismically vulnerable housing could reduce the potential for concentrated housing damage and the cascading effects that could follow in a major earthquake. This would provide community resilience benefits to the region as well as individual neighborhoods and communities. Such a program would require multijurisdictional, regionwide cooperation and collaboration, expanded development of code-compliant standards for the range of seismically vulnerable housing types in the region, enhanced permitting, construction, inspection mechanisms, and technical assistance, dedicated funding sources, and equitable incentives for both single-family and multifamily housing. New and existing legislative vehicles for funding sources could possibly include bond measures, taxes, and tax incentives. Social vulnerability data, such as the ABAG/BCDC community vulnerability indicators, could be used to determine where governmental interventions, especially financing mechanisms, may be needed to help target socially vulnerable communities, preserve affordable housing, and prevent initial displacement caused by construction and subsequent displacement caused by gentrification.

Such a program could also incorporate mitigations to reduce the potential for post-earthquake fires. Recent wildfires and heightened concerns about utility-related fire ignitions across California highlight the threat posed by urban fires and the need for increased attention to mitigating fire risk in our housing stock.

Some financial programs already support home retrofits. For example, the State of California's Property Assessed Clean Energy financing program allows property owners to borrow private-lender funding to pay for energy, water, and (or) seismic retrofits, spread the cost of the upgrade over 20-plus year terms and transfer those assessments with the property upon sale (PACENation, 2019). In January 2017, the State of California expanded the seismic strengthening improvements allowed under the Property Assessed Clean Energy program, which may enhance its viability as a mitigation financing tool for the region's seismically vulnerable housing.

The Earthquake Brace + Bolt (EBB) program, created in 2011 by the California Earthquake Authority and the California Governor's Office of Emergency Services, is an example of an incentivized and systematic seismic retrofit program that targets single-family homeowners (California Residential Mitigation Program, 2019a). The EBB program offers as much as $3,000 toward a code-compliant seismic retrofit for certain kinds of single-family homes built before 1979. From 2014 to 2017, the EBB program awarded retrofit grants to more than 1,600 homeowners in the San Francisco Bay region (California Earthquake Authority, 2018) and the program expanded to 126 ZIP codes across the region in 2019; see figure 14. As of September 2019, the California Earthquake Authority reports nearly 3,000 retrofits completed in the region since the program's inception (Steven Martinez, California Earthquake Authority, written commun., 2019). It is eventual goal of the California Earthquake Authority and the California Governor's Office of Emergency Services that the EBB program will be available to qualifying homeowners in all high-seismic-hazard regions of the State.

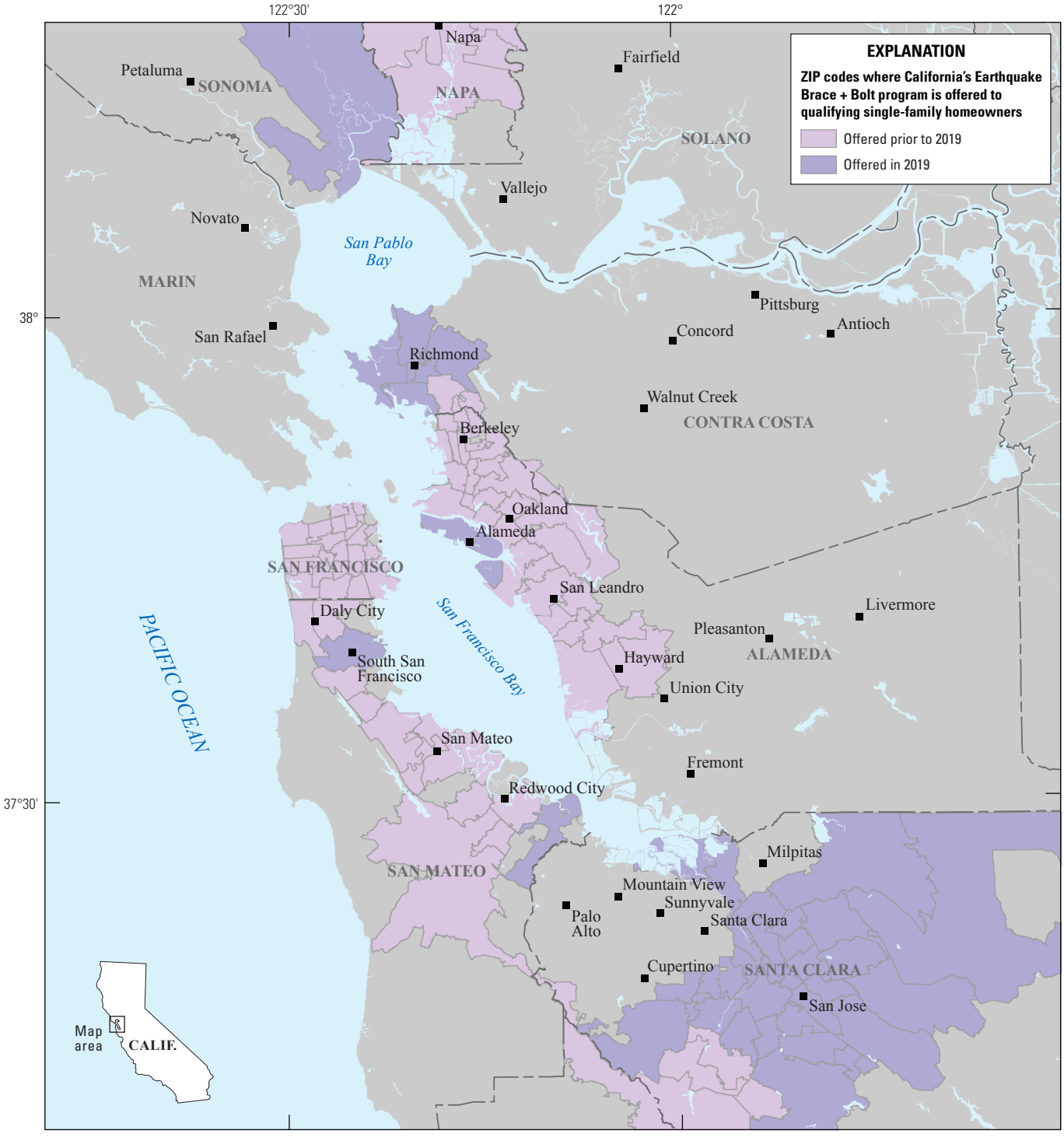


Figure 14. Map of the San Francisco Bay region, California, showing ZIP codes where the California Earthquake Brace + Bolt program is offered to qualifying single-family homeowners in northern California as of 2019. Data from the California Residential Mitigation Program (2019b).

2. Strengthen or Replace Infrastructure

The HayWired scenario shows that seismically vulnerable systems, such as old water distribution pipelines, directly threaten the recovery of some communities and can also have cascading consequences for the region. There are substantial resilience benefits to be gained if the region's governmental and utility agencies were to undertake a more systematic and regionally shared approach to setting lifeline infrastructure performance objectives and using those objectives to prioritize and finance upgrades to the region's most seismically vulnerable lifeline infrastructure. The HayWired scenario provides important new data that can be used in assessing system vulnerabilities and impacts, and establishing community and regional lifeline infrastructure performance objectives, including restoration times.

Since the 1989 Loma Prieta earthquake, as much as $33 billion has been invested in utilities and transportation in the San Francisco Bay region to improve the resilience of regional infrastructure systems (Brocher and others, 2018). The largest investments have been in the retrofit and replacement of transportation infrastructure by the California Department of Transportation and Bay Area Rapid Transit (BART) and the seismic strengthening of water supply and sewer systems. Funding has largely come from Federal and State programs, bridge toll increases, and voter-approved bond measures. That investment has not been consistent, however, across different utility sectors, and seismically vulnerable systems continue to threaten regional disaster resilience (ABAG, 2014). ABAG (2015b) recommends the establishment of a regional lifelines council, building off of the collaborative efforts by the City and County of San Francisco's Lifeline Council and other initiatives, to address vulnerabilities in the region's infrastructure systems by improving collaboration and the sharing of risk-assessment information, recovery plans, projects, and priorities.

3. Build More Housing for All Income Groups

The HayWired scenario analysis of potential population movements shows how the San Francisco Bay region's decades-long housing supply and affordability crisis could be exacerbated by a major earthquake, leading to potentially widespread and extended population displacement as well as other cascading effects that commonly follow major disasters, such as financially and mentally stressed households, overcrowding, and extended occupancy of substandard housing (Esnard and Sapat, 2014; Peacock and others, 2014). The regional rates of new housing construction since 2010 have been less than 10,000 units per year, which is half or less than the annual rates in previous decades; affordable housing construction has been especially limited (ABAG, 2015a).

A concerted, regionwide effort to build a substantial amount of new housing per year for all income groups in safe locations and to modern construction standards—or even higher construction standards that exceed the current "life safety" seismic provisions in the California Building Code—would provide multiple resilience benefits to the region. It would improve the physical quality of the region's housing stock, increase housing quantity (which in turn improves the availability and affordability of housing and relieves stress on overcrowded and rent-burdened households), and reduce the amount of household displacement outside the region, both pre- and postdisaster.

The "life safety" standards of the current codes do not prevent the possibility of collapse or costly post-earthquake repairs. An increased supply of seismically resilient rental housing in the region could significantly reduce the risk of widespread population displacement and relocation outside the region for extended periods of time, even permanently, after a major earthquake. If the State of California and cities in the San Francisco Bay region were to require that all new buildings, including housing, be built to exceed select "life safety" seismic provisions of the latest International Building Code, it is estimated that construction costs would only be about one percent higher overall but that building impairment caused by earthquake-related damage would be reduced by 75 percent (Porter, 2018b). For every dollar invested in constructing new buildings that exceed the seismic provisions of the 2015 model building codes, there is an estimated $4 savings (Porter and others, 2018).

4. Promote Seismic Resilience in Land Use and Development Policies

Many of the areas with concentrated damage and high social vulnerabilities identified in the analysis of communities at risk in the HayWired scenario coincide with priority development areas in the "Plan Bay Area 2040" (MTC and ABAG, 2017). A concerted emphasis on seismic risk reduction in local and regional land use, housing, economic development, infrastructure, and hazard mitigation policy and plans could help to direct more investment and focus to upgrading the seismic resilience of existing communities—the existing housing stock and lifeline infrastructure—while future and more resilient communities are being planned and built. The San Francisco Bay Area Metropolitan Transportation Commission and ABAG are taking an important step in this direction with the Horizon planning initiative which includes a magnitude 7 earthquake on the Hayward Fault as one of seven key external forces that San Francisco Bay region residents may face within the regional planning horizon of 2050 (MTC and ABAG, 2019).

The analysis of housing damage, damage concentrations, and population vulnerabilities and impacts in the HayWired scenario can be useful in assessments of future regional housing needs and the development and updates of local and regional housing policy and plans. The updates of local hazard mitigation plans and the land use and safety elements of local general plans would benefit from consideration of the social vulnerabilities of residents in addition to the potential risks caused by concentrated land and building damage in future earthquakes.

5. Address Population Movements and Long-Term Displacement in Local, Regional, and State Preparedness, Response, and Recovery Plans

The analysis of communities at risk shows that population displacement, and all the effects thereof, is one of the most significant and long-term impacts that a major earthquake will have on the San Francisco Bay region and a central component of the region's seismic resilience. The data and insights from the HayWired scenario, especially on post-earthquake fires, areas of concentrated land and building damage, social vulnerabilities, and extensive damage to water delivery systems and other lifeline infrastructure, can be valuable in updating emergency preparedness, response, and recovery plans. The plans could consider some of the hardest hit and most vulnerable communities; partnering and planning for the handling of displaced populations in potential receiving communities; ensuring swift and equitable access to disaster recovery resources and information; and preplanning for temporary workforce housing. Organizations also could plan for emergency, interim, and temporary housing and need also to recognize the dynamics of these phenomena across time and space. A few local governments in the region, such as the City and County of San Francisco, have examined their post-earthquake housing vulnerabilities and displacement risk in detail (Kornfield and others, 2011; SPUR, 2012; Harvard Kennedy School, 2014); other communities may require technical and financial support to do the same.

In addition to government, faith-based and nonprofit community service providers also could be informed and engaged in helping to prepare for and provide a more integrated set of services and streamlined process of providing services to disaster-induced displaced individuals and households. This includes planning to track, monitor, and support the psychological and social aspects of displaced individuals and households. Citizen Emergency Response Team plans and training and individual and household earthquake preparedness campaigns and training might also be enhanced by insights gained from the HayWired scenario, including the consideration of evacuation and relocation situations in addition to their current emphasis on preparations to shelter-in-place for as long as seven days. Business preparedness could also benefit from considering scenarios like the HayWired scenario, in which employees are displaced for extended periods of time. There is a need for substantially expanded "telework" protocols, systems, and training.

6. Plan for the Management of Long-Term Recovery at All Levels of Government

The analysis of communities at risk in the HayWired scenario puts a spotlight on the significance of spatial and temporal aspects of concentrated damage and population displacement and underscores the importance of local, regional, State, and Federal agencies looking beyond the moment of the earthquake and planning for the management of long-term recovery after a major earthquake in the San Francisco Bay region. Predisaster recovery planning efforts by all levels of government could be expanded and enhanced to include more detailed, operation-level planning, policies, and procedures for: areawide land damage and geologic hazard investigations; access control and temporary moratoriums on rebuilding; expedited repair and rebuilding permit processing; equitable and demographically inclusive community engagement in postdisaster planning processes; site development, building code, land use, and zoning changes that may include voluntary buyout and land acquisition programs; ongoing psychological and social service support for the most vulnerable and impacted residents; and recovery budgeting and financial planning. These planning efforts may need technical and financial resources and to involve a wide array of departments and agencies that may not be as familiar with emergency response or disaster recovery planning, such as agencies involved in land use planning, development and construction, housing, public works, historical and cultural preservation, and economic development.

7. Develop a Recovery Financing Strategy

The HayWired scenario confirms that the costs to rebuild homes, businesses, services, and infrastructure damaged by a major earthquake will dwarf anything that the region, and even the State, has experienced in modern times—and funding sources will be limited. Only a small portion of the building damage caused by ground shaking, landslide, liquefaction, and fires following a major earthquake in the San Francisco Bay region is likely to be covered by private insurance and disaster assistance programs that come with State and Federal disaster declarations. Supplemental State and Federal disaster assistance would need to be sought, which would require State and Congressional legislative action and executive leadership support. Additionally, a considerable amount of private investment and nonprofit, philanthropic, and private investors would be required to finance a recovery effort of this unprecedented magnitude in California.

Now is the time to identify key shortfalls and develop creative means of filling those financial gaps. A timely and effective postdisaster recovery process depends, in great part, on the resources available to a particular community, as well as the creativity and resourcefulness of the State and local governments, residents, and businesses to pursue new and innovative funding resources beyond what the formal disaster assistance programs can offer. The philanthropic community, nongovernmental organizations, private nonprofit entities, faith-based organizations, and community and corporate foundations will be essential to providing both material and financial assistance to individuals, families, community organizations, and local governments, especially those that currently have few resources or that have difficulty accessing postdisaster resources.

The HayWired scenario can be a useful resource for local, regional, and State government agencies to use in assessing the likely fiscal impacts of a major regionwide disaster; evaluating what assistance is and is not available for key aspects of recovery; developing and implementing action plans to enhance recovery resources ahead of time; and ensuring that the necessary planning, training, and staffing are in place to maximize opportunities for assistance once disaster strikes (SPUR, 2013). This might include working to increase the availability and uptake of insurance for individuals, businesses, and institutions at all income levels and seeking innovative ways to finance potential recovery needs, such as public-private partnerships and special districts (for example, infrastructure financing districts, community-based economic development districts, and geologic hazard abatement districts).

Conclusion

Disaster impact analyses typically focus on direct damages, injuries, and economic losses and do not account for the all the social, financial, and political factors that also influence how quickly and equitably different populations and communities are able to recover or the long-term challenges that they are likely to face. The communities-at-risk analysis of the HayWired scenario considers spatial and temporal factors that past disasters have shown to displace people and significantly impair long-term community recovery.

New methodologies were developed to integrate analysis of property damage (buildings and contents) caused by ground shaking, liquefaction, landslides, and fires following the M_w 7.0 mainshock of the HayWired scenario; identify areas of concentrated damage; estimate the potential size and composition of people and households at risk of displacement from building damage, lifeline outages, and other influencing factors; and identify areas that are likely to require governmental interventions and replanning actions in order to recover.

In the 30 years since the 1989 Loma Prieta earthquake struck the San Francisco Bay region, substantial investments have been made in critical infrastructure upgrades as well as extensive retrofitting of seismically vulnerable residential, commercial, and public buildings. Nonetheless, this analysis reveals the significant housing, infrastructure, social, and financial vulnerabilities to a major earthquake that remain and are only likely to continue to grow, unless fundamental shifts in the scale of attention and investment given to reducing the region's seismic risk are made. The seven policy implications for improving community seismic resilience in the San Francisco Bay region stem directly from insights gained in this analysis of communities at risk.

The communities-at-risk analysis of the HayWired scenario also provides an approach to expand thinking about population displacement and long-term community recovery challenges resulting from the cumulative effects of multiple hazards, damages, and disruptions from a major earthquake striking the San Francisco Bay region. This body of work relies heavily on the experience and research resulting from past disasters in order to anticipate what may occur after a major earthquake in the San Francisco Bay region. The analysis also highlights implications for the recovery of other communities with physical and (or) social vulnerabilities to earthquakes as well as other hazard types.

There are gaps in the research literature and the analytical methods of this analysis that merit further attention as part of future disaster research and study. There are also opportunities to enhance and refine the analyses performed in this and other parts of the HayWired scenario to improve our understanding of the region's potential long-term recovery challenges after a major earthquake as well as the key opportunities for improving community resilience before the next earthquake strikes.

Open research questions pertain to:

- Definition of concentrated damage that can have cascading consequences for a community;
- Understanding preexisting conditions and decision-making of affected populations;
- Planning for shelters and receiving communities and monitoring movements of evacuated and displaced populations;
- Evaluating recovery funding needs, sources, and gaps;
- Representation of building repair times and community recovery status over time; and
- Costs, benefits, and unintended consequences of community land use policies, planning, and resilience opportunities.

These research questions are fundamental to this study and more broadly to other approaches that simulate community recovery. We invite others to evaluate methodologies used in this analysis for potential improvements to quantitative metrics and models for long-term disaster recovery at a community scale. We also hope this analysis encourages more in-depth evaluation of the associated costs and benefits of the resilience opportunities (for example, accelerated housing mitigation and building of more housing) identified by this analysis, as well as ways to overcome persistent barriers to adoption.

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Sections A–C

Section A

Integrated Building Damages and Areas of Concentrated Damage

Introduction

Past disasters have shown that the degree of physical damages to housing and other structures is closely tied to the degree and patterns of population displacement as well as the ability of impacted communities, businesses, and residents to recover (Comerio, 1998; Groen and Polivka, 2010; Esnard and others, 2011; Peacock and others, 2014). Structures that sustain high levels of damage are likely to be uninhabitable until repaired. Past disasters have also shown that areas of spatially concentrated building damage are likely to experience more extended and complicated recovery trajectories (Olshansky and others, 2006; Peacock and others, 2014).

A 2012 study by the San Francisco Bay Area Planning and Urban Research Association (SPUR) looked at seven disaster cases from around the United States and the world to understand how the extent of housing damage affected the overall recovery of impacted communities (SPUR, 2012). In these cases, the percentage of uninhabitable housing units ranged from 1 to 50 percent in the affected areas and evidence showed that even when the loss of housing units was as low as 5 to 10 percent, the time to repair or rebuild uninhabitable housing units was long and community recovery was impeded owing to population outmigration, sometimes permanently, and accompanying social and economic impacts.

In volume 2 of the HayWired earthquake scenario, building damage caused by the earthquake hazards of ground shaking, landslide, and liquefaction for the moment magnitude (M_w) 7.0 mainshock and aftershock sequence are analyzed by Seligson and others (2018) using the Hazus-MH 2.1 loss-estimation software and customized analyses; we refer to this collective work as the Hazus analysis. The damage to buildings from post-earthquake fires is analyzed by Scawthorn (2018). What is lacking is an integrated view of building damage caused by the combined effects of the earthquake hazards and fires or an indication of where areas of concentrated damage are likely.

This foundational part of this analysis of communities at risk presents the methodology developed to create an integrated view of building damage owing to ground shaking, landslide, liquefaction, and fires. Areas of concentrated building damage are identified by mapping the census tracts that have 20 percent or more of the total building square footage in an extensive or complete damage state for eight different occupancy groupings.

Integration of Building Damage Caused by Ground Shaking, Landslide, Liquefaction, and Fire

A methodology using Ersi's ArcGIS v. 10.4 software suite and Microsoft Excel was developed that first combines the results of the Hazus analysis of the M_w 7.0 mainshock of the HayWired scenario for building damage caused by the earthquake hazards of ground shaking, landslide, and liquefaction (see Seligson and others, 2018, for methods and Seligson and Jones, 2019, for data) with the damage to buildings from post-earthquake fires that were analyzed separately (see Scawthorn, 2018, for methods and Scawthorn, 2019, for data).

Earthquake Hazard Building Damage Data (Without Fire)

The Hazus methodology makes assumptions about the level of damage and the timeframes for the repair and return to function for buildings in 33 occupancy classes (Federal Emergency Management Agency, 2012). Hazus estimates building damages in terms of five damage states: none, slight, moderate, extensive, and complete. The slight and moderate damage states can be associated with a "green tag" from a post-earthquake building safety inspection, which, in most cases, would allow residents to stay in their homes while repairs are completed. The extensive damage state can be associated with a "yellow tag" from a post-earthquake building safety inspection, which limits the building's use until repairs are completed. The complete damage state can be associated with a "red tag" from a post-earthquake safety inspection, which restricts all use of the building until repairs are completed because it is unsafe to occupy. Hazus repair time assumptions for the most common housing occupancy classes (single-family, duplex, and multifamily homes) are shown in table A1; repair times increase with damage state (or repair costs as a percentage of the building replacement cost). These assumptions are consistent with disaster data analyses by Comerio and Blecher (2010), Peacock and others (2014), and Despotaki and others (2017) that found that more heavily damaged buildings and multifamily dwellings take longer to repair than less-damaged buildings and single-family dwellings.

Table A1. Hazus damage and repair-time assumptions for single-family, duplex, and multifamily dwellings.

[Codes in parentheses are Hazus occupancy classes. Single-family and duplex dwellings are listed separately since Hazus assigns the same repair cost ratios and recovery times to duplexes as it does to other multifamily dwellings. Data from Federal Emergency Management Agency (2012)]

Residential dwelling type	Hazus damage state			
	Slight	Moderate	Extensive	Complete
Structural and nonstructural repair cost ratios (percentage of building replacement cost)				
Single family (RES1)	2	10	44.7	100
Duplex (RES3A)	2	10	41.3	100
Multifamily (RES3B–F)	2	10	41.3	100
Median time for building repair and return to function (number of days)				
Single family (RES1)	2–5	30–120	90–360	180–720
Duplex (RES3A)	5–10	30–120	120–480	240–960
Multifamily (RES3B–F)	5–10	30–120	120–480	240–960

Table A2. Residential and nonresidential building occupancy groupings created from 33 Hazus occupancy classes (from Wein, Belzer, and others, this volume).

Building occupancy groupings	Hazus occupancy classification	Description
Nonresidential		
Industrial/warehouse	COM2	Warehouse
	IND1	Industrial-Heavy
	IND2	Industrial-Light
	IND3	Industrial-Food/drugs/chemicals
	IND4	Industrial-Metals/minerals processing
	IND5	Industrial-High tech
	IND6	Industrial-Construction
Offices	COM4	Professional/technical services
Retail/commercial	COM1	Retail trade
	COM10	Parking
	COM3	Personal and repair services
	COM5	Banks
	COM8	Entertainment and recreation
	COM9	Theaters
	RES4	Hotel/motel
Household serving	COM6	Hospital
	COM7	Medical office/clinic
	EDU1	Grade schools
	EDU2	Colleges/universities
	GOV1	Government-General services
	GOV2	Government-Emergency response
	REL1	Church/nonprofit
Agricultural uses	AGR1	Agriculture
Residential		
Single family/duplex	RES1	Single family
	RES3A	Duplex
	RES2	Mobile home
Multifamily	RES3B	Multifamily (3–4 units)
	RES3C	Multifamily (5–9 units)
	RES3D	Multifamily (10–19 units)
	RES3E	Multifamily (20–49 units)
	RES3F	Multifamily (50+ units)
Group living	RES5	Dormitories
	RES6	Nursing home

Table A2 provides a mapping of the Hazus occupancy classes to eight building occupancy groupings that were developed for the HayWired scenario spatial economic analysis (Wein, Belzer, and others, this volume). The three residential building occupancy groupings are: single-family/duplex dwellings, multifamily dwellings, and group-living uses. Single family/duplex dwellings include single-family homes, mobile homes, and duplex housing that are either owner or renter occupied. Multifamily dwellings include structures with three or more housing units and also can be owner or renter occupied, such as apartment complexes and condominiums. The five nonresidential building occupancy groupings are: retail/commercial, offices, industrial/warehouse, household serving, and agricultural uses.

Analyses by Seligson and others (2018) and Seligson and Jones (2019) use year 2000 U.S. Census tract boundaries. To align Seligson and Jones' (2019) results with 2010 census data, the year 2000 tract-based damage results were converted into 2010 tract geographies. The conversion relied on official census relation files to parse the relations (Aksel Olsen, Association of Bay Area Governments, written commun., 2017). Housing units were used as weights when disaggregating the Hazus data. For example, where a 2000 tract was split into two smaller 2010 tracts, the building damages were distributed to the new tracts in proportion to their housing count rather than their share of the original tract area. This method has benefits and drawbacks. It is more accurate for housing but less representative of the commercial distribution because housing may be scarcer in commercial areas.

Earthquake Hazard Plus Fire Building Damage Data (With Fire)

The additional damage from fires following the earthquake, estimated by Scawthorn (2018), was integrated with the damages from the other earthquake hazards. All fire damage was categorized as complete damage—to keep the total square footage in the region unchanged, the additional square footage damaged from fire was redistributed to the complete damage state for the earthquake hazards from the other damage states. To do this, first burned building square footage was converted from Voronoi areas[5] to 2000 census tracts. The allocation of burned building square footage to occupancy classes used the profile of burned buildings from the Northridge earthquake (Scawthorn and others, 1996). The "burned rubble" (potential double counting of losses for buildings with both fire and other earthquake damage) was removed before the complete fire damage state was integrated with the damage states from the other earthquake hazards.

The notation used to describe the series of steps taken to integrate earthquake damages with fire damages uses the following definitions:

V_i burned building square footage in Voronoi area i

D_{ij} proportion of developed Voronoi area i in census tract j

B_j, B_l burned building square footage in census tract j or l

F_j, F_l proportion of regional burned building square footage in census tract j or l

P_k percentage of burned building square footage in occupancy class k (see table A4)

R_k regional sum of burned building square footage in occupancy class k

O_{jk}, O_{lm} proportion of regional occupancy class k or l in census tract j or m

W_{jk} weight for distributing burned building square footage in occupancy class k to census tract j

A_{jk}, A_{jm} burned building square footage in occupancy class k or m allocated to census tract j

B_{jk} burned building square footage in occupancy class k in census tract j

E_{jks}, E_{jkt} earthquake hazard building square footage in damage state s or t in occupancy class k in census tract j

E_{jm5} earthquake hazard building square footage in damage state 5 (complete) in occupancy class m in census tract j

N_{jk5} additional building square footage in damage state 5 (complete) from fire in occupancy class k in census tract j

D_{jks} integrated earthquake and fire building square footage in damage state s in occupancy class k in census tract j.

[5]A Voronoi area is a polygon whose sides are equidistant between the point the Voronoi area is centered around and any neighboring points—a line is drawn between two points, the midpoint of that line is found, a perpendicular line is drawn through that midpoint, and this is repeated for all neighboring points to complete a Voronoi polygon for a specific point.

The calculations begin with converting the burned square footage in Voronoi areas to a burned square footage in census tracts by mapping the area classified as low, medium, or high intensity developed land in the 2011 National Land Cover Database (NLCD) (Homer and others, 2015) in each Voronoi area of the Scawthorn analysis (Scawthorn, 2018). This was done by:

- Overlaying census tracts and calculating the proportion of each Voronoi developed area that intersects with each census tract,
- Assuming the burned buildings are uniformly distributed in the developed area, and
- For each census tract, calculating burned building square footage as the sum of the Voronoi developed area proportions multiplied by Voronoi burned building square footages, such that

$$B_j = \sum_i (D_{ij} \times V_i) \quad (1)$$

The burned building square footage in census tracts was distributed to occupancy classes by creating a distribution of burned buildings across occupancy classes in the San Francisco Bay region. Table A3 shows the occupancy distribution of building ignitions for fires following the 1994 Northridge earthquake published in Scawthorn and others (1996), which was used as a reference for the San Francisco Bay region distribution (Scawthorn, 2018). Most of the fires after the Northridge earthquake were confined to the buildings with ignitions. In contrast, the HayWired fire following earthquake analysis of ignitions, fire-fighting capacity, and water availability results in fire spread. In the absence of results for burned square footage of building occupancy classes, we used the Northridge earthquake proportion of burned buildings in each occupancy as the proportion of square footage burned in each occupancy. This assumption means that fires disproportionately spread into residential neighborhoods of single-family homes. The distribution of burned square footage developed for the HayWired scenario is shown in table A4. The "unknown" and "other" occupancies from Scawthorn and others (1996) were applied to the Hazus occupancies that were not referenced in their study.

Table A3. Distribution of burned buildings in the 1994 Northridge earthquake, by building occupancy (adapted from Scawthorn and others, 1996).

Occupancy	Number of buildings	Percentage of total buildings
Single family/duplex	35	51
Multifamily	20	29
Office	4	6
Education	2	3
Restaurant	1	1
Commercial	1	1
Power production	1	1
Other	4	6
Unknown	1	1
Total	**69**	**100**

Table A4. Distribution of burned buildings for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California, by building occupancy.

Hazus occupancy	Percentage of burned building stock
Retail/commercial	8.70
Government	0.34
Industrial	5.92
Multifamily	28.99
Single family	50.72
Religion	0.75
Education	2.90
Hotels	0.26
Dormitories	1.37
Nursing homes	0.06
Agriculture	0.00
Total	**100.00**

The allocation of burned square footage to census tracts and occupancy classes was conducted in two steps. First, the regional burned occupancy square footage of each occupancy class was allocated across census tracts weighted by burned square footage and occupancy square footage in the census tract. Regional burned occupancy square footage was calculated as the percentage of burned square footage in an occupancy class (table A4) multiplied by the total burned square footage for each census tract:

$$R_k = P_k \times \sum_j B_j \tag{2}$$

For a census tract, the weight for burned square footage was calculated as the proportion of burned square footage in the census tract:

$$F_j = \frac{B_j}{\sum_l B_l} \tag{3}$$

Similarly, the census tract weight for occupancy class square footage was calculated as the proportion of the regional occupancy in the census tract. The allocation weight was determined as a normalized product of the two proportions:

$$W_{jk} = \frac{F_j \times O_{jk}}{\sum_{l,m} (F_l \times O_{lm})} \tag{4}$$

Subsequently, the allocation of the regional occupancy class burned area to a census tract is:

$$A_{jk} = R_k \times W_{jk} \tag{5}$$

Thus, the occupancy burned building area allocations to census tracts were weighted by burned building area and occupancy class building area in census tracts.

The second step adjusted these allocations back to the burned area assigned to the census tract by rescaling as follows:

$$B_{jk} = B_j \times \frac{A_{jk}}{\sum_m A_{jm}} \tag{6}$$

Therefore, the uncertain burned occupancy distribution influenced, rather than determined, the allocations of burned area in a census tract to building occupancy classes.

Finally, the burned building estimates were adjusted to reduce double counting of structures that were destroyed by other earthquake hazards. To do so, it was assumed that there is independency between complete damage from earthquake hazards and complete damage from fire because of fire spread. Thus, the proportion of "burned rubble" in each occupancy class represents the proportion of buildings that are completely damaged by earthquake hazards multiplied by the proportion of burned buildings in each occupancy class. The amount is subtracted from the amount of previously calculated burned occupancy square footage to yield the additional square footage of complete damage from fire following the earthquake.

$$N_{jk5} = B_{jk}\left(1 - \frac{E_{jk5} \times A_{jk}}{\sum_m E_{jm5} \times \sum_m A_{jm}}\right) \tag{7}$$

The additional complete damage from fire was transferred from other damage states (none [1], slight [2], moderate [3], and extensive [4]) in proportion to the amount of square footage in each earthquake damage state in the census tract. The integrated earthquake and fire building square footage damage is:

$$D_{jks} = E_{jks} - N_{jk5}\left(\frac{E_{jks}}{\sum_{t<5} E_{jkt}}\right) \text{ for } s = 1, 2, 3, 4 \text{ damage states} \tag{8}$$

$$D_{jk5} = E_{jk5} + N_{jk5} \text{ for } s = 5 \text{ damage state} \tag{9}$$

This procedure estimated that about 5 million square feet of 79 million square feet burned was already completely damaged by the earthquake hazards.

Integrated Building Damage Results

Tables A5 and A6 show county-level total damages as well as those buildings with extensive or complete damage by building square footage and building count from ground shaking, landslide, liquefaction, and fire from the M_w 7.0 mainshock of the HayWired scenario. Figure A1 shows the county-level distribution of building counts with slight or moderate damage and extensive or complete damage for both residential and nonresidential occupancies. Around 11 percent of the residential and 15 percent of the nonresidential damaged building square footage for the 17-county region is in an extensive or complete damage state. Nearly all the damage, however, especially all the extensive and complete damage, is concentrated in the nine counties bordering San Francisco Bay. These are Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties. Thus, emphasis is given within these studies of communities at risk to the nine-county region.

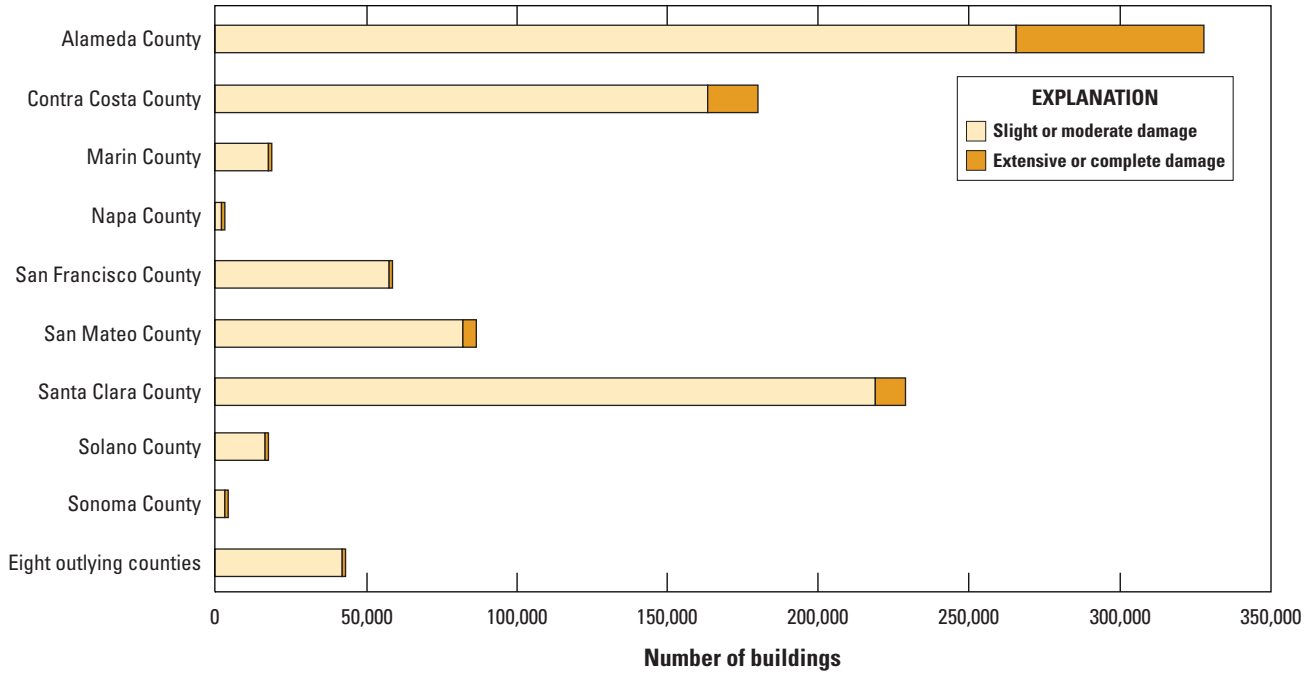
Table A5. Total undamaged and damaged building square footage by county for residential and nonresidential occupancy groupings caused by ground shaking, landslide, liquefaction, and fire from the moment magnitude 7.0 mainshock of the HayWired scenario in the San Francisco Bay region, California.

County name	Residential building occupancy damages			Nonresidential building occupancy damages		
	None	Slight, moderate, extensive, or complete	Extensive or complete	None	Slight, moderate, extensive, or complete	Extensive or complete
San Francisco Bay region counties						
Alameda	776,608,819	634,721,112	136,399,814	56,714,274	301,196,666	91,199,812
Contra Costa	559,972,058	323,578,087	33,585,094	51,471,295	106,057,086	19,134,436
Marin	166,861,355	36,077,656	3,200,805	51,095,752	18,585,631	1,290,814
Napa	77,096,420	4,764,244	24,435	31,533,554	3,096,710	14,474
San Francisco	414,895,937	156,506,482	3,846,743	145,204,333	111,562,288	4,232,691
San Mateo	400,627,949	163,565,556	8,773,479	80,902,371	74,463,569	4,437,852
Santa Clara	890,063,720	427,911,954	21,097,150	159,315,268	214,066,490	13,336,359
Solano	209,901,136	32,461,025	3,778,764	45,676,816	9,890,530	662,878
Sonoma	287,154,722	5,304,866	114,275	94,575,948	3,349,919	25,203
Subtotal	**3,783,182,116**	**1,784,890,982**	**210,820,559**	**716,489,611**	**842,268,889**	**134,334,519**
Outlying counties						
Merced	96,634,272	1,987,967	2,339	20,701,435	604,954	935
Monterey	197,113,918	4,472,112	5,153	71,620,273	2,873,385	5,069
Sacramento	679,996,024	3,771,034	4,016	208,572,586	1,623,393	1,380
San Benito	26,798,156	2,954,435	29,066	4,854,479	1,188,984	32,140
San Joaquin	278,649,337	32,866,145	105,256	67,263,254	12,136,661	61,247
Santa Cruz	154,579,774	15,628,071	57,256	47,110,347	6,834,010	35,127
Stanislaus	222,188,203	11,092,773	18,890	59,793,794	5,274,672	14,101
Yolo	85,741,649	1,313,799	734	33,462,724	813,187	851
Subtotal	**1,741,701,333**	**74,086,336**	**222,710**	**513,378,892**	**31,349,246**	**150,850**
Region total	**5,524,883,449**	**1,858,977,318**	**211,043,269**	**1,229,868,503**	**873,618,135**	**134,485,369**

Table A6. Total number of undamaged and damaged buildings by county for residential and nonresidential occupancy groupings caused by ground shaking, landslide, liquefaction, and fire from the moment magnitude 7.0 mainshock of the HayWired scenario in the San Francisco Bay region, California.

County name	Residential building occupancy damages			Nonresidential building occupancy damages		
	None	Slight, moderate, extensive, or complete	Extensive or complete	None	Slight, moderate, extensive, or complete	Extensive or complete
San Francisco Bay region counties						
Alameda	402,176	327,744	62,140	2,426	13,145	4,022
Contra Costa	316,488	180,036	15,913	2,494	4,998	894
Marin	90,850	19,340	1,553	2,471	886	56
Napa	44,054	2,677	15	1,402	136	1
San Francisco	162,907	59,405	1,295	6,981	5,285	188
San Mateo	215,236	86,675	4,369	3,601	3,235	185
Santa Clara	484,052	229,126	10,282	6,782	8,971	531
Solano	119,323	18,082	1,645	2,139	462	34
Sonoma	166,805	3,167	65	4,259	145	1
Subtotal	**2,001,891**	**926,252**	**97,277**	**32,555**	**37,263**	**5,912**
Outlying counties						
Merced	56,426	1,254	2	941	29	0
Monterey	107,766	2,370	3	3,342	115	0
Sacramento	372,097	2,219	3	10,208	76	0
San Benito	16,179	1,780	12	248	60	2
San Joaquin	157,171	18,602	58	3,158	560	3
Santa Cruz	88,695	9,282	33	2,142	300	2
Stanislaus	129,128	6,506	11	2,771	233	1
Yolo	45,185	675	0	1,412	35	0
Subtotal	**972,647**	**42,688**	**122**	**24,222**	**1,408**	**8**
Region total	**2,974,538**	**968,940**	**97,399**	**56,777**	**38,671**	**5,920**

***A.* Residential occupancies**



***B.* Non-residential occupancies**

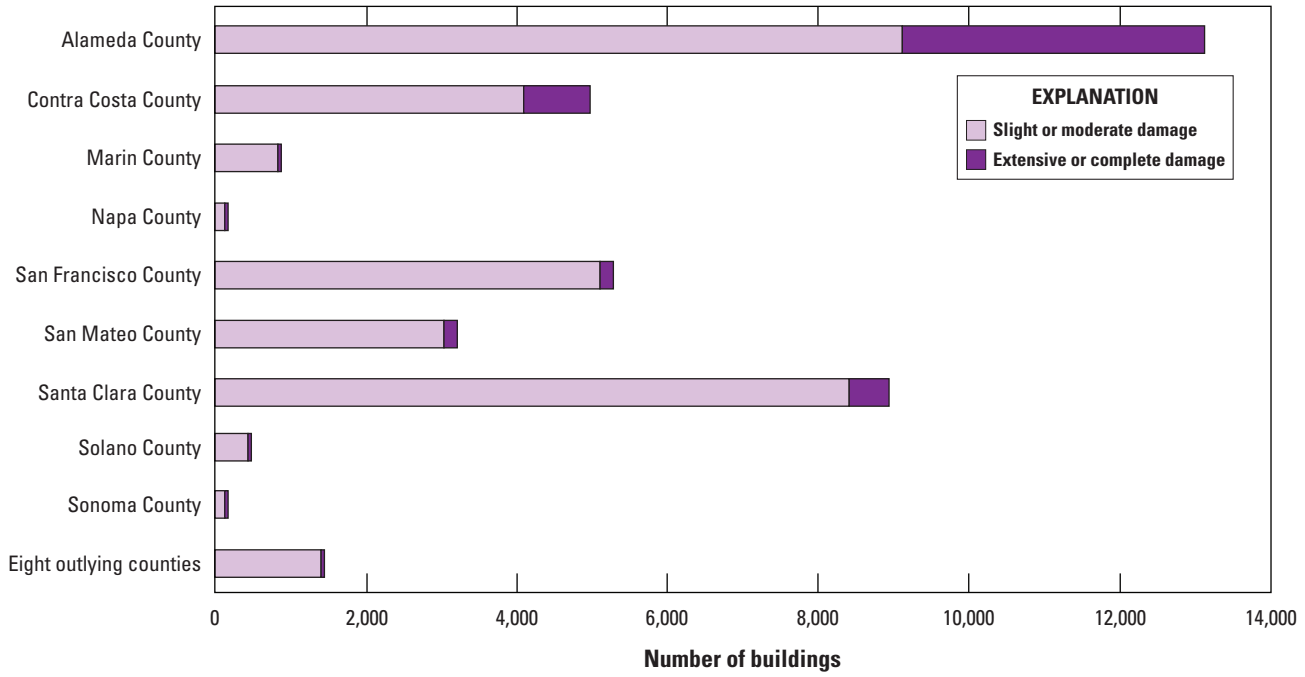


Figure A1. Graphs showing the county-level distribution of buildings with slight or moderate damage and extensive or complete damage for residential and nonresidential occupancy groupings for the HayWired earthquake scenario in the San Francisco Bay region, California. The eight outlying counties refer to Merced, Monterey, Sacramento, San Benito, San Joaquin, Santa Cruz, Stanislaus, and Yolo Counties. *A*, Residential occupancy groupings (single family/duplex, multifamily, and group living uses). *B*, Nonresidential occupancy groupings (industrial/warehouse, retail/commercial, office, household serving, and agricultural uses).

For the nine-county region, 12 percent of the damaged residential building square footage and 16 percent of the damaged nonresidential building square footage is in an extensive or complete damage state for the M_w 7.0 mainshock of the HayWired scenario. The analysis also shows that building damage is greatest in Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco Counties, with damage most acute in Alameda County. Eighteen percent of the total residential building square footage and 25 percent of the total nonresidential building square footage in Alameda County is in an extensive or complete damage state.

Table A7 provides a summary of damaged building square footage and building counts for all five damage states for each of the residential and nonresidential building occupancy groupings. Nearly one million residential buildings sustain some level of damage from the earthquake, of which about 10 percent, or 97,397 buildings, are in an extensive or complete damage state. Single-family/duplex dwellings compose 84 percent of the total residential building square footage, of which about one-third sustains some level of building damage. Of the damaged single-family/duplex dwellings, 90 percent, or 839,316 buildings, are in a slight to moderate damage state and 10 percent, or 89,812 buildings, are in an extensive to complete damage state. Multifamily dwellings and group-living uses make up about 16 percent of the total residential building square footage, of which about 40 percent sustain some level of building damage. Of the damaged multifamily dwellings and group-living uses, 80 percent, or 39,812 buildings, are in a slight to moderate damage state and 20 percent, or 7,586 buildings, are in an extensive or complete damage state. Thus, multifamily dwellings and group-living uses sustain proportionally higher damage levels than single-family/duplex dwellings in the HayWired scenario.

Nearly 39,000 nonresidential buildings sustain some level of damage from the M_w 7.0 mainshock of the HayWired scenario, of which about 15 percent, or 5,920 buildings, are in an extensive or complete damage state. Retail/commercial occupancies represent 35 percent of the total nonresidential building square footage, of which 38 percent sustains some level of building damage. Industrial/warehouse occupancies represent 29 percent of the total nonresidential building square footage, of which 47 percent sustains some level of building damage. Offices and household-serving occupancies also represent significant portions of the total nonresidential building square footage (22 and 12 percent, respectively) that also sustain high levels of building damage (44 and 38 percent, respectively). Of the damaged nonresidential building square footage, all of the nonresidential occupancies have more than 10 percent of buildings in an extensive or complete damage state.

Table A7. Damage distribution for residential and nonresidential occupancy groupings in terms of building square footage and building counts caused by ground shaking, landslide, liquefaction, and fires from the moment magnitude 7.0 mainshock of the HayWired scenario in the San Francisco Bay region, California.

[ft², square feet]

Occupancy grouping	Total exposure	Hazus damage state						
		None	Slight	Moderate	Extensive	Complete	Slight, moderate, extensive, or complete	Extensive or complete
Residential occupancy groupings								
Single family/duplex (ft²)	4,634,481,745	3,133,607,453	984,293,986	372,454,614	80,921,045	63,204,647	1,500,874,292	144,125,692
Single family/duplex (number)	2,875,553	1,946,425	608,387	230,929	50,225	39,587	929,128	89,812
Multifamily (ft²)	769,783,442	449,124,980	170,213,623	89,744,057	25,678,403	35,022,379	320,658,462	60,700,782
Multifamily (number)	94,159	55,845	20,529	10,448	2,931	4,406	38,314	7,337
Group living (ft²)	120,618,262	83,173,698	20,510,257	10,717,512	3,089,245	3,127,550	37,444,564	6,216,795
Group living (number)	4,825	3,327	820	429	124	125	1,498	249
Subtotal (ft²)	**5,524,883,449**	**3,665,906,131**	**1,175,017,866**	**472,916,183**	**109,688,693**	**101,354,576**	**1,858,977,318**	**211,043,269**
Subtotal (number)	**2,974,537**	**2,005,597**	**629,736**	**241,806**	**53,279**	**44,118**	**968,940**	**97,397**
Nonresidential occupancy groupings								
Retail/commercial (ft²)	739,636,465	457,940,955	152,650,778	85,756,140	25,569,972	17,718,620	281,695,510	43,288,592
Retail/commercial (number)	51,124	31,049	10,891	6,157	1,863	1,164	20,075	3,027
Offices (ft²)	472,023,992	266,520,014	114,901,530	64,512,599	16,901,404	9,188,445	205,503,978	26,089,849
Offices (number)	5,900	3,332	1,436	806	211	115	2,569	326
Industrial/warehouse (ft²)	608,072,797	322,324,688	142,518,490	94,012,681	29,526,041	19,690,897	285,748,109	49,216,938
Industrial/warehouse (number)	19,316	10,263	4,513	2,975	939	626	9,053	1,565
Household serving (ft²)	248,803,733	155,588,546	50,503,418	27,565,628	7,822,383	7,323,758	93,215,187	15,146,141
Household serving (number)	17,943	11,217	3,708	2,040	569	408	6,725	977
Agricultural uses (ft²)	34,949,651	27,494,300	4,768,876	1,942,626	486,797	257,052	7,455,351	743,849
Agricultural uses (number)	1,165	916	159	65	16	9	249	25
Subtotal (ft²)	**2,103,486,638**	**1,229,868,503**	**465,343,092**	**273,789,674**	**80,306,597**	**54,178,772**	**873,618,135**	**134,485,369**
Subtotal (number)	**95,448**	**56,777**	**20,707**	**12,044**	**3,598**	**2,321**	**38,671**	**5,920**

Areas of Concentrated Damage

Groen and Polivka's (2010) study of post-Hurricane Katrina population displacement and return defined high-damage areas as those with at least 20 percent of housing units classified as severely damaged. They found that population return in these areas in the first 13 months after the storm was profoundly lower than in less-damaged areas. Unfortunately, their study did not extend further in time. After the 1994 Northridge earthquake, the City of Los Angeles Housing Department (LAHD) identified 17 neighborhoods where the concentrations of housing damage resulted in high levels of resident displacement, blight, and crime and required targeted housing recovery strategies (LAHD, 1995). Each of the 17 neighborhoods were located in one of the 38 census tracts that was identified as having more than 100 vacated apartment housing units and in which more than 60 percent of the housing units were either heavily damaged or destroyed.

Discussions with disaster recovery experts suggest that the actual point at which spatial concentrations of housing and building damage can lead to systemic and cascading consequences, as defined by Alesch and others (2009), is much lower than 60 percent and more likely to be closer to 20 percent or even lower (Mary Comerio, University of California at Berkeley, written commun., 2015; Ann-Margaret Esnard, Georgia State University, written commun., 2015).

A threshold of 20 percent was therefore selected to identify areas where there were concentrations of building damage in an extensive or complete damage state, and thus deemed uninhabitable until necessary repairs or rebuilding are completed (mapped as orange or red in figures A2–A10). Maps were prepared for each building occupancy grouping and for the combined regional total to show the distribution of building damage.

The mapping of the damage concentrations was constrained to developed areas because some census tracts are expansive and include large areas of undeveloped land; however, buildings are mostly located in developed areas. The boundaries of developed areas (not including developed open space) were created using the 2011 National Land Cover Database (Homer and others, 2015) and then used to clip out the undeveloped areas of the census tracts. This is the same layer that was used to constrain landslide building damage results and fire damage results to developed areas (in Seligson and others, 2018, and above).

Figures A2–A10 show the percentages of the total building square footage in either an extensive or complete damage state from the M_w 7.0 mainshock of the HayWired scenario for the following building occupancy groupings:

- Figure A2—All occupancies combined
- Figure A3—Multifamily dwellings
- Figure A4—Single-family and duplex dwellings
- Figure A5—Group-living uses
- Figure A6—Household-serving buildings
- Figure A7—Retail and commercial buildings
- Figure A8—Offices
- Figure A9—Industrial and warehouse buildings, and
- Figure A10—Agricultural uses.

In each figure, the left panel shows the percentages of total building square footage in either an extensive or complete damage state from shaking, landslide, and liquefaction only (without fire). The right panel shows the percentages of total building square footage in either an extensive or complete damage state from shaking, landslide, liquefaction, and fire (with fire). The building occupancy exposure data used to create these figures is available in Jones and others (2020).

The orange- and red-colored tracts are the areas where 20 percent or more of the total building square footage is in an extensive or complete damage state—and, therefore, define areas of concentrated damage. All these maps show similar patterns of concentrated building damage in the urbanized portion of the entire east bay corridor; in the Santa Clara, San Ramon, Livermore, and other inland valley areas; and in flat lands surrounding San Francisco Bay. Some areas, such as central Hayward, sustain very high concentrations of damage across multiple occupancy groupings. The maps also show the expanded and intensified levels of concentrated building damage that result from fire. Table A8 lists the number of census tracts in the nine-county region that have concentrated damage for each of the nine building occupancy groupings (with and without fire).

Table A8. Number of census tracts in the nine-county San Francisco Bay region, California, that have concentrated damage resulting from the HayWired earthquake scenario mainshock for each building occupancy groupings (both with and without fire).

Percentage of total buildings damaged	All	Nonresidential					Residential		
		Industrial/ warehouse	Offices	Retail/ commercial	Household serving	Agricultural uses	Single family/ duplex	Multi-family	Group-living uses
All hazards (ground shaking, landslides, liquefaction, and fire)									
Less than 20	1,414	1,288	1,332	1,321	1,315	1,446	1,503	1,252	1,353
20 to 60	173	248	244	254	258	137	85	316	227
More than 60	1	52	12	13	15	5	0	20	8
Earthquake hazards only (no fire)									
Less than 20	1,473	1,296	1,339	1,330	1,350	1,446	1,548	1,352	1,386
20 to 60	115	242	237	246	230	137	40	234	196
More than 60	0	50	12	12	8	5	0	2	6

In the areas of concentrated damage for all occupancies combined, shown in figure A2*A*, there are 115 census tracts (or roughly about 7 percent of the 1,588 tracts in the nine-county region) that have concentrated building damage from earthquake hazards; these are primarily located in Alameda and Contra Costa Counties. If fire damage is included (fig. A2*B*), the area expands to 174 census tracts (or 11 percent of the total tracts in the nine-county region) and also

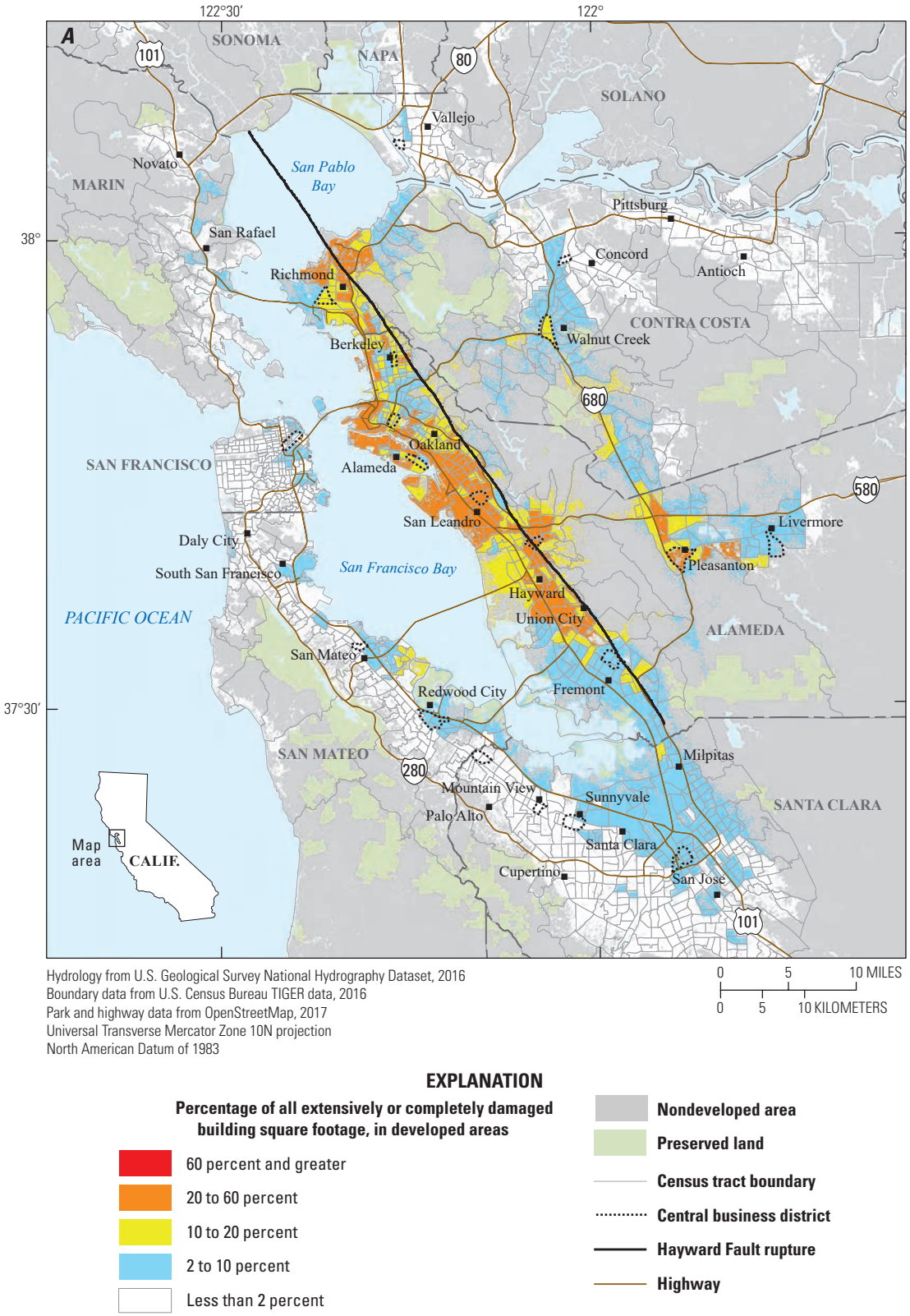


Figure A2. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage for all building occupancies (that is, the total building stock) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

includes small portions of Solano and Marin Counties. The concentrated-damage tracts are mainly in the east bay corridor from Point Pinole in the north to Fremont in the south, with additional areas in the San Ramon Valley, Vallejo, and Novato.

The areas of concentrated building damage for multifamily dwellings, shown in figure A3, follows a similar pattern in the east bay corridor, but covers 236 census tracts (or 15 percent of the total tracts in the nine-county region)

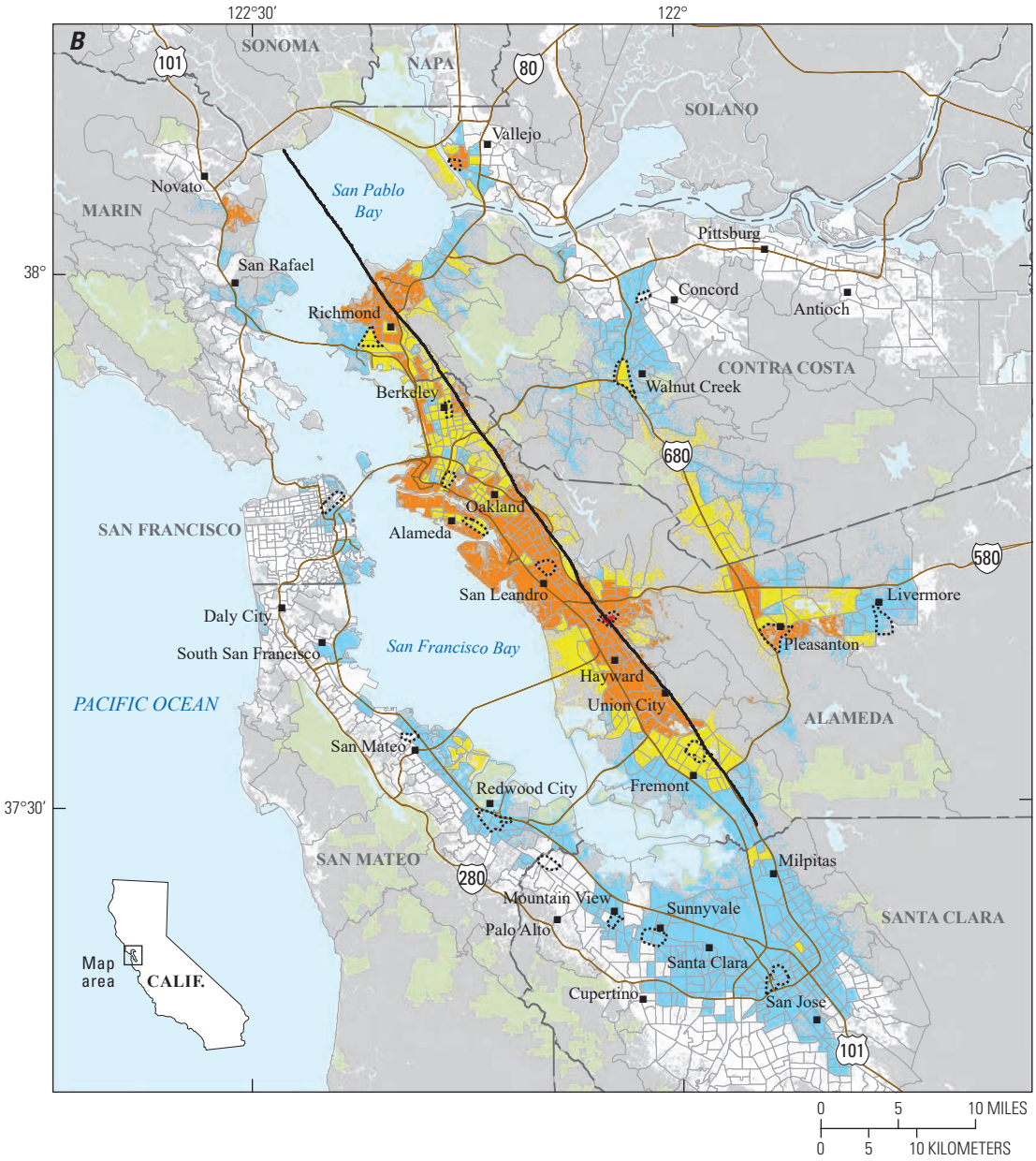


Figure A2.—Continued

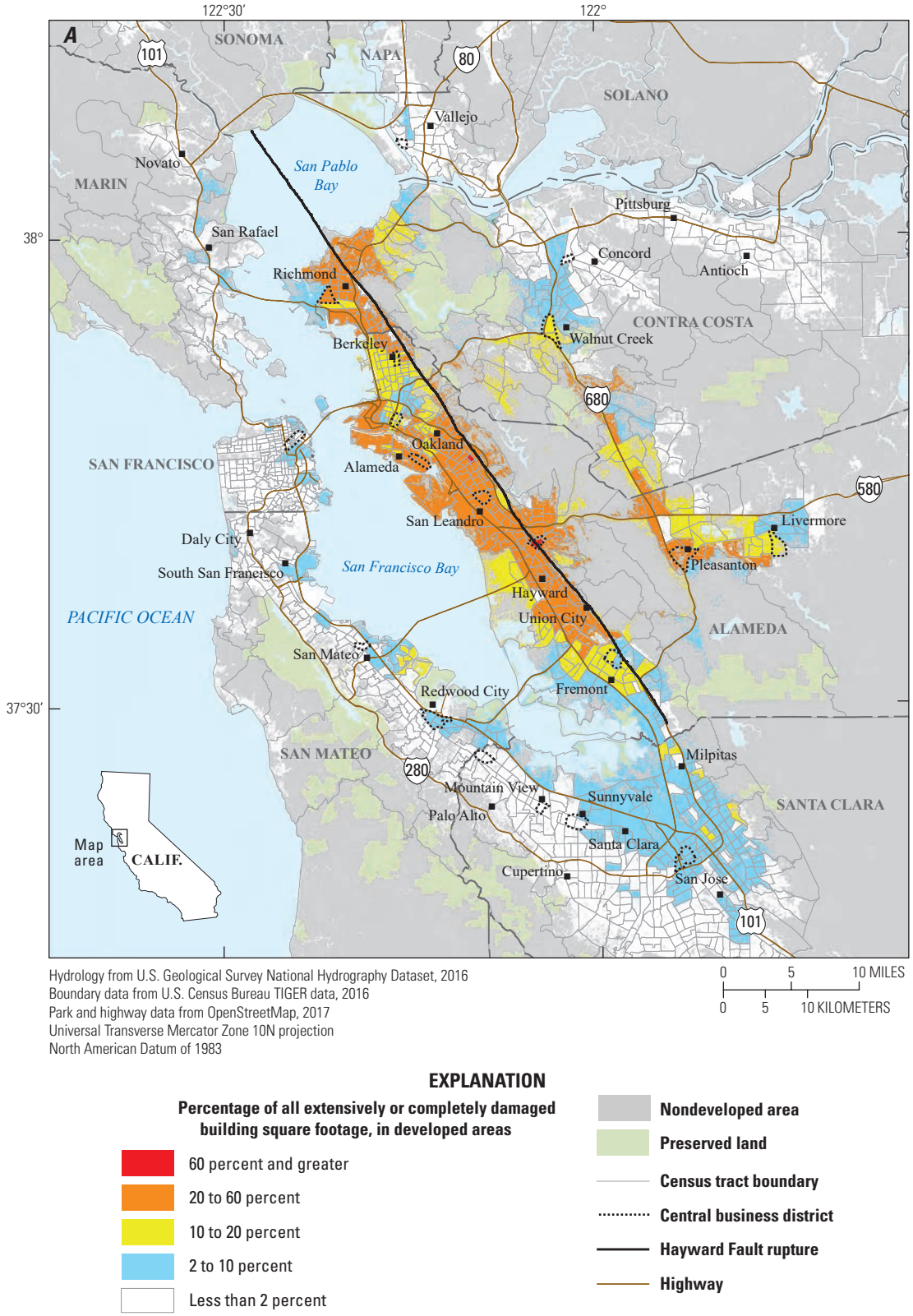


Figure A3. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage for multifamily dwellings (for example, three or more housing units per structure) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

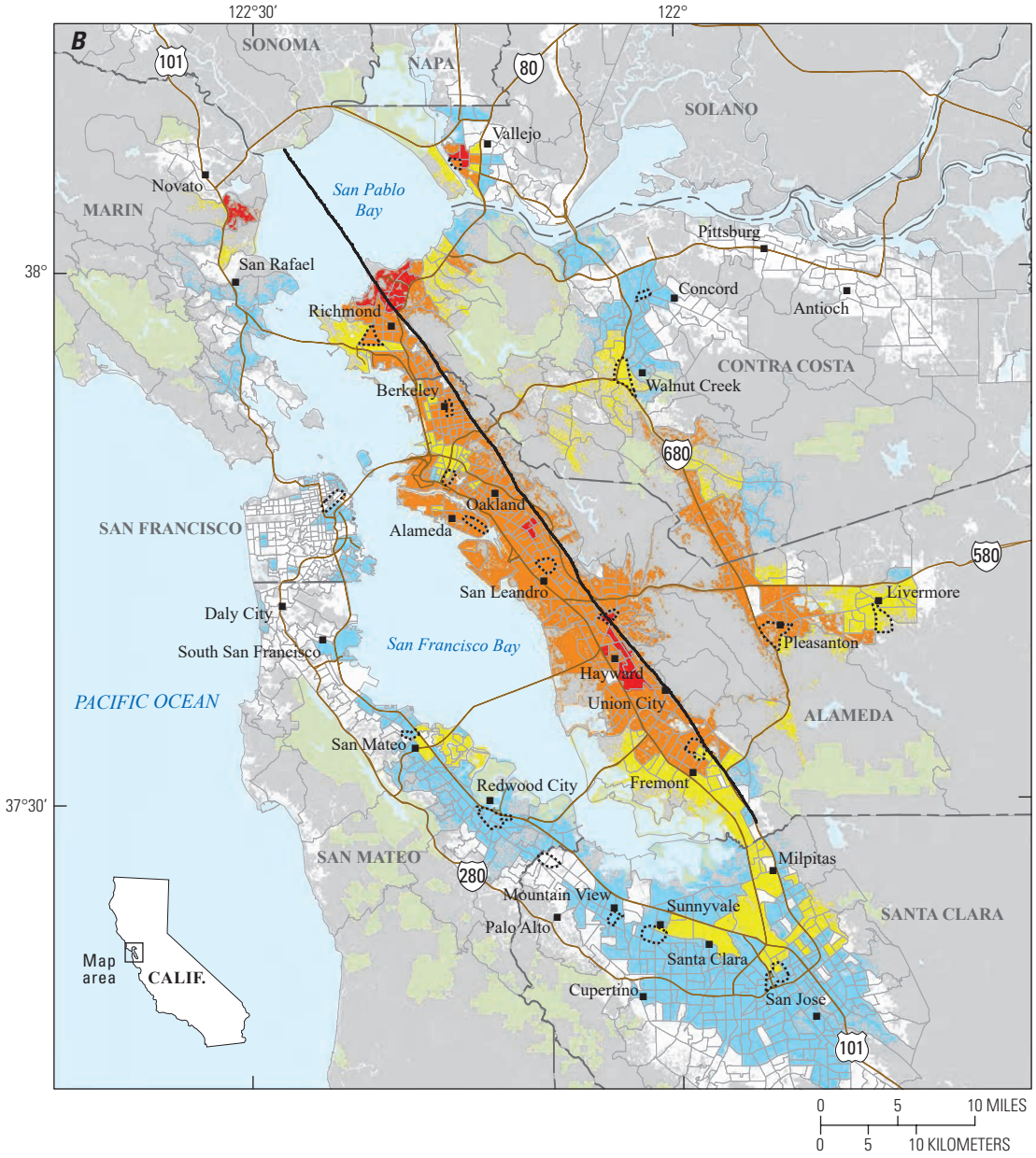


Figure A3.—Continued

with concentrated building damage from earthquake hazards (fig. A3*A*). The area expands to 336 census tracts (21 percent of the total tracts) if fire damage is included (fig. A3*B*). The area of concentrated damage for single-family/duplex dwellings, shown in figure A4, also has the same general pattern, but only covers 40 census tracts (or 3 percent of the total tracts) for earthquake hazards (fig. A4*A*), and 85 census tracts (5 percent of the total tracts) with fire damage included (fig. A4*B*). Concentrated damage to group-living uses, shown in figure A5, also follows the same general pattern as the areas of concentrated damage for multifamily and single-family/duplex dwellings, but represents only a very small share of residential square footage.

Figures A6 and A7 show the areas of concentrated damage for household-serving and retail and commercial uses, respectively. Old business districts with highly vulnerable buildings in the east bay corridor from Crockett in the north to Fremont in the south, as well as business districts in Walnut Creek, San Ramon, Dublin, Pleasanton, and Livermore sustain heavy damage. A few building occupancy groupings do have expanded patterns of concentrated damage, notably household-serving uses (fig. A6) and industrial/warehouse uses (fig. A9). Industrial/warehouse, retail/commercial, and multifamily dwellings account for the most significant damage concentrations from all hazards. Office and single-family/duplex structures generally sustain lower levels of damage than the other uses but may still be affected by their location in neighborhoods of more vulnerable buildings.

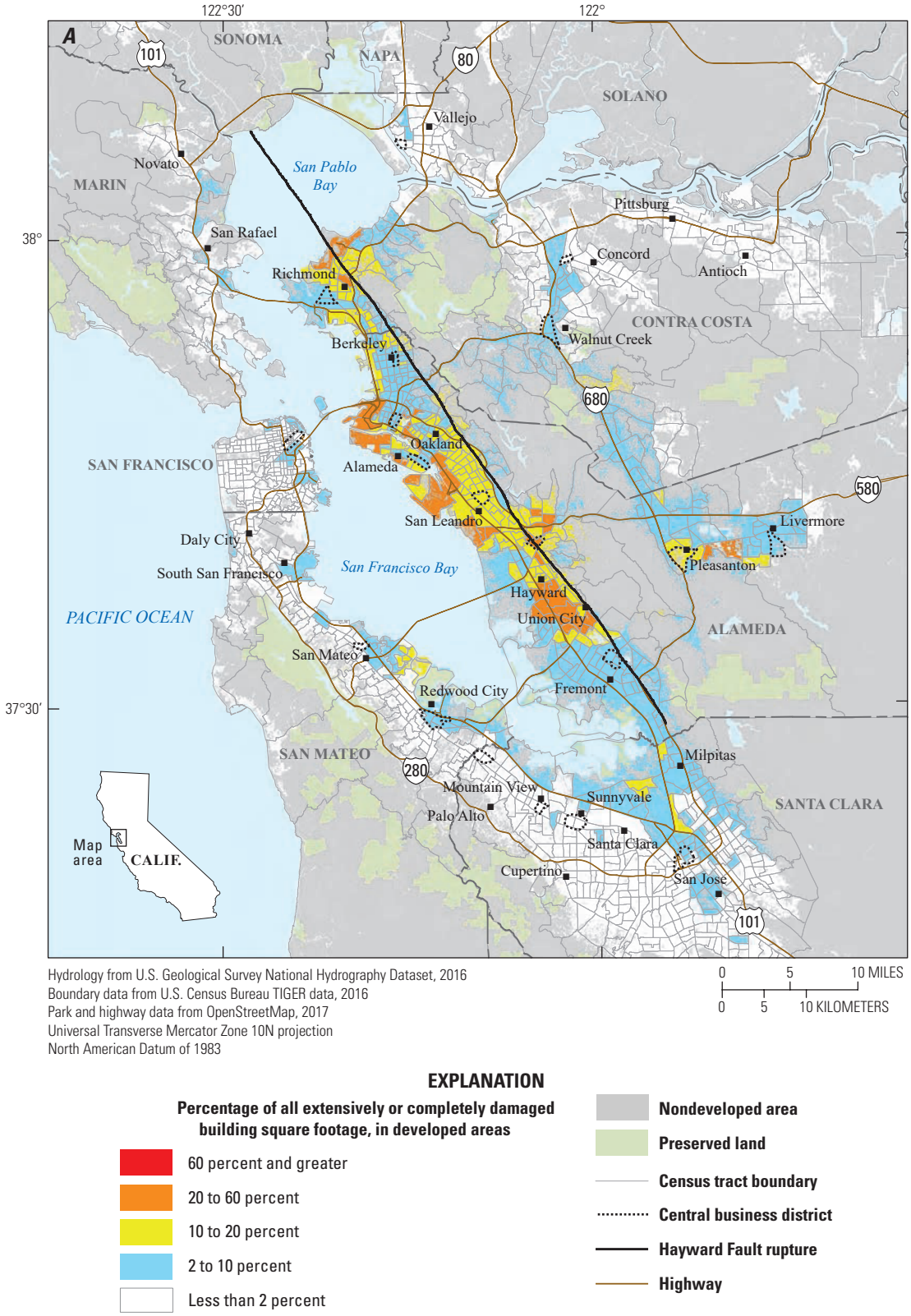


Figure A4. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage for single-family and duplex dwellings in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

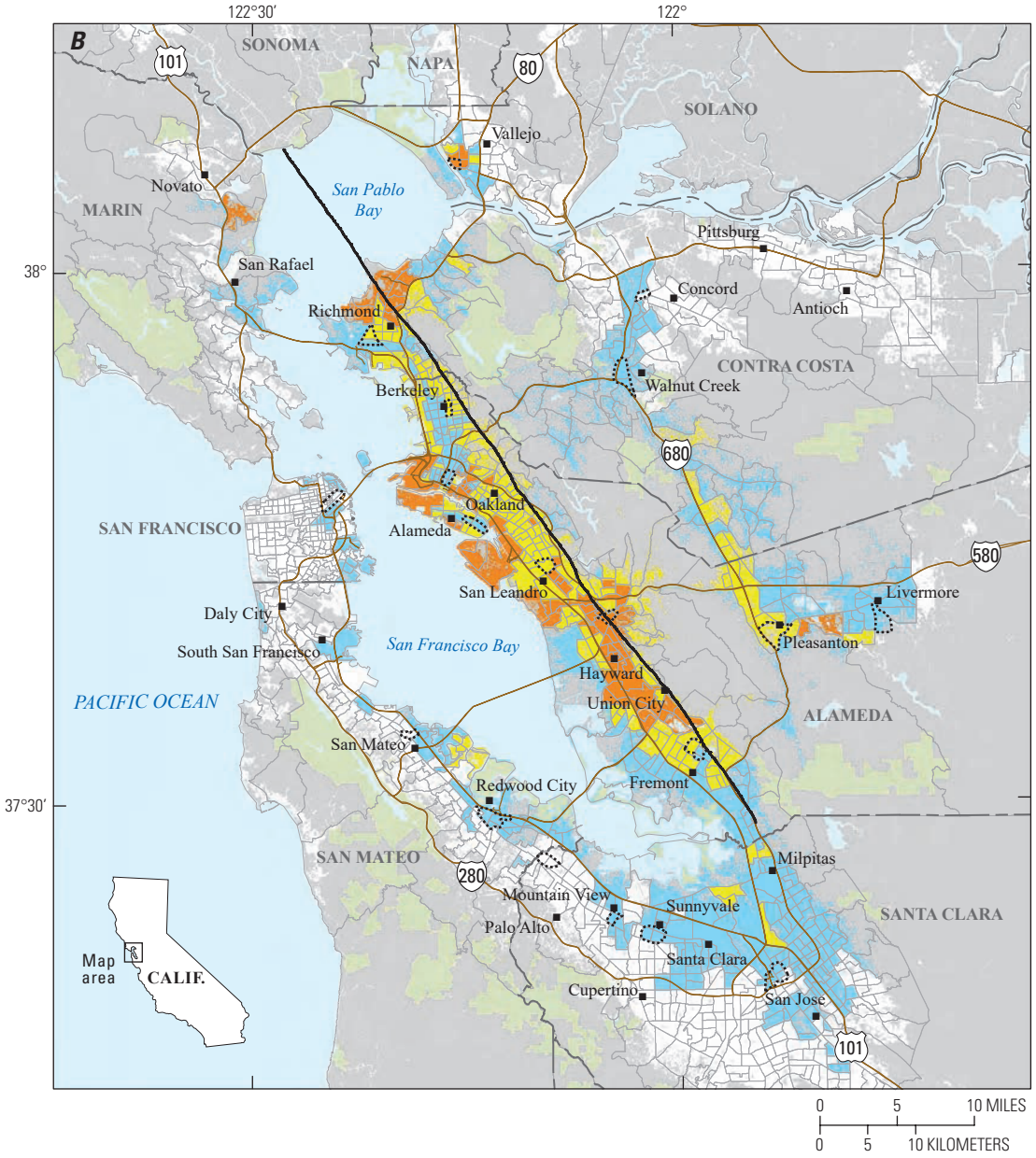


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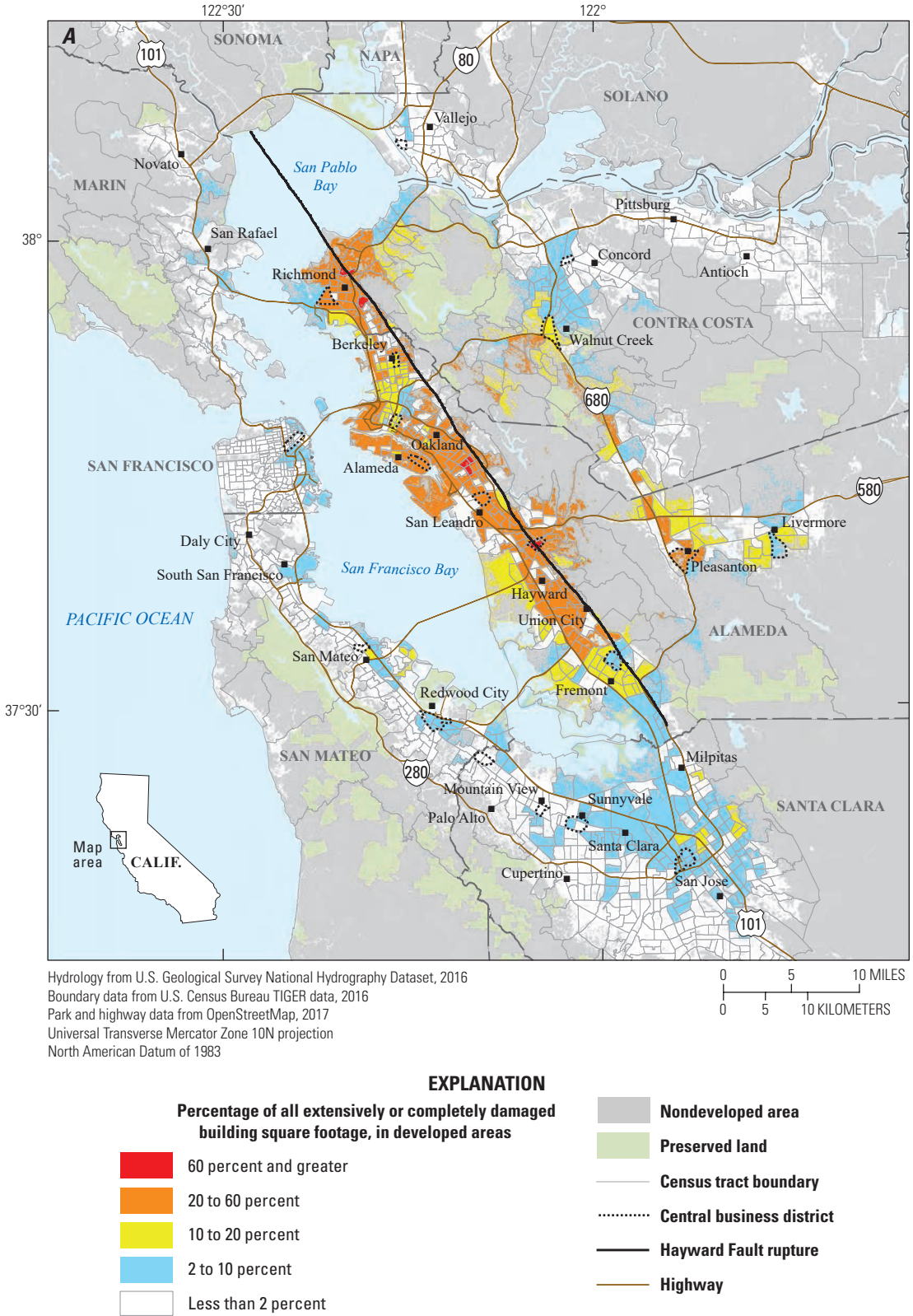


Figure A5. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage for group-living uses (for example, dormitories, nursing homes, and jails) in the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

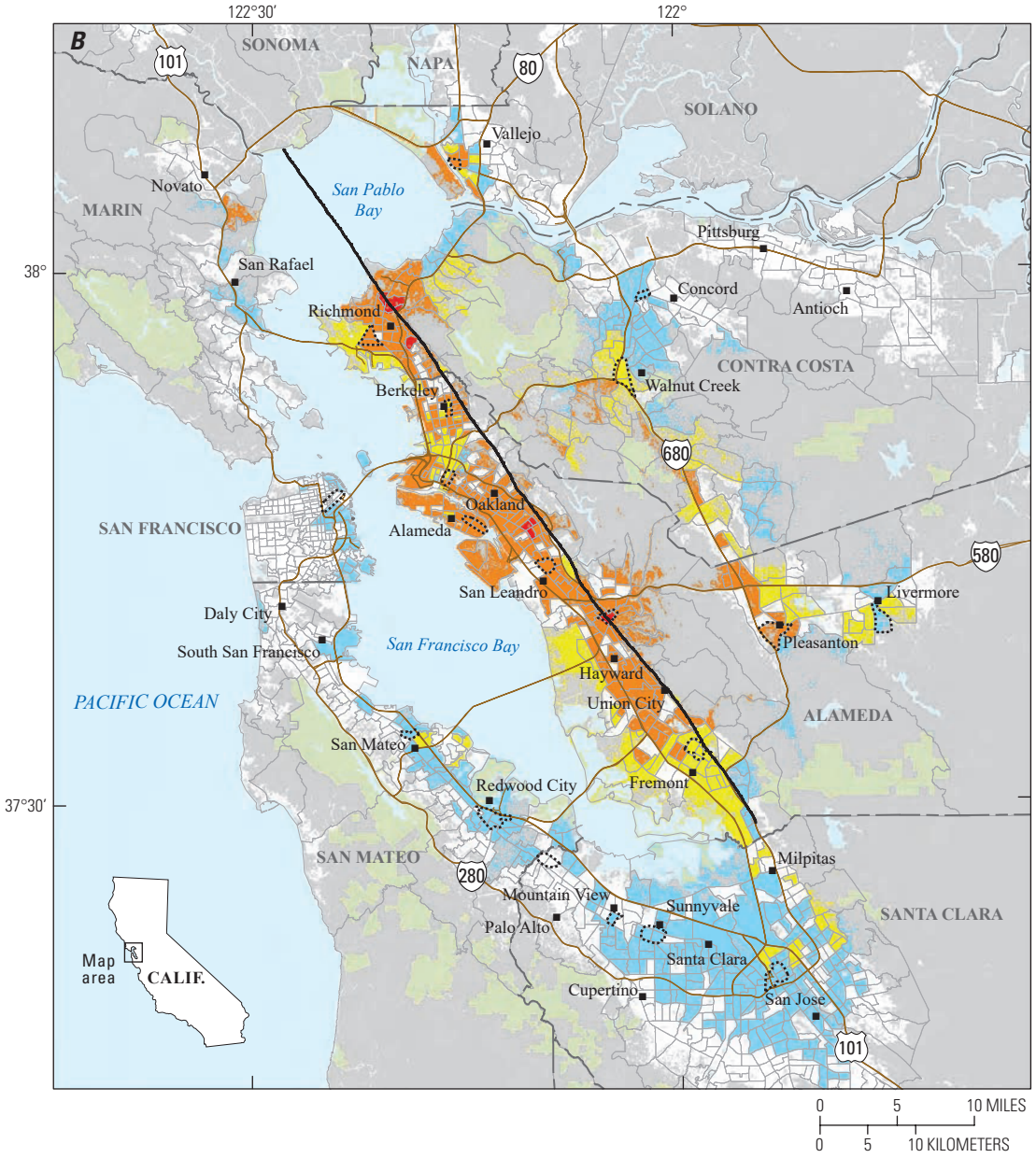


Figure A5.—Continued

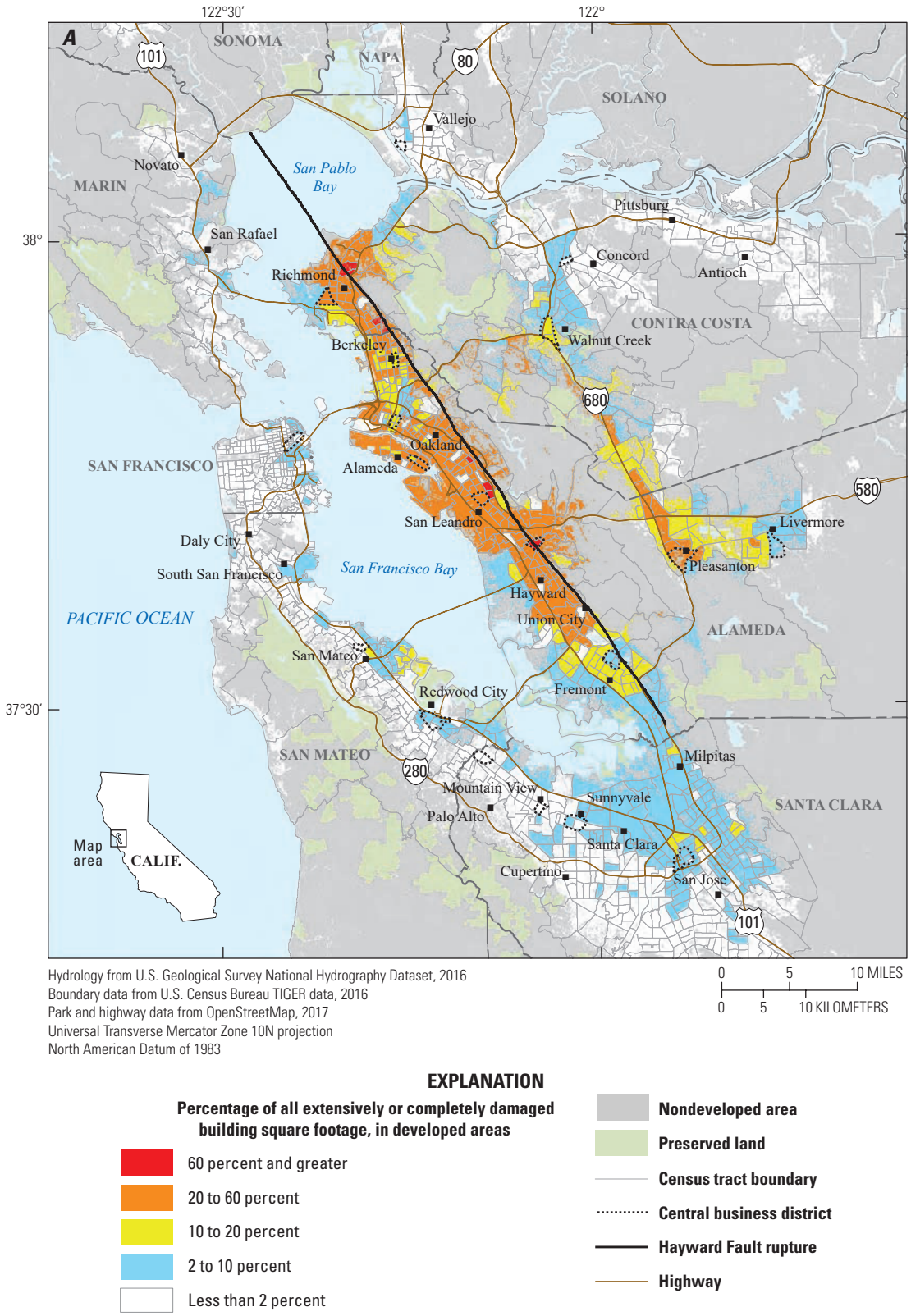


Figure A6. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of damage to household-serving uses (for example, hospitals, schools, and places of worship) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

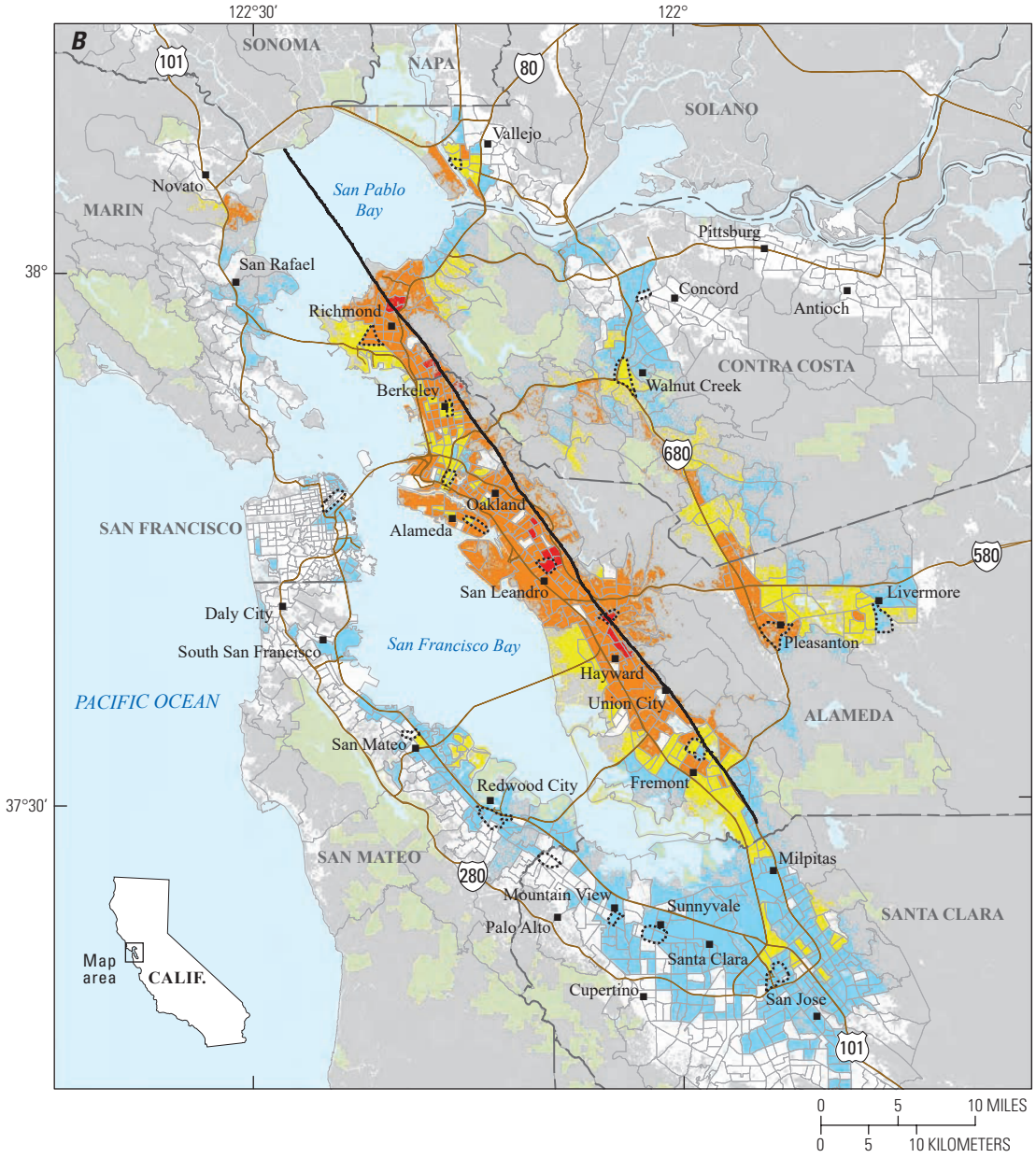


Figure A6.—Continued

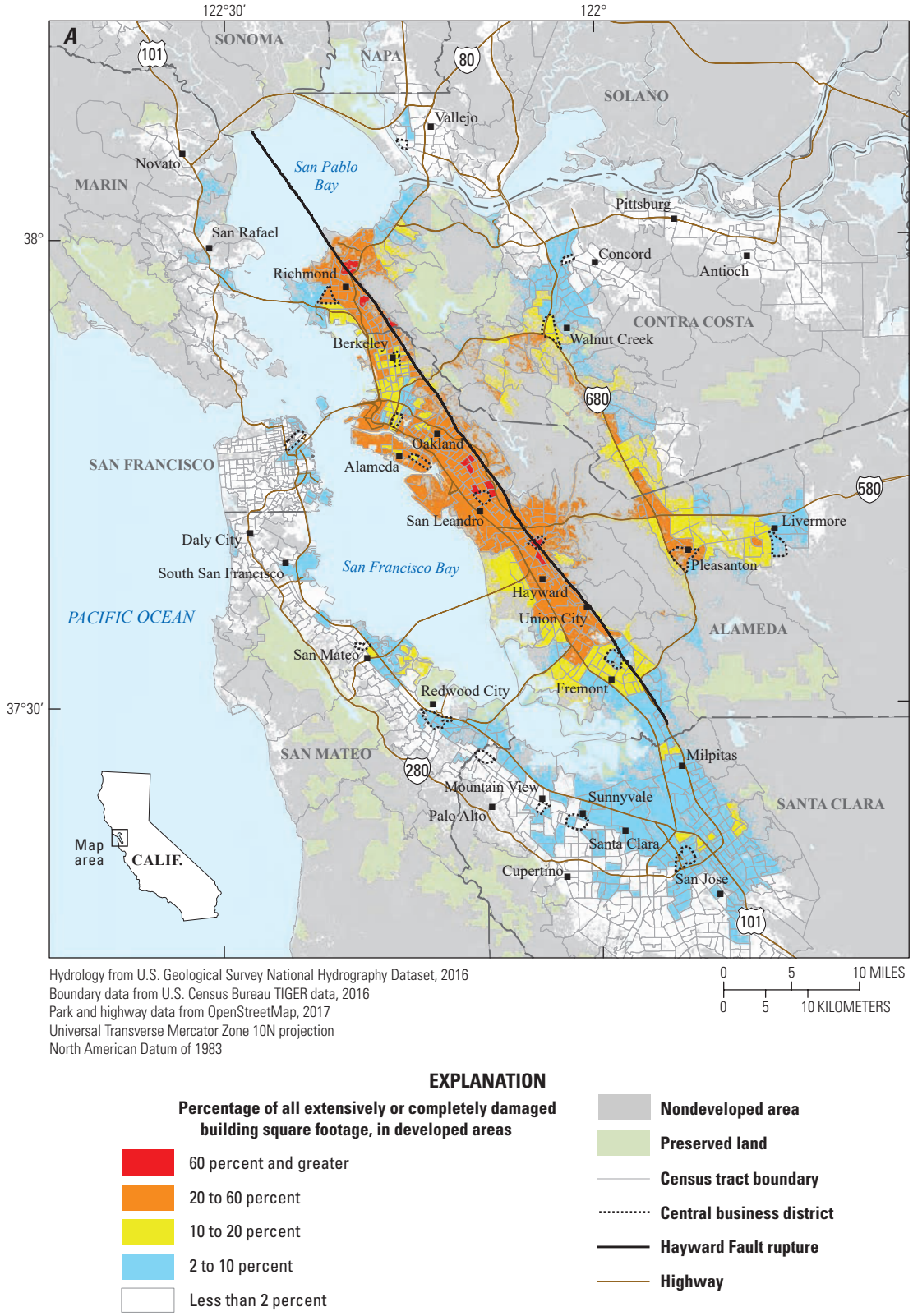


Figure A7. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage to retail and commercial uses (for example, hotels, retail trade, banks, entertainment and recreation, and parking) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

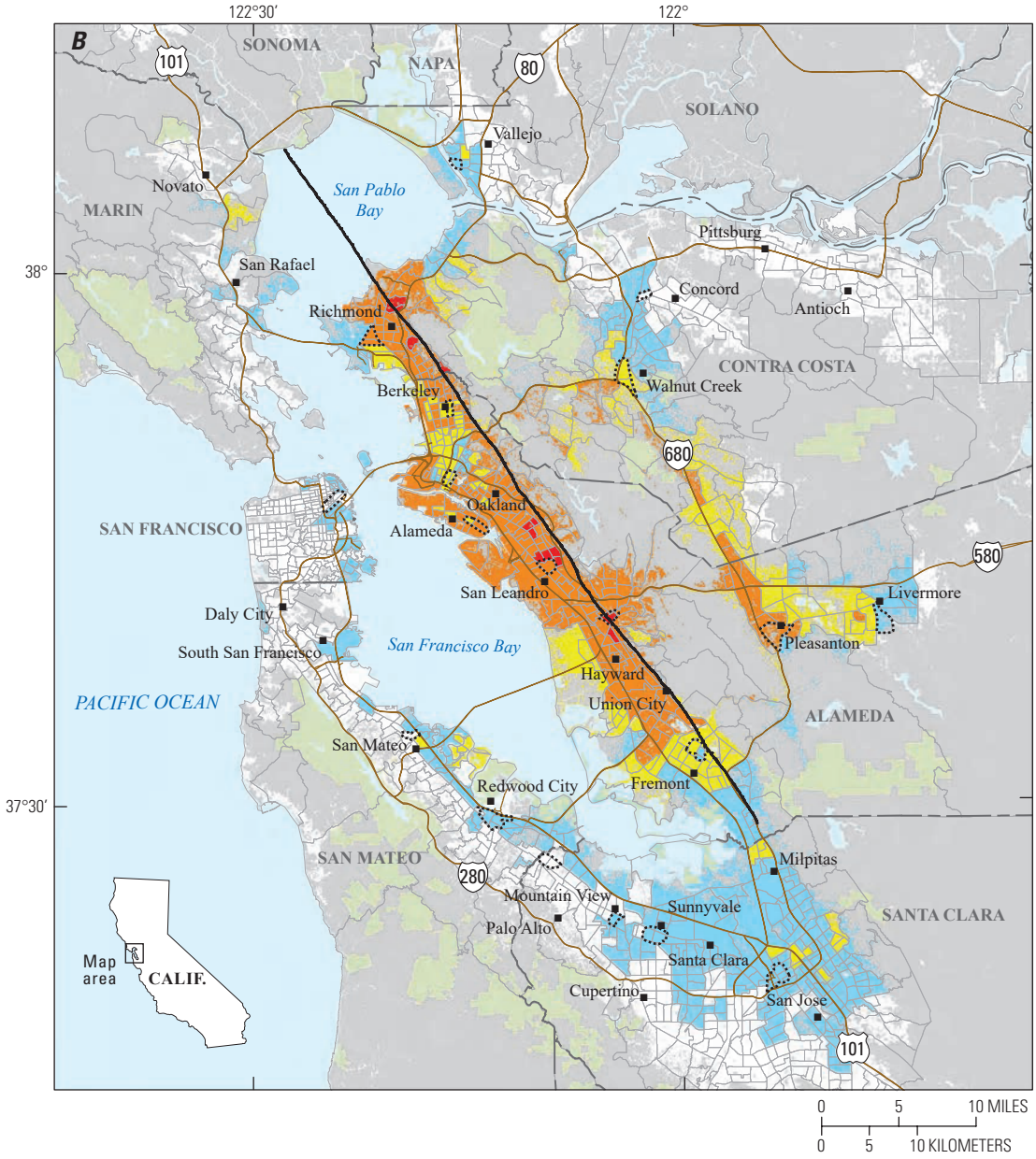


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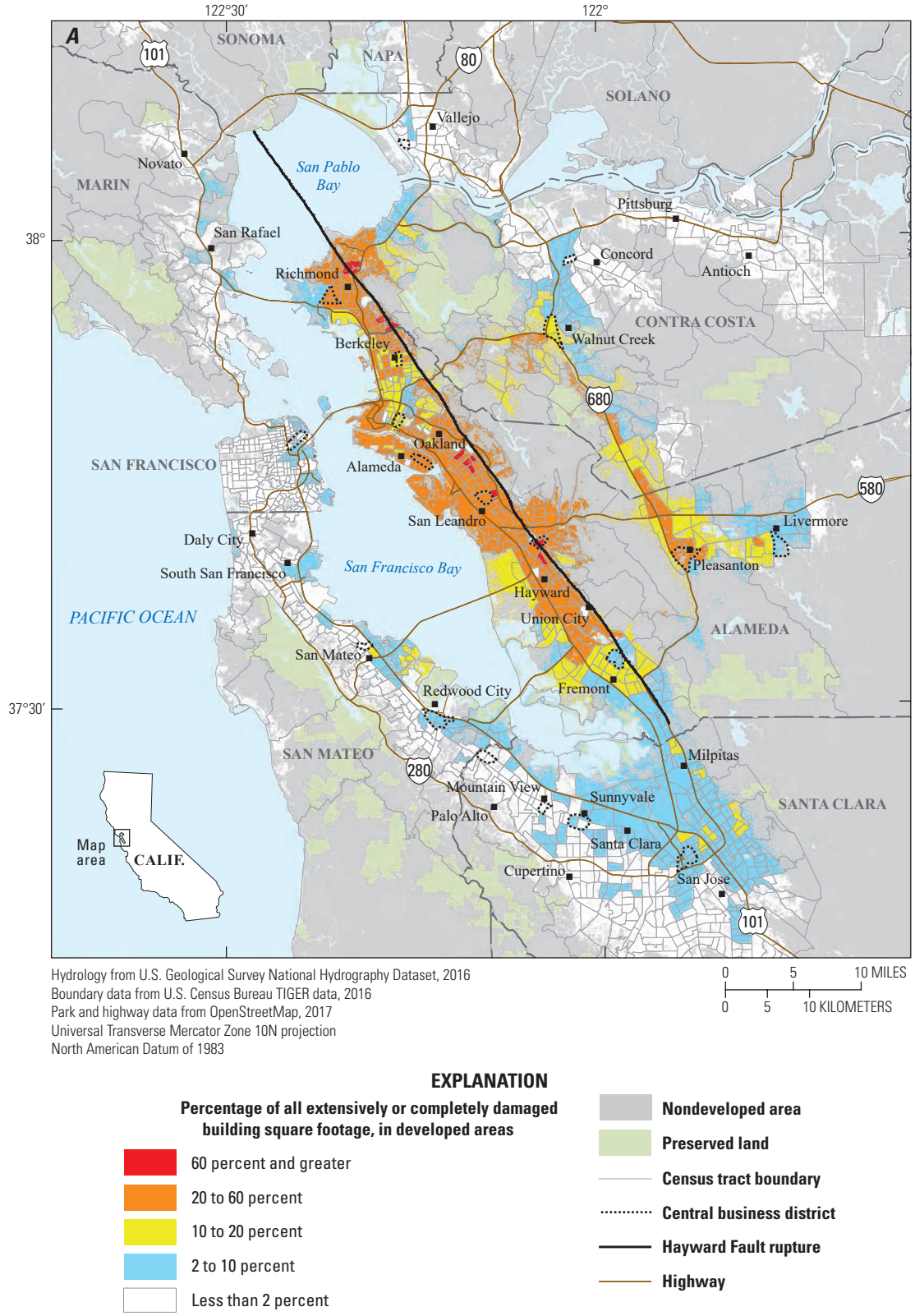


Figure A8. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage to office uses (for example, professional and technical services) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

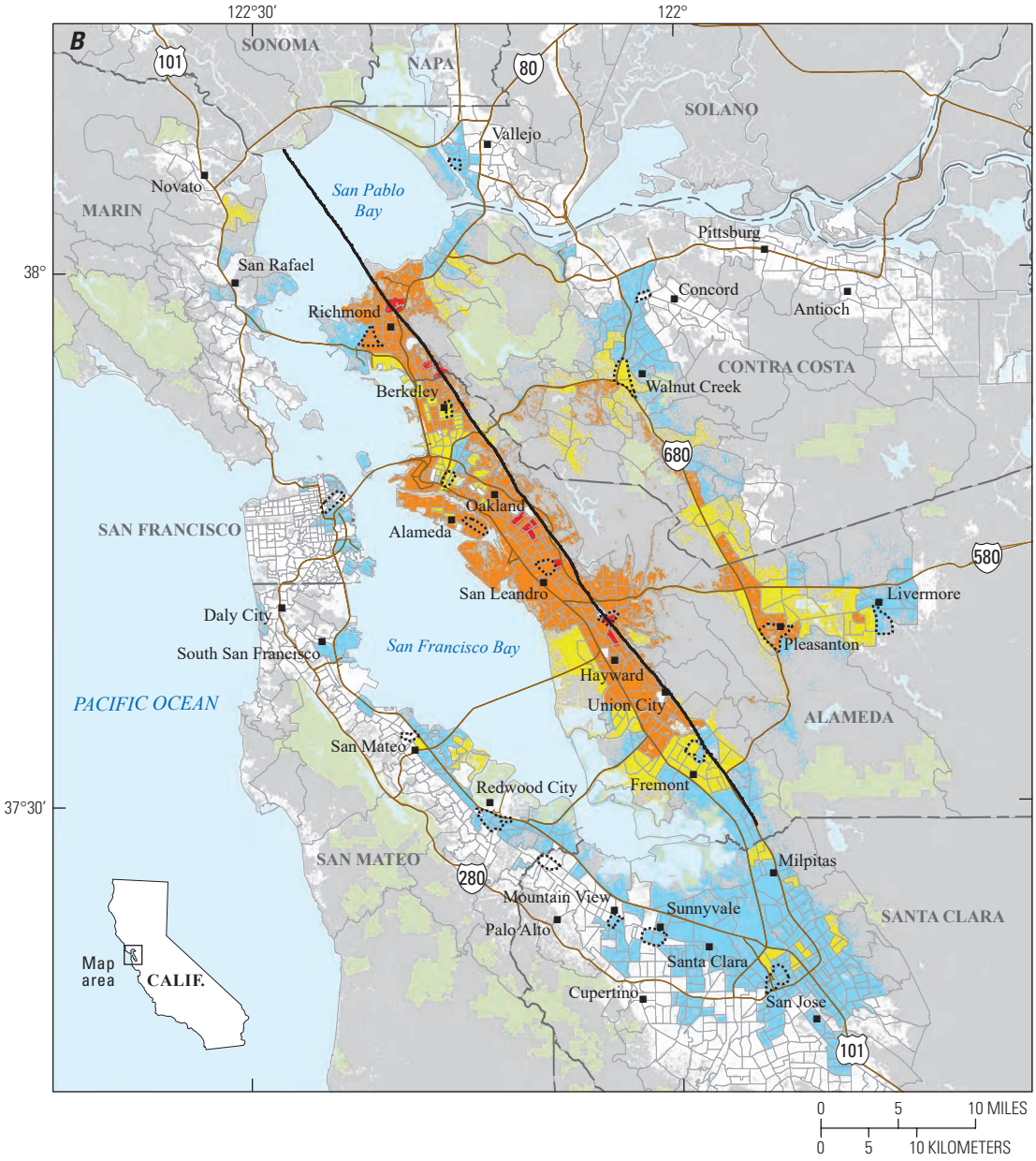


Figure A8.—Continued

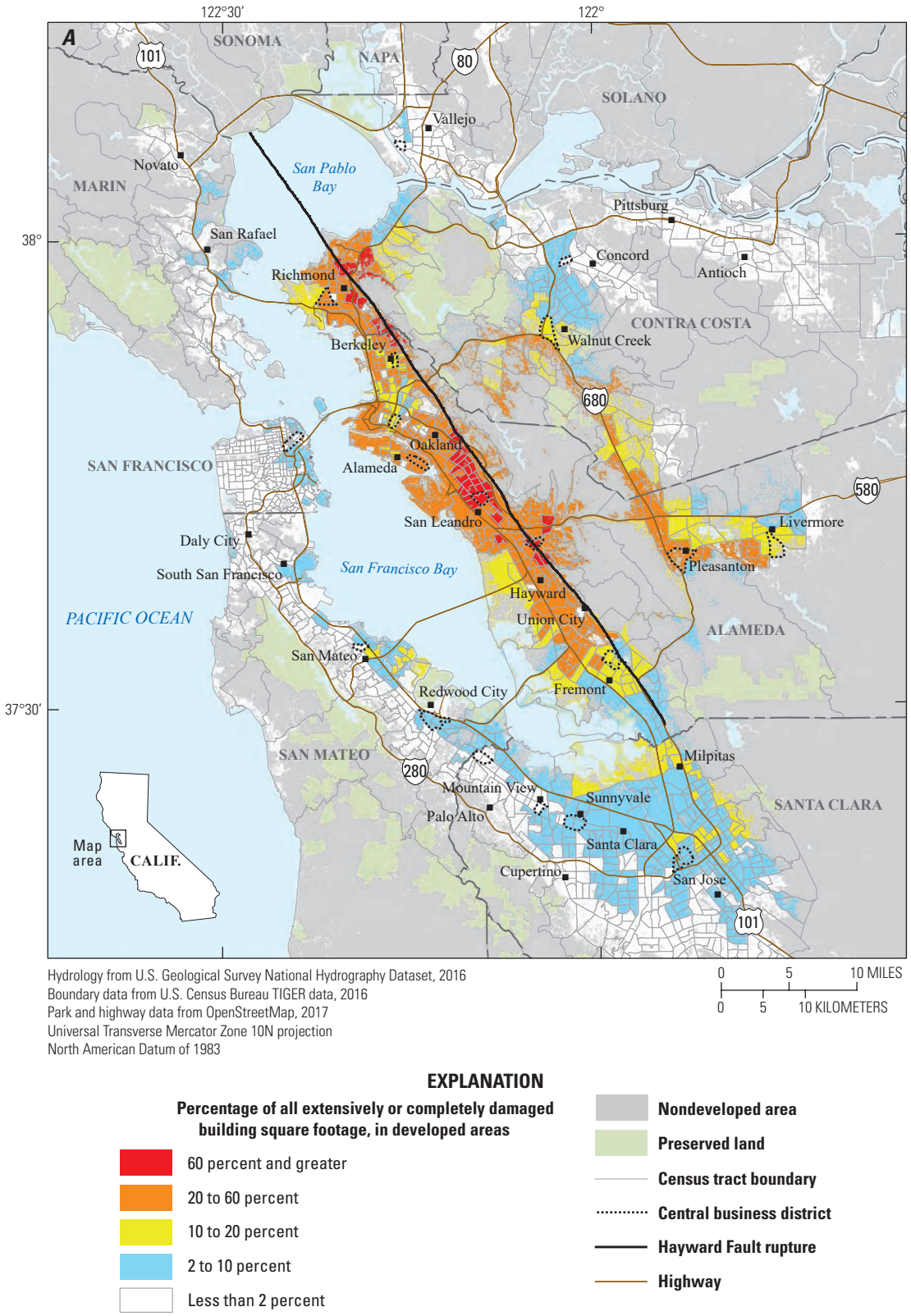


Figure A9. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of building damage to industrial and warehouse uses (for example, heavy and light industrial uses; food, drug, chemical, or metal processing; high technology; and construction) in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

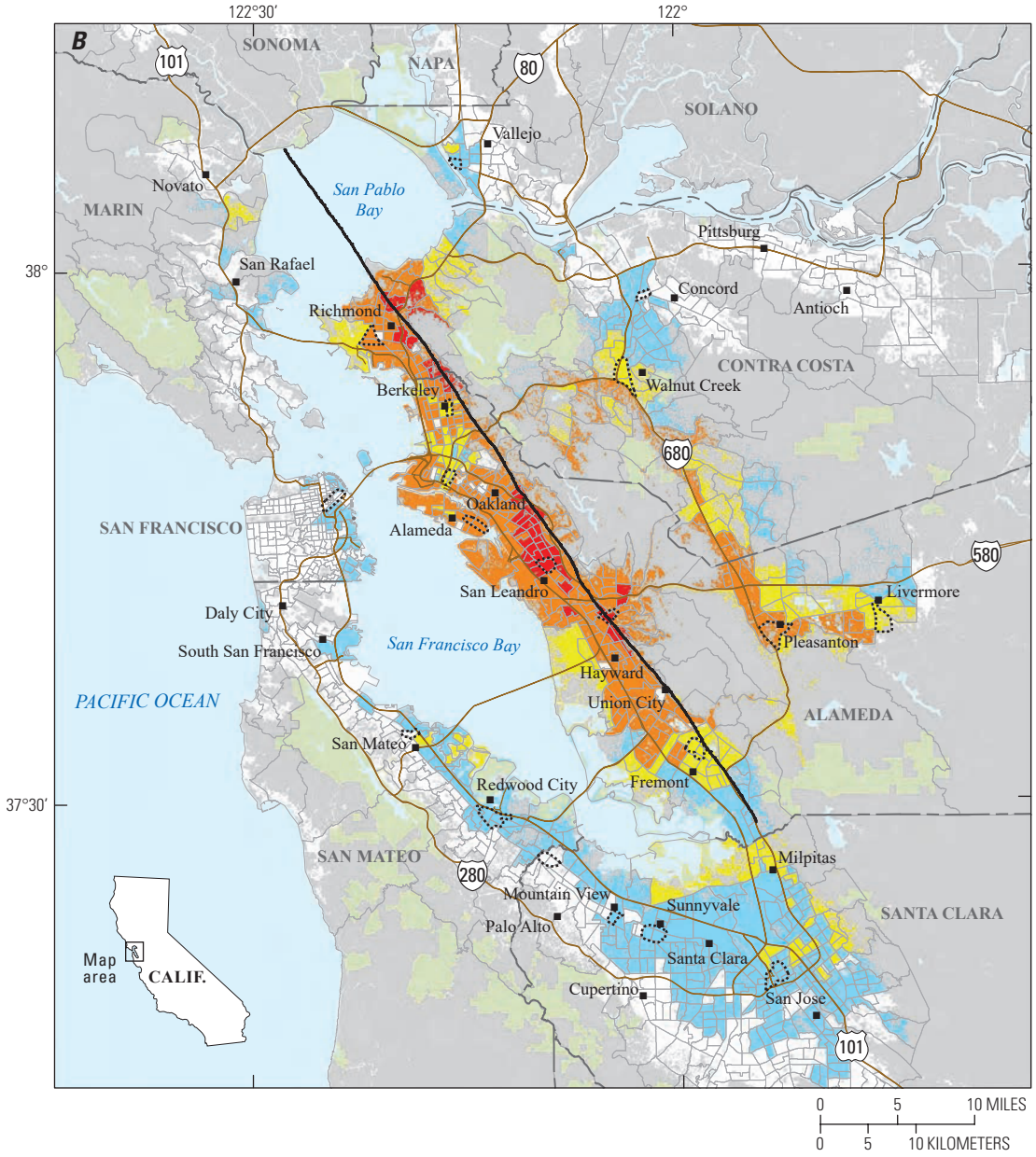


Figure A9.—Continued

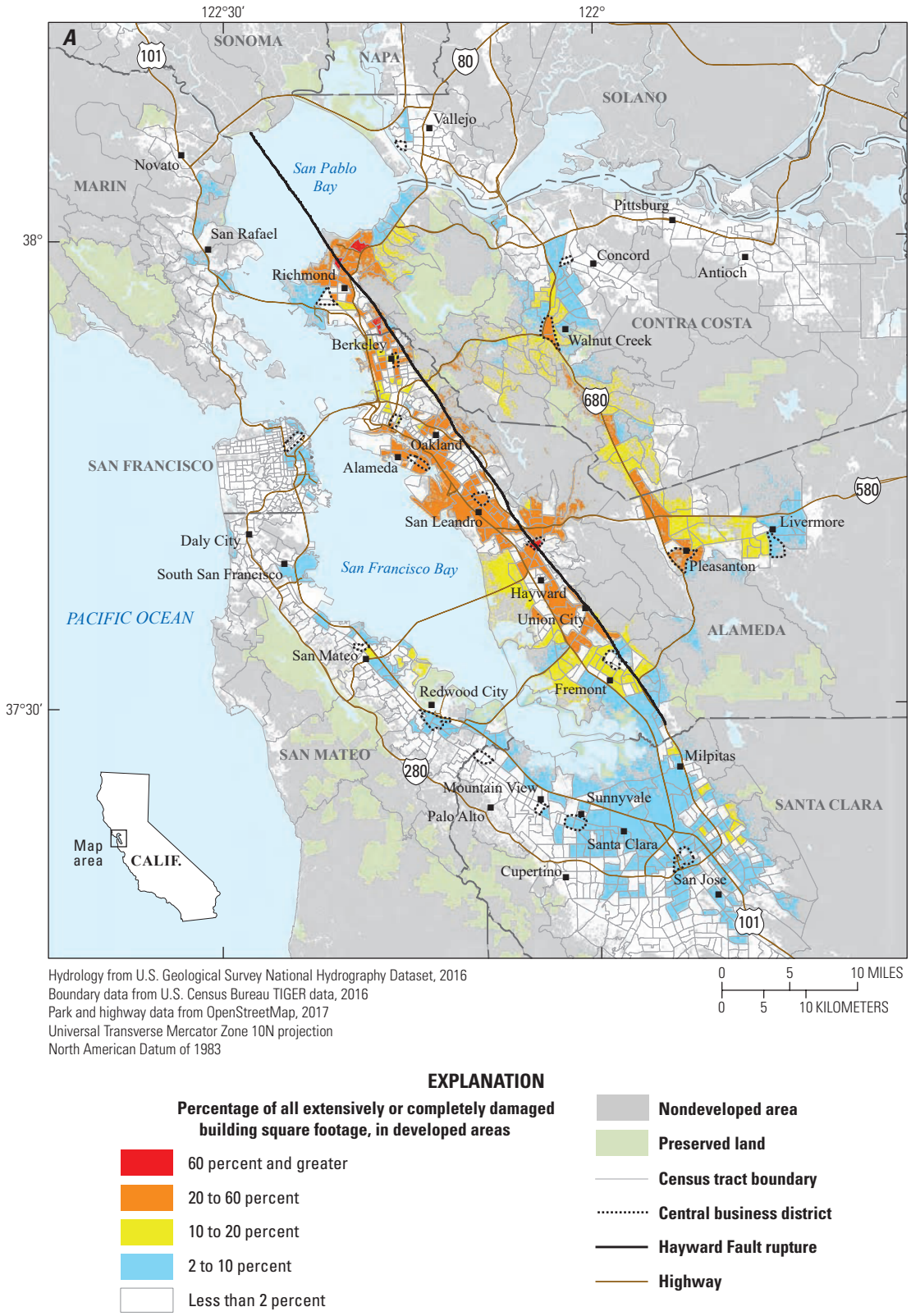


Figure A10. Maps of the San Francisco Bay region, California, showing census tracts with concentrations of damage for agricultural uses in the HayWired earthquake scenario mainshock. *A*, Shaking, landslide, and liquefaction hazards only (without fire). *B*, Shaking, landslide, liquefaction, and fire hazards (with fire).

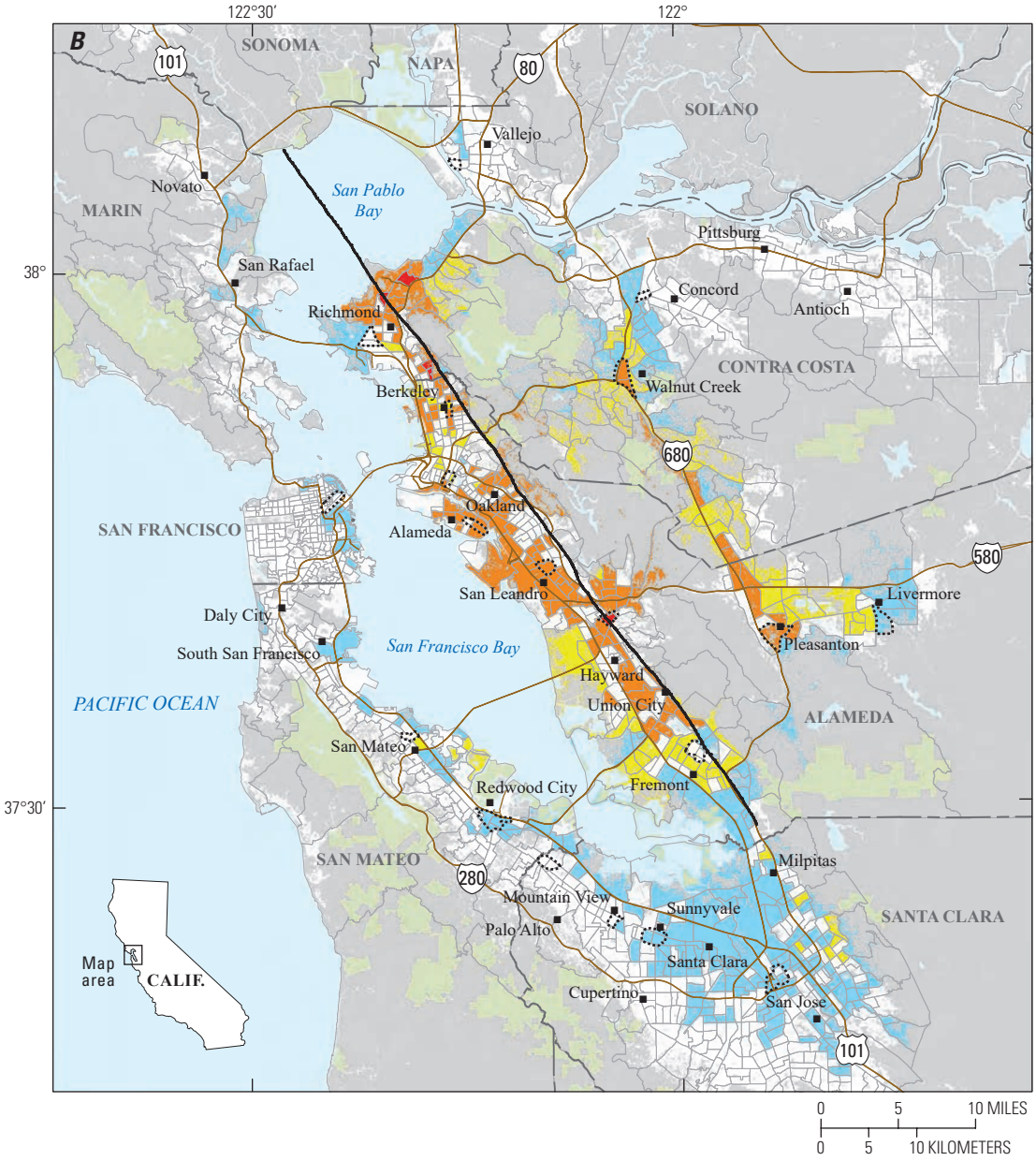


Figure A10.—Continued

Discussion

Past disasters have shown that the degree and pattern of physical damages to housing and other structures is a strong indicator of the potential population at risk of displacement as well as potential long-term community recovery challenges. Although scenario studies generally contain different hazard analyses, seldom are they mathematically combined to provide an integrated view of the spatial extent and concentration of damage caused by different hazards, such as ground shaking and post-earthquake fires.

This section provides a detailed description of the methodology developed to create an integrated view of building damage owing to ground shaking, landslide, liquefaction, and fires from the HayWired earthquake scenario. The methodology integrates the damage state information for eight different building occupancy groupings that were developed for the HayWired scenario spatial economic analysis. The profile of burned buildings after the Northridge earthquake was used to allocate burned building square footage to different building occupancy classes and the burned building estimates were adjusted to reduce double counting of structures that were destroyed by other earthquake hazards.

The integration of building damage caused by ground shaking, landslide, liquefaction, and fires results in an estimated $74 billion in cumulative property damage for the mainshock of the HayWired scenario, with damage to 1 million residential (containing 1.37 million housing units) and nearly 39,000 nonresidential buildings. It also shows that around 11 percent of the residential and 15 percent of the nonresidential damaged building square footage of the 17-county region is in an extensive or complete damage state, and thus deemed uninhabitable until necessary repairs or rebuilding are completed. Nearly all the damage, especially all the extensive and complete damage, is concentrated in the nine counties that border San Francisco Bay. The building damage is greatest in Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco Counties, with damage most acute in Alameda County.

Supplementing limited disaster data with expert opinion, a threshold of 20 percent or more of the total building square footage in an extensive or complete damage state is used to identify areas of concentrated building damage. Census tracts with 20 percent or more of the total building square footage in an extensive or complete damage state are mapped for all eight building occupancy groupings. The mapping of damage concentrations is constrained to the developed areas of the census tracts.

For all occupancies combined, the areas of concentrated damage are in 174 census tracts (or about 11 percent of the 1,588 tracts in the nine-county region). A consistent pattern of concentrated damage for residential and nonresidential occupancies occurs in the urbanized parts of Alameda County and western Contra Costa County, the Novato area of Marin County, and the Vallejo area of Solano County.

Development of this integrated view of property damage and areas of concentrated damage are foundational steps in understanding which people and places are most vulnerable to long-term community recovery challenges in the HayWired scenario, as discussed in this chapter and accompanying sections. These methodologies can also be applied in future scenario studies for earthquakes as well as other hazards.

Assumptions and approaches taken in development of the integrated view of property damage and areas of concentrated damage are drawn from past disaster experiences and expert judgment. More systematic, neighborhood-level postdisaster damage data collection and longitudinal study is needed to refine the 20-percent-damage threshold used to identify areas of concentrated damage and to further understand the tipping points at which spatial concentrations of housing and other types of building damage can lead to systemic and cascading consequences, such as population displacement and community recovery challenges.

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Section B

Population Movements and Vulnerabilities

Introduction

"Exposure to a disaster is among the most complex environmental contributors to poor health that individuals and communities may face" (Abramson and others, 2015, p. 3). In large-scale disasters, individuals and communities can face an "exposure continuum"—an ongoing exposure to hazards and adverse consequences that can unfold over an extended period of time and cascade through communities (Abramson and others, 2015, p. 3). When the uncertainty and risks associated with these exposures are high, individuals and disaster managers may engage in voluntary or forced movements of individuals and communities away from an endangered area. These movements also can happen over time, in what Sorensen and Sorensen (2007, p. 183) and Esnard and Sapat (2014, p. 19) refer to as an "evacuation continuum," which encompasses myriad voluntary or forced movements of people and communities following disasters.

In both the disaster research and emergency planning fields, the term "evacuation" is most commonly used to describe the movement of people in advance of a threat or hazard incident, or soon after an incident occurs in response to the primary or secondary effects of the incident. Typically, evacuations last a few days to weeks, but may be longer if evacuees lose access to their communities and housing.

The term "displacement" is increasingly used to describe the long-term and potentially permanent dislocation, relocation, migration, and resettlement of people—forced or voluntary—in response to physical, economic, or environmental danger or harm (Oliver-Smith, 2009). Population displacement is "both an outcome and cause of vulnerability" (Esnard and others, 2011, p. 853). Hazard vulnerability science emphasizes the various ways in which people are vulnerable to the physical impacts of natural hazards and have unequal social capacities to anticipate and respond to them (Elliott, 2014). Thus, predisaster social vulnerability and inequality can increase the likelihood of forced evacuations and permanent displacement for some people; disaster-related damage and disruptions in social and economic services and postdisaster policies and governance processes can also exacerbate these outcomes (Fothergill and Peek, 2015; Johnson and Olshansky, 2017; Kroll-Smith, 2018). Population inmigration is also a factor in postdisaster recovery as new people decide to move to the impacted region for jobs and other opportunities that arise in the postdisaster period (Fussell, 2015).

Much of what is known about the causes of mass population movements has come from outside the field of disaster research, and outside the United States (Oliver-Smith, 2009); but this is changing. Between 2008 and 2013, 150 million people were displaced worldwide following natural disasters, which is believed to be twice as many people as in the 1970s, with much of that growth attributed to increased urbanization in high-risk areas of developing countries (Eastern Kentucky University, 2014). In the United States, disaster research has mainly focused on short-term, localized population displacements and resulting applications in disaster-related planning and policies for evacuations, emergency and temporary sheltering, and population care; much less is known and data is lacking on long-term displacement and inmigration (Esnard and Sapat, 2014; Fussell, 2015).

Combining U.S. Census data on households and the data from thousands of recorded natural hazards during the late 1990s, Elliott (2014) completed a nationwide, locally comparative analysis of the influence of natural hazard disasters, in various forms, to residential mobility and, thus, population redistribution in society as a whole. It considered both the population displacement as well as inmigration that can follow a disaster and showed that natural hazards do increase household mobility, locally and to more distant places, and that hazard-related property damage—more than hazard frequency—is the strongest, most consistent contributor to such heightened mobility (Elliott, 2014). The results also indicated that high rates of homeownership reduced mobility regardless of race; however, because racial and ethnic minorities are less likely to own housing, they also tend to be among the most mobile postdisaster households. Finally, results indicate that inmigration, as well as outmigration, correlates positively with local hazard-related property damage and that the migratory pull is particularly strong among Asians and Latinos. Areas of spatially concentrated building damage can experience even higher rates of population displacement and slower rates of return than areas of less-concentrated damage (Olshansky and others, 2006; Groen and Polivka, 2010; Peacock and others, 2014).

Research on large-scale disasters that have displaced people from their homes and communities for extended periods of time have also shown that displacement is "a process that derives from preexisting and shifting physical and socioeconomic vulnerabilities and societal problems that are exacerbated after a disaster" (Esnard and Sapat 2014, p. 64). The preexisting and shifting physical and socioeconomic vulnerabilities include the poor, elderly and physically challenged, people lacking social ties, institutionalized persons, children, renters, and those inhabiting substandard housing and living in hazard-prone areas. The societal problems include racial and ethnic biases, lack of social cohesion and social capital, and inequitable policies and politics both pre- and postdisaster (Bolin, 2007; Weber and Peek, 2012; Esnard and Sapat, 2014; Kroll-Smith, 2018). Table B1 provides a brief examination of some postdisaster displacement experiences in the United States, and other industrialized countries like Japan and New Zealand.

Table B1. Postdisaster population displacement examples.

[M_w, moment magnitude; FEMA, Federal Emergency Management Agency; SPUR, San Francisco Bay Area Planning and Urban Research Association]

Disaster event	Description of displacement
1906 San Francisco earthquake and fire, northern California	A combination of trains, ferries, and naval ships helped to evacuate more than 300,000 of San Francisco's 410,000 residents to other cities in the region. This helped to spawn, in part, the growth and establishment of new communities in Berkeley and elsewhere in the east bay and on the San Francisco Peninsula. Overtly racist and discriminatory acts after the earthquake also displaced Chinese and other Asian residents of San Francisco. (Sources: Kroll-Smith, 2018; The Virtual Museum of the City of San Francisco, 2018.)
1989 M_w 6.9 Loma Prieta earthquake, northern California	Heavy damage in parts of San Francisco, Oakland, Santa Cruz, Watsonville, and the Santa Cruz Mountains displaced residents for months to years. More than 1,000 residents left the Santa Cruz and Watsonville area, including a disproportionately high number of Hispanics and migrant workers; Oakland reported 2,500 new homeless people and similar numbers are assumed for San Francisco. In some cases, this displacement had long-term effects on neighborhood-serving businesses, local economies, and local government finances. (Sources: Comerio, 1998; Johnson, 1999; SPUR, 2012.)
1994 M_w 6.7 Northridge earthquake, southern California	Some of the hardest hit neighborhoods in Los Angeles had large concentrations of damaged multifamily rental housing, many of which became known as "ghost towns" because of the major outmigration of residents soon after the earthquake. These areas required sustained intervention and support by the City of Los Angeles to secure, repair, and reconstruct damaged properties. It is important to note that the city's outmigration was minimal; most people rehoused in vacant units, given the city's high (9.3 percent) vacancy rate at the time of the earthquake. (Sources: Comerio, 1998; Olshansky and others, 2006.)
1995 M_w 6.7 earthquake, Kobe, Japan	Approximately 15 percent of the housing units in the City of Kobe were destroyed by earthquake shaking, ground failure, and fires, leading the population to decline by nearly 100,000 (a drop of more than 6.3 percent). It took 11 years for the city to return to its pre-earthquake population, but the population distribution and resettlement patterns are significantly different from before the earthquake. (Sources: Olshansky and others, 2005; City of Kobe, 2014; Johnson and Olshansky, 2017.)
2005 Hurricane Katrina, Louisiana, Mississippi and Alabama Gulf Coast	Millions of people evacuated ahead of Hurricane Katrina's landfall and following widespread flooding and devastation. Many people were able to return to their communities within days after the storm passed and roadways were cleared of debris. However, for those who resided in low-lying coastal areas and in the City of New Orleans, it took months to years to return and restore their homes and communities. In total, FEMA assisted 1.07 million individuals and households with housing- and disaster-related expenses and the applications came from every state, the District of Columbia, and Puerto Rico. Many displaced residents, especially African Americans, people of low socioeconomic status and with disabilities, the elderly, families with school-age children, and those who had lived in the most hard-hit communities, never returned. (Sources: Ericson and others, 2005; Plyer and Ortiz, 2011; FEMA, 2015; The Data Center, 2019.)
2011 M_w 6.3 earthquake, City of Christchurch and Canterbury region, New Zealand	An estimated 55,000 to 70,000 people, or approximately 12 to 15 percent of the region's 464,000 residents, initially left because of uninhabitable homes, lack of basic services, and continuing aftershocks. Four months after the earthquake, there was an estimated net loss of 8,900 residents; women and families with young children made up a significant portion of the loss. A series of damaging aftershocks, widespread damage to the Christchurch central business district and residential neighborhoods in the eastern and northern suburbs, and government policies limiting access and offering voluntary buyouts in areas of severe ground failure resulted in waves of business and residential displacement and relocation for the first five years after the earthquake. (Sources: Newell and others, 2012; McSaveney, 2013; Johnson and Olshansky, 2017.)

Hurricane Katrina, in particular, brought to light the potential for a large-scale and lengthy postdisaster population displacement in the United States and the disproportionate effects on physically and socioeconomically vulnerable populations and communities (Olshansky and Johnson, 2010; Weber and Peek, 2012; Xiao and Nilawar, 2013; Sastry and Gregory, 2014; Fussell, 2015). The rather swift and far-flung displacement of hundreds of thousands of individuals and families to communities across the country was an unprecedented event in America, and it had long-term recovery implications for New Orleans and other hard-hit communities; see sidebar 1.

This part of the analysis of communities at risk focuses on the people and households that could face long-term displacement and community recovery challenges in a major earthquake, like the HayWired scenario. We first consider the potential size of the population that is at risk of displacement and then explore a series of socioeconomic vulnerabilities and attributes that could

Sidebar 1—Population Displacement from the City of New Orleans, Louisiana, after Hurricane Katrina

More than 90 percent of the City of New Orleans' estimated 455,000 residents evacuated ahead of Hurricane Katrina's onset or during the subsequent flooding that destroyed more than 80 percent of all the buildings in the city (City of New Orleans, 2007). In the poststorm days, as flood waters filled the city, the Federal Government helped to commission military, commercial, and private planes as well as buses to evacuate remaining residents to shelters across the country. Applications for Hurricane Katrina-related disaster assistance came from every state in the country, but the greatest numbers were in less-impacted areas of Louisiana and nearby Texas (Ericson and others, 2005).

About three of every four habitable units in the city were either damaged or destroyed, including nearly all the low- and moderate-income housing (City of New Orleans, 2007). It took nearly two months to "dewater" most of New Orleans, but half of the city's households were still without power and the city was nearly empty, with the exception of the higher elevation areas along the Mississippi River (Olshansky and Johnson, 2010).

The city's tax base was instantly ruined by the population loss and loss of tourism-based revenue. The city laid off half of its work force within weeks and the extended closure of damaged businesses, schools, and hospitals and economic downturn also led to significant job losses and displacement (City of New Orleans, 2007).

The National Flood Insurance Program and private insurers covered a large proportion of the housing recovery costs (City of New Orleans, 2007). But, to help fill the gaps, the State of Louisiana launched the "Road Home" homeowner and rental repair programs that included an option for owners to sell their homes to the State; 7,000 New Orleans homeowners chose this option (Johnson and Olshansky, 2017). The city and U.S. Department of Housing and Urban Development (HUD) designated almost 5,000 public housing units for demolition and mixed-use redevelopment under the HUD HOPE-VI program (Olshansky and Johnson, 2010). These policies added considerable strain onto the already depleted housing market, particularly the rental market, which had composed half of the city's pre-storm housing stock; private market rentals increased by 45 percent over pre-storm values by summer 2007 (Liu and Plyer, 2008). New Orleans experienced a housing supply shock and an increase in average housing prices during the first years of the recovery (Husby and Koks, 2017). Slow rates of housing recovery in those early years were caused by delays in Road Home funding, loans, or insurance settlements; lack of affordable options; lack of reliable utility services; uncertainty about neighbors' decisions to return; and concern about future flood risk (City of New Orleans, 2007).

As a result, the city's population was slow to return in the first five years but return rates did improve in the second five years. The 2015 population was estimated to be 390,711—or 80 percent of the city's pre-storm population (U.S. Census Bureau, 2018). However, a proportion of that population gain came from new residents, not returning residents. Many displaced residents, particularly the elderly, African-Americans, single mothers, persons with disabilities, low-income workers, former residents of rental and public housing, and those who had lived in the most hard-hit neighborhoods or had school-age children, had lower return rates than other cohorts (Plyer and Ortiz, 2011). Several post-Katrina studies also showed that postdisaster recovery policies, such as the destruction of public housing and the overhaul of the New Orleans public school system actively worked to keep some residents away (Fussell, 2015; Lincove and others, 2017). More in-depth neighborhood-level analyses showed that more than half (40) of New Orleans' 72 neighborhoods recovered more than 90 percent of their pre-Katrina population by 2015 (The Data Center, 2018). However, of the 32 neighborhoods that had not, four had less than half the population they had prior to Hurricane Katrina, including the heavily damaged Lower Ninth Ward and three communities where public housing was being redeveloped into mixed-income housing developments.



Evacuees at New Orleans International Airport, September 1, 2005. Photograph courtesy of Michael Reiger, Federal Emergency Management Agency.

contribute to postdisaster population displacement and people's ability to return. We also look at issues related to emergency sheltering and interim (or temporary) housing that may impact displacement, as well as the potential issues influencing population return. The analyses rely on data available from the 2010 census, 2017 population and housing units estimates, and 2014 and 2016 5-year American Community Survey (ACS) data (U.S. Census Bureau, 2018). Estimates generated by the Hazus-MH 2.1 loss-estimation software are derived from 2000 census data.

Estimating Populations at Risk of Displacement in the HayWired Scenario

As Esnard and Sapat (2014) describe, a large shock, such as a moment magnitude (M_w) 7.0 earthquake on the Hayward Fault, can induce myriad voluntary or forced movements of people and communities over time. This section examines the number and composition of people and households that could be displaced as a result of key physical impacts of the HayWired earthquake scenario.

Three different approaches are taken for this examination. The first looks at the household displacement estimates developed by Seligson and others (2018) using a customized analysis completed with the Hazus-MH 2.1 loss-estimation software (hereafter referred to as Hazus). Since their analysis did not account for potential population impacts caused by landslides and fires, our second analysis uses the integrated building damage data from ground shaking, liquefaction, landslides, and fires from the M_w 7.0 mainshock of the HayWired scenario to estimate potential household displacement. The third analysis looks at the population in the areas of concentrated damage and the effects that concentrated building damage can have on potential population displacement. Because damages are spatially concentrated in Alameda, Contra Costa, Marin, and Solano Counties, parts of these counties were also divided into economic subareas to provide some geographic context for the damage concentrations (Wein, Belzer, and others, this volume); we use the same subarea divisions in this analysis so the results from our analysis can be reviewed in context with Wein, Belzer, and others' results and vice versa.

Hazus-Derived Estimates

Seligson and others (2018) used Hazus to estimate the number of households displaced because of building damage and the number of people requiring publicly provided short-term shelter for both the M_w 7.0 mainshock and the aftershock sequence of the HayWired scenario. The aftershock sequence includes 175 M_w 4.0 or larger earthquakes and 16 M_w 5.0 or larger earthquakes over a two-year period (Wein and others, 2017). The four largest aftershocks happen at night in two clusters: on May 28, 2018 (M_w 6.2 earthquake at 4:47 a.m. and M_w 5.7 earthquake at 11:53 p.m.), about six weeks after the mainshock and centered near Palo Alto; and September 30 and October 1, 2018 (M_w 6.0 earthquake at 8:16 p.m. on September 30th and M_w 6.4 earthquake at 12:33 a.m. on October 1st), about six months after the mainshock and centered close to Mountain View and Cupertino. These aftershocks, in particular, may damage housing and displace additional people.

Seligson and others (2018) used both the Hazus default values and a set of customized weighting factors to estimate displaced households for single-family/duplex and multifamily dwellings in the moderate, extensive, and complete damage states caused by the earthquake-related hazards of ground shaking and liquefaction. The customization parameters were developed for the hypothetical magnitude-7.8 South San Andreas earthquake "ShakeOut" scenario (Jones and others, 2008), and are derived from population survey data from the 1994 Northridge and 1989 Loma Prieta earthquakes. In particular, the customized parameters increase the displacement weighting factor for single-family/duplex and multifamily dwellings in a moderate damage state and single-family/duplex dwellings in an extensive damage state, and decrease the displacement weighting factor for multifamily dwellings in an extensive damage state. These changes correspond with survey responses about displacement and levels of damage; see the appendix in Seligson and others (2018) for further discussion. In all, approximately 16 percent of survey respondents following the Northridge earthquake and 22 percent of the respondents following the Loma Prieta earthquake were displaced from their homes.

The Hazus methodology for calculating short-term shelter requirements recognizes that only a portion of those displaced from their homes will seek public shelter, and some will seek shelter even though their residences may have lesser levels of damage. The customized Hazus shelter model parameters presented by Seligson and others (2018) use population data and weighting factors for income and ethnicity to estimate the fraction of residents in displaced households that may seek public shelter. Table B2 provides the customized Hazus estimates of displaced households and the portion of the population from those displaced households that is likely to seek public shelter for the M_w 7.0 mainshock and the four largest aftershocks of the HayWired scenario; the household displacement estimates for the other aftershocks were negligible (Seligson and others, 2018).

Thus, totals for the Seligson and others (2018) analysis are 155,283 households, or 420,607 people, in the nine-county region at risk of displacement from the M_w 7.0 mainshock and aftershock sequence of the HayWired scenario. It is important to note, however, that their hypothetical mainshock calculations are based upon the estimates of residential damage caused by ground shaking and liquefaction only and neglect the potentially significant population displacement and sheltering needs caused by building damage from landslides and fires. Their aftershock calculations only consider the displacement and sheltering needs caused by residential damage ground shaking; all other building damage causes, including liquefaction, are excluded.

Table B2. Displaced households and shelter demands in the nine-county San Francisco Bay region, California, for the hypothetical mainshock and aftershock sequence of the HayWired scenario (adapted from Seligson and others, 2018).

[In Hazus, the earthquake hazards used to estimate displaced households and short-term shelter needs for the mainshock were ground shaking and Hazus default liquefaction (not the customized liquefaction results of Jones and others [2017]), with revised displacement parameter weights as discussed by Seligson and others (2018). Only the ground shaking earthquake hazard was used in Hazus to estimate displaced households and short-term shelter needs for the modeled aftershocks]

Location or event	Displaced households[1]	Displaced people[2]	People seeking short-term shelter
Mainshock shaking and Hazus default liquefaction			
Alameda County	87,629	236,598	28,922
Santa Clara County	24,179	70,119	7,408
Contra Costa County	21,856	60,541	6,623
San Francisco County	11,741	26,535	2,986
San Mateo County	6,167	16,959	1,640
Nine-county region[3] total	**152,438**	**412,954**	**48,050**
Aftershock cluster shaking			
May 28, 2018 near Palo Alto, CA	792	2,130	435
September 30–October 1, 2018 near Mountain View and Cupertino, CA	2,053	5,523	1,176
Nine-county region total across aftershock clusters	**2,845**	**7,653**	**1,611**
Total across HayWired earthquake sequence	**155,283**	**420,607**	**49,661**

[1]Uses 2000 U.S. Census data.

[2]To reflect a more accurate population estimate, we use average household size by county from 2010 census data to calculate county-level displaced population estimates for the mainshock. Displaced population estimates for the aftershocks use an average of 2.69 persons per household for the nine-county region from the 2010 census.

[3]The other county estimates are far lower than the five listed counties, with Marin County (513 displaced households and 155 people seeking shelter) and Solano County (310 displaced households and 110 people seeking shelter) being the next highest; Napa and Sonoma Counties had fewer than 50 displaced households and people seeking shelter.

Integrated Building Damage Estimates

In order to consider the population at risk from all major causes of building damage, particularly fire, the second analysis uses the integrated building damage data for single-family/duplex dwellings and multifamily dwellings derived from the Hazus analysis (methods in Seligson and others, 2018; data in Seligson and Jones, 2019) and the fire analysis (methods in Scawthorn, 2018; data in Scawthorn, 2019) and presented in section A (Jones and others, 2020). The customized Hazus displacement parameters for single-family/duplex and multifamily dwellings, detailed in the appendix to Seligson and others (2018), are applied to the unit counts for single-family/duplex dwellings and multifamily dwellings in a moderate, extensive, or complete damage state. The 2010 census data average persons per household for the nine counties are then applied to develop displaced population estimates for single-family/duplex and multifamily dwellings.

As shown in table B3, taking this approach, there is an estimated 176,901–222,925 households, or 475,864–599,668 people, at risk of displacement because of residential damage

Table B3. Potential displaced households and population for single-family/duplex and multifamily dwellings caused by residential building damage from ground shaking, landslide, liquefaction, and fires from the moment magnitude 7.0 mainshock of the HayWired scenario in the nine-county San Francisco Bay region, California.

[Estimates use customized Hazus displacement parameters from Seligson and others (2018)]

Residential occupancy characteristic	Hazus damage state			Total
	Moderate	Extensive	Complete	
Single-family/duplex residences				
Number of dwellings	233,789	51,977	41,282	327,048
Displaced households	46,758	20,791	41,282	108,831
Displaced population	127,964	56,700	112,400	297,064
Multifamily residences (low and high estimate unit counts)				
Number of dwellings	68,140–115,124	19,526–33,128	27,050–45,277	114,716–193,528
Displaced households	27,256–46,050	12,692–21,533	27,050–45,277	66,998–112,859
Displaced population	73,383–123,952	34,396–58,349	73,690–123,308	181,469–305,609
Total residences (low and high estimate unit counts)				
Number of dwellings	**301,928–348,913**	**71,502–85,104**	**68,333–86,559**	**441,763–520,576**
Displaced households	**74,014–92,807**	**33,482–42,324**	**68,333–86,559**	**175,829–221,690**
Displaced population	**201,348–251,916**	**91,095–115,048**	**186,090–235,708**	**478,533–602,672**

caused by ground shaking, landslide, liquefaction, and fires from the M_w 7.0 mainshock of the HayWired scenario. The range of estimates accounts for the variation in housing units possible within each multifamily residential occupancy class in Hazus. For example, the RES3B multifamily residential occupancy class is for three- to four-unit multifamily occupancies. Therefore, the low estimate assumes three units in each building and the high estimate assumes four units in each building.

Estimates in Areas of Concentrated Damage

A third analysis looks at the effects that concentrated building damage can have on potential population displacement. The areas of concentrated damage (specifically, census tracts with 20 percent or more of the building square footage in an extensive or complete damage state from the M_w 7.0 mainshock of the HayWired scenario) for three building occupancy groupings—all occupancies combined, single-family/duplex dwellings, and multifamily dwellings—presented in section A were used for this analysis. The 2010 census-tract-level population data were assigned to the tracts in the areas of concentrated damage (without and with fire damage integrated) to determine the total household and population counts in these specific areas.

Because damages are spatially concentrated in Alameda, Contra Costa, Marin, and Solano Counties, several economic subareas were defined by Wein, Belzer, and others (this volume) to provide a general geographic context for the most significant concentrations of damage. The economic subareas were defined using census tract boundaries; the cities included in each subarea are listed here. Multicity subareas avoided problems where census tracts crossed city lines; a single tract can straddle two cities.

- Northern Alameda County subarea: Berkeley, Emeryville, north Oakland, West Oakland, downtown Oakland, Albany, and Alameda
- Central Alameda County subarea: east Oakland, San Leandro, Castro Valley, San Lorenzo, Hayward, and Union City
- Southern Alameda County subarea: Fremont and Newark
- Dublin-Pleasanton subarea: Dublin and Pleasanton
- Western Contra Costa County subarea: El Cerrito, Richmond, San Pablo, and Pinole
- Novato subarea: Novato
- Vallejo subarea: Vallejo

Figures B1 and B2 show the population density for all the census tracts in the areas of concentrated damage for all occupancies combined, without and with fire damage integrated. Table B4 compares the 2010 census data in the nine-county region with the number of households and population in the areas of concentrated damage (without and with fire damage integrated) for all occupancies combined, single-family/duplex dwellings, and multifamily dwellings. Table B5 reframes the population and household counts in the areas of concentrated damage to focus on the seven economic subareas used by Wein, Belzer, and others (this volume).

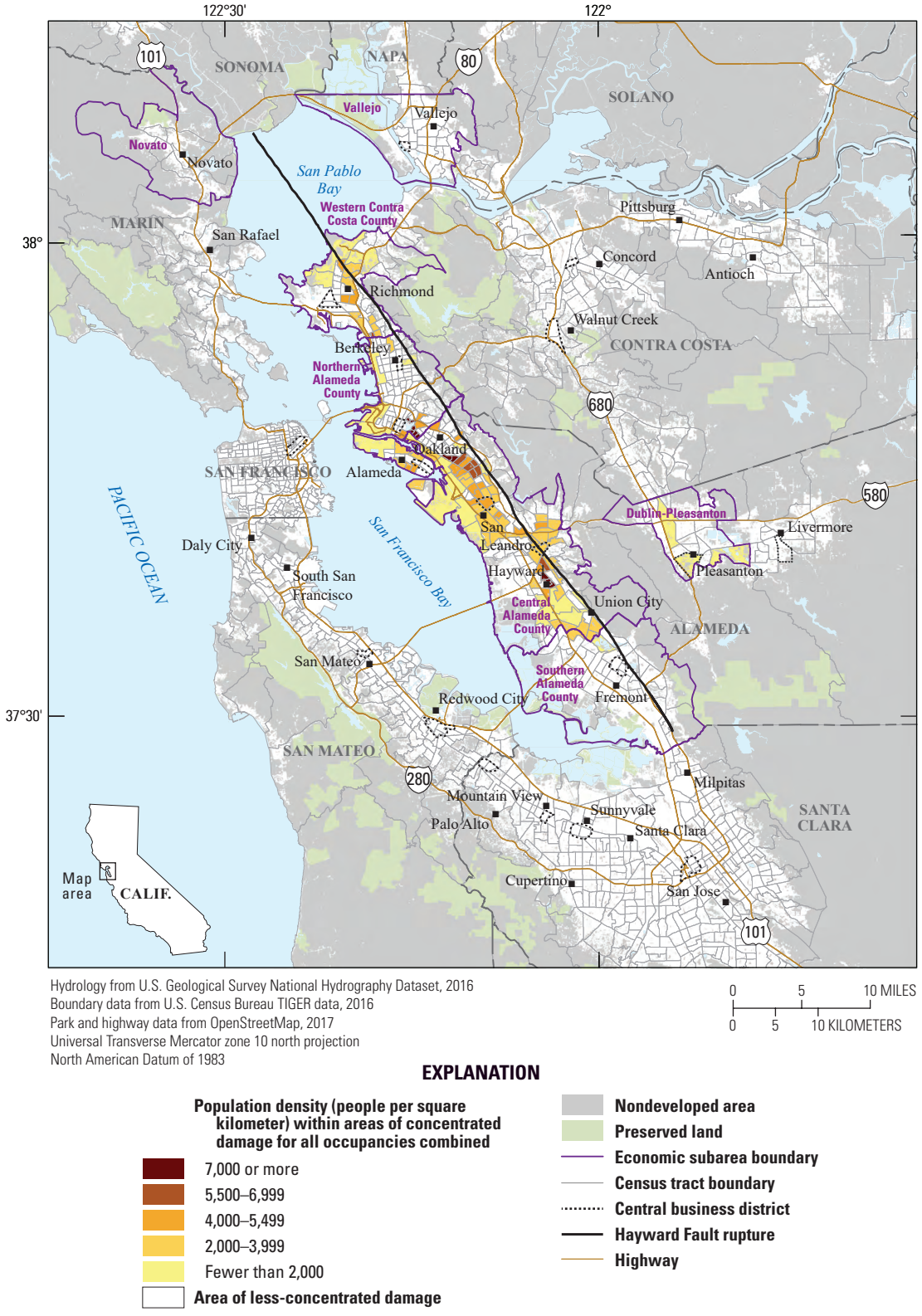


Figure B1. Map of the San Francisco Bay region, California, showing population density (from the 2010 census) in each of the census tracts that have 20 percent or greater building square footage damage from shaking, landslide, and liquefaction only (without fire damage integrated) resulting from the HayWired earthquake scenario mainshock, for all building occupancies combined. Data from U.S. Census Bureau (2018).

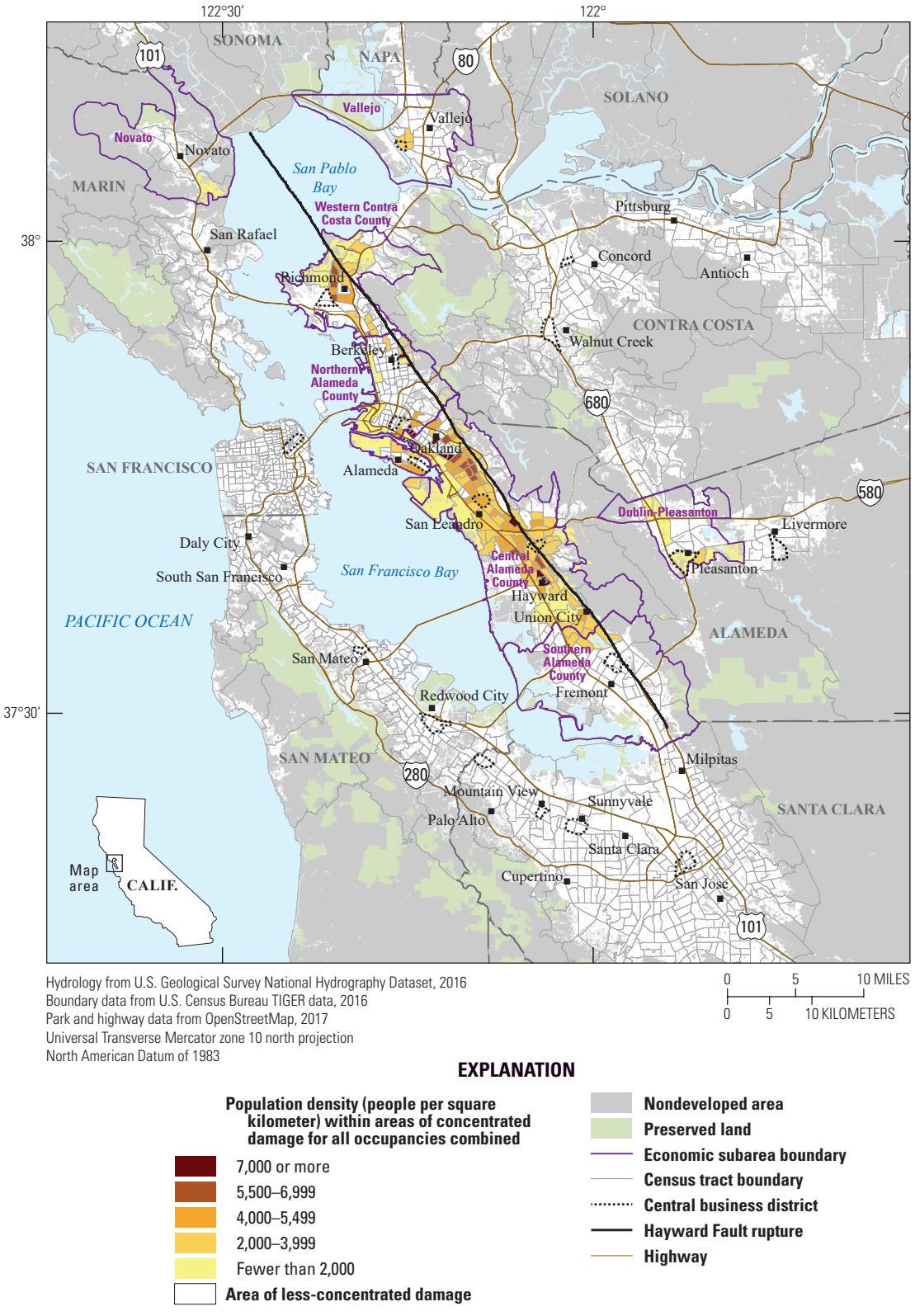


Figure B2. Map of the San Francisco Bay region, California, showing population density (from the 2010 census) in each of the census tracts that have 20 percent or greater building square footage damage from shaking, landslide, liquefaction, and fire (with fire damage integrated) resulting from the HayWired earthquake scenario mainshock, for all building occupancies combined. Data from U.S. Census Bureau (2018).

Table B4. Comparison of households and populations in areas of concentrated damage (all occupancies, single-family/duplex dwellings, and multifamily dwellings) with 2010 census data and households and population estimates from the customized Hazus analysis of the HayWired earthquake scenario mainshock for the nine-county San Francisco Bay region, California.

[Data from U.S. Census Bureau (2018), Seligson and Jones (2019), and Wein, Belzer, and others (this volume). %, percent]

County or region	2010 U.S. Census		Customized displacement estimates[1]			Total in areas of concentrated damage[2]								
						All occupancies combined			Single-family/duplex dwellings			Multifamily dwellings		
	Households	Population	Households	Population[3]	County total[4] (%)	Households	Population	County total (%)	Households	Population	County total (%)	Households	Population	County total (%)
Earthquake damage estimates														
Nine-county region	2,608,023	7,150,739	152,438	412,954	6	172,484	487,698	7	60,994	170,206	2	361,948	1,024,266	14
Alameda County	545,138	1,510,271	87,629	236,598	16	146,119	413,231	27	55,665	153,355	10	287,427	813,192	54
Santa Clara County	604,204	1,781,642	24,179	70,119	4	0	0	0	0	0	0	0	0	0
Contra Costa County	375,364	1,049,025	21,856	60,541	6	26,365	74,467	7	5,329	16,851	2	74,521	211,074	20
San Francisco County	345,811	805,235	11,741	26,535	4	0	0	0	0	0	0	0	0	0
San Mateo County	257,837	718,451	6,167	16,959	2	0	0	0	0	0	0	0	0	0
Marin County	103,210	252,409	513	1,211	0.5	0	0	0	0	0	0	0	0	0
Solano County	141,758	413,344	310	877	0.2	0	0	0	0	0	0	0	0	0
Napa County	48,876	136,484	29	78	0.1	0	0	0	0	0	0	0	0	0
Sonoma County	185,825	483,878	14	36	0	0	0	0	0	0	0	0	0	0
Integrated (earthquake and fire) damage estimates														
Nine-county region	2,608,023	7,150,739	175,829–221,690	478,533–602,672	7–9	267,631	765,402	10	128,543	363,215	5	520,210	1,451,838	20
Alameda County	545,138	1,510,271	98,266–123,721	265,318–334,048	18–23	226,146	644,056	42	106,049	298,111	20	417,269	1,166,435	77
Santa Clara County	604,204	1,781,642	26,333–33,256	76,366–96,443	4–6	0	0	0	0	0	0	0	0	0
Contra Costa County	375,364	1,049,025	28,874–35,359	79,981–97,945	8–9	34,281	103,574	10	15,490	47,332	5	92,270	258,236	25
San Francisco County	345,811	805,235	7,928–11,398	17,918–25,759	2–3	0	0	0	0	0	0	0	0	0
San Mateo County	257,837	718,451	8,720–10,924	23,979–30,041	3–4	0	0	0	0	0	0	0	0	0
Marin County	103,210	252,409	2,432–3,021	5,740–7,130	2–3	2,560	6,590	3	2,560	6,590	3	2,560	6,590	3
Solano County	141,758	413,344	3,104–3,818	8,785–10,804	2–3	4,644	11,182	3	4,644	11,182	3	8,111	20,577	6
Napa County	48,876	136,484	70–80	187–214	0.1–0.2	0	0	0	0	0	0	0	0	0
Sonoma County	185,825	483,878	102–113	260–288	0.1	0	0	0	0	0	0	0	0	0

[1]The customized Hazus estimate of displaced households uses data from the 2000 U.S. Census and considers only the damage caused by ground shaking and liquefaction, not landslides and fires. The integrated damage estimate of displaced households applies customized parameters to moderate, extensive, or complete residential damages ranges to reflect the low and high estimates of the number of units in multifamily dwellings.

[2]The household and population estimates within areas of concentrated damage use data from the 2010 U.S. Census. An area of concentrated damage was defined as all census tracts where the extensive or complete damage to the occupancy grouping of interest was greater than 20 percent of the total building square footage for the occupancy grouping.

[3]The Hazus-based displaced population estimates were calculated by multiplying the Hazus estimates of displaced households by the county-level estimates of persons per household from the 2010 U.S. Census.

[4]The 2010 U.S. Census estimates of the total population and number of households for each county were used to estimate the displaced percentages for the Hazus estimates.

Table B5. Economic subarea comparison of household and population counts in the areas of concentrated damage (without and with fire damage integrated) defined by all occupancies combined for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Data are from U.S. Census Bureau (2018) and Wein, Belzer, and others (this volume). %, percent]

Region name	2010 U.S. Census		Total in areas of concentrated damage[1]								
			All occupancies combined			Single-family/duplex dwellings			Multifamily dwellings		
	Households	Population	Households	Population	County or sub-area total[2] (%)	Households	Population	County or sub-area total[2] (%)	Households	Population	County or sub-area total[2] (%)
Nine-county region, without fire damage											
Region total	2,608,023	7,150,739	172,484	487,698	7	60,994	170,206	2	361,948	1,024,266	14
Economic subareas total	688,739	1,778,967	172,484	487,698	27	60,994	170,206	10	342,831	970,910	55
Alameda County economic subareas, without fire damage											
Alameda County total	545,138	1,510,271	146,119	413,231	27	55,665	153,355	10	287,427	813,192	54
Economic subareas total	540,512	1,395,220	146,119	413,231	30	55,665	153,355	11	284,060	802,778	58
Central Alameda County subarea	225,786	635,900	105,750	316,559	50	36,800	110,289	17	188,306	564,042	89
Dublin-Pleasanton subarea	37,334	102,277	7,079	19,035	20	1,781	4,576	5	20,522	54,635	53
Northern Alameda County subarea	188,231	394,313	30,433	69,225	18	15,390	33,257	9	62,156	144,607	37
Southern Alameda County subarea	89,161	262,730	2,857	8,412	3	1,694	5,233	2	13,076	39,494	15
Contra Costa County economic subareas, without fire damage											
Contra Costa County total	375,365	1,049,025	26,365	74,467	7	5,329	16,851	2	74,521	211,074	20
Western Contra Costa County subarea	79,212	207,969	26,365	74,467	36	5,329	16,851	8	58,771	168,132	81
Marin County economic subareas, without fire damage											
Marin County total	103,210	252,409	0	0	0	0	0	0	0	0	0
Novato subarea	24,066	58,562	0	0	0	0	0	0	0	0	0
Solano County economic subareas, without fire damage											
Solano County total	141,758	413,344	0	0	0	0	0	0	0	0	0
Vallejo subarea	44,949	117,126	0	0	0	0	0	0	0	0	0
Nine-county region, with fire damage integrated											
Region total	2,608,023	7,150,739	267,631	765,402	10	128,743	363,215	5	520,210	1,451,838	20
Economic subareas total	688,739	1,778,967	265,586	758,999	42	128,743	363,215	20	478,985	1,339,133	75
Alameda County economic subareas, with fire damage integrated											
Alameda County total	545,138	1,510,271	226,146	644,056	42	106,049	298,111	20	417,269	1,166,435	77
Economic subareas total	540,512	1,395,220	224,101	637,653	45	106,049	298,111	21	409,543	1,143,834	82
Central Alameda County subarea	225,786	635,900	157,116	471,489	75	71,664	215,800	34	209,104	631,523	99
Dublin-Pleasanton subarea	37,334	102,277	10,884	29,771	30	1,781	4,576	5	28,880	78,104	76
Northern Alameda County subarea	188,231	394,313	46,633	108,681	28	24,980	55,576	14	124,755	293,444	74
Southern Alameda County subarea	89,161	262,730	9,438	27,712	11	7,624	22,159	9	46,804	140,763	54
Contra Costa County economic subareas, with fire damage integrated											
Contra Costa County total	375,365	1,049,025	34,281	103,574	10	15,490	47,332	5	92,270	258,236	25
Western Contra Costa County subarea	79,212	207,969	34,281	103,574	49	15,490	47,332	22	58,711	168,132	81
Marin County economic subareas, with fire damage integrated											
Marin County total	103,210	252,409	2,560	6,590	3	2,560	6,590	3	2,560	6,590	3
Novato subarea	24,066	58,562	2,560	6,590	11	2,560	6,590	11	2,560	6,590	11
Solano County economic subareas, with fire damage integrated											
Solano County total	141,758	413,344	4,644	11,182	3	4,644	11,182	3	8,111	20,577	6
Vallejo subarea	44,949	117,126	4,644	11,182	11	4,644	11,182	11	8,111	20,577	18

[1]The household and population estimates for areas of concentrated damage use data from the 2010 U.S. Census. An area of concentrated damage was defined as all census tracts where extensive or complete damage to the occupancy grouping of interest was greater than 20 percent of the total building square footage for the occupancy grouping.

[2]An averaging and rounding up of household and population percentages was done in order to provide one estimate of the likely percentages.

For the nine-county region, the customized Hazus analysis estimated that about 6 percent of the total households could be displaced following the mainshock of the HayWired scenario. About 40 percent of all building damage in an extensive or complete damage state is in the areas of concentrated damage (without fire integrated) for all occupancies, consisting of 172,484 households and 487,698 people (or 7 percent of the nine-county region totals). Integrating fire damage, these estimates increase to 267,631 households and 765,402 people (or 10 percent of the nine-county region totals).

The household and population estimates for single-family/duplex dwellings and multifamily dwellings in areas of concentrated damage are included for comparative purposes and should be viewed as alternative (not additive) perspectives to the estimates for all occupancies combined in areas of concentrated damage. This is because many of the same census tracts are included in all three maps of concentrated damage. In the area of concentrated damage for multifamily dwellings (without fire damage integrated), there are a total of 361,948 households and a population of 1,024,266 (or 14 percent of the nine-county totals). If fire damage is integrated, these figures increase to 520,210 households and 1,451,838 people (or 20 percent of the nine-county totals). It is emphasized that these are the total household and population counts for the areas of multifamily damage concentrations, and not just the population in multifamily dwellings in the areas.

The county-level comparisons show some distinct differences between the customized Hazus calculations and the concentrated damage analyses. The customized Hazus analysis calculates displaced households in 13 counties, whereas the areas of concentrated damage are in only 4 counties—Alameda, Contra Costa, Marin, and Solano Counties. Also, for all the areas of concentrated damage, the county-level household and population estimates are considerably higher if fire damage is integrated—a condition that was not accounted for in the customized Hazus analysis.

The county-level comparisons also show the high percentage of households and population in Alameda County in the areas of concentrated damage. The customized Hazus estimate of 87,629 displaced households in Alameda County is nearly 60 percent of the total displacement estimate in the customized Hazus analysis, and about 16 percent of the county's total number of households. In comparison, the number of households and people in the areas of concentrated multifamily dwelling damage in Alameda County are as much as 77 percent of the county totals.

Closer inspection of the population and household estimates for the economic subareas shows that about 25 percent of all households and population in the nine-county region reside in the seven economic subareas, and nearly 80 percent of the total economic subarea households and population are in the four economic subareas in Alameda County. The central Alameda County economic subarea has about 36 percent of the total economic subarea households and population. The Dublin-Pleasanton, northern Alameda County, southern Alameda County, western Contra Costa County, and Vallejo economic subareas also have high numbers of households and population, and high percentages of the total population and households for the respective economic subarea, in the areas of concentrated damage.

Potential Effects of Lifeline Infrastructure Outages and Environmental Hazards

Ground shaking, surface fault rupture, liquefaction, landslide, and fires following the HayWired scenario mainshock and aftershocks also damage transportation and utility systems (Porter, 2018; Jones and others, this volume), and are likely to trigger major environmental health threats (Plumlee, 2017). Both lifeline infrastructure outages and environmental hazards are not considered in the Hazus displacement and sheltering models or the other analyses in this section, which all focus entirely on residential building damage.

Plumlee (2017) identified a wide range of potential environmental contaminants and environmental health threats that could occur in the HayWired scenario. Hazardous chemical releases into the air, water, or soils from damaged and (or) burning industrial facilities; hazardous smoke, gases, or other combustible products from fires; contaminants, such as asbestos, in the dusts and debris from building collapses; and the releases of raw sewage from damaged sewer lines and wastewater treatment plants are all major concerns given the density of industrial facilities and older structures in the east bay.

Potential health concerns include: immediate increases in heart attacks, strokes, and asthma caused by exposures to high airborne particulate matter in smoke and dust; acute, gas-specific health effects from exposures to hazardous gases; near-term increases in gastrointestinal illnesses and skin infections as a result of exposures to sewage pathogens; and long-term health effects from exposures to hazardous chemicals or other contaminants that are poorly understood. Any of these conditions or concerns could incite health-related evacuations or lead to protracted population displacements and restrictions on population return in a particular area. Also, additional areas could be impacted via airborne plumes (depending upon the wind direction) from fires, refineries along Richmond Marina and San Pablo Bays, and chemical plants in the southern end of the east bay corridor. Unfortunately, without more detailed modeling for the HayWired scenario, it is difficult to estimate the specific numbers of people who might be impacted by environmental hazards.

Jones and others (this volume) have investigated the exposure of five lifeline infrastructure systems to all of the different hazards from the M_w 7.0 mainshock of the HayWired scenario (ground shaking, surface fault rupture, liquefaction, landslide, and fire). The lifeline infrastructure systems assessed are water, electric power, oil and gas, transportation, and telecommunications, which altogether are composed of hundreds of thousands of infrastructure assets, both facilities and conveyances. A 51,000 square kilometer (km^2) geographic area was analyzed, out of which an area of 178 km^2 had four overlapping mainshock hazards as well as a small 0.2 km^2 area along the Hayward Fault trace where all five mainshock hazards overlap (Jones and others, this volume). Figure B3 shows the areas exposed to multiple high-intensity mainshock hazards and figure B4 shows the points of collocation for three or more lifeline infrastructure assets and their exposure level to multiple concomitant mainshock hazards.

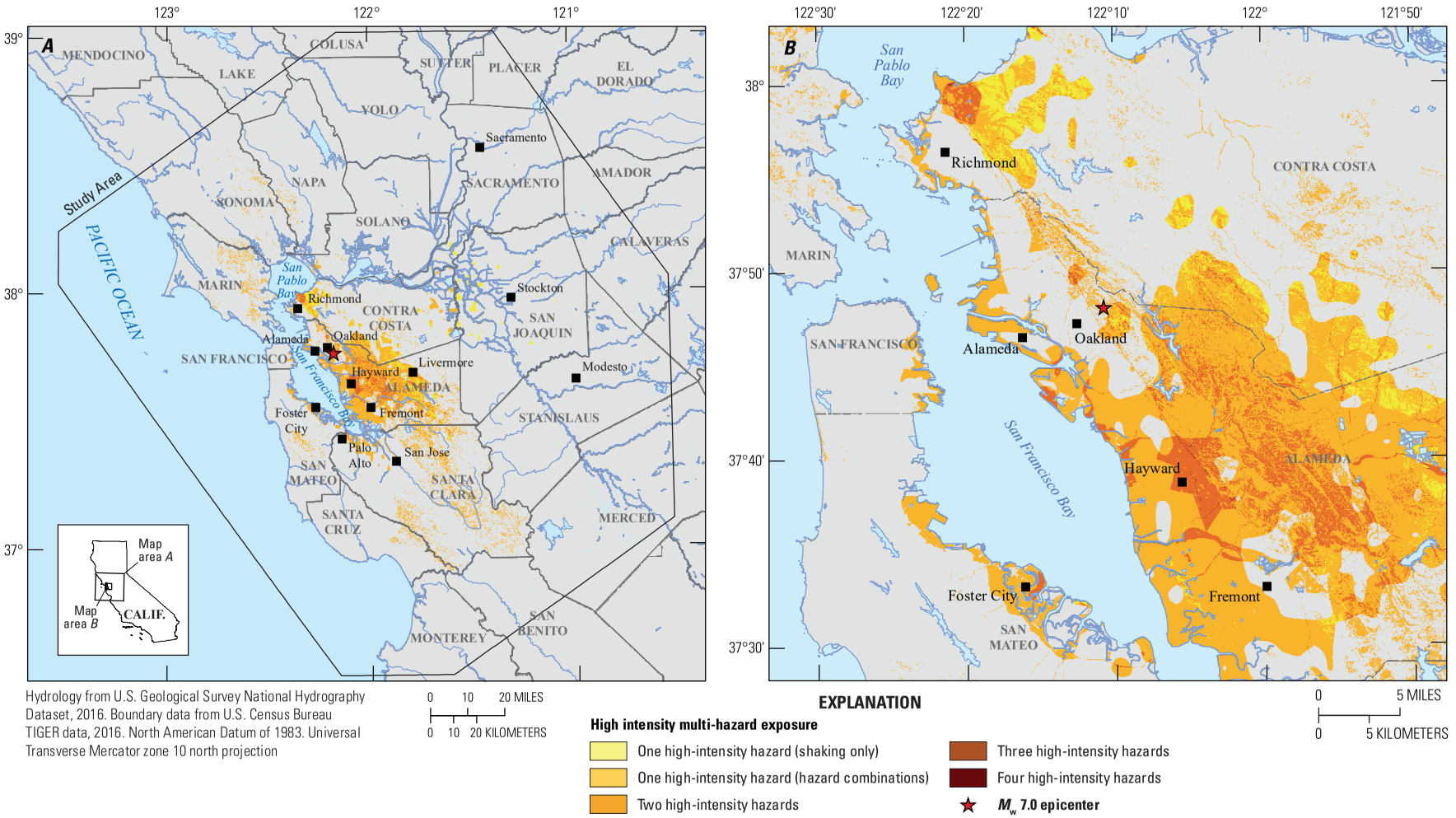


Figure B3. Maps of the San Francisco Bay region, California, showing areas exposed to one or more high-intensity hazard of ground shaking, surface fault rupture, landslide, liquefaction, and fire from the moment magnitude (M_w) 7.0 mainshock of the HayWired scenario. *A*, High-intensity hazard exposure for the entire study region. *B*, High-intensity hazard exposure for the region centered on the mainshock epicenter. Modified from Jones and others (this volume).

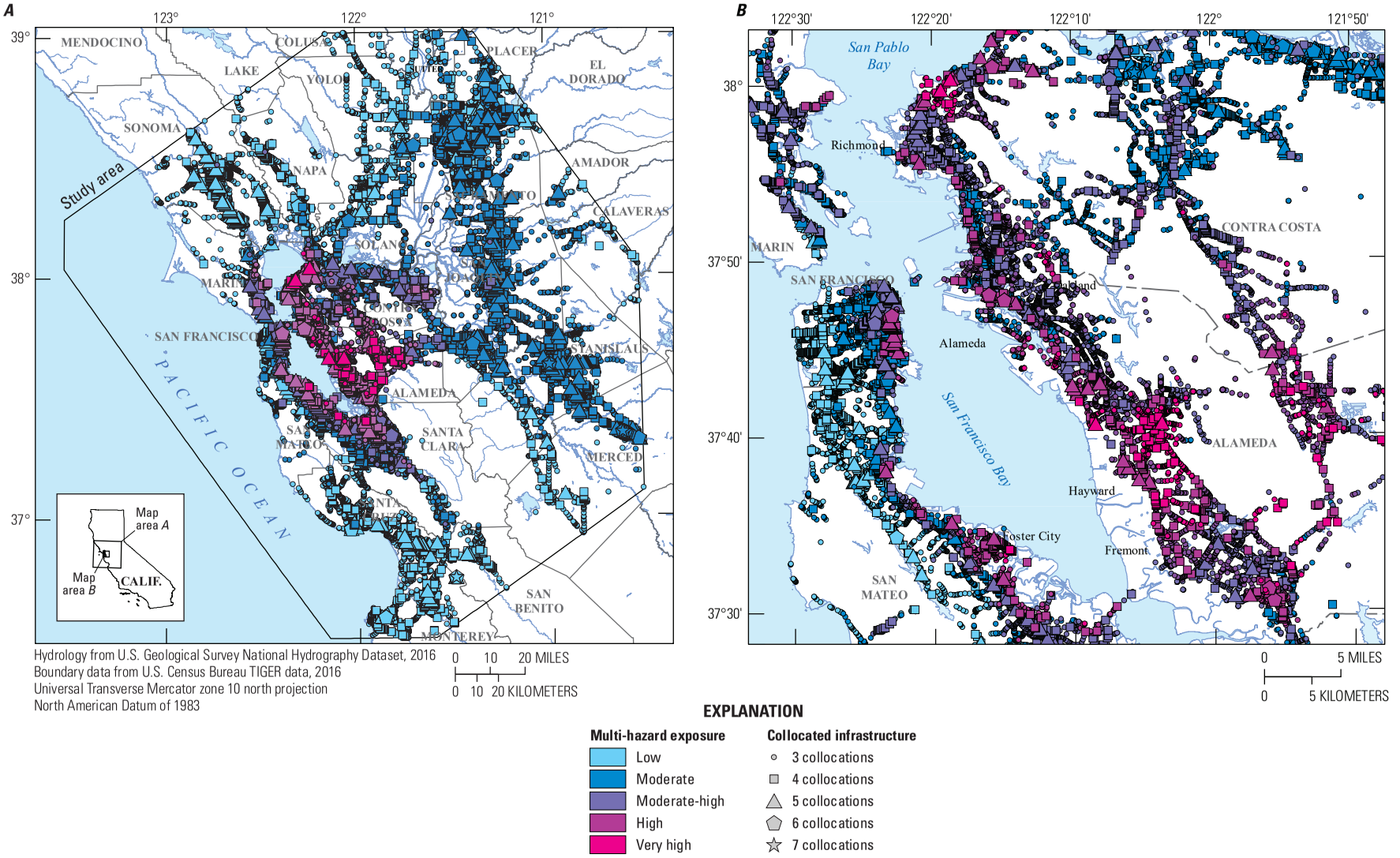


Figure B4. Maps of the San Francisco Bay region, California, showing collocated infrastructure points and exposure to multiple HayWired earthquake scenario mainshock hazards (three or more collocated infrastructure assets only). The symbol shape corresponds to the number of infrastructure assets collocated at each point, ranging from 3 (smallest) to 7 (largest). Colors correspond to level of exposure, ranging from low (cyan) to very high (magenta). *A*, Entire study region. *B*, Region centered on the mainshock epicenter. Modified from Jones and others (this volume).

Table B6. Lifeline utility impacts resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Data from Jones and others (this volume)]

Lifeline infrastructure system	Potential system impacts
Road network	More than a hundred highways, secondary roads, and surface streets cross the Hayward Fault rupture zone—more than any other lifeline infrastructure system. Roadways in the areas of concentrated damage, especially in Oakland and other highly developed areas that experience high-intensity ground shaking, could be impeded by debris. Safe egress from the east bay, especially from ensuing fires, might well be west across the bridges over San Francisco Bay rather than to the east. Road network and bridge repair times of three months or longer are possible along Highways 37 and 24 and Interstates 880, 580, and 680.
Bay Area Rapid Transit (BART)	Several stations and an operations facility are exposed to high-intensity ground shaking and several miles of track run through high-intensity landslide hazard areas. BART stations (which service urban areas) are generally more exposed to fire hazards than other transportation infrastructure. All the BART stations in the central Alameda County economic subarea (such as Fruitvale, Coliseum, San Leandro, Bay Fair, and Hayward) as well as the BART yard maintenance facility in Hayward could have severe damage and take at least one year to repair. BART's Orinda, Rockridge, and South Hayward stations could take as long as nine months to repair. Temporary stations would need to be constructed to provide BART access in these areas while repairs are undertaken.
Water supply and wastewater	Two major water conveyances (the San Pablo Tunnel and the Mokelumne Aqueduct) to residents and business in the east bay cross the fault rupture zone where measurable coseismic slip occurs in the HayWired scenario. Whereas considerable investment has been made in upgrading the regional water transmission system, extensive damage to the water distribution systems in Alameda, Contra Costa, and Santa Clara Counties is likely. In particular, the potential damage to the water distribution system in the east bay could cause the average customer in Alameda County to be without water for six weeks, and some customers may lack water service for six months. Wastewater treatment plants are exposed to high probability of liquefaction hazard.
Oil and gas	Petroleum and natural gas pipelines cross the Hayward Fault 15 times in locations with measurable coseismic slip. Contra Costa County, in particular, has several pipelines crossing the fault rupture zone in areas with measurable coseismic slip.
Electric power	Whereas electric transmission lines cross the fault eight times in locations with measurable coseismic slip, all but one of these crossings occur for aerial transmission lines (which are not generally impacted by surface offset). The remaining crossing occurs on a subterranean transmission line running through San Pablo Bay. Substations and power generation plants are exposed to high-intensity ground shaking and high liquefaction probability. Service restoration is on the order of 3–4 weeks.
Telecommunications	Fiber optic routes cross the Hayward Fault 123 times in locations with measurable coseismic slip (102 interoffice distribution and 21 long-haul transmission). Fiber optic routes also run through high probability liquefaction areas. Cellular sites on buildings and monopoles are most vulnerable to high-intensity ground shaking and liquefaction. Fiber-lit buildings are most frequently exposed to high shaking intensity and sometimes in high-probability liquefaction areas. Telecommunications infrastructure systems are more exposed to the HayWired aftershock sequence than other infrastructure. Voice and data service restoration may take days to weeks.

Jones and others (this volume) also gathered damage impact assessments and downtime potential for select lifeline infrastructure systems and looked at the interdependencies among multiple systems. Some of their key findings that could affect population evacuations and first-responder access, especially in areas with post-earthquake fires, as well as the risk of long-term population displacements, are shown in table B6.

Together, these maps provide a useful indication of potential hotspots of lifeline impacts, where lifeline infrastructure damage and outages could be significant and add to the risks of population displacement. Many of these areas overlap with the areas of concentrated building damage in the economic subareas of western Contra Costa County, northern, central and southern Alameda County, and Dublin-Pleasanton. However, areas in Santa Clara, San Mateo, and San Francisco Counties, particularly in the flat lands close to San Francisco Bay, have multiple lifeline infrastructure assets exposed to multiple high-intensity hazards.

Figure B5 shows the restoration curves compiled by Jones and others (this volume) for water, electric power, voice and data communications, California Department of Transportation bridges, and Bay Area Rapid Transit (BART) services for Alameda County for the HayWired scenario mainshock. Voice and data communications and electric power have faster restoration rates than water or BART service. Given the building damage concentrations and potential long-term water infrastructure outages in Alameda County, as well as parts of Contra Costa and Santa Clara Counties, the risk of population displacement from water service disruption and potential wastewater system damage could be substantially increased in these areas.

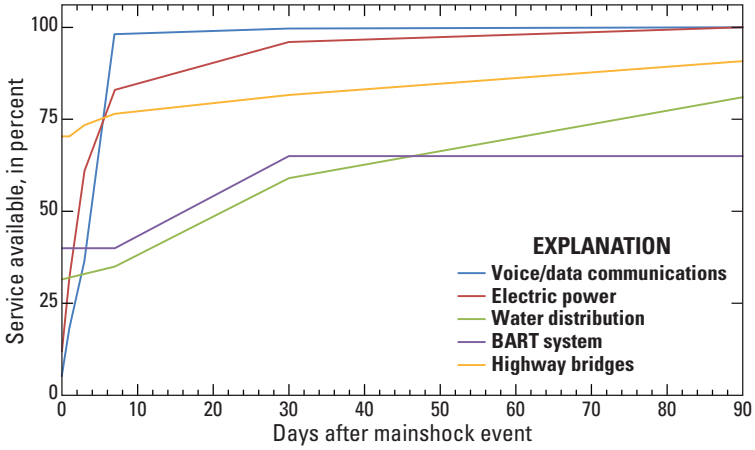


Figure B5. Line graph showing the lifeline restoration curves (voice and data, electric power, water distribution, Bay Area Rapid Transit [BART] service, and California Department of Transportation bridges) for Alameda County for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. From Jones and others (this volume).

Studies following the 1994 Northridge and 1989 Loma Prieta earthquakes in California found that somewhere between 20 and 50 percent of residents with power and water outages were displaced from their homes (Seligson and others, 2018). Seligson and others (2018) recommend increasing the Hazus estimates for population displacement and sheltering needs by 20 percent to account for utility outages. The multi-month water outages estimated for much of Alameda and Contra Costa Counties in the HayWired scenario (Porter, 2018) also suggest that an additional 20 percent weighting factor is a reasonable adjustment for this displacement analysis.

Using this weighting factor, adjusted totals for estimates of potential population at risk of displacement increase to 183,455 households and 497,158 people (7 percent of the nine-county totals) for the customized Hazus damage analysis and 212,281–267,510 households or 571,037–719,601 people (8 to 10 percent of the nine-county totals) for the integrated building damage analysis. The estimates for areas of concentrated damage remain unchanged since these are actual counts of households and populations in these areas.

Specific Population Groups Vulnerable to Displacement

In the context of disasters, many of the socioeconomic vulnerability indicator tools help to identify places and populations that are vulnerable to hurricane and flood disasters (Cutter and others, 2003), but do not explicitly link these vulnerabilities to specific and long-term postdisaster consequences, such as population displacement and mobility. Esnard and others (2011) analyzed Hurricane Katrina and other posthurricane data and distilled the disaster research literature to identify the potentially predictive variables of postdisaster population displacement. Their displacement risk index (DRI) is the first of its kind and focuses on hurricanes that strike the U.S. mainland. The DRI accounts for hazard exposure, physical vulnerability, socioeconomic vulnerability, and community resilience to estimate both the potential magnitude and spatial variation of displacement risk.

Table B7 is an adaptation of the DRI by Esnard and others (2011) that generalizes the variables they identified to address a natural hazard scenario, rather than being specific to hurricane displacement risk. The directional effects of each indicator on vulnerability or resilience is shown with a (+) or (−) sign after the definition. A main takeaway from this index development effort is that there is a broad base of household and community-scale socioeconomic characteristics that affect population displacement risk that go well beyond the traditional social vulnerability measures of race, income, and age.

Table B7. Generalized hazard scenario version of a displacement risk index (adapted from Esnard and others, 2011).

[+ and − symbols after each variable refer to the directional effect on the vulnerability or resilience, where + is a positive correlation and – is a negative correlation. The household data are averages at the county level. Variables for the State performance and institutional resilience indicators are collected at the State level]

Physical vulnerability	Socioeconomic vulnerability	Community resilience
Built environment (percentage of housing units): Hazard vulnerable (+), Owner occupied (−), Renter occupied (+), Population density (+), Percentage urbanized (+)	Income: Households below poverty line (+), Household median income (−), Per capita income (−), Households using more than 30 percent of income for housing (+)	Economic resilience: Foreclosure rate (−), Percentage of housing vacancies (+), Social capital groups per 10,000 persons (+), Nongovernmental organizations per 10,000 persons (+)
Hazard exposure: Percentage of urban area in hazard zone (+), Percentage of county area in hazard zone (+), Other hazard vulnerability index (+)	Employment: Percentage of economic sector vulnerable (+), Percentage of employment gain/loss (−), Unemployment rate (+)	Emergency capacity (per 10,000 persons): Hospitals (+), Medical services (+), Physicians (+)
	Race/ethnicity (percentage of population that is): White (−), Latino (+), African-American (+), Native American (+), Asian (−), Other (+), Non-English speaking (+)	State performance: Pew Center state government performance score[1] (+) Institutional resilience (percentage of population covered by): Existence of state plan (+), Local mandates (+), Mandatory hazards element (+), Geographic coverage of local mandatory hazards element (+), Postdisaster recovery plan requirement (+)
	Age (percentage of population that is): Over 65 (+), Over 75 (+), Under 18 (+), Under 6 (+)	
	Housing affordability: Percentage of households that rent (+), Affordable housing unit need as a percentage of total housing units (+)	
	Disadvantaged groups: Single-female households (+), Single-parent households (+), Single-person households over the age 65 (+), Households on public assistance (+), Households with disabilities (+), Households without cars (+)	
	Residence: Percentage of population born in state (−)	
	Education level (percentage of population with): Less than a high school education (+), Less than an 8th grade education (+)	

[1]Barrett and Greene (2008).

Esnard and others (2011) suggest other data that can be useful but were not available at the time the index was constructed. Factors potentially missing from the displacement risk index include ecological vulnerabilities and postdisaster sociopolitical and economic policies and processes that can exacerbate the predisaster social and economic vulnerabilities and inequalities of different people and communities, and further disadvantage certain groups in the recovery.

In the next sections of the displacement analysis, we consider the socioeconomic vulnerabilities of populations at risk of displacement in the HayWired scenario. Specifically, we explore socioeconomic vulnerability characteristics of populations in the areas of concentrated damage for all occupancies combined. Though there are populations with high socioeconomic vulnerabilities across the affected region, these analyses focus on the population in the areas of concentrated damage since these areas are likely to have more challenging and longer recovery trajectories than less-damaged areas, thus increasing the likelihood of long-term population displacement.

It is important to note, however, that disasters can become mechanisms for accelerating neighborhood gentrification and exclusion trends underway before the disaster, only further disadvantaging already marginalized populations (Esnard and Sapat, 2014). The "Plan Bay Area 2040" includes an analysis of gentrification and population displacement occurring or likely to occur in the San Francisco Bay region without consideration of the effects of a major disaster, such as the HayWired scenario (Zuk and Chapple, 2015; Metropolitan Transportation Commission and Association of Bay Area Governments, 2017). Many low-income neighborhoods are already experiencing displacement and high-income neighborhoods are also rapidly losing their existing low-income populations. Neighborhoods with rail stations, historical housing stock, and rising housing prices are especially at risk of losing low-income households. Many of these at-risk neighborhoods correspond with areas of concentrated damage in the east bay in the HayWired scenario.

Population with High Community Vulnerability Indicator Scores

In their 2015 study "Stronger Housing, Safer Communities," the Association of Bay Area Governments (ABAG), San Francisco Bay Conservation and Development Commission (BCDC), and partners used the "communities of concern" methodology developed by the San Francisco Bay region Metropolitan Transportation Commission to identify census block groups in the San Francisco Bay region that have higher than average concentrations of 10 socioeconomic characteristics known to affect the abilities of individuals and households to prepare for, respond to, and recover from a disaster (ABAG and BCDC, 2015; Brechwald and others, 2015; BCDC, 2016). This analysis was updated by BCDC for their "Adapting to Rising Tides" project in 2016 (BCDC, 2016). Each indicator is numerically measurable and based on data that is accessible and able to be georeferenced.

Table B8 lists the ABAG/BCDC community vulnerability indicators (CVIs), the way they are measured, and the threshold percentage or amount per census block group that must be met for the block group to receive a CVI score. For example, block groups with greater than 9 percent of the population 75 years of age or older would be given a score for that particular indicator. For any area, there can be a total possible score of 10.

Table B8. Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) community vulnerability indicators and measures.

[Data from ABAG and BCDC (2015) and Brechwald and others (2015); updated by BCDC (2016). Thresholds for defining the presence of indicators were determined by calculating the regional mean for each indicator and adding one-half the standard deviation to the regional mean]

Indicators	Measure	Percentage per census block group	Score
Housing cost burden	Percentage of household monthly spending on housing is >50 percent of gross monthly income	≥35 (renters) and (or) ≥19 (owners)	1
Transportation cost burden	Percentage of gross monthly income used for transportation costs	≥18	1
Home ownership	Percentage of housing not owner occupied	≥55	1
Household income	Percentage of households with income <50 percent of the region's median income	≥33	1
Education	Percentage of persons ≥25 years of age without a high school diploma	≥19	1
Racial/cultural composition	Percentage of non-white races or ethnicities	≥68	1
Transit dependence	Percentage of households without a vehicle	≥15	1
Non-English speakers	Percentage of households where no one ≥15 years of age speaks English well	≥14	1
Age—Young children	Percentage of young children <5 years of age	≥8	1
Age—Elderly	Percentage of elderly people ≥75 years of age	≥9	1
Total possible community vulnerability indicator (CVI) score			**10**

These indicators are consistent with the DRI by Esnard and others (2011) (see table B7), with two exceptions. The DRI does not include transportation cost burden and transit dependence. However, given the extensive commuting patterns in the San Francisco Bay region that could be significantly interrupted in a major earthquake, it seems reasonable to include these characteristics.

For this analysis, the CVI data (ABAG and BCDC, 2016) were evaluated by associating the CVI block group data with the areas of concentrated damage for all occupancies combined (with fire damage integrated). The CVI data provides a CVI score (of the number of qualifying indicators for a census block group) and the actual indicators that form the score for each block group. Since some indicators are population-based (for example, age) and some are household-based (for example, household income), the household counts were converted to population counts by multiplying households by persons per household block group census data. This means that, for any unit of aggregation (for example, economic subarea or county), the population in block groups associated with each vulnerability indicator and a total CVI score of 0 to 10 can be tabulated. Figure B6 shows the CVI scores by census block group for the population in the areas of concentrated damage for all occupancies combined. The darker colors on the map corresponds to higher CVI scores. The block-group-scale results can also be found in Jones and others (2020).

Figures B7 and B8 show the total population distribution by CVI score in the areas of concentrated damage for all occupancies combined in each county and economic subarea, as well as the population-weighted prevalence of each indicator within each CVI score (data available in Jones and others, 2020). For example, block group populations in the areas of concentrated damage with a CVI score of 1 are summed to determine the total population that has a CVI score of 1, and the colors of the bar graph show composition of indicators that contributed to that score. For block group populations in the areas of concentrated damage with a CVI score of 2 or more, each indicator's contribution is calculated as the population with the indicator for the score divided by the number of the CVI score (to remove repeated counting of the same population). The contribution of each indicator adds up to the total population in the specific subregion in the areas of concentrated damage with the CVI score, such that the figures show the total population with each CVI score and the relative prevalence of each indicator.

Note that the height of the bars in figures B7 and B8 represent the total population in the block groups in the areas of concentrated damage with each of the CVI scores and the colors show the prevalence for each indicator that makes up a particular CVI score. The colors do not, however, indicate how many people have a specific indicator because a single person may belong to several (or no) groups. The nature of the available data used prohibit isolating subgroups in a population and counting the number of people with different combinations of CVI indicators in a block group. It is only possible to consider how common different indicators are within a particular CVI score.

Compared with the population counts provided in tables B4 and B5, these figures show that more than 350,000 people reside in block groups with CVI scores of 5 or greater in the areas of concentrated damage. Of that group, a large portion (around 285,000 people) resides in Alameda County (or 18 percent of the county population), approximately 55,000 people reside in Contra Costa County (or 5 percent of the county population), and more than 9,000 people reside in Solano County (or 2 percent of the county population). More specifically, the greatest concentrations of people reside in block groups with high CVI scores of 5 or more in the economic subareas of central Alameda County (40 percent of the subarea population), western Contra Costa County (26 percent of the subarea population), and Vallejo (8 percent of the subarea population).

The prevalence of vulnerability indicators for residents of areas of concentrated damage varies by CVI score. Transportation cost burden dominates in the less-vulnerable block groups (for example, with CVIs of 3 or less). The racial and cultural composition indicator dominates the mid-range of the CVI scores (4 to 7). The elderly indicator contributes the least overall to the CVI scores, especially higher CVI scores. In areas with CVI scores of 5 or more, there is a greater prevalence of housing- and income-related indicators (for example, lack of home ownership, high housing-cost burden, low household incomes) and literacy indicators (for example, low levels of education and more non-English speakers). The high CVI scores (8 or greater) involve more indicators and, therefore, their prevalence is more balanced—more populations qualify for the same combination of indicators.

School-Age Children

Past disasters have shown that families with school-age children have higher rates of protracted or permanent displacement or relocation, especially if they find better schools or more affordable housing elsewhere (Plyer and Ortiz, 2011; Fothergill and Peek, 2015). When neighborhood schools close, some families may move to other parts of the community, the region, or even outside the region in order to keep their children in school.

Since the early 1930s, public schools in California have been subject to special design requirements, regulations, and seismic retrofit programs (Barclay, 2003) that are likely to substantially reduce damage to many public primary, secondary, and higher education facilities in the HayWired scenario. However, some public school buildings may still sustain shaking-related damage—from both structural and nonstructural elements—that renders them inoperable. Others could be impacted by any combination of liquefaction, landslides, and fires. Furthermore, the seismic regulations for private school buildings have been significantly less stringent and, unfortunately, there is evidence that some private school buildings in the San Francisco Bay region could have significant damage in a major earthquake (City and County of San Francisco, 2013).

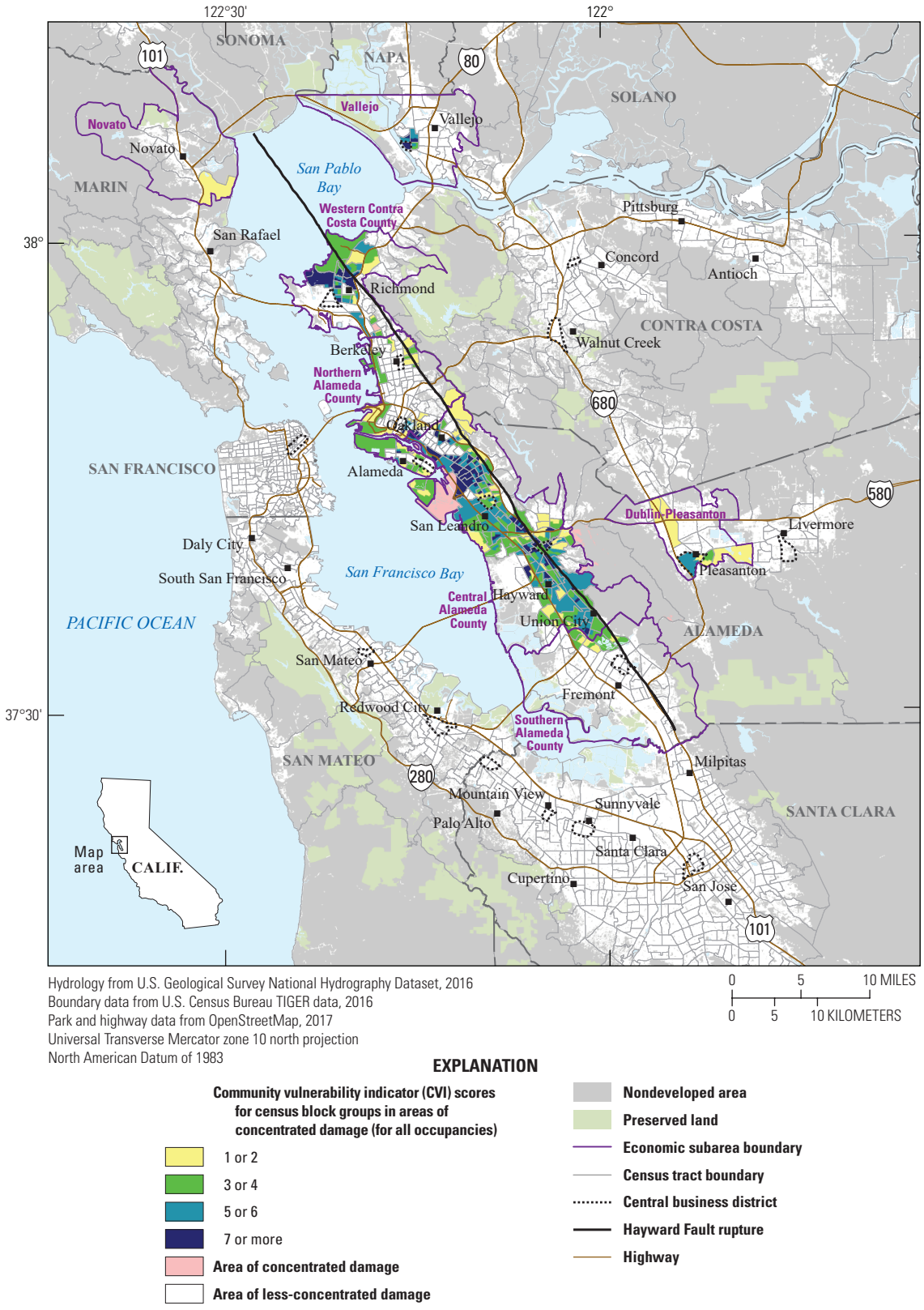


Figure B6. Map of the San Francisco Bay region, California, showing Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) community vulnerability indicator (CVI) scores for census block groups in the areas of concentrated damage (with fire damage integrated) resulting from the HayWired earthquake scenario mainshock for all occupancies combined. Areas in pink are in the areas of concentrated damage but have CVI scores of zero. Data from ABAG and BCDC (2016).

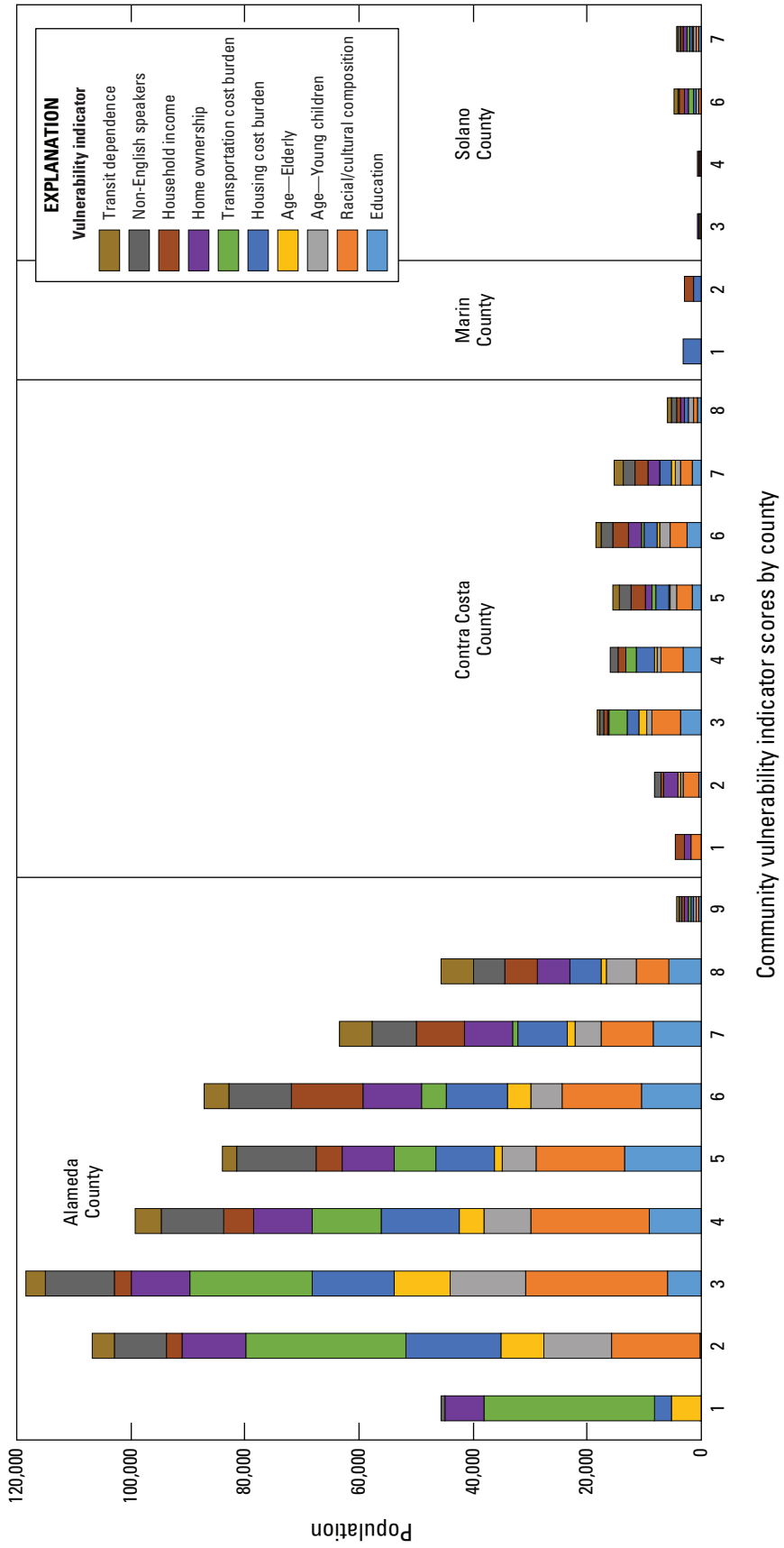


Figure B7. Bar chart showing the total population with different Association of Bay Area Governments and San Francisco Bay Conservation and Development Commission community vulnerability indicator (CVI) scores in the areas of concentrated damage resulting from the HayWired earthquake scenario mainshock for all occupancies combined (with fire damage integrated) in each county of the San Francisco Bay region, California.

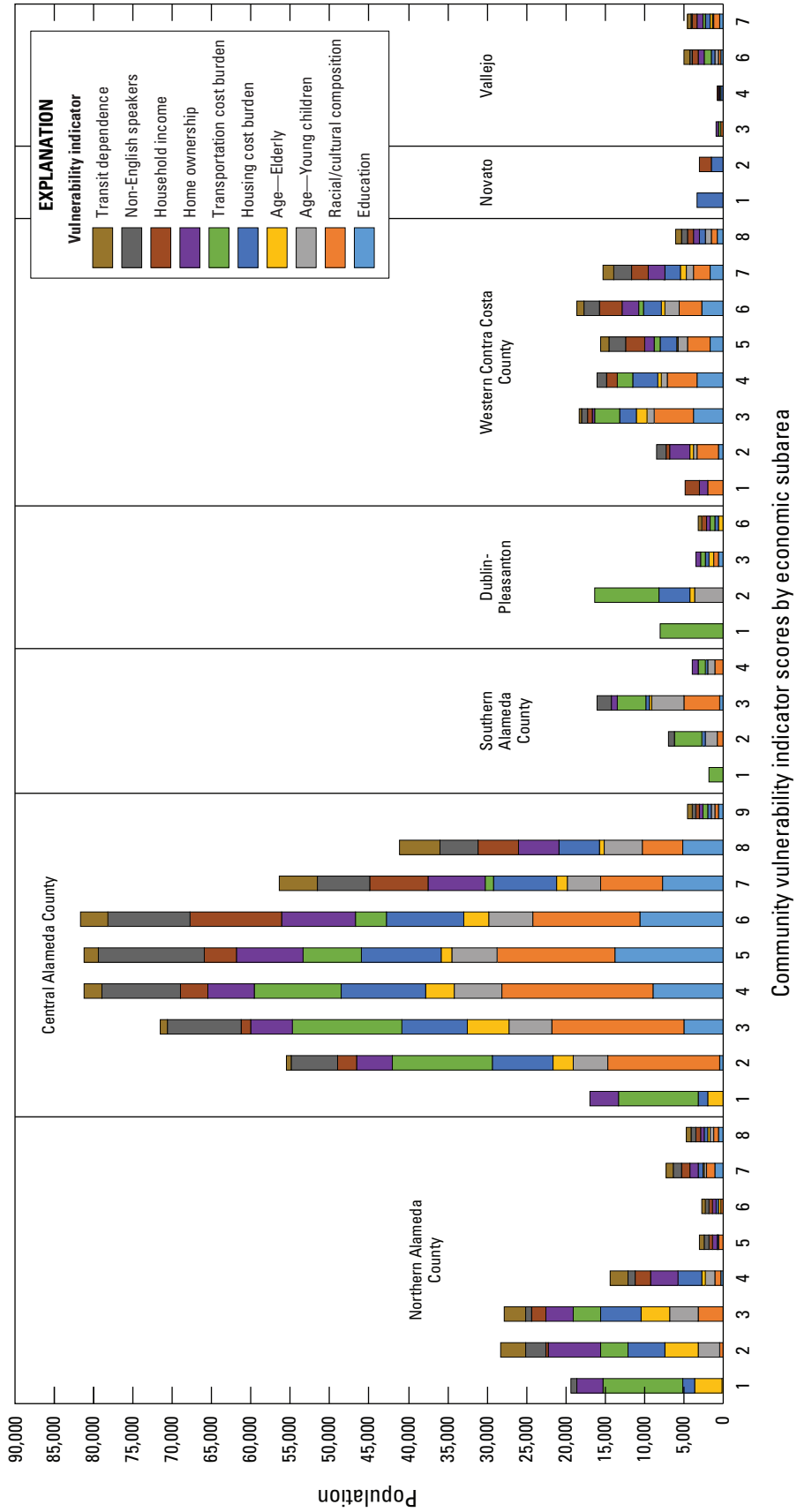


Figure B8. Bar chart showing the total population with different Association of Bay Area Governments and San Francisco Bay Conservation and Development Commission community vulnerability indicator (CVI) scores in the areas of concentrated damage resulting from the HayWired earthquake scenario mainshock for all occupancies combined (with fire damage integrated) in each economic subarea of the San Francisco Bay region, California.

The 2010–14 5-year American Community Survey (ACS) census data on households with very young children (less than 5 years) are part of the CVIs (ABAG and BCDC, 2016) and a contributing indicator in the areas of concentrated damage in Alameda County, especially the central Alameda County economic subarea. The 2012–16 ACS 5-year estimates were used to obtain a more current view of school-age children (U.S. Census Bureau, 2018). The ACS reports on the population enrolled in primary schools, which are defined as kindergarten through 12th grade, and which we define as "school-age children" whose families may have higher rates of protracted or permanent displacement or relocation.

Table B9 lists the 2012–16 ACS 5-year estimates of school-age children for the nine counties in the San Francisco Bay region. There is a total of 1,168,694 school-age children in the nine counties. Santa Clara, Alameda, and Contra Costa Counties have the highest numbers, with an estimated 314,838 (31 percent), 248,253 (27 percent), and 197,854 (21 percent) school-age children, respectively. Of these, an estimated 130,455 school-age children reside in areas of concentrated damage, with the majority (108,087 school-age children) residing in the areas of concentrated damage in Alameda County. The central Alameda County subarea has the largest number (85,067) of school-age children residing in areas of concentrated damage.

In the areas of concentrated damage, there are 64,300 school-age children in 2010 census block groups where the concentrations of school-age children are much higher than other block groups. These areas were identified by calculating the mean for the percentage of the total population in a block group that are school-age children for the nine-county region and then adding one-half standard deviation (also calculated using the same nine-county block groups) to the regional mean. To be considered an area with a high concentration of school-age children, more than 18.35 percent of the total population for a block group must be school-age. This method is consistent with the approach used to obtain the threshold values for the CVIs. These data are available in Jones and others (2020).

Table B9. Number of school-age (kindergarten through 12th grade) children in the nine counties of the San Francisco Bay region, California.

[Data from U.S. Census Bureau (2018)]

County	School-age children
Alameda County	248,253
Contra Costa County	197,854
Marin County	40,976
Napa County	23,558
San Francisco County	75,446
San Mateo County	117,266
Santa Clara County	314,838
Solano County	73,410
Sonoma County	77,093
Nine-county total	**1,168,694**

Figure B9 shows the 2010 census block groups that have high concentrations of school-age children in the areas of concentrated damage. The block groups in the areas of concentrated damage that have a CVI score of 5 or more are also shown. There are notable overlapping areas with high concentrations of school-age children and areas with a CVI score of 5 or more in the central Alameda County, western Contra Costa County, and Vallejo subareas. This provides some indication of where school-age children may be yet another indicator of displacement risk in the areas of concentrated damage.

Persons with Disabilities

The California Governor's Office of Emergency Services (Cal OES) defines persons with access and functional needs as being or having: physical, developmental, or intellectual disabilities; chronic conditions or injuries; limited English proficiency; older adults; children; low income, homeless, and (or) transportation-disadvantaged (for example, dependent on public transit); and pregnant women (Cal OES, 2019). These individuals are likely to be more dependent on having access to functioning hospitals, doctor's offices, general health care services, social and personal care services, and other community services and may be vulnerable to displacement if these services are impacted in the HayWired scenario. The physical and emotional effects of a major earthquake, and subsequent aftershocks, could add further stress on already overwhelmed healthcare and community service systems and providers, increasing the vulnerabilities for this population group. The "Bay Area Earthquake Plan" estimates that there are about 675,000 children under the age of five and more than 2.5 million individuals with access and functional needs out of a population of about 10.2 million people in the 16-county planning area (Cal OES, DHS, and FEMA, 2016).

Whereas some of the criteria that define access and functional needs populations are included in the CVI score (ABAG and BCDC, 2016), individuals with physical, developmental, or intellectual disabilities or chronic conditions or injuries, the homeless, and pregnant women are not. The 2012–16 ACS 5-year estimates were used to consider the number of disabled residents in the nine-county region and in the areas of concentrated damage. Specifically, we considered the data on receipt (or not) of Federal food stamps and (or) the Supplemental Nutrition Assistance Program in the past 12 months by disability status, to estimate total number of households with at least one disabled resident.

Table B10 lists the 2012–16 ACS 5-year estimates of households with at least one disabled resident for the nine counties in the San Francisco Bay region. There is a total of 550,901 households with at least one disabled resident in the nine-county region. Alameda, Santa Clara, and Contra Costa Counties have the highest numbers, with an estimated 115,389 (21 percent), 111,598 (20 percent) and 92,963 (17 percent) households with at least one disabled resident, respectively. Of these, there are an

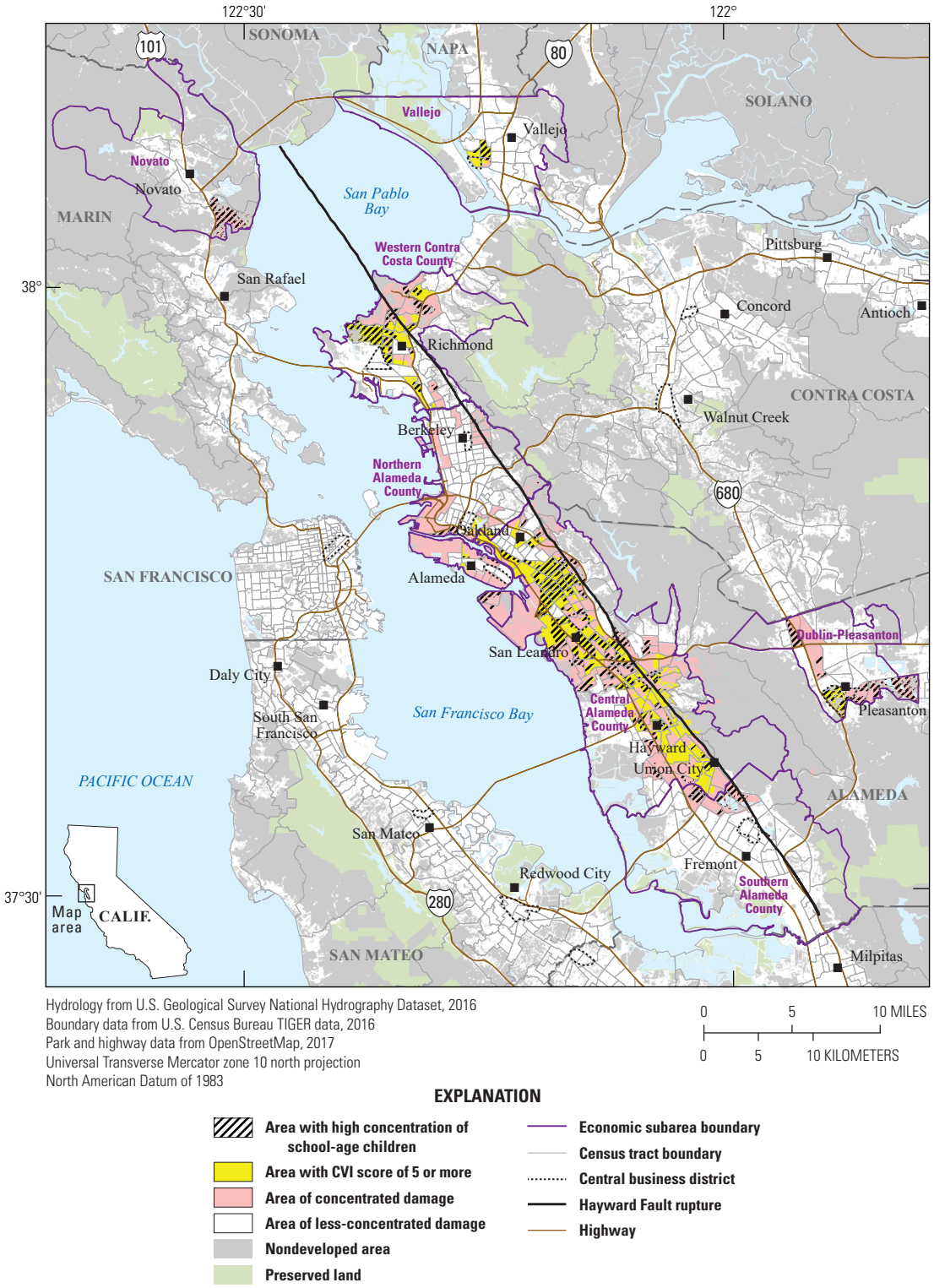


Figure B9. Map of the San Francisco Bay region, California, showing the census block groups in the areas of concentrated damage resulting from the HayWired earthquake scenario mainshock where the percentage of school-age (kindergarten through 12th grade) children is greater than the regional mean plus one-half standard deviation (that is, 18.35 percent). The block groups in the areas of concentrated damage that have a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are also shown. Data from ABAG and BCDC (2016) and U.S. Census Bureau (2018).

Table B10. Number of households with at least one disabled resident in the nine counties of the San Francisco Bay region, California.

[Data from U.S. Census Bureau (2018)]

County	Households with one or more disabled residents
Alameda County	115,389
Contra Costa County	92,963
Marin County	18,748
Napa County	11,794
San Francisco County	70,595
San Mateo County	46,351
Santa Clara County	111,598
Solano County	38,122
Sonoma County	45,341
Nine-county total	**550,901**

estimated 63,408 households with at least one disabled resident in the areas of concentrated damage. The majority are in the areas of concentrated damage in Alameda County. The central Alameda County subarea has the greatest number of households (39,031) with at least one disabled resident in areas of concentrated damage.

In the areas of concentrated damage, there are 31,993 households with at least one disabled resident in the 2010 census block groups where the concentrations of households with at least one disabled resident are much higher than other block groups. These areas were identified by calculating the mean for the percentage of the total households in a block group that have at least one disabled resident for the nine-county region and then adding one-half standard deviation (also calculated using the same nine-county block groups) to the regional mean. To be considered an area with a high concentration of households with at least one disabled resident, more than 26.14 percent of the total households for a block group must have at least one disabled resident. This method is consistent with the approach used to obtain the threshold values for the CVIs. These data are available in Jones and others (2020).

Figure B10 shows the 2010 census block groups that have high concentrations of households with at least one disabled resident in the areas of concentrated damage. The block groups in the areas of concentrated damage that have a CVI score of 5 or more are also shown. There are notable overlapping areas with high concentrations of households with at least one disabled resident and areas with a CVI score of 5 or more in the western Contra Costa County and the central Alameda County economic subareas. This provides some indication of where persons with disabilities may be yet another indicator of displacement risk in the areas of concentrated damage.

Homeless Populations

Homeless populations in the San Francisco Bay region will also be affected by a major earthquake with potential limitations on access to heavily damaged neighborhoods, loss of social and community services, and damage to homeless shelters, and could be at risk of displacement or protracted relocation.

There are four federally defined categories under which individuals and families might qualify as homeless: literally homeless, imminent risk of homelessness, homeless under other Federal statutes, and fleeing or attempting to flee domestic violence (HUD, 2012). The U.S. Department of Housing and Urban Development (HUD) requires that communities receiving Federal funding conduct an annual count of all persons living in emergency shelters and transitional housing; unsheltered homeless populations counts are required every other year. These homeless point-in-time surveys identify whether a person is an individual, a member of a family unit, or an unaccompanied youth under the age of 18 or between ages 18 and 24, and whether a person is chronically homeless or has a disability (National Alliance to End Homelessness, 2012). Unfortunately, this data is only available for counties and select cities.

Table B11 provides the sheltered and unsheltered homeless populations in the nine counties based upon the most recently available point-in-time surveys (County of San Mateo Human Services, 2017; Applied Survey Research, 2018; Contra Costa Health Services, 2018; County of Napa, 2018). The total homeless population for the nine counties is 28,213 with the largest percentages in San Francisco (27 percent), Santa Clara (26 percent), and Alameda (20 percent) Counties. However, it is important to note that Contra Costa and San Mateo Counties did not have sheltered homeless counts available; for those counties, the total homeless population and unsheltered homeless population are the same. Of the cities that have one or more census tracts located in an area of concentrated damage, those that have the largest homeless populations in their respective counties are: Oakland (2,761, or 49 percent of the Alameda County total), Berkeley (972, or 17 percent of the Alameda County total), Richmond (population 270, or 18 percent of the Contra Costa County total), Novato (population 350, or 31 percent of the Marin County total), and Vallejo (population 402, or 37 percent of the Solano County total).

Young and Mobile Populations

Young and moderate- to high-income renters were not identified in the ABAG/BCDC community vulnerability indicators, but may represent a cohort of the population with means, mobility, and a lack of social ties or tolerance for staying in the region after a major earthquake like that in the HayWired scenario. A major regional disruption to housing, jobs, and transit could be the tipping point for many people to voluntarily relocate to another city or region, and this group may be especially likely to do so if they can continue working for the same employer, if their employer sustains significant damage or disruption, or if their employer chooses to relocate for some other reason. This occurred in a few of the more affluent neighborhoods of Sherman Oaks, California, that suffered heavy damage to multifamily rental units and condominiums and experienced voluntary outmigration by residents, even from undamaged properties after the 1994

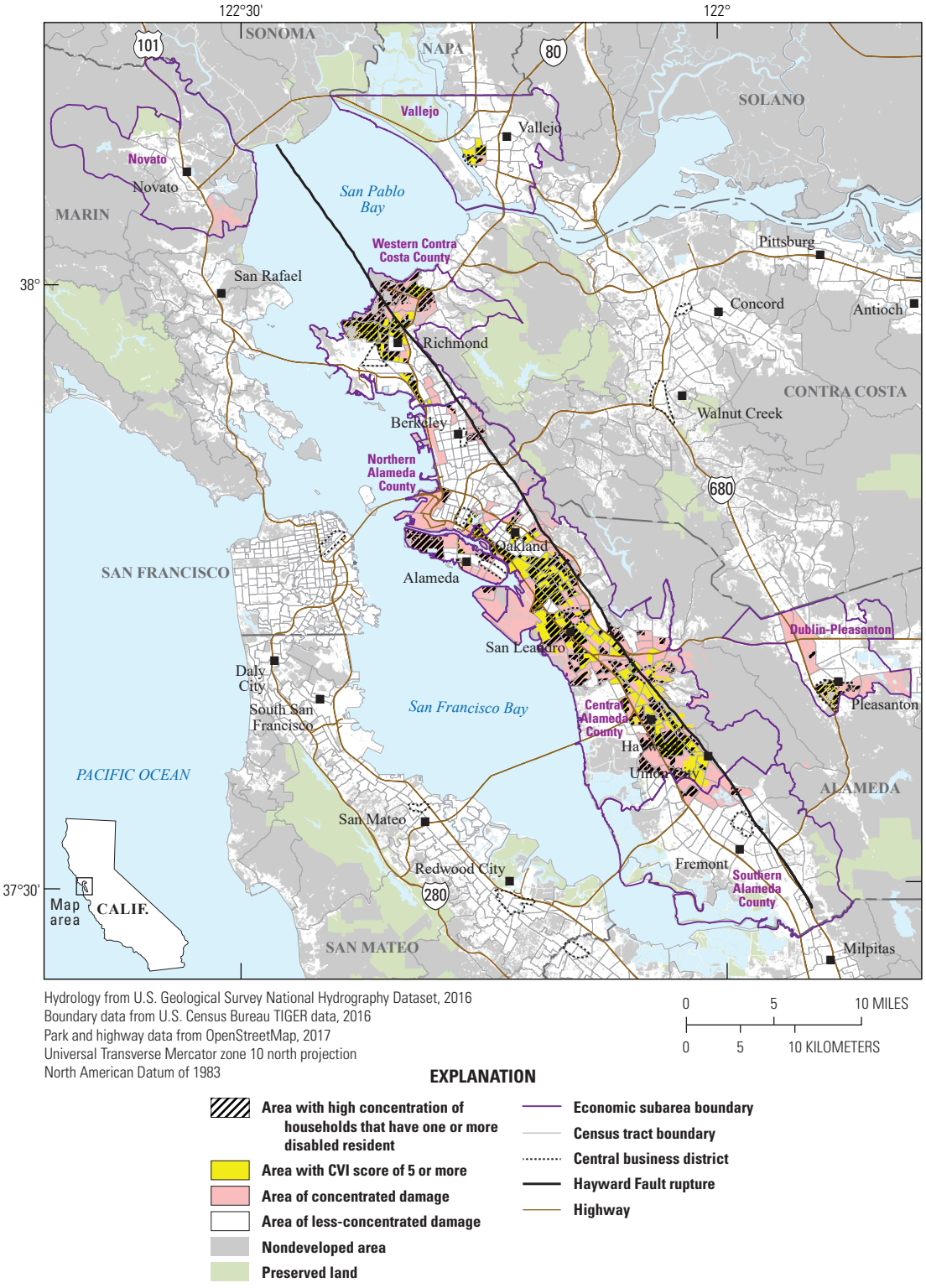


Figure B10. Map of the San Francisco Bay region, California, showing the census block groups in the areas of concentrated damage resulting from the HayWired earthquake scenario mainshock where the percentage of households with at least one disabled resident is greater than the regional mean plus one-half standard deviation (that is, 26.14 percent). The block groups in the areas of concentrated damage that have a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are also shown. Data from ABAG and BCDC (2016) and U.S. Census Bureau (2018).

Table B11. Sheltered and unsheltered homeless populations for the nine counties in the San Francisco Bay region, California.

[--, no data available]

County	Year collected	Sheltered homeless population		Unsheltered homeless population		Total homeless population	
		Population	Percentage	Population	Percentage	Population	Percentage
Alameda County[1]	2017	1,766	20	3,863	20	5,629	20
Contra Costa County[2]	2018	--	--	1,537	8	1,537	5
Marin County[1]	2017	409	5	708	4	1,117	4
Napa County[3]	2018	168	2	154	1	322	1
San Francisco County[1]	2017	3,146	36	4,353	22	7,499	27
San Mateo County[4]	2017	--	--	637	3	637	2
Santa Clara County[1]	2017	1,946	22	5,448	28	7,394	26
Solano County[1]	2015	287	3	795	4	1,082	4
Sonoma County[1]	2018	1,067	12	1,929	10	2,996	11
Region total	**2015–2018**	**8,789**	**100**	**19,424**	**100**	**28,213**	**100**

[1]Data from Applied Survey Research (2018).

[2]Data from Contra Costa Health Services (2018).

[3]Data from County of Napa (2018).

[4]Data from County of San Mateo Human Services (2017).

Northridge earthquake (Olshansky and others, 2005). Such outmigration could potentially hinder community-level recovery as well as the recovery of the regional economy.

A 2017 poll found that 51 percent of voters in the San Francisco Bay region have considered leaving because of rising housing costs (Robertson, 2017). According to another recent study, millennials feel especially priced out of housing in the region, with only 24 percent surveyed believing that they will be able to afford a desirable home (Scheinin, 2016). Heavy transportation burden could also influence relocation decisions in this population group.

According to the 2012–16 ACS 5-year estimates, there are 1,625,852 persons between the ages of 20 and 34 in the nine-county San Francisco Bay region. The 2012–16 ACS 5-year estimates also offer data on a number of household characteristics that could help target potential mobile households that are younger, more affluent, and lack family ties and obligations. Table B12 provides the number of households and percentage of households in the nine-county region with a select set of characteristics that together could help identify clusters of potentially young and mobile populations. They are: householders between the ages of 25 and 34 who identified as renters and thus may have fewer obligations and ties than younger homeowners; more affluent householders under age 45 with income greater than the county median; households with rental costs that are higher than the county median who may, thus, have an incentive to voluntarily relocate; and, non-family households without children and, thus, with potentially fewer obligations and ties.

Across the nine-county region, approximately two-thirds of renter householders between the ages of 25 and 34 (212,327 households) reside in block groups where the concentrations of young renter householders are greater than the regional mean plus one-half standard deviation (16.47 percent). Of these, approximately 79 percent, or 168,663 renter householders between the ages of 25 and 34, reside in block groups that also have at least one other mobile-population attribute in concentrations higher than the defined threshold values (26.43 percent, householders under 45 with income greater than county median; 75.87 percent, households with rent higher than county median; 41 percent, non-family households without children). This suggests that there are neighborhoods throughout the nine-county region with high concentrations of potentially young and mobile populations.

In the areas of concentrated damage for the HayWired scenario, there are 24,243 renter householders between the ages of 25 and 34 in block groups where the concentration of young renter householders is greater than the regional mean plus one-half standard deviation. Of these, 14,110 young renter householders (or 58 percent) reside in block groups that also have at least one other attribute with concentrations higher than the defined threshold values. These data are available in Jones and others (2020).

Figure B11 shows the 2010 census block groups that have high concentrations of renter householders between the ages of 25 and 34 in the areas of concentrated damage and those block groups that have high concentrations of young renter householders who also have at least one other mobile-population attribute with concentrations above the defined

Table B12. Households in the nine-county San Francisco Bay region, California, with selected attributes of potentially young and mobile populations.

[Data from U.S. Census Bureau (2018)]

Demographic characteristic	Number in the nine-county region	Percentage of the nine-county region
Renter householders between 25 and 34	321,507	12
Householders under 45 with income greater than county median	583,286	22
Households with rent higher than county median	706,971	59
Non-family households without children	906,520	34

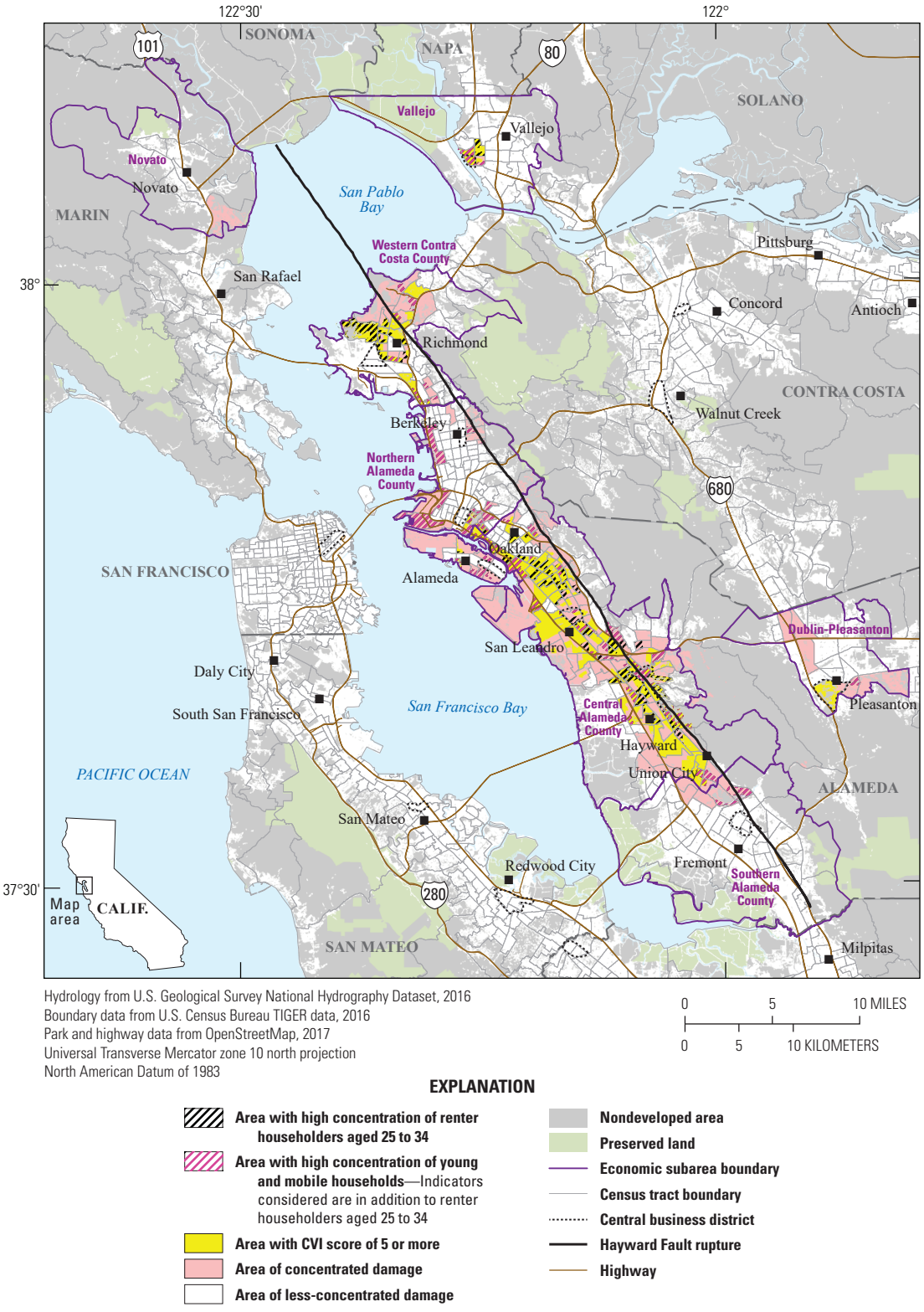


Figure B11. Map of the San Francisco Bay region, California, showing the census block groups in the areas of concentrated damage (all building occupancies) resulting from the HayWired earthquake scenario mainshock where the percentage of renter householders aged 25 to 34 is greater than the regional mean plus one-half standard deviation and those areas that also have one additional young and mobile indicator that exceeds the regional mean plus one-half standard deviation. The block groups in the areas of concentrated damage that have a community vulnerability indicator (CVI) score of 5 or more from the Association of Bay Area Governments (ABAG) and San Francisco Bay Conservation and Development Commission (BCDC) are also shown. Data from ABAG and BCDC (2016) and U.S. Census Bureau (2018).

threshold values. The block groups in the areas of concentrated damage that have a CVI score of 5 or more are also shown. There are a few overlapping areas with high concentrations of potentially young and mobile populations and areas with a CVI score of 5 or more, most notably in Vallejo, Pinole, areas near Lake Merritt, near the west side of Oakland, and Union City. These are areas where young and mobile populations might choose to voluntarily relocate because of the high levels of damage and neighborhood disruption, as well as displacement of more socioeconomically disadvantaged neighbors.

Emergency Sheltering and Interim Housing Influences on Population Movements through Time

Quarantelli (1995) defined four types of postdisaster housing recovery: emergency shelter, temporary shelter, temporary housing, and permanent housing. Emergency shelter typically refers to the quarters that actual or potential disaster victims seek outside their own homes for short periods (on the order of hours to days). Temporary shelter refers to the quarters that accommodate displaced people with an expected short or temporary stay (on the order of days to a few weeks). Temporary housing, also referred to as interim housing, typically provides more than just shelter, but an opportunity for occupants to reestablish normal household routines, responsibilities, and activities to the extent possible (on the order of months to years). Permanent housing constitutes rebuilt homes as well as new quarters that disaster survivors occupy on a permanent basis.

Though there is a progressive nature to these descriptions, disaster survivors do not necessarily follow them in a successive order and some distinctions are not always clear, such as when temporary housing becomes permanent or when emergency shelters transition into temporary shelters out of necessity (Quarantelli, 1995). Furthermore, members of a disaster-impacted community can be found simultaneously in every type, skip certain types, and have many repetitive stays as well as extended stays in any of the postdisaster housing types (Peacock and others, 2007).

It is now established practice for Federal, State, and local emergency management plans and policies to address emergency shelter and mass care needs, including for large-scale, urban disasters like the HayWired scenario. Planning and policy development for interim and permanent housing is much newer, stimulated to a great extent by Congress's mandate, following Hurricane Katrina, to Federal agencies to develop a national disaster housing strategy (Federal Emergency Management Agency [FEMA], 2009). Table B13 identifies some of the key features of Federal, State, and local emergency plans that are likely to guide emergency shelter and interim housing policies and actions following a major earthquake in the San Francisco Bay region.

The concept of operations for how government and nongovernmental organizations will coordinate to assist with immediate sheltering, feeding, tracking, and ground transportation for populations in transit during the first hours and days after a major earthquake are generally well described. However, the longer term, forced or voluntary, displacements of people and the interim and permanent housing needs resulting from building damage and fires, lifeline infrastructure damage and outages, and environmental health threats following a major earthquake are not as well addressed in these plans.

Potential Population Needing Emergency Shelter and Interim Housing

The analyses of building damage, lifeline infrastructure outages, and population in the areas of concentrated damage offer a range of perspectives on the number of households that may need emergency shelter and interim housing following the M_w 7.0 mainshock of the HayWired scenario. Table B14 provides a summary of the different estimates that have been developed in previous parts of this section. The analyses of the combined effects of potential residential building damage and lifeline utility outages produces ranges of 60,994 to 520,210 households and 170,206 to 1,451,838 people at risk of displacement from the M_w 7.0 mainshock, or 2 to 20 percent of the nine-county region totals.

For comparison, a study of the spatial economic demand shifts in Louisiana, Mississippi, and Alabama found that, one year after Hurricane Katrina, the counties and parishes encompassing the core disaster area lost an average of 23.1 percent of their population (Xiao and Nilawar, 2013). The "Bay Area Earthquake Plan" estimates that approximately 330,000 individuals would immediately seek sheltering support after a major earthquake on the San Andreas or Hayward Faults (Cal OES, DHS, and FEMA, 2016), and the Bay Area Urban Area Security Initiative (Bay Area UASI) "Regional Catastrophic Earthquake Interim Housing Plan" estimates 400,000 displaced households, of which 160,000 households will still need shelter one year after a M_w 7.9 earthquake on the San Andreas Fault (Bay Area UASI, 2011). Neither of these plans considers the possibility of widespread fires and extensive lifeline utility disruptions. Thus, the customized Hazus analysis estimates by Seligson and others (2018) of nearly 153,000 displaced households (or 6 percent of the nine-county households) and 48,050 people seeking public shelters (less than 1 percent of the nine-county population) might be considered lower bounds of the region's likely needs in the HayWired scenario. Other estimates provided by the analyses herein may be more appropriate.

Table B13. Key Federal, State, and regional plans that will guide emergency response in a major San Francisco Bay region, California, earthquake.

[DHS, Department of Homeland Security; FEMA, Federal Emergency Management Agency; Cal EMA, California Emergency Management Agency; Cal OES, California Governor's Office of Emergency Services; Bay Area UASI, Bay Area Urban Area Security Initiative; M_w, moment magnitude]

Federal, State, or regional plan	Key purpose, objectives, and guiding principles
National Response Framework (FEMA, 2013)	Defines the Federal structure for disaster response in a federally declared emergency or disaster as well as the core capabilities and specific emergency support functions that the Federal Government will address in disaster response. These include public information and warning; transportation; mass care, emergency assistance, temporary housing, and human services; public health and medical services; and public safety and security. All State and local governments are expected to plan their role in these areas as well.
Mass Evacuation Incident Annex of the National Response Framework (FEMA, 2008)	Provides an overview of Federal functions, agency roles and responsibilities, and the overarching guidelines for supporting the evacuation of large numbers of people in incidents where State, Tribal, or local governments may or have become overwhelmed or incapacitated and mass evacuation support is required in a federally declared emergency or disaster. It acknowledges the responsibility of States in affected areas, in conjunction with other States, to decide on the destinations for evacuees and to regulate the flow of transportation assets accordingly.
National Disaster Housing Strategy (FEMA, 2009)	Defines the principles, roles, and responsibilities of Federal, State, and local governments and nongovernmental organizations in the provision of emergency shelters, interim housing, and permanent housing in a federally declared emergency or disaster. It establishes a National Disaster Housing Task Force, composed of Federal agency partners, to provide technical expertise and calls for State-led task forces to take the lead in developing interim housing options postdisaster.
State of California State Emergency Plan (Cal EMA, 2009)	Describes the State's emergency operations and processes for mutual aid, resource mobilization, public information, and continuity of government during a State-level emergency or disaster. It also defines the Standardized Emergency Management System that all State and local organizations are to follow in order to enhance coordination among response organizations and facilitate the flow of emergency information and resources within and between the organizational levels. It also specifically designates local government as the first level of response for meeting the disaster needs of people, such as emergency care and shelter, within its jurisdiction. Local government can contract with recognized community organizations to provide these facilities and services.
Bay Area Earthquake Plan (Cal OES, DHS, and FEMA, 2016)	Developed by the State of California, in cooperation with DHS and FEMA, it provides a general framework for how State and Federal agencies will respond to a catastrophic earthquake. It specifically addresses the access and movement of response-related resources into the earthquake-affected region and calls for the establishment of State and Federal task forces to execute strategies to support survivor movement operations and mass care and feeding operations. These include coordinating with local and regional agencies and organizations to provide mass care support at pre-identified sites along survivor movement routes and assisting with the tracking, feeding, and ground transportation of people in transit. If the earthquake occurs during the workday period, it assumes that most of the commuting population will require movement support to return to their homes. It also addresses immediate housing needs, specifically the evacuation and short-term (or temporary) sheltering needs. It assumes that most residents impacted by the disaster will be able to shelter in place in their homes or neighborhoods, requiring life-sustaining supplies such as food and water, and that some survivors will choose to evacuate outside of the affected area. It notes that sheltering areas exist across 16 northern California counties and that there is additional capacity available elsewhere in California and the adjoining states of Oregon, Nevada, and Arizona.
Bay Area Urban Area Security Initiative Regional Catastrophic Earthquake Interim Housing Plan (Bay Area UASI, 2011)	Part of a series of catastrophic planning documents for the region, it is consistent with State and Federal response planning and should be viewed as a supporting plan to the "Bay Area Earthquake Plan." It takes an in-depth look at the regional need for interim housing, using a M_w 7.9 earthquake on the San Andreas Fault for its scenario. It sets goals and objectives for the provision of interim housing during the first 12 months after the earthquake and defines roles and responsibilities for Federal, State, and local governments as well as the private and nongovernmental sectors.

Table B14. Estimates of potential populations at risk of displacement following the moment magnitude 7.0 mainshock of the HayWired earthquake scenario in the San Francisco Bay region, California.

Displacement analysis method	Displaced households[1]	Displaced people[2]	Percentage of nine-county region totals
Nine-county region			
Customized Hazus analysis	152,438	412,954	6
Customized Hazus analysis with 20-percent increase for lifeline outages	183,457	497,158	7
Integrated building damage data analysis with 20-percent increase for lifeline outage[3]	212,281–267,510	571,037–719,601	8–10
Areas of concentrated damage[4]			
All occupancies combined	172,484–267,631	487,698–765,402	7–10
Single-family/duplex occupancy class	60,994–128,543	170,206–363,215	2–5
Multifamily occupancy class	361,948–520,210	1,024,266–1,451,838	14–20

[1]Uses 2000 U.S. Census data.

[2]County-level average household size from the 2010 U.S. Census was used to calculate displaced population estimates for the mainshock.

[3]A range of estimates is provided to account for the variations in housing units possible in each of the multifamily residential occupancy classes.

[4]The lower bound for ranges in this section are total households or people in areas of concentrated damage caused by earthquake hazards (ground shaking, landslides, and liquefaction) and the upper bounds are total households or people in areas of concentrated damage caused by earthquake hazards and fire. It is not likely that all households or people in areas of concentrated damage would be displaced, but neighborhood-serving infrastructure and services and heavy levels of surrounding building damage could lead to higher rates of displacement than less damaged areas.

Emergency Shelter Issues

Since the hypothetical mainshock of the HayWired scenario strikes on April 18, 2018 at 4:18 p.m., it is likely that a large part of the region's workday commuting population will require initial shelter, at least for the first night, as well as movement support in order to return home in the days that follow. However, transportation system damage, ensuing fires, environmental hazards, and access controls may exacerbate and prolong emergency shelter needs.

For those residents who are able to shelter in place in their homes or neighborhoods, many may still require life-sustaining supplies, such as food and water. Some survivors will voluntarily evacuate outside the affected area, seeking public shelter or to stay with family and friends or in available hotels, motels, and other short-term options.

The "Bay Area Earthquake Plan" looks at catastrophic-level scenarios on both the San Andreas and Hayward Faults—with a M_w 7.0 earthquake on the Hayward Fault that is centered roughly 4 kilometers (km) northeast of the City of Richmond (Cal OES, DHS, and FEMA, 2016). The Mass Care Task Force defined by the plan—to be composed of State and Federal agencies and augmented by nongovernmental organizations, such as the American Red Cross—is responsible for addressing the needs of an estimated 550,000 commuters and approximately 330,000 individuals immediately seeking sheltering support after a major earthquake and feeding operations for approximately 1.75 million people per day and water services for as many as 5 million people.

The "Bay Area Earthquake Plan" also estimates that there are about 2,000 shelters in the 16-county region[6] that, as of January 2014, could accommodate about 800,000 evacuating individuals and 280,000 individuals who require temporary shelter. However, damage to potential shelter sites and personnel shortages (including a shortage of building inspectors to assess safe entry to these sites), may substantially reduce the actual available number. Shelters also need to be accessible to persons with disabilities or other access and functional needs.

In the HayWired scenario, available shelters in the nine-county region may quickly reach capacity, especially in heavily impacted areas, such as Alameda and Contra Costa Counties. In this case, the "Bay Area Earthquake Plan" identifies potential host areas in surrounding counties, such as Mendocino, Sacramento, Yolo, San Joaquin, San Benito, Monterey, and Santa Cruz Counties that are less likely to sustain heavy damage. If the immediate sheltering needs exceed the 16-county regional sheltering capacity, some people may need to relocate to other parts of California or adjoining States. The "Bay Area Earthquake Plan" estimates that there is additional shelter capacity for millions elsewhere in California and the adjoining States of Oregon, Nevada, and Arizona. As revealed after Hurricane Katrina, people who are displaced farther away from their home communities are more likely to have difficulty returning, especially socioeconomically vulnerable populations (Weber and Peek, 2012; Esnard and Sapat, 2014).

[6]This includes the nine-county region abutting San Francisco Bay, plus adjoining counties of Mendocino to the north; San Joaquin, Yolo, and Sacramento to the east; and Santa Cruz, San Benito, and Monterey to the south.

Interim Housing Issues

In the days and weeks following the M_w 7.0 mainshock of the HayWired scenario, many displaced residents may be able to return to their neighborhoods and homes as access controls are lifted, lifeline utility services are restored, and structures are deemed safe to reoccupy. The occupants of damaged housing units will most likely need alternative, or interim, housing while repairs and rebuilding take place, or until other permanent housing is available. Interim housing needs could also increase significantly if the recovery times for critical sewer, water, energy, transportation, education, and health services are extensive.

The "Bay Area Earthquake Plan" calls for the postdisaster formation of a joint State and Federal housing task force to expedite Federal assistance and develop programs that provide adequate, affordable, and appropriate housing for all affected communities, including those with access and functional needs (Cal OES, DHS, and FEMA, 2016). Three assistance programs that tend to dominate the form and pace of interim housing supplies after federally declared disasters are as follows:

- FEMA's Transitional Sheltering Assistance pays hotels and motels directly for short-term lodging for disaster survivors and evacuees for an initial period of 5–14 days, with extensions possible (FEMA, 2018; Webster, 2019).
- The FEMA Individual Assistance programs provide funds to homeowners to repair damages and for temporary housing assistance, typically in the form of manufactured homes and directly leased multifamily rental properties for as long as 18 months, with extensions possible. FEMA can also provide direct assistance to repair moderately damaged homes for applicants with limited resources (FEMA, 2019).
- The HUD Housing Choice Voucher program, public housing program, and project-based rental assistance programs provide temporary housing for individuals and families who were receiving assistance before the disaster as well as others (McCarty and others, 2005).

The "Bay Area Earthquake Plan" and the "Regional Catastrophic Earthquake Interim Housing Plan" are consistent with the "National Disaster Housing Strategy" in prioritizing the use of existing housing resources, such as vacant rental properties, hotels, and motels, to the extent that they are available, ahead of temporary housing installations, such as manufactured homes or other forms of interim housing that have to be constructed (FEMA, 2009; Bay Area UASI, 2011; Cal OES, DHS, and FEMA, 2016).

Using existing housing resources will be difficult. The San Francisco Bay region has been experiencing housing shortages and affordability issues for both for-sale and rental housing and at all income levels since at least the 1990s (Metcalf, 2017). In 2016, RealtyTrac reported that housing vacancies were nearly nonexistent, with the San Jose metropolitan area at 0.2 percent and San Francisco at 0.3 percent (Pacific Union, 2016). The post-earthquake demand for interim housing will rapidly deplete any available rental units, as well as hotel and motel rooms that will also be in demand by post-earthquake response and recovery personnel.

Temporary housing units (for example, trailers, manufactured homes, and alternative units) may need to be constructed or brought into the region. At its peak capacity, FEMA has been able to provide direct housing support for more than 10,000 households per month using temporary housing units such as manufactured homes (Bay Area UASI, 2011). At this rate of production and installation, it would take months to meet the demand following a major earthquake like the HayWired scenario. Single-unit installations of temporary housing, such as on an existing single-family home site, are generally faster to complete than the construction of group, or community, temporary housing sites. Community temporary housing sites may require site preparation, utilities, access roads, and security structures and typically take 60 to 90 days to complete (Bay Area UASI, 2011). Such sites also need access to transportation, schools, health care, and other community services.

With the available housing stock reduced, for-sale and rental housing prices are also likely to increase, perhaps dramatically, in the nine-county region. Housing price escalations occurred in Sonoma County and the northern bay region following the 2017 wildfires, requiring local officials to prohibit rental housing price gouging (City of Santa Rosa, 2017) and consider additional eviction protections for renters (McCallum, 2017).

As of March 2019, the median home sale price for the nine-county region was $830,000, which is nearly four times the national average, with the median prices in Alameda and Contra Costa Counties at $822,000 and $603,000, respectively (CoreLogic, Inc., 2019). ADOBO puts San Francisco, Oakland, and San Jose in the top ten highest rent cities in the country (Weber, 2017). Rents averaged $2,731 monthly in the San Francisco Bay region in October 2018, an increase of 4.5 percent year over year, with San Francisco rents reaching an average of $3,650, the highest in the country (Littman, 2018). As a result, homeowners and renters in the nine-county region have been spending more of their income on housing than anywhere else in the United States, averaging more than 40 percent in San Francisco and San Jose in 2017 (Zillow Research, 2017). Many low-income neighborhoods in the San Francisco Bay region have already been undergoing gentrification and displacement and high-income neighborhoods have been rapidly losing their existing low-income populations (Zuk and Chapple, 2015).

Renters, particularly lower income renters, and people with access and functional needs may have more difficulty finding alternative housing. Displaced households from public housing or those displaced individuals and families relying on Housing Choice Vouchers (HCV) or other housing subsidies may be especially vulnerable to displacement, or have a harder time finding alternative housing, because of their financial constraints. In recent years, the San Francisco Bay region's housing shortage and high rental prices have dramatically affected low income people using HCVs and other forms of housing subsidies. As an example, between 2014 and 2016, the City of Oakland lost 1,200 of its 7,000 HCV landlords

(Drummond, 2016). HCV households present a long-term recovery challenge (see section C).

Past disaster studies have also shown that individuals and families enduring interim and irregular housing situations for months and years after a disaster are more vulnerable to physical, social, and mental disorders, including suicide, substance abuse, and physical and verbal abuse (Enarson and others, 2007; Tatsuki, 2007; Nielsen, 2015). After the 2010–11 Canterbury, New Zealand, earthquake sequence, semi-annual surveys of the wellbeing of the region's residents identified major individual and household stressors that included anxiety caused by ongoing aftershocks and added pressures resulting from living in a damaged environment, insurance settlement issues, difficult transport, and additional work-related demands (Nielsen, 2015). Aftershocks in the HayWired scenario would not add substantial numbers to the interim housing demands but there could be ripple effects for mental health, displacement, and housing.

Potential Receiving Communities for Displaced Populations

In a major earthquake, like that in the HayWired scenario, widespread housing damage and preexisting housing market constraints in the San Francisco Bay region will make it extremely challenging to provide quick and affordable interim housing resources and keep people near their home communities, especially in areas of concentrated damage. Socially and economically vulnerable populations have a much harder time finding alternative housing near their home communities (Peacock and others, 2014; Fussell, 2015). As a result, tens of thousands of households may be required to leave their home communities to find available housing. More distant and more permanent relocations may also result from the lack of interim housing resources.

The "Bay Area Earthquake Plan," "Regional Catastrophic Earthquake Interim Housing Plan," "National Disaster Housing Strategy," and other Federal, State, and local emergency plans identified in table B13 do not offer much guidance on the potential "receiving communities" for residents displaced from their home communities by a major earthquake, like the HayWired scenario. However, past disaster experiences have shown that emergency sheltering and interim housing decisions made and actions taken early on in a major disaster by local, State, and Federal response personnel may greatly influence the geographic pattern of population displacement and locations of potential receiving communities (Mueller and others, 2011; Esnard and Sapat, 2014). Studies of the spatial economic demand shift in Louisiana, Mississippi, and Alabama after Hurricane Katrina showed that people migrated to places at the edge of the disaster area with minimal to no damage and, in some instances, stayed there for several years (Xiao and Nilawar, 2013).

Similarly, after Hurricane Katrina, jobs migrated to the edge of the disaster area; the area was predisposed for growth and there were advantages of staying close (Xiao and Nilawar, 2013). Wein, Belzer, and others (this volume) find that nearly 420,000 employees live and (or) work in areas of concentrated damage; specifically, about 230,000 employees work in areas of concentrated damage and about 96,000 people also live in these areas. Residents in Alameda County work closer to home, but tens of thousands of employees living in areas of concentrated damage work further afield in San Francisco and Santa Clara Counties (about 50,500 and 32,500 employees, respectively). The availability of interim housing for displaced households in the vicinity of San Francisco and Santa Clara County jobs could influence whether these households would remain in the region.

Given these insights and constraints, it is likely that communities with the capacity to become major receiving communities will be outside the central urbanized core and in less-damaged edge communities of the nine-county region as well as in the seven surrounding counties—Mendocino, Sacramento, Yolo, San Joaquin, San Benito, Monterey, and Santa Cruz Counties—and particularly larger cities within these counties, such as Sacramento, Stockton, Modesto, and Salinas. However, the combination of damaged regional highways and the BART system could severely impede commuter transport. Regional emergency transportation plans to provide added capacity to the region's ferry and public transportation network after a major disaster (Cal OES, DHS, and FEMA, 2016; San Francisco Bay Area Water Emergency Transportation Authority, 2016) would need to be extended both further afield and over a longer period of time to enhance the viability and desirability of interim housing options in some of these areas. Others may relocate to other parts of California, the adjoining states of Oregon, Nevada, and Arizona, or even further afield.

All displaced households will require much more than housing and there will be simultaneous increased demands on community services and infrastructure in receiving communities. Displaced households will have needs for basic necessities, health care and employment assistance, childcare and access to schools, and other community services. It is important that receiving communities plan for and have support for these services, and that the services be offered simultaneously or sequenced in a way that helps settle residents and enhance their recovery (Tobin-Gurley and others, 2010).

Anticipating Population Return

There are factors internal and external to disaster-impacted areas that can influence the duration of displacement and rate of population return (Fraser and others, 2003; Greer, 2015; Husby and Koks, 2017). The restoration of damaged housing or construction of new housing are major factors. Past disasters have shown that it takes at least two years to replace a significant portion of housing; multifamily and affordable housing is much more difficult and slower to replace than single-family, market-rate housing (San Francisco Bay Area Planning and Urban Research Association [SPUR], 2012). Aftershocks and an array of postdisaster conditions, including additional damage; lack of schools, health care, and other services; lack of social ties; delays

in the recovery efforts; and concerns about future earthquake risks, could also delay population return and increase potential outmigration from the region. Furthermore, if displaced residents find better schools, more affordable housing, and new jobs in other places, they may delay returning or choose not to return to their home communities, no matter how fast or effective the rebuild.

In Kroll and others (this volume), the macroeconomic response to output losses from earthquake and fire damages to buildings are compared to the San Francisco Bay region economic forecast for employment, population, and gross regional product. These economic indicators drop in the first year (2018), start recovering in the second year, and the path back to the forecasted levels takes at least 10 years. In the first year, population declines caused by economic impacts range from 80,000 (with a recovery financing stimulus) to 336,000 (with larger than forecasted outmigration). The largest uncertainty in recovery is found to be increased construction costs that exacerbate population losses until 2040. A technology-industry exodus emerges as potentially the most enduring impact on employment, population, and the gross regional product of the region and does not fully recover by 2040.

Past disasters have also shown that population recovery in some communities does not necessarily equate to a return of predisaster residents (Johnson and Olshansky, 2017). Postdisaster changes in the demographic composition of impacted communities is common, with new people, notably recovery workers and the reconstruction labor force, moving in, sometimes permanently. For example, there is a larger population of young adults and Latinos in the recovered city of New Orleans than before Hurricane Katrina (The Data Center, 2019). The population of Christchurch, New Zealand, is also younger and more male than before the 2010–11 Canterbury earthquake sequence (Canterbury District Health Board, 2013).

Discussion

Disaster research in the United States has mainly focused on short-term, localized population displacements and disaster-related planning and policies for evacuations, emergency and temporary sheltering, and population care; much less is known about—and data is lacking on—long-term population displacement and inmigration. Hurricane Katrina brought to light the myriad voluntary and forced movements of people that can occur over time and the disproportionate effects on physically and socioeconomically vulnerable populations and communities as a result of direct and indirect disaster impacts as well as disaster policies and plans.

This section uses past disaster research and experiences to consider the potential size and composition of the San Francisco Bay region's population and households that could be displaced as a result of key physical impacts of the HayWired earthquake scenario. The analysis explores a series of socioeconomic vulnerabilities and attributes that could contribute to postdisaster population displacement and people's ability to return. Other sections of the chapter also look at: (1) Federal, State, and local emergency response policies and plans, (2) other issues related to emergency sheltering and temporary housing that may impact displacement, and (3) potential issues influencing population return.

Three different approaches are taken to estimate populations and households at risk of displacement owing to building damage and other physical impacts of the HayWired scenario. The lower end of household displacement estimates uses a customized analysis in Hazus to estimate 152,438 households and 412, 954 people (or 6 percent of the nine-county region's total households and population) displaced by shaking and liquefaction damages to buildings from the mainshock of the HayWired scenario. Based on prior earthquakes, power and water outages are thought to increase these estimates by 20 percent. The upper end estimate includes damages from landslides and fires and the compounding effects of concentrated damage (specifically, census tracts with 20 percent or more of the building square footage in an extensive or complete damage state) from the HayWired mainshock. The largest population exposure is in areas with concentrated damage to multifamily dwellings, where a total of 520,210 households and 1,451,838 people reside (or 20 percent of the nine-county totals). County-level comparisons show as much as 23 percent of households and population in Alameda County reside in the areas of concentrated damage.

Longer term, forced or voluntary displacements of people and the interim and permanent housing needs resulting from building damage and fires, lifeline infrastructure damage and outages, and environmental health threats following a major earthquake are not well addressed in regionally focused earthquake response plans. Neither the "Bay Area Earthquake Plan" (estimating around 330,000 individuals will require shelter after a major San Andreas Fault earthquake) nor the "Regional Catastrophic Earthquake Interim Housing Plan" (estimating around 400,000 displaced households after a M_w 7.9 San Andreas Fault earthquake) consider the possibility of widespread fires and extensive lifeline utility disruptions.

The short-term sheltering and interim housing affects outcomes for displacement. Available shelters in the nine-county region may quickly reach capacity, especially in heavily impacted areas, such as Alameda and Contra Costa Counties. The "Bay Area Earthquake Plan" identifies additional shelter capacity in California and the adjoining States of Oregon, Nevada, and Arizona. Populations who need to use these more distant shelter options would be more likely to have difficulty returning, especially socioeconomically vulnerable populations, as seen after Hurricane Katrina (Weber and Peek, 2012; Esnard and Sapat, 2014).

Returning occupants of damaged housing units will most likely need alternative, or interim, housing while repairs and rebuilding take place, or until other permanent housing is available. The "Bay Area Earthquake Plan" and the "Regional Catastrophic Earthquake Interim Housing Plan" prioritize the use of existing housing resources, but housing shortages and affordability will limit this option. It would take FEMA months to meet the demand for temporary housing after a major earthquake

like the HayWired scenario. With the available housing stock reduced, for-sale and rental housing prices are also likely to increase, perhaps dramatically, in the nine-county region. Renters, particularly lower income renters, and people with access and functional needs may have more difficulty finding alternative housing through already impacted housing subsidy programs.

As indicated above, displacement is exacerbated by socioeconomic vulnerability of affected populations. We explore socioeconomic vulnerability characteristics of populations in areas of concentrated damage of all building occupancies. A series of ten socioeconomic characteristics, known to affect the abilities of individuals and households to prepare for, respond to, and recover from a disaster, are used to identify the prevalence of vulnerability indicators for residents of areas of concentrated damage. The analysis found that more than 350,000 people reside in block groups with ABAG/BCDC community vulnerability indicator (CVI) scores of 5 or greater in the areas of concentrated damage in Alameda, Contra Costa, and Solano Counties. These areas correspond to a greater prevalence of housing- and income-related indicators (for example, lack of home ownership, high housing-cost burden, low household incomes) and literacy indicators (for example, low levels of education and more non-English speakers).

To fill in some gaps in identifying population groups that past disasters have shown to have protracted or permanent displacement or relocation, additional analyses using 2012–2016 ACS 5-year estimates were performed to identify households with school-age children, persons with disabilities, homeless populations, and young and mobile populations that might voluntarily or forcibly be displaced from their home communities in the HayWired scenario. Young and mobile populations may represent a cohort of the population with means, mobility, and a lack of social ties or tolerance for staying in the region after a major earthquake like that in the HayWired scenario. They were identified in terms of young (25–34 years old) renter householders, households without children, and above median county income or rental costs.

Communities with the capacity to become major receiving communities will likely be outside the central urbanized core and in less-damaged edge communities of the nine-county region as well as larger cities in the seven surrounding counties—Mendocino, Sacramento, Yolo, San Joaquin, San Benito, Monterey, and Santa Cruz Counties. These receiving communities will need plans to support increases in necessary community services (health care, schooling, and so on) to help the inmigrating population settle and recover.

Many factors affect whether displaced residents return to their homes following a major disaster like the HayWired earthquake scenario. Protracted housing stock restoration times (particularly for multifamily housing), postdisaster conditions (for example, recurring aftershocks), lack of community services, lack of social ties, and flexibility of job locations, among others, could delay population return or exacerbate outmigration. In addition, some displaced people may prefer the amenities (schools, jobs, and so on) in their receiving communities and choose to stay there rather than returning. Postdisaster changes in the demographic composition of impacted communities is common, with new people, notably recovery workers and the reconstruction labor force, moving in, sometimes permanently.

Assumptions and approaches taken in this analysis draw heavily on the studies of forced and voluntary movements of people after Hurricane Katrina, particularly in New Orleans. Some areas of potential follow-up study to enhance our understanding of the potential post-earthquake population displacement risks in the San Francisco Bay region include:

- Systematic and integrated data collection on preexisting physical (built and environmental), social, economic, and political conditions of disaster-vulnerable communities in the San Francisco Bay region. Although some such data are available, particularly socioeconomic data, they are rarely integrated with physical and political conditions.

- Gather more detailed information on emergency shelter facilities and locations in the San Francisco Bay region to evaluate their likely seismic performance and actual sheltering capacity in this scenario and other potential earthquake scenarios, which could then be used to compare the potential population movements with shelter capacity and better understand the relation between sheltering and displacement.

- Research on the extent to which potential receiving counties and cities in the San Francisco Bay region and other parts of California are planning for resettlement of disaster-displaced populations.

Areas of research revealed by this analysis that would enhance the understanding of postdisaster population movements and vulnerabilities and our ability to forecast and potentially mitigate these risks include:

- Systematic and longitudinal study, in a variety of postdisaster cases, of the factors influencing recovery decision making by affected residents and governments and the physical location, demographic composition, and size of displaced population groups, as well as the likely timing and conditions for their return or replacement, especially within major racial/ethnic groups, for different household income levels, and for different damage thresholds and concentrations.

- Development of post-event monitoring and forecasting tools for widespread and long-term population displacement that go beyond current considerations of income, race, and ethnicity to consider the effects of land and building damage concentrations, utility outages, secondary hazards of fire and environmental spills, aftershocks, and other subsequent disasters.

- Development of postdisaster population retention goals and targets for displacement management that ensure community well-being and the social infrastructure that communities, especially vulnerable communities, depend on remain intact after a major earthquake.

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Section C

Long-Term Community Recovery Challenges

Introduction

"Reconstruction Following Disaster," by Haas and others (1977), was one of the first studies to take a comprehensive and multidisaster view of community recovery after a disaster. They found that the overall time that a community needs to recover is a function of preexisting trends, damages suffered, resources available for recovery, and leadership, planning, and organization (Haas and others, 1977). Other longitudinal studies of community recovery have observed the process of postdisaster community recovery as being quite complex, with: differential rates of recovery across communities (Alesch and others, 2009); an array of social, political, and economic forces influencing the recovery trajectories and outcomes for individuals, households, and communities (Bolin and Stanford, 1998; Esnard and Sapat, 2014; Johnson and Olshansky, 2017; Sapat and Esnard, 2017); and a phenomena of postdisaster "time compression" resulting from the simultaneous demand to replace lost capital stock and services (Olshansky and others, 2012, p. 173). Moreover, researchers also now caution that recovery is not necessarily a given outcome, as some communities never fully recover and change is an inevitable part of the process (Alesch and others, 2009).

Reestablishing permanent housing is crucial to both household and community-scale disaster recovery (Peacock and others, 2007). If housing recovery is impaired, then other dimensions of community recovery are also delayed. Looking at a diverse range of natural disasters both in the United States and abroad, Comerio (1998, p. 166–169) identified five characteristics of the housing stock and its inhabitants that can inform the capacity of a community to contain the degree of postdisaster housing challenges:

- Composition of the housing stock, particularly single-family versus multifamily structures, with multifamily structures typically presenting greater recovery challenges;
- Age and physical condition of the housing stock, as indicators of structural vulnerability;
- Housing market conditions and vacancy rates and trends, which tend to be amplified by a disaster;
- Rebuilding cost-to-debt ratios, which influence the building-by-building decisions of owners; and the
- Social and economic status of survivors.

Even in a moderately-sized earthquake, like the 2014 moment magnitude (M_w) 6.0 South Napa earthquake, California, the amount of earthquake damage, predisaster household earnings, and wealth of the population were found to be major predictors of housing recovery (Despotaki and others, 2017). Longitudinal studies of housing recovery following the 1989 Loma Prieta and 1994 Northridge earthquakes (Comerio and Blecher, 2010), 1992 Hurricane Andrew and 2008 Hurricane Ike (Peacock and others, 2014), and 2005 Hurricane Katrina (Groen and Polivka, 2010; Fussell, 2015) found that owner-occupied housing and higher income neighborhoods generally suffered less damage and recovered more quickly than rental housing and lower income neighborhoods. Furthermore, multifamily housing tends to recover more slowly and is more vulnerable to abandonment, blight, neighborhood destabilization, and change than single-family housing.

After a disaster, both people and housing face a host of complex recovery dependencies and interdependencies with each other and with other major elements of a community, like infrastructure, critical services, and businesses, as they all work to reconstitute themselves and recover (Miles and Chang, 2006; Hayashi, 2007; Peacock and others, 2007). The resilience of varying community elements, including residents, housing, infrastructure, and institutions, can help to contain the degree of postdisaster challenges and other cascading consequences. Also, pre- and postdisaster policies, planning interventions, decisions, and actions can strongly influence the cascading consequences of disasters and the overall pace and effectiveness of the recovery process (Smith and Wenger, 2007; Johnson and Olshansky, 2017).

The complexity of the postdisaster recovery process and the lack of systematic data on preexisting conditions, physical repair and recovery times, and outcomes from past disasters have limited the development of quantitative metrics and models for long-term disaster recovery at a community scale (Olshansky and Chang, 2009; Despotaki and others, 2017). The Federal Emergency Management Agency's (FEMA) Hazus-MH 2.1 (hereafter referred to as Hazus) and other computer-based loss estimation tools mainly provide estimates and information on the immediate impacts, response needs, and economic costs of disasters. Understanding the factors that most strongly influence long-term recovery, as well as how certain policy and planning interventions and other external factors can affect recovery, are essential to advancing the development of community-scale recovery modeling and metrics (Olshansky and Chang, 2009; Siembieda, 2012; Nejat and Ghosh, 2016; Burton and Kang, 2017; Despotaki and others, 2017).

This section of the communities-at-risk analysis examines the long-term community recovery challenges that may result from a major earthquake in the San Francisco Bay region, like that in the HayWired earthquake scenario. It is organized around three key issues: assembling the financing resources for recovery, repairing and rebuilding damaged housing, and addressing areas that require substantial governmental interventions and replanning in order to recover. Chapters V1–V5 of the HayWired scenario volume 3 provide a complementary perspective on potential

impacts on businesses and jobs in different economic sectors, relations between jobs and housing, as well as issues and timelines associated with the region's economic recovery.

Assembling the Financial Resources for Recovery

Money fuels disaster recovery and its availability largely determines the pace and scope of community recovery (Johnson and Olshansky, 2017). In a major earthquake sequence like that in the HayWired scenario, it will be difficult for residents, businesses, and governmental and nongovernmental agencies to quickly assemble the substantial resources necessary to fund repairs and rebuilding.

Estimates of Total Losses in the HayWired Scenario

The HayWired scenario loss estimates are derived using Hazus. These can be compared to loss estimates for insurance purposes.

Hazus Loss Estimates

Seligson and others (2018) present their "best estimate" of the losses for all building occupancy types caused by the HayWired scenario mainshock and the 16 largest aftershocks as totaling $82.6 billion in 2016 U.S. dollars. This includes:

- $53.3 billion in damage to the region's buildings.
- $17.0 billion in damage to contents and commercial inventories.
- $12.3 billion in building-damage-related income losses (such as relocation costs, lost rent, and so on).

This estimate does not include damage to the region's utilities and transportation infrastructure, the losses resulting from post-earthquake fires, or the indirect and induced economic impacts that could result in considerable additional losses across the region for several years. In the economics chapters of this volume, Kroll and others (this volume) examine the effects of building-damage-related output losses and transportation disruption on gross regional product, population, and employment and Sue Wing and others (this volume) analyze direct, indirect, and induced economic impacts of building capital losses and utility disruption.

Separately, Scawthorn (2018) estimates that fires following the M_w 7.0 mainshock of the HayWired scenario would cause about $30 billion (2016 U.S. dollars) in losses for the replacement of structures, contents, and other improvements, as well as additional living expenses. It is important to note that the Seligson and others (2018) and Scawthorn (2018) estimates are not directly additive because they assume different replacement cost values. In addition, some buildings will have both fire and other earthquake damage that, individually, might sum to more than the total replacement value of the building.

In section A, fire-based building damage was integrated with the Hazus property-damage assessments to remove the potential double counting of losses for buildings with both fire and other earthquake damage (referred to as "burned rubble"). The additional complete property damage from fire is calculated by taking the total building exposure (structural and nonstructural) and the total building content exposure in the Hazus inventory for each occupancy class and multiplying these exposures by the additional proportion of the occupancy class square footage burned by fire in each census tract. Applying Hazus replacement values, additional losses from fire are about $20 billion (2016 U.S. dollars). The difference is (1) removal of "burned rubble" and (2) the lower average replacement cost of $168 per square foot for the region's buildings in Hazus (2016 dollars),[7] which is less than Scawthorn's (2018) estimate of $200 per square foot. These results can be found in Jones and others (2020).

An overall estimate of losses, based on (1) the Hazus methodology for property and direct income losses across the entire HayWired scenario earthquake sequence and (2) Hazus property replacement costs applied to the Scawthorn (2018) fire following earthquake (mainshock) damages after removing burned rubble, sums to around $102 billion in damages (2016 U.S. dollars). Of this, about 43.5 percent are residential losses and 56.5 percent are nonresidential losses.

CoreLogic Loss Estimates

CoreLogic, Inc. (2018) calculated the potential losses for the HayWired scenario using the U.S. Geological Survey ShakeMaps for the M_w 7.0 HayWired scenario mainshock and the 16 largest magnitude aftershocks. Their estimate of $167.3 billion in potential damage to commercial and residential property as well as automobiles caused by earthquake ground shaking, landslide, liquefaction, and fire hazards includes $23.7 billion in damage generated by the aftershock sequence. Commercial property includes nonresidential properties that are contained in the county assessor data, including government-occupied buildings that pay property taxes. These damage estimates were developed using the CoreLogic U.S. Earthquake Model, Risk Quantification and Engineering modeling platform, and a proprietary database of property insurance exposure data for commercial, residential, and automobile lines of business. The commercial and residential exposure data are for the general property insurance exposures, and not the earthquake-specific peril policies. They represent the total insured values for building, contents, and time element coverages (for example, additional living expenses and business interruption).

Table C1 shows the county distribution of the CoreLogic, Inc. (2018) estimates of total damage for commercial and residential property and automobiles, including damage-related business interruption, for the M_w 7.0 mainshock of the HayWired

[7]Average replacement cost is calculated from the Hazus exposure value divided by the Hazus square footage in the region. U.S. dollar values for 2005 are adjusted to 2016 U.S. dollars using the Consumer Price Index value of 1.23.

Table C1. CoreLogic, Inc. county-level estimates (in millions of dollars) of property damage for the moment magnitude 7.0 HayWired scenario mainshock and aftershock sequence in the San Francisco Bay region, California.

[Values in millions of 2016 U.S. dollars. Totals may not sum exactly because of rounding. Data from CoreLogic, Inc., 2018. %, percent]

County	Commercial	Residential	Automobile	Total	Percentage of total damage
County details					
Alameda	$28,065	$32,235	$208	$60,509	43
Contra Costa	$13,139	$7,620	$50	$20,809	15
Marin	$1,150	$806	$6	$1,962	1
Napa	$751	$343	$5	$1,099	1
San Francisco	$7,902	$1,975	$18	$9,895	7
San Mateo	$4,407	$3,209	$25	$7,641	5
Santa Clara	$14,241	$10,471	$83	$24,795	18
Solano	$1,297	$681	$8	$1,986	1
Sonoma	$3,601	$1,890	$21	$5,512	4
Surrounding counties[1]	$4,269	$1,123	$26	$5,418	4
Subtotal of county property damage for the mainshock	**$78,821**	**$60,352**	**$451**	**$139,625**	
Miscellaneous details					
Percentage of county property damage subtotal for the mainshock	56.5%	43.2%	0.3%		
Fire damage total for the mainshock[2, 3]	$1,000	$1,000		$2,000	
Sprinkler damage total for the mainshock[3]	$1,000	$1,000		$2,000	
Cumulative damage from aftershocks	$14,789	$8,762	$134	$23,685	
Total	**$95,610**	**$71,114**	**$585**	**$167,310**	

[1]Includes Merced, Monterey, Sacramento, San Benito, San Joaquin, Santa Cruz, Stanislaus, and Yolo Counties.

[2]Automobile fire damage is included in the commercial and residential fire damage estimates.

[3]Fire and sprinkler damage totals were originally reported in billions, but have been converted to millions here.

scenario. More than 56 percent of the estimated damage is from commercial property losses and 43 percent from residential property losses. Also, more than 40 percent of the damage is incurred in Alameda County. Contra Costa and Santa Clara Counties also have high proportions of the total property damage, at 15 and 18 percent, respectively. Additional fire and sprinkler damage caused by the mainshock amounts to $4 billion and is split equally between the commercial and residential lines of business; the automobile fire damage is included in the commercial and residential fire damage estimates.

Comparison of HayWired and CoreLogic Loss Estimates

The CoreLogic, Inc. (2018) analysis of insured commercial and residential property damage for the HayWired scenario provides a comparable estimate to the HayWired integrated property damage estimate. Neither estimate accounts for damage to the region's infrastructure, contingent business interruption (resulting from supply chain disruptions), or other longer term indirect and induced economic impacts of damages from such a major disaster. Also, the CoreLogic, Inc. (2018) estimates do not account for workers compensation exposures or some government exposures.

Some of the differences between the CoreLogic and HayWired integrated losses are likely the rebuilding cost assumptions. CoreLogic estimates the repair and rebuild costs for each building depending on fit and finish, materials, and labor. The region's average building replacement value assumed in the Hazus analysis is $168 per square foot (in 2016 U.S. dollars), and Scawthorn (2018) estimates that even the $200 per square foot of building replacement used in the fire-following-earthquake analysis for the HayWired scenario is conservative, given prevailing construction rates in the San Francisco Bay region. At $330 per square foot, San Francisco already has the second highest construction costs in the country, behind only New York City (Sawyer, 2017). Furthermore, large-scale disasters place simultaneous demands on construction labor, materials, and equipment, which then inflate postdisaster construction costs (Olsen, 2012). Thus, the actual cost of repairs and rebuilding could be substantially higher than the Hazus estimate because of the already high construction costs in the region and postdisaster construction cost inflation.

CoreLogic, Inc. (2018) estimates $2 billion in fire-related insurance losses in the HayWired scenario. Scawthorn (2018) estimates that there could be close to $30 billion in replacement value for properties damaged by fires in the HayWired scenario, and a significant portion of that damage would likely be covered

by general property insurance. For comparison, in the 1991 fire in the east bay hills, 3,500 homes were lost, resulting in about $1 billion in insured losses (1992 U.S. dollars; $1.72 billion in 2016 U.S. dollars) (Scawthorn, 2018), and the 2017 northern California wildfires resulted in more than $11 billion in insured losses from damage to more than 21,000 homes and 2,800 businesses (Verma, 2017; Aon Benfield, 2018).

In a prior analysis, Risk Management Solutions modeled potential losses from a major earthquake on the Hayward Fault (Grossi and Zoback, 2013). Their estimates of residential and commercial property damage for three M_w 7.0 earthquake scenarios that rupture the entire Hayward Fault vary between $172.5 and $186.5 billion (2013 U.S. dollars; between $177.7 and $192.1 billion in 2016 U.S. dollars). The Grossi and Zoback (2013) county distributions of losses and percentages of values are comparable to the CoreLogic, Inc (2018) values, with Alameda, Contra Costa, and Santa Clara Counties having the greatest losses.

Though there are some significant discrepancies between the Hazus-based and insurance modelers' building-related loss estimates, the important point to consider is the scale of loss—a loss that does not yet account for the longer term indirect and induced losses that are not directly related to property damage but caused by social and economic disruption. These estimates vastly surpass any modern disaster experience in the San Francisco Bay region. For perspective, the M_w 6.9 Loma Prieta earthquake of 1989 caused about $10 billion in economic losses at the time (approximately $19.6 billion in 2016 U.S. dollars) and the M_w 6.0 South Napa earthquake of 2014 caused more than $700 million in economic losses (Insurance Information Institute, 2018).

Recovery Funding Sources

Table C2 summarizes the kinds of resources and programs that are typically used to fund recovery from major disasters that are declared as both State and Federal disasters. They include insurance, Federal disaster grants and loans, State disaster grants and loans, local government resources, and philanthropic and private investments. Two of the most significant sources of recovery funding—insurance and Federal and State government resources—are discussed in the following sections.

Insurance Resources for Recovery

In most areas of the United States, insurance is a foundational element of a community's disaster recovery. According to national surveys, about 95 percent of homeowners have basic residential insurance coverage (Wilkinson, 2016). In California, however, earthquake insurance is generally offered as a separate policy from the general property insurance. The California Department of Insurance (CDI) regularly conducts a data call to estimate the residential property insurance coverage across the State; the latest published data available is from December 31, 2017 (CDI, 2017). Table C3 provides the residential fire and earthquake insurance policy counts for homeowners, condominiums, renters, and mobile homes for the nine-county San Francisco Bay region. The residential fire insurance policy is comparable to a general property insurance policy, and among all policyholders in the nine-county region, only about 10 percent have an earthquake insurance policy. About two-thirds of the residential earthquake insurance policies statewide are provided by the California Earthquake Authority, which is a not-for-profit, privately funded, and publicly managed organization.

Most of the commercial earthquake insurance in the State covers large commercial buildings. Smaller commercial businesses do not typically buy earthquake insurance because of the cost, the short time horizon of small businesses, and the small amount of assets at risk (CDI, 2012).

CoreLogic, Inc. (2018) estimates $30.2 billion in insured losses for the HayWired scenario, which means that about 18 percent of their total loss estimate is covered by insurance. Table C4 shows CoreLogic, Inc.'s (2018) county-level estimates of earthquake property insurance payments for the M_w 7.0 mainshock of the HayWired scenario, as well as insured losses for fire and sprinkler damage for the mainshock and cumulative insured losses for the aftershock sequence. CoreLogic, Inc. (2018) also calculates $21.2 billion in insured losses to commercial and residential properties, as well as automobiles, caused by earthquake-hazard-related damages (such as ground shaking, landslide, and liquefaction). Insured losses for fire and sprinkler damage add $4 billion to the mainshock estimate and the cumulative insured losses for the aftershock sequence totals $5 billion. These estimates do not include the insured losses for damage to the region's infrastructure, workers compensation exposures, and government exposures that are not part of the commercial, residential, and automobile lines of business, or the longer term indirect and induced economic impacts of a major disaster.

About 75 percent of the CoreLogic, Inc. (2018) estimated insured property loss would cover commercial losses (such as buildings, contents, and business interruption) and 25 percent of the total insured property loss would cover residential losses (such as buildings, contents, and additional living expenses). Of the CoreLogic, Inc. (2018) total loss estimates for the HayWired mainshock, insurance would cover about 20 percent of commercial losses and 9 percent of residential losses (calculated by dividing the subtotal of insured losses in table C4 by subtotal of mainshock losses in table C1). Including fire and aftershock losses, insurance would cover about 23 percent of commercial losses and 12 percent of residential losses (total results in table C4).

Approximately 87 percent of the CoreLogic, Inc. (2018) estimate of total insured losses is incurred in Alameda, Contra Costa, and Santa Clara Counties—the three counties with the highest damage levels; but in each, insurance is likely to only cover a small portion of the total damage. For example, about 60 percent of the total insured loss is incurred in Alameda County, but it only covers about 21 percent of the total earthquake-hazard-related losses in the county. Most counties, as well as many cities and municipal districts, in the San Francisco Bay region belong to risk pools that provide workers compensation and property

Table C2. Types of funding available for community recovery after a major disaster.

Funding type	Description
	Insurance
Private market insurance	Policies generally cover structures, contents, and the costs of additional living expenses (residential) or business interruption (commercial and public sector). In California, residential earthquake insurance is provided by the California Earthquake Authority (CEA) as well as private market insurers. The CEA is a not-for-profit, privately funded, and publicly managed entity in which 75 percent of California residential property insurance companies participate and offer CEA earthquake policies. See https://www.earthquakeauthority.com for more information.
State and local insurance pools	Intergovernmental risk pools are formed under state-specific legislation allowing for joint "pooling" of resources to address risks ranging from property loss to employee benefits, tort liability, workers compensation, and more. Pools are owned and governed collectively by their member entities. See https://www.agrip.org/education/pooling-basics for more information.
	Federal disaster grants and loans
Federal Emergency Management Agency (FEMA)	Individual Assistance provides an array of grants and other forms of assistance, including crisis counseling, legal services, and disaster unemployment, directly to renters and displaced homeowners that register with FEMA for assistance and reside within the boundaries of a Federal disaster declaration region. See https://www.fema.gov/individual-disaster-assistance for more information. Public Assistance provides grants to State and local government agencies, private nonprofit organizations, and federally recognized Tribal organizations for debris removal, emergency protective measures, and the repair, replacement, or restoration of disaster-damaged facilities and infrastructure in federally declared disasters. See https://www.fema.gov/public-assistance-local-state-tribal-and-non-profit for more information. Hazard Mitigation Grant Program funding is directed to States and Tribal organizations for hazard mitigation planning and projects in federally declared disasters. See https://www.fema.gov/hazard-mitigation-grant-program for more information. The Community Disaster Loan Program provides loans to assist local governments that suffer a substantial loss of at least 5 percent of its total tax base to maintain existing governmental functions or expand those functions to meet disaster-related needs after federally declared disasters. See https://www.fema.gov/media-library/assets/documents/176527 for more information.
U.S. Department of Housing and Urban Development (HUD)	HUD can expedite the annual awards made through the Community Development Block Grant (CDBG) and HOME Investment Partnerships (HOME) programs for use in a disaster area and also provide mortgage assistance funds; see https://www.hud.gov/info/disasterresources for more information. Congress can also appropriate supplemental emergency funds to HUD for CDBG Disaster Recovery and, to a smaller extent, HOME programs to help rebuild areas affected by major disasters declared by the President; see https://www.hudexchange.info/cdbg-dr for more information. The Federal Housing Administration at HUD provides single-family and multifamily mortgage insurance, the rules of which become more flexible after a disaster; see https://www.hud.gov/info/disasterresources for more information.
U.S. Small Business Administration	Disaster assistance in the form of loans for businesses of all sizes, private nonprofit organizations, and homeowners and renters for damage restoration. See https://disasterloan.sba.gov/ela/Information/Index for more information.
U.S. Economic Development Administration	Grants to disaster-impacted local governments and economic development agencies for planning, infrastructure, and technical assistance with long-term economic recovery. See https://www.eda.gov/disaster-recovery for more information.
Federal Highway Administration	Emergency Relief program funds for freeway and highway repair and restoration. See https://www.fhwa.dot.gov/map21/factsheets/er.cfm for more information.
	State disaster grants and loans
State emergency management agencies	Typically administer the Stafford Act programs and may provide matching funds. The California Disaster Assistance Act also authorizes the director of the California Governor's Office of Emergency Services to provide financial assistance for costs incurred by local governments as a result of a local emergency or other disaster event where State assistance is requested; it does not need to be a federally declared emergency or disaster. It does not include provisions for State financial assistance for households that have been impacted by disasters. See https://www.caloes.ca.gov/cal-oes-divisions/recovery/public-assistance/california-disaster-assistance-act for more information.
Other State agencies and legislatures	May provide a share of matching funds to the Stafford Act programs. Can authorize tax credits and other forms of temporary relief or incentives to help stimulate rebuilding. Involved in recovery, liaising with their counterparts at both the national and local levels. For example, State housing agencies may manage the distribution of Federal funding via HUD's CDBG program to disaster-impacted local governments and residents.

Table C2.—Continued

Funding type	Description
	Local governments
Counties, cities, and special districts, including school and utility districts	Local revenue and reserves. Capital improvements programs can be amended to include infrastructure and public facilities repairs and reconstruction projects associated with disaster recovery. Enhanced infrastructure financing districts can be established in heavily damaged areas to earmark a portion of the taxes paid by property owners who benefit from the improvements to finance the construction or rehabilitation of a wide variety of public infrastructure and private facilities. Public-private partnerships can provide private capital and operational resources to the recovery process. Special taxing and assessment districts can be established, or existing districts can possibly be repurposed or expanded, to collect taxes, fees, or other assessments from property owners located in the designated area in order to help fund recovery programs and projects. Impact fees can be used to underwrite the expansion of or addition to infrastructure and public facilities in postdisaster recovery. Special bonds, loans, and taxes can be used to raise revenue to fund disaster recovery, but there are challenges in assuming an additional debt and in getting an electorate to support them.
	Philanthropic and private investment
Nongovernmental organizations, private nonprofit entities, faith-based organizations, foundations, and businesses	Provide both material and financial assistance to individuals, families, community organizations, and local governments, including needs unmet by Federal disaster assistance, private lender loans, or insurance. Local community foundations can also act as the fiscal agent for local governments to receive monetary donations, which are then disbursed to qualified service-providers in the affected community.

Table C3. Residential fire and earthquake policies per county for the nine-county San Francisco Bay region, California.

[Data are from California Department of Insurance (2017), published December 31, 2017, for insurance residential lines of business. Homeowner columns refer to homeowners and dwellings; condos refer to condominiums (unit interiors)]

County	Fire insurance policy counts				Earthquake insurance policy counts				Earthquake insurance policy take-up rates[1]			
	Homeowners	Condos	Mobile homes	Renters	Homeowners	Condos	Mobile homes	Renters	Homeowners	Condos	Mobile homes	Renters
Alameda	326,816	48,272	4,035	108,645	36,588	3,247	642	14,984	11%	7%	16%	14%
Contra Costa	277,240	39,002	3,225	62,981	20,281	2,313	479	6,631	7%	6%	15%	11%
Marin	65,799	10,767	886	19,835	12,542	1,245	204	3,602	19%	12%	23%	18%
Napa	35,001	2,294	2,590	8,553	2,816	205	478	1,063	8%	9%	18%	12%
San Francisco	114,930	46,729	4	96,453	13,241	4,559	1	19,715	12%	10%	25%	20%
San Mateo	157,107	25,456	1,329	56,387	18,975	2,069	280	6,421	12%	8%	21%	11%
Santa Clara	359,371	66,422	12,180	151,350	41,446	4,023	2,496	13,431	12%	6%	20%	9%
Solano	111,693	5,547	2,145	27,305	7,407	315	429	6,073	7%	6%	20%	22%
Sonoma	131,485	10,153	7,064	35,002	15,558	823	1,417	4,420	12%	8%	20%	13%
Regional total	1,579,442	254,642	33,458	566,511	168,854	18,799	6,426	76,340	11%	7%	19%	13%

[1]A take-up rate is the percentage of fire insurance policy holders who also choose to obtain an earthquake insurance policy.

insurance coverages and, thus, would be providing additional insurance resources for recovery.

Though the CoreLogic, Inc. (2018) and Scawthorn (2018) fire loss differences are not reconciled, an insurance industry loss of more than $30 billion would be comparable in size to the insured property losses after the 2012 Hurricane Sandy (Munich RE, 2015), but less than the expected $135 billion insured losses from the 2017 hurricane season (Kim, 2017; Munich RE, 2018). Nonetheless, as this analysis has shown, a considerable portion of the total losses from a major earthquake, like that in the HayWired scenario, would not be covered by insurance payouts, making it significantly different from most major hurricane and wildfire disasters in the United States.

It is difficult to draw direct comparisons between the insurance estimates for this scenario and the insured losses from the 1989 Loma Prieta and 1994 Northridge earthquakes because the insurance market has changed so much since then. Nonetheless, for the 1989 Loma Prieta earthquake, there was an insured loss of $960 million at the time ($1.9 billion in 2016 dollars) or nearly 10 percent of the total losses and, for the 1994

Table C4. CoreLogic, Inc. county-level estimates of earthquake property insurance payments (in millions of dollars) for the moment magnitude 7.0 HayWired scenario mainshock and aftershock sequence in the San Francisco Bay region, California.

[Values in millions of 2016 U.S. dollars. Totals may not sum exactly because of rounding. Data from CoreLogic, Inc., 2018. %, percent]

County	Commercial	Residential	Automobile	Total	Percentage of insured total loss	Percentage of estimated total damage
County details						
Alameda	$8,994	$3,670	$36	$12,700	60%	21%
Contra Costa	$1,727	$523	$0.4	$2,251	11%	11%
Marin	$70	$95	<$0.1	$165	1%	8%
Napa	$57	$6	<$0.1	$63	0%	6%
San Francisco	$860	$97	<$0.1	$956	5%	10%
San Mateo	$692	$269	$0.2	$962	5%	13%
Santa Clara	$2,997	$524	$0.4	$3,522	17%	14%
Solano	$131	$7	<$0.1	$138	1%	7%
Sonoma	$242	$81	$0.1	$324	2%	6%
Surrounding counties[1]	$73	$12	<$0.1	$86	0%	2%
Subtotal of county insured property loss for the mainshock	**$15,844**	**$5,286**	**$37**	**$21,167**	**100%**	**15%**
Miscellaneous details						
Percentage of county insured property loss subtotal for the mainshock	74.8%	25%	0.2%	100%		
Fire damage insured loss for the mainshock[2, 3]	$1,000	$1,000		$2,000		
Sprinkler damage insured loss for the mainshock[3]	$1,000	$1,000		$2,000		
Cumulative insured loss from aftershocks	$4,020	$1,020		$5,050		
Total	**$21,864**	**$8,306**	**$37**	**$30,210**		
Percentage of estimated total damage	**22.9%**	**11.7%**	**6.3%**	**18%**		

[1]Includes Merced, Monterey, Sacramento, San Benito, San Joaquin, Santa Cruz, Stanislaus, and Yolo Counties.

[2]Automobile fire damage is included in the commercial and residential fire damage estimates.

[3]Fire and sprinkler damage totals were originally reported in billions, but have been converted to millions here.

Northridge earthquake, insurance losses were $15.3 billion at the time ($24.8 billion in 2016 dollars), or 35 percent of the total losses (Munich RE, 2015).

Federal and State Resources for Recovery

A major earthquake like the M_w 7.0 mainshock of the HayWired scenario would almost certainly trigger State and Federal disaster declarations and the provision of disaster assistance programs and activities defined by the California Disaster Assistance Act (California Government Code 8680-8692) and the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Public Law 93-288, as amended) as well as other State and Federal disaster assistance programs and activities.

For Federal fiscal years 2005 through 2014, FEMA obligated more than $104.5 billion from the Disaster Relief Fund for federally declared disasters across the country (U.S. Government Accountability Office [GAO], 2016). The Disaster Relief Fund supports three major Federal postdisaster assistance program areas defined by the Stafford Act and administered by FEMA—Individual Assistance, Public Assistance, and the Hazard Mitigation Grant Program (HMGP). As the GAO (2016) study notes, however, the Disaster Relief Fund provides only a portion of Federal disaster assistance. During the same 10-year period, at least $277.6 billion across 17 Federal departments and agencies was provided for Federal disaster assistance programs and activities (GAO, 2016). Of this, $132.2 billion was obligated for disaster-specific programs and activities outside of the Disaster Relief Fund. Some of the larger obligations were for the Department of Homeland Security, Department of Housing and Urban Development (HUD), Department of Agriculture, Department of Transportation, and Department of Defense, which includes work by the U.S. Army Corps of Engineers.

Many of these obligations must be authorized by Congress as supplemental funds to help rebuild areas affected by federally declared disasters. The HUD Community Development Block Grant Disaster Recovery (CDBG-DR) program is a rapidly growing piece of the Federal government's disaster recovery toolkit and, for recent major disasters like Hurricanes Katrina and Sandy, it has been a crucial resource for State and local governments and homeowners in addressing unmet disaster recovery needs (Olshansky and Johnson, 2014). Also, after major disasters, Congress or the President may authorize tax credits and other forms of temporary relief or incentives to help stimulate

rebuilding. "Disaster Assistance: Guide to Recovery Programs" (FEMA, 2005) identifies an array of Federal programs that may be available for disaster recovery.

Some of the likely sources of Federal and State assistance for individuals and households, businesses, local governments, and community services are reviewed here. Studies from past disasters have shown, however, that race, ethnicity, gender, income, language fluency, cultural differences, and political connectedness can differentially influence the accessibility and distribution of formal disaster assistance, especially from government sources (Bolin, 2007; Enarson and others, 2007; Aldrich, 2011). For the HayWired scenario, some of the hardest hit communities also have high levels of social and economic vulnerability, as indicated by the Association of Bay Area Governments and San Francisco Bay Conservation and Development Commission community vulnerability indicator scores in areas of concentrated damage (see section B), and thus many individuals, households, and business owners in these areas may have difficulty obtaining formal disaster assistance. Language and education limitations, fear of authorities, complicated forms, and limited web-based access to services are just a few of the barriers that socioeconomically disadvantaged groups face (Bolin and Stanford, 1998; Tobin-Gurley and others, 2010; Abramson and others, 2015).

Individuals and Households

The FEMA Individual Assistance programs provide financial and direct services to eligible individuals and households—both renters and owners—affected by a federally declared disaster. The application process includes a home inspection to determine eligibility; only U.S. citizens, non-citizen nationals, or other qualified residents may apply. The maximum amount of FEMA Individuals and Households Program assistance that can be provided for any single emergency or major disaster is adjusted annually to account for inflation. The maximum allowable amount per household for an emergency or major disaster declared on or after October 1, 2018, is $34,900 (FEMA, 2018a).

This assistance is intended to meet basic needs and, by law, FEMA cannot duplicate the assistance provided by insurance. Thus, the actual amount awarded to most individuals and households is well below the maximum allowable amount, and subject to delays in its approval and distribution. For comparison, eligible applicants to the FEMA Individual Assistance programs received an average of $2,670 after the 2014 South Napa earthquake (FEMA, 2018b), and the two-month delay in Federal authorization of the program hindered community recovery (Johnson and Mahin, 2016). Following Hurricane Katrina, eligible applicants to the FEMA Individual Assistance programs received an average of $7,114 (FEMA, 2018c). In the City of New Orleans, 278,500 eligible applicants received, on average, $10,413 from the FEMA Individuals Assistance programs (FEMA, 2015).

FEMA may also provide direct housing services to eligible individuals and households if alternative housing resources are limited postdisaster; it generally works in collaboration with HUD on the individual case management and provision of services. This direct form of temporary housing assistance may include manufactured housing, multifamily lease and repair, and permanent or semipermanent home repair, and (or) construction services and is not counted toward the Individuals and Households Program maximum award amount. The Federal government has been a significant resource for temporary housing after major disasters, but it has not been without controversy about quality, costs, and delays (U.S. Department of Homeland Security Office of Inspector General, 2013).

The U.S. Small Business Administration (SBA) provides loans to homeowners and renters to repair or replace damaged property in federally declared disasters. Homeowners may borrow as much as $200,000 to replace or repair their primary residence with as much as a 20 percent loan increase to make disaster resilience improvements to the property; renters and homeowners may borrow as much as $40,000 to replace or repair damaged personal property, such as clothing, furniture, cars, and appliances (SBA, 2018). Secondary homes or vacation properties are not eligible, but qualified rental properties can apply for SBA business loans of as much as $2 million with as much as a 20 percent loan increase to make disaster resilience improvements to the property. These loans are for uninsured or underinsured losses, and any proceeds from insurance coverage are considered in determining the loan amount. Repayment terms of as much as 30 years are available and interest rates vary. For perspective, in one of its busiest years—Federal fiscal year 2006—the SBA approved 145,164 home loans with an average value of $61,564 (Lindsay, 2011). These largely went to applicants with housing damage sustained in the 2005 hurricanes.

Also following the 2005 hurricanes and 2012 Hurricane Sandy, Congress passed supplemental disaster legislation that provided HUD CDBG-DR funding for housing repairs and rebuilding not covered by the National Flood Insurance Program and private insurance. The States of Mississippi, Louisiana, New Jersey, and New York, as well as New York City, developed and ran multi-billion-dollar programs to fund repairs and replacement of damaged single-family and multifamily housing (Johnson and Olshansky, 2017); however, the unmet needs from a major earthquake, like that in the HayWired scenario, would far exceed past CDBG-DR allocations. The largest of these was Louisiana's $10 billion housing program, called the Road Home, which paid more than $8.53 billion to 128,000 homeowners to make repairs or sell their property to the State (Louisiana Recovery Authority, 2010). Also, it can take considerable time for Congress to approve allocations, for receiving states and communities to design and implement funding programs, and thus for recipients to actually receive the funds.

FEMA Hazard Mitigation Grant Program (HMGP) funds have also been obligated to enhance the disaster resilience of housing after disasters. The California Residential Mitigation Program, a joint powers authority operated by the California Earthquake Authority, has funded the seismic retrofit of 100 houses in Napa County with funding provided in part by FEMA HMGP funds available after the 2014 South Napa earthquake (California Earthquake Authority, 2017). After Hurricanes Katrina and Sandy, Louisiana and New Jersey used

FEMA HMGP funds in combination with HUD CDBG-DR funds to assist homeowners with home elevations and other disaster resilience improvements as part of their housing repair programs (Johnson and Olshansky, 2017).

The California Disaster Assistance Act does not define any postdisaster assistance programs for individuals and households. However, the California Governor's Office of Emergency Services works with FEMA to administer Individual Assistance and Hazard Mitigation Grant Program funding that has been applied toward improving the disaster resilience of housing.

The California Department of Housing and Community Development has recent experience administering HUD CDBG-DR funding and supplemental awards after the 2017 and 2018 wildfires (California Department of Housing and Community Development, 2018). Some of the funds have been awarded to eligible fire-impacted communities to assist with housing rehabilitation and housing buyouts in high wildfire risk areas, as well as the construction of affordable rental housing.

Businesses

The SBA business loan program is the major form of Federal disaster assistance for business recovery following federally declared disasters. The SBA physical disaster loans provide as much as $2 million to qualified businesses or private nonprofit organizations to repair or replace damaged property, including equipment and inventory, and with as much as a 20 percent loan increase to make disaster resilience improvements to the property (SBA, 2018). Small businesses, agricultural cooperatives, and private nonprofit organizations may also be eligible for as much as $2 million from the SBA Economic Injury Disaster Loan program to help meet financial obligations and operating expenses, regardless of whether the business suffered any property damage. A business may qualify for both an Economic Injury Disaster Loan and a physical disaster loan, but the maximum combined loan amount is $2 million. As with the SBA disaster home loan program, any proceeds from insurance coverage are considered in determining the loan amount. Repayment terms cannot exceed 30 years and interest rates vary. In 2006, after the damaging 2005 hurricane season, the SBA approved 24,819 business loans with an average value of $118,785 (Lindsay, 2011).

To a much more limited extent than housing, HUD CDBG-DR funds have also been used by states and cities to fund business recovery after federally declared disasters. Business recovery grant programs, job and workforce development and retention grant programs, and grants for specific business and economic development and construction programs are just some of the examples of CDBG-DR funds obligated toward business recovery after the 2001 World Trade Center disaster and Hurricanes Katrina and Sandy (Johnson and Olshansky, 2017). Postdisaster funding provided by the U.S. Economic Development Administration has also been used to capitalize or recapitalize revolving loan funds through nonprofit and governmental entities to provide below-market-rate loans to businesses to help provide gap financing and to support new business development (U.S. Economic Development Administration, 2019).

The California Disaster Assistance Act does not define any postdisaster assistance programs for businesses. The California Department of Housing and Community Development has awarded HUD CDBG-DR funding for economic development activities (California Department of Housing and Community Development, 2018).

Local Governments and Community Services

The FEMA Public Assistance program is the major source of Federal assistance to States, Tribes, territorial and local governments, and other governmental and qualifying private nonprofit organizations after federally declared disasters, and is FEMA's largest disaster assistance program (FEMA, 2017). It provides grants for debris removal and other emergency protective measures as well as the permanent repair, replacement, or restoration of disaster-damaged, publicly owned, or nonprofit facilities and disaster resilience measures.

FEMA Public Assistance grants are awarded on a cost-share basis, and the Federal government is statutorily obligated to provide at least 75 percent of the eligible costs. States usually serve as the grant recipient and determine how the non-federal share (as much as 25 percent) is split between the State and eligible applicants. In California, the California Governor's Office of Emergency Services serves as the grant recipient for FEMA Public Assistance, and under the California Disaster Assistance Act, the California Governor's Office of Emergency Services administers State financial assistance for costs incurred by local governments for certain emergency activities and repairs or replacement of public infrastructure and facilities damaged by a State-declared disaster, with or without a Federal disaster declaration.

After the 2014 South Napa earthquake, FEMA awarded $29.7 million in Public Assistance funds, of which $5.35 million was for emergency measures and $22.5 million was for permanent works, such as facility repairs (FEMA, 2018b). By comparison, FEMA obligated more than $13.5 billion in Public Assistance funding after the 2005 Hurricane Katrina, of which $3.1 billion covered debris removal and other emergency measures and nearly $10 billion went to permanent works (FEMA, 2018c).

The FEMA Community Disaster Loan program was created by Congress after Hurricane Katrina to assist eligible jurisdictions in a federally declared disaster area that has suffered a substantial loss of tax and other revenue. The jurisdiction must demonstrate a need for financial assistance to perform its governmental functions and provide essential services, and loans are not to exceed 25 percent of the local government's annual operating budget for the fiscal year in which the major disaster occurs, with a maximum of $5 million. However, after Hurricanes Katrina and Rita in 2005, Congress passed special legislation allocating more than $1.37 billion for loans far exceeding this maximum limit for financially distressed State and local governments to cover operating expenses, particularly for staffing essential services, such as law enforcement, schools, and fire services (Brown, 2012). After Hurricane Sandy, more than $174 million in Community Disaster Loans of as much as $5 million each were awarded

to 60 local governments and municipal districts in New Jersey (FEMA, 2013).

Although it requires supplemental funding by Congress, HUD CDBG-DR funding can also be a major source of Federal disaster assistance for communities to fund infrastructure and facilities recovery and resilience projects. The CDBG-DR funds may not be used to reimburse activities or serve as the required match for other Federal disaster assistance, like the FEMA Public Assistance program. Projects must also benefit low- and moderate-income persons or households that earn 80 percent or less of the county-wide median income adjusted for family size.

As mentioned above, Federal disaster assistance extends well beyond FEMA and the statutory obligations of the Federal government under the Stafford Act. Many of these other Federal disaster-specific programs and activities target government and community-scale recovery needs. Examples include the infrastructure repair funding from the Federal Transit Administration and Federal Highway Administration, as well as the work of the U.S. Army Corps of Engineers in emergency rehabilitation and construction of waterways and flood control defenses. In many cases, comparable State agencies, like the California Department of Transportation, are also involved in project management and funding administration.

It is also important to note that the major Federal disaster assistance programs, like FEMA's Public Assistance and the HUD CDBG-DR programs, have not been particularly well suited to large-scale disasters (GAO, 2008, 2009). Funding delays, inflexible regulations, and lengthy approval processes all complicate and limit their effectiveness. With a Federal disaster declaration likely for a major earthquake like that in the HayWired scenario, there could be hundreds of public and nonprofit sector applicants for Federal disaster recovery funds, which could create administrative challenges at both the State and Federal levels in both processing and reimbursing grant applications. The FEMA Public Assistance program is a reimbursement-based funding stream, which means that applicants must document and finance the costs of repairs and replacement and await repayment. FEMA has been developing a "new delivery model" for the Public Assistance program that it has been testing at certain locations since 2015 before implementing it nationwide (GAO, 2017). Nonetheless, many cities, counties, and other local applicants could face significant recovery financing challenges, especially those that already have budget problems caused, in part, by rising employee pension costs (Joffe, 2017).

Earthquake damage and losses could also reduce State and local tax revenues, adding further stress on local applicants to finance repairs and rebuilding and delaying community recovery. (See Kroll and others, this volume, for some discussion of local tax effects.) Local applicants may look to the State of California and other financiers for loans, to voters for approval of bond measures, and for other forms of assistance to help manage cashflow. After Hurricane Katrina, the State of Louisiana set up a $200 million revolving loan account for the City of New Orleans to draw from in order to meet short-term obligations while revenues, including FEMA Public Assistance funds, were pending (Louisiana Recovery Authority, 2010).

Repairing and Replacing Damaged Housing

There is nearly 1.9 billion square feet of residential building damage, valued at $42.4 billion, caused by the combined effects of ground shaking, landslide, liquefaction, and fires for the M_w 7.0 mainshock of the HayWired scenario (see section A). The seismic vulnerability of common housing types in the San Francisco Bay region is well known and was a major factor that defined the areas of concentrated damage for the HayWired scenario. For its "Stronger Housing, Safer Communities" study, the Association of Bay Area Governments created a typology of housing types that are fragile to earthquake effects (Brechwald and others, 2015). Table C5 combines the Association of Bay Area Governments seismically fragile housing types data with hazard assumptions and data resulting from the HayWired scenario analyses to provide a typology of housing vulnerable to earthquake ground shaking, landslides, liquefaction, and fires.

Financing housing repair and replacement depends on the extent of damage. Financial challenges could pertain to low-income property owners, mortgage defaults, and affordable housing. Government-led intervention and support will likely be needed. Also, housing recovery is affected by interdependencies with business recovery, household services, and utility and transportation services. These aspects are addressed below. Financing the repair and replacement of damaged business establishments is addressed in chapters V1–V5, which focus on economics, of the HayWired scenario volume 3.

Repairing Residential Buildings in a Slight to Moderate Damage State

Of the nearly one million residential buildings and 1.37 million housing units that sustain some level of damage from all hazards in the HayWired scenario, nearly 90 percent are single-family or duplex buildings in a slight to moderate damage state (most likely caused by ground shaking). Most of these buildings have light wood-frame construction and, at slight to moderate damage levels, there could be cracks in walls, chimneys, and masonry veneers, and possibly the toppling of tall masonry chimneys (FEMA, 2012). In most instances, post-earthquake safety inspections would likely result in a "green tag," deeming these structures safe to occupy while being repaired.

There are also about 290 million square feet of multifamily and group-living occupancies (in 32,200 buildings and containing 336,500 multifamily housing units) in a slight to moderate earthquake damage state. These occupancies are composed of a variety of construction types. However, for two- and three-story wood-frame multifamily buildings commonly found across the region, the level of damage would likely entail cracks in walls, chimneys, and masonry veneer (FEMA, 2012).

Table C5. Typology of seismically vulnerable housing in the San Francisco Bay region, California (adapted from Brechwald and others, 2015, and Harris, 2017).

[MMI, Modified Mercalli Intensity; km, kilometers; GIS, Geographic Information Systems]

Hazard description	Vulnerable housing type	Housing vulnerability description and (or) location
Ground shaking		
Areas subjected to shaking levels of MMI VIII or above are most vulnerable to building damage. See Aagaard, Boatwright, and others (2017).	1- or 2-unit wood-frame homes with cripple walls	Typically, these homes were built before 1940. The foundations are commonly not bolted and bracing is lacking on the wood-framed exterior walls enclosing the crawl space (for example, cripple wall). They are prevalent in older "bedroom communities" that are now more established neighborhoods.
	1- or 2-unit wood-frame homes over an attached garage	These buildings are commonly 2 to 3 stories tall and were constructed between 1920 and 1970. The garage lacks the interior walls and strength to support the living space above it during an earthquake. They are common in dense pre-1950s neighborhoods as well as post-1950s neighborhoods with ranch-style homes and multicar garages.
	Multi-unit wood-frame buildings with cripple walls	These buildings can be more than 2 stories tall and were typically built before 1920. The foundations are commonly not bolted and bracing is lacking on the wood-framed exterior walls enclosing the crawl space. They are prevalent in older "bedroom communities" that are now more established neighborhoods.
	Multi-unit "soft story" or "tuck-under" wood-frame buildings	These buildings are commonly 3 to 5 stories tall and built before the mid-1970s. A soft-story describes the large opening on the first floor—typically for open or enclosed parking or commercial space—that lacks adequate bracing to support the upper floors of residential units during an earthquake. These buildings are common in older, mixed and high-density neighborhoods as well as older, large suburban developments.
	Multi-unit unreinforced masonry buildings	These buildings are commonly 3 to 5 stories tall and built before 1933. The load-bearing walls, nonload-bearing walls, or other structures, such as chimneys, are made of brick, cinderblock, tiles, adobe, or other masonry material that is not braced by reinforcing material, such as rebar. These buildings compose a very small portion of the region's building stock but are concentrated in the oldest neighborhoods.
	Multi-unit nonductile concrete buildings	These buildings were built between 1950 and 1971 and are typically 3 or more stories tall. The concrete columns lack adequate steel reinforcing bars to provide ductility—the ability to bend without breaking during an earthquake. They are found in the highest density urban and suburban neighborhoods.
Fault rupture		
63 km of the fault rupture length is on land, with as much as 2 meters of coseismic slip as well as 0.5–1.5 meters of afterslip. See Aagaard, Schwartz, and others (2017).	Most homes and multi-unit buildings located on top of a surface fault rupture zone	The Hayward Fault runs through a highly developed area and most buildings, pipelines, buried electrical transmission lines, roads, bridges, and tunnels straddling the fault are vulnerable to damage from either the coseismic slip occurring during the earthquake rupture or the longer duration slip on the fault, called afterslip. This includes most structures and infrastructure that are not specifically designed to withstand displacement associated with coseismic slip or afterslip. Using satellite imagery and GIS data for the Hayward Fault (Lienkaemper, 2007), more than 600 structures—including nearly 600 residential buildings—are seen within areas of surface offset from coseismic slip and potential afterslip along the Hayward Fault for the HayWired scenario mainshock. The number of structures within the buffer of uncertainty around the fault (Lienkaemper, 2007) is nearly 3,000—including more than 2,800 residential buildings. Surface rupture is not explicitly included in the Hazus damage estimates developed by Seligson and others (2018).
Landslides		
Areas of strong ground shaking (greater than 20 centimeters per second of peak ground velocity); geologic-material strength parameters and slope gradient were used to estimate and map the likelihood of landslide. See McCrink and Perez (2017).	Hillside homes and multi-unit buildings	Areas of steep to very steep slopes and on existing landslides are most vulnerable. Areas in the east bay hills near the hypothetical rupture zone of the Hayward Fault, even on gentler to moderate slopes, are also susceptible to landslides or slope failure. Hillside homes and multi-unit buildings can also experience damage caused by ground shaking.

Table C5.—Continued

Hazard description	Vulnerable housing type	Housing vulnerability description and (or) location
	Liquefaction	
Detailed information was used to estimate and map the likelihood of liquefaction in western Alameda and northern Santa Clara Counties. See Jones and others (2017). The Hazus methodology was used to estimate the likelihood of other susceptible areas. See Seligson and others (2018).	Homes and multi-unit buildings less than 10 stories tall	Buildings less than 10 stories tall typically lack pilings and other engineered foundation features to withstand the differential settlement caused by liquefaction. Homes and small multifamily structures in areas of soft, water-saturated soils or poorly compacted fill along creeks, watersheds, and the margins of San Francisco Bay are most vulnerable.
	Fire following earthquake	
A full probabilistic methodology for analysis of fire following earthquake looked at the sources of ignition, processes of fire discovery and reporting, and abilities of fire department response and suppression. See Scawthorn (2018).	All single-family and duplex homes and multi-unit buildings	Areas that experience strong ground shaking (MMI VI or greater) and have high-density wood construction and population densities greater than 3,000 people per square kilometer are most vulnerable to post-earthquake fires. About half of all fire ignitions are electrical, a quarter are gas related, and the remainder are due to a variety of other causes, including chemical reactions. Based on the 1994 Northridge earthquake experience, about 70 percent of all ignitions occur in residential occupancies. Seismically vulnerable water-supply infrastructure and other firefighting capacity and impairment issues can also increase fire-following-earthquake vulnerabilities.

For the vast majority of residential structures with slight to moderate damage in the HayWired scenario, likely loss levels would be within the range of financing available with SBA disaster loans and FEMA Individual Assistance grants. For the small minority of these building owners who are likely to have earthquake insurance coverage, the structural loss levels may not exceed their deductibles. Some owners may need to seek conventional loans or rely on their individual savings to fund repairs, sell their home and relocate, or receive assistance from philanthropic or nonprofit funders (Johnson and Mahin, 2016).

Repairing or Replacing Residential Buildings in an Extensive or Complete Damage State

In the HayWired scenario, an estimated 97,397 residential buildings are in an extensive or complete damage state because of ground shaking, fault rupture, liquefaction, landslides, and (or) fire. Of these, there are 89,812 single-family and duplex buildings, with 93,381 units (accounting for two-unit duplex buildings) and 7,586 multifamily and group-living use buildings; 7,337 extensively or completely damaged multifamily buildings contain as many as 78,445 housing units (in about 60.7 million square feet). Fire damage contributes approximately 64.5 million square feet in 29,000 residential buildings and as many as 53,600 housing units to the complete damage state.

Light wood-frame residential construction in an extensive damage state caused by ground shaking could have large cracks in the walls and foundations, toppling of masonry chimneys, and permanent lateral movement of the floors and roof that could cause a partial collapse of the building (FEMA, 2012). Such damage can be associated with a "yellow tag" post-earthquake safety inspection, limiting the building's use until repairs are completed. Light wood-frame buildings in a complete damage state would have major foundation damage, large permanent lateral displacement, and be in imminent danger of collapse; a small percentage could be expected to be collapsed (FEMA, 2012). These buildings would likely have a "red tag" post-earthquake safety inspection that deems them unsafe to occupy until repairs are completed.

Most housing types that are in an extensive or complete damage state will likely require detailed engineering investigations and repair schemes. Housing that experiences significant damage caused by fault rupture, liquefaction, or landsliding may also require detailed geotechnical investigations, site stabilization, and foundation repair schemes. Replacement may be a more cost-effective solution in some cases. Housing that experiences fire will most likely need to be reconstructed.

For the owners of single-family homes or multifamily units with extensive or complete damage, the loss may only be partly covered by SBA disaster loans and FEMA Individual Assistance, and conventional loans or individual savings would be needed to fund repairs and rebuilding. Owners may also sell damaged buildings or receive assistance from philanthropic or nonprofit funders. For those with fire damage, a large portion of the loss would be covered by insurance. For the small minority of owners who are likely to have earthquake insurance coverage, the losses caused by extensive or complete damage levels would likely exceed the deductible levels. All insureds would still need to fund the deductible amounts and there may be instances of underinsurance—where the insurance limits do not sufficiently cover the costs of rebuilding, especially in areas where there has been a rapid increase in asset values prior to the disaster (Lloyd's, 2018). Housing recovery financing could also fall short because of temporary increases in construction costs that commonly occurs after major natural disasters, known as "demand surge" (Comerio, 2006).

For reference, the 1989 Loma Prieta earthquake damaged 43,000 housing units, of which 11,500 were severely damaged

or destroyed, and the 1994 Northridge earthquake damaged 500,000 housing units, of which 60,000 were severely damaged or destroyed (Comerio, 1998). Comerio (1998) reports that two years after the 1994 Northridge earthquake, more than 265,000 households had collected private insurance claims, 98,000 received SBA disaster loans, and 288,000 obtained small grants from FEMA for minimal home repairs. Sidebar 2 describes the housing repair programs developed and managed by the City of Los Angeles after the 1994 Northridge earthquake that targeted uninsured residential damage. For the HayWired scenario, residential damages and repair and replacement costs would be greater than that for 1989 Loma Prieta earthquake damages, but, compared with the Northridge earthquake, the insurance coverage would be considerably lower.

Other Housing Recovery Financing Challenges

Low-Income Housing Building Owners

Whereas all residential building owners are likely to have significant recovery financing challenges, owners with lower income levels may face greater difficulties qualifying for SBA loans, obtaining conventional financing, and lacking the necessary savings to fund repairs or rebuilding. Multifamily building owners also tend to have greater difficulty assembling the necessary resources to finance repairs and rebuilding than single-family building owners; condominium owners have the added burden of assembling agreement and financing among all the unit owners (Comerio, 1998; Olshansky and others, 2005; Peacock

Sidebar 2—City of Los Angeles' Housing Repair Programs after the 1994 Northridge Earthquake

The moment magnitude 6.7 Northridge earthquake damaged more than 25,000 businesses and 100,000 housing units and left 22,000 people homeless (Olshansky and others, 2005). At the time, it was the costliest disaster in U.S. history, with total losses of $44 billion ($71.3 billion in 2016 dollars), of which insurance covered $15.3 billion ($19.6 billion in 2016 dollars), or 35 percent (Munich RE, 2015).

The City of Los Angeles (population 3.5 million at the time) sustained the majority of the region's damage, with heavy concentrations of residential damage in the San Fernando Valley suburbs north of downtown. Of more than 440,000 housing units inspected, 7,000 single-family homes, 2,000 mobile homes, and 49,000 multifamily units received either red- or yellow-tags (Comerio and others, 1996; Comerio, 2006).

The City of Los Angeles Housing Department (LAHD) identified 17 clusters of damaged and abandoned apartment buildings that were located in one of the 38 census tracts that had more than 100 vacated apartment housing units, and in which more than 60 percent of the housing units were either heavily damaged or destroyed (LAHD, 1995).These higher density residential neighborhoods were dubbed "ghost towns" because the major outmigration of tenants from both damaged and undamaged buildings and the empty buildings had become hideouts for gangs and clusters of crime and prostitution. Many of the damaged apartment buildings were repairable, but building owners generally lacked insurance or discovered that their high insurance deductibles made repairs prohibitive. Furthermore, deflated property values, high vacancy rates, declining rental income, and high debts limited multifamily building owners' abilities to get loans and make repairs (Olshansky and others, 2005). Even if their unit was habitable, some renters did not want to stay in "ghost town" areas. Also, some condominium owners who could not finance building repairs allowed their units to be foreclosed on, further contributing to the "ghost town" conditions of some neighborhoods.

The City of Los Angeles Housing Department, with support from the Federal government, established a special division in the department to develop and implement an array of interventions that included securing and clearing damaged and uninhabited buildings, neighborhood crime reduction programs, rental housing repair loan programs, and technical assistance and personalized interventions for damaged condominium building owners (Olshanksy and others, 2005). The City of Los Angeles Housing Department managed more than $300 million in Federal Community Development Block Grant funds earmarked by Congress for housing recovery and provided loans and other support to apartment building owners to demolish, repair, and reconstruct the more than 1,000 properties and 17,000 residential units in ghost town neighborhoods (LAHD, 1995). The loans provided as much as $35,000 per unit, with various low- to no-interest rates and payment deferral terms and the repairs had to meet the latest building code standards; loans greater than $525,000 per building were also subject to approval by the Mayor and City Council (Olshansky and others, 2005). To qualify, applicants had to have been rejected by the Federal Emergency Management Agency and the U.S. Small Business Administration or prove that they had insufficient funds. It took more than two years to get the repair program structured and underway, and more than five years to repair most buildings (and more than 12,000 multifamily units) with loan repayments beginning by that time (Olshansky and others, 2005). Though most of the ghost town neighborhoods rebounded, they required organized and sustained interventions by the city and recovery took significantly longer in these neighborhoods than in other residential neighborhoods.



U.S. Geological Survey photograph of apartment buildings damaged in the Northridge earthquake.

and others, 2014). With about 350,000 people living in areas of concentrated damage that have five or more Association of Bay Area Governments and San Francisco Bay Conservation and Development Commission community vulnerability indicators (see section B), residential building owners in these areas may face recovery financing challenges.

Mortgage Defaults

Mortgage defaults could also present added difficulties for housing recovery in some neighborhoods. Residential home loans in California are typically "non-recourse" loans, whereby the lender's interest is secured by liens on the property, but the borrower is not personally obligated to repay the loan (Larsen and others, 2015). Borrowers may default on loans if they do not have the resources to repair and rebuild or these costs significantly exceed the value of their investment. There were many instances of mortgage defaults after the 1994 Northridge earthquake, particularly among the owners of damaged condominium units whose property values had already declined significantly before the earthquake occurred (Olshansky and others, 2005).

Replacing Affordable Housing

Replacing affordable housing will also be a major housing recovery challenge in a major earthquake like that in the HayWired scenario. Federal government programs and postdisaster funding, both provided mainly through HUD, have also been essential to repairing and rebuilding damaged affordable housing after major disasters. These include the HUD CDBG-DR and Housing Choice Voucher (HCV) programs.

The HCV program is the Federal government's major program for assisting very low-income families, the elderly, and persons with disabilities to afford private rental housing. In 2017, there were nearly 300,000 families in California using housing vouchers, of which around 70,000 families (or nearly 24 percent) resided in the nine-county San Francisco Bay region (HUD, 2018a). Publicly owned affordable housing developments and low-income housing tax credit properties are two of the major sources of affordable housing in the region.

Figure C1 shows the number of HCV program families by census tract as well as the locations of both publicly owned affordable housing developments and low-income housing tax credit properties across the San Francisco Bay region, with insets focusing on part of Alameda County (fig. C1*A*) and part of Santa Clara County (fig. C1*B*). There are visibly high numbers of HCV families and affordable housing properties across the region and in close proximity to the Hayward Fault in Alameda County.

Government-Led Housing Repair Programs

Significant uninsured housing repair costs will likely require some level of governmental intervention and support. Several large government-led housing repair programs have been created to address housing recovery financing gaps after Hurricanes Katrina and Sandy in the United States and the 2010–11 Canterbury earthquakes in New Zealand, as well as other major disasters. In a few cases, they also helped to manage the widespread and simultaneous construction demands and postdisaster cost increases (Johnson and Olshansky, 2017).

In the United States, multi-billion-dollar housing repair and rebuilding programs were designed and operated by the States of Mississippi, Louisiana, New Jersey, and New York, as well as New York City, with HUD CDBG-DR funding. These programs helped to provide valuable financial resources to single-family homeowners, multifamily rental properties, and affordable housing construction. The single-family homeowner grant programs have been generally limited to as much as $150,000 and awards deducted the funds that applicants received from insurance or other disaster assistance programs. These programs also took many months, even years, to design and launch and the HUD CDBG-DR funding required supplemental disaster appropriations by Congress that commonly took months to years to approve.

In New Zealand, the national government, through the Earthquake Commission (the national earthquake insurance program), managed repairs of 72,500 moderately damaged to severely damaged homes with insurance claims in the range of $15,000 to $100,000 in New Zealand dollars (about $10,050 to $67,000 in U.S. dollars as of December 2018) (New Zealand Earthquake Commission [EQC], 2014). By establishing the more centrally managed process, the national government aimed to help restore confidence in the housing market and manage the costs of construction materials and labor, but the program was also plagued with complaints about the quality of materials and workmanship (Johnson and Olshansky, 2017).

Other Housing Recovery Interdependencies and Issues

Household-level decisions to stay and rebuild depend on more than just housing damage and access to recovery resources. Other important factors include: the speed, strength, and certainty of economic recovery; availability of jobs and businesses; speed with which utilities, critical community services, and nearby businesses are restored; and regulatory changes to inspections, planning, construction, or zoning (Comerio, 2006; Groen and Polivka, 2010; Xiao and Van Zandt, 2011; Xiao and Nilawar, 2013; Elliott, 2014; Greer, 2015). Delays in the restoration of important community facilities and services, including schools, hospitals, doctor's offices, general health care services, fire and police stations, city and county administration buildings, and social services can deter population return and impede housing recovery.

As discussed by Porter (2018) and Jones and others (this volume), the M_w 7.0 mainshock and aftershocks of the HayWired scenario will cause infrastructure disruptions and damage, particularly to transportation and water distribution systems, that

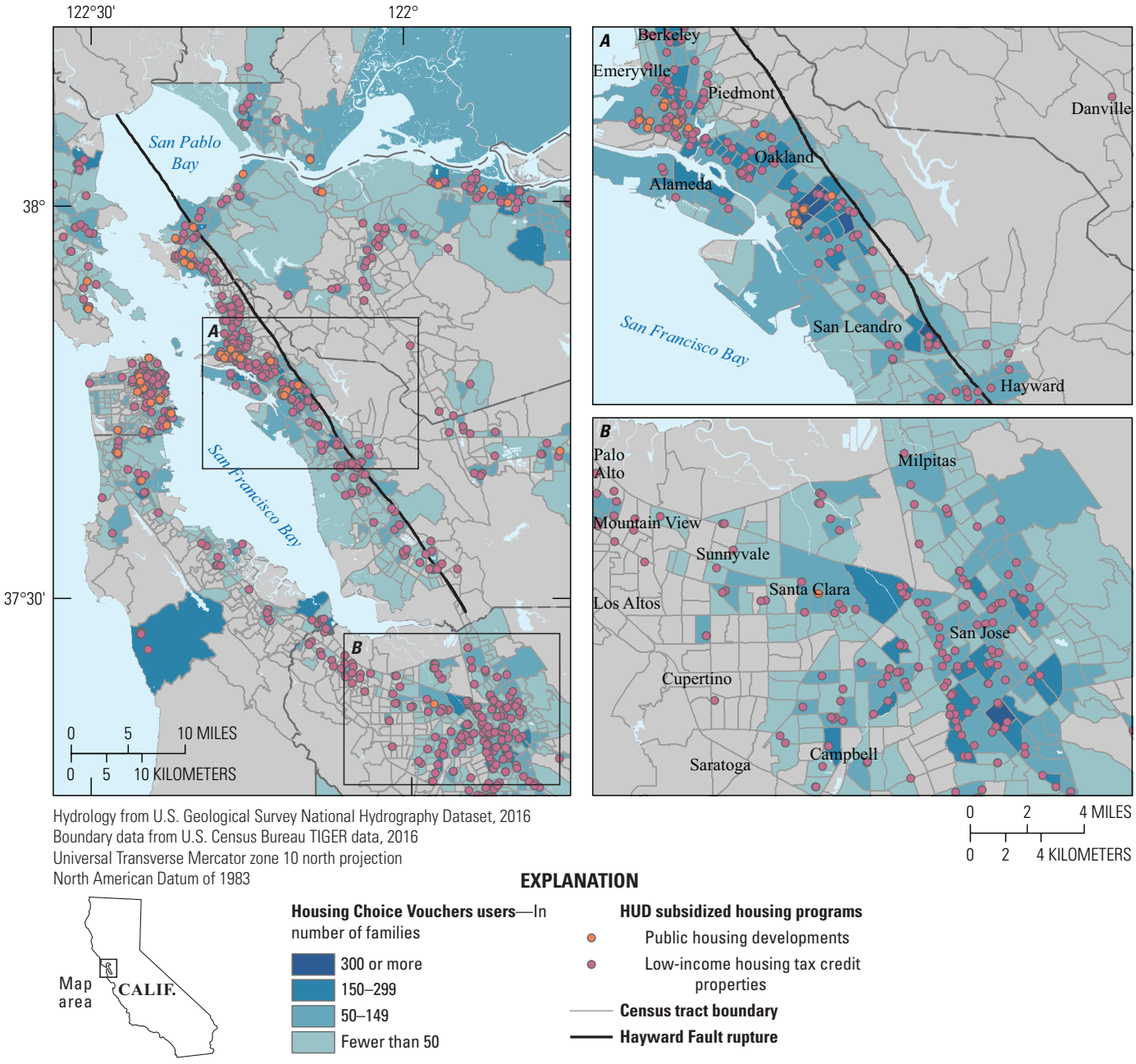


Figure C1. Maps of the San Francisco Bay region, California, showing the number of families using Housing Choice Vouchers by census tract and the locations of publicly owned housing developments and low-income tax credit properties in areas potentially affected by strong ground shaking as a result of the HayWired earthquake scenario mainshock. *A*, Inset map showing parts of Alameda County. *B*, Inset map showing parts of Santa Clara County. Data from the U.S. Department of Housing and Urban Development (HUD) (2017, 2018a, 2018b).

would impede housing recovery. Figure C2 shows the water distribution restoration curves by county for the M_w 7.0 mainshock of the Hayward scenario. Significant restoration delays are possible for customers in parts of Alameda, Contra Costa, San Mateo, and Santa Clara Counties, where water distribution system damage could be most severe. In particular, the potential damage to the water distribution system of the East Bay Municipal Water District could cause the average customer in Alameda County to be without water for six weeks, and some customers could lack water service for six months (Porter, 2018).

In general, for a housing unit to be deemed habitable, it must have access to water, sewer, and electricity (Bay Area Urban Area Security Initiative, 2011). It is possible that occupants of habitable housing units in areas that have extensive water system damage may be displaced for an extended period of time because of water service outages. There may also be instances where the owners of damaged single-family and multifamily buildings may delay or decide against repairs and rebuilding until utility services are restored. The many aftershocks in the HayWired scenario could also cause additional housing and utility damage and essentially "reset the clock" for many housing recovery efforts.

The restoration of transportation systems is crucial to regional economic recovery, as well as housing and community recovery. The combination of damaged regional highways and the Bay Area Rapid Transit system in the HayWired scenario (see Jones and others, this volume) could essentially sever north-south transport through central Alameda County and hamper housing recovery throughout the east bay corridor. The analysis of the jobs-housing relation by Wein, Belzer, and others (this volume) informs the commute analysis by Kroll and others (this volume), which considers the potential effects of roadway and highway damages and extended repair times on economic recovery.

Local government planning and permitting processes can also influence the pace of housing recovery. The high costs and extensive bureaucracy of local housing approvals and construction are commonly blamed for the region's housing affordability and supply crisis (Hanlon, 2017). Hard-hit communities, in particular, could be overwhelmed by the planning and permitting needs resulting from a major earthquake. After the 2017 wildfires, both the City of Santa Rosa and Sonoma County established special permit review teams and reduced permit costs for fire-damaged properties in order to help homeowners rebuild as quickly as possible (County of Sonoma, 2018; City of Santa Rosa, 2019).

Areas Requiring Substantial Governmental Intervention and Replanning

After a major earthquake, like that in the HayWired scenario, there will be immense psychological, economic, and political pressures to enable repairs and reconstruction as quickly as possible. Taking time to evaluate damage causes and patterns, assess future risks, and consider actions to reduce future risk may be seen as interfering with rapid recovery. However, the postdisaster period can provide unprecedented financial resources and other opportunities to reduce future risk and make other improvements. Some areas may also be so extensively damaged that market forces alone cannot facilitate recovery and governmental interventions and replanning may be required.

Determining which areas can successfully recover according to existing plans and policies and which will need to be replanned is a difficult task that largely falls to local governments to address. It is possible to identify the types of areas that may require governmental interventions and replanning after a major earthquake. Table C6 provides a typology of these potential

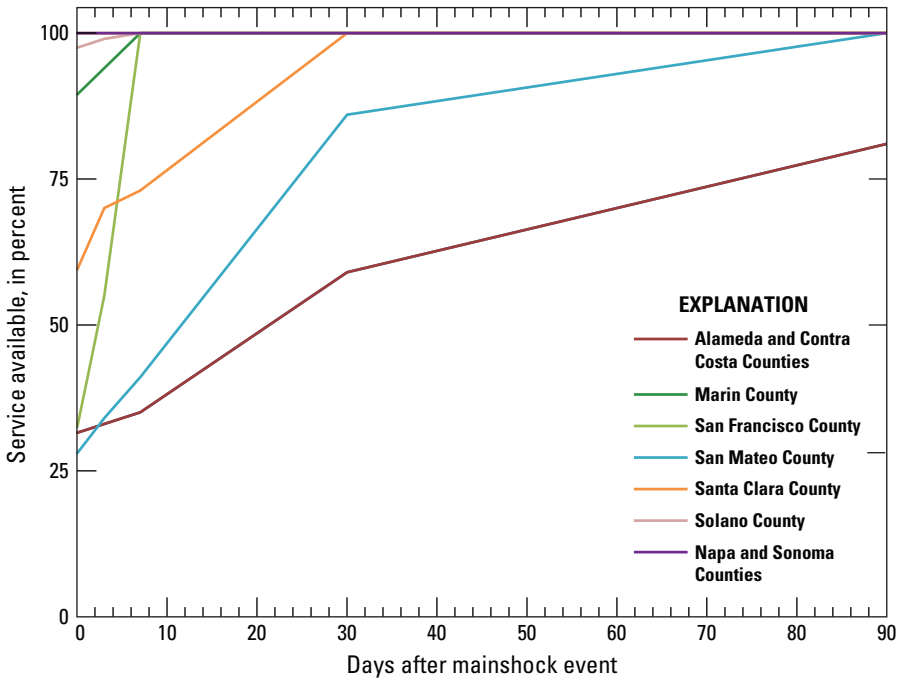


Figure C2. Line graph showing the water distribution restoration curve by county for the HayWired earthquake scenario mainshock in the nine-county San Francisco Bay region, California. Data originally from Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) and modified for Alameda, Contra Costa, and Santa Clara Counties by Porter (2018). Figure from Jones and others, this volume.

Table C6. Potential areas that may require governmental interventions and replanning to facilitate recovery in the HayWired scenario, San Francisco Bay region, California.

[km, kilometers; km^2, square kilometers; MMI, Modified Mercalli Intensity; M_w, moment magnitude; BART, Bay Area Rapid Transit]

Area	Past earthquake example(s) and key references	Potential communities at risk in the HayWired scenario	Potential damage, hazard, and risk considerations	Potential government interventions and replanning actions
Areas with substantial land, building, and infrastructure damage caused by liquefaction	Christchurch, New Zealand, 2010–11 earthquakes (van Ballegooy and others, 2014; Rogers and others, 2014; Johnson and Olshansky, 2017)	Neighborhoods along San Francisco, Richmond Marina, and San Pablo Bays, especially those built on bay muds or artificial fill and along major inland drainage ways; see Jones and others, 2017, and Seligson and others, 2018. Areas of potentially concentrated building damage caused by liquefaction are in Richmond, San Pablo, unincorporated North Richmond, Albany, Berkeley, Emeryville, Oakland, City of Alameda, San Leandro, Hayward, Union City, and Fremont. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.	Damage to building foundations and structural integrity Damage to roads and buried infrastructure Additional damage from aftershocks (such as repeated liquefaction, slope failures, fault rupture, or building and infrastructure damage) Increased vulnerability to flooding (current and future) in liquefaction areas Increased vulnerability to slope failures in landslide areas Uncertainty about the feasibility and affordability of land remediation for liquefaction, landslide, and other ground failure damage Uncertainty about the feasibility and affordability of repairs to existing buildings and infrastructure Building owner mortgage loan defaults Occupant displacement and (or) voluntary relocation Property blight Decline in property values Loss of property tax revenues	Access control Emergency structural and land stabilization measures Potential zones of required investigation, in accordance with the California Seismic Hazards Mapping Act and Alquist-Priolo Earthquake Fault Zoning Act Areawide (not site-specific) geologic hazard investigation to assess future risks Multi-hazard considerations, including current and future flood risks for liquefaction areas and winter storm and wildfire hazards for landslide areas Regional and local planning considerations, such as priority development areas and priority conservations areas in the "Plan Bay Area 2040" Community engagement in hazard evaluations, planning, and rebuilding decisions Psychological and social service support Temporary building moratorium until investigations and planning are completed Areawide remediation approaches Site development and building code changes Land use and zoning changes Voluntary buyout program or land acquisition for replanning areas Funding for access control, emergency measures, hazard investigation, planning and community engagement, areawide remediation, property buyouts, and building, road, and infrastructure repairs and replacement
Areas with substantial land, building, and infrastructure damage caused by landslides	Santa Cruz Mountains, 1989 Loma Prieta earthquake (Tyler, 1995) Anchorage, Alaska, 1964 earthquake (Pruess, 1995; Tyler and others, 2002) Niigata, Japan, 2004 earthquake (Iuchi, 2014)	Neighborhoods on steep to very steep slopes and on existing landslides in the east bay hills near the hypothetical rupture zone of the Hayward Fault and other parts of the region, especially those areas of strong ground shaking (greater than 20 centimeters per second), poor geologic-material strength and steep slope gradient; see McCrink and Perez, 2017. Areas of potentially concentrated building damage from landslide are just to the east of the Hayward Fault trace in parts of Oakland, Berkeley, and unincorporated Kensington. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		
Areas with surface fault rupture, including afterslip	Napa, 2014 earthquake (Hudnut and others, 2014) San Fernando, 1971 earthquake (William Spangle and Associates, 1980)	Neighborhoods along the 63-km stretch of the Hayward Fault that ruptures on land from Point Pinole in the north to the Warm Springs area of Fremont in the south, with as much as 2 meters of coseismic slip as well as 0.5–1.5 meters of afterslip; see Aagaard, Schwartz, and others, 2017. The Hayward Fault runs through a highly developed area and most structures and infrastructure are not specifically designed to withstand displacement associated with coseismic slip or afterslip. There are 577 structures—including 535 residential buildings—in the areas of measurable offset from coseismic slip and afterslip along the Hayward Fault for the mainshock of the HayWired scenario. There are 2,654 structures—including 2,515 residential buildings—in the zone of uncertainty along either side of the fault rupture zone in the HayWired scenario. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		

Table C6.—Continued

Area	Past earthquake example(s) and key references	Potential communities at risk in the HayWired scenario	Potential damage, hazard, and risk considerations	Potential government interventions and replanning actions
Areas with concentrated building damage caused by ground shaking and fire	Downtown Santa Cruz, 1989 Loma Prieta earthquake (Mader and Tyler, 1991; Tyler and others, 2002) Los Angeles "ghost towns," 1994 Northridge earthquake (Comerio, 1998; Olshansky and others, 2005, 2006) Kobe, Japan, 1995 earthquake (Olshansky and others, 2005, 2006; City of Kobe, 2010; Edgington, 2010)	Areas subjected to shaking levels of MMI VIII or above are most vulnerable to building damage; see Aagaard, Boatwright, and others, 2017. Those areas that also have high-density wood construction and population densities greater than 3,000 people per km^2 are most vulnerable to post-earthquake fires; see Scawthorn, 2018. Areas of concentrated building damage caused by ground shaking and fires in the economic subareas[1] of western Contra Costa County; northern, central, and southern Alameda County; Dublin-Pleasanton; Novato; and Vallejo. Areas with concentrations of multifamily housing and (or) low-income renters in north Richmond, Pinole, east Oakland, Hayward, and Union City. Older neighborhood-serving retail districts in Pinole, Richmond, Kensington, Albany, Berkeley, Oakland, Piedmont, San Leandro, Alameda, Castro Valley, and Hayward. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.	Damage to building foundations and structural integrity Damage to roads, bridges, and other lifeline infrastructure facilities Additional building and infrastructure damage from aftershocks Uncertainty about the feasibility and affordability of repairs to existing buildings and infrastructure Building owner mortgage loan defaults Occupant displacement and (or) voluntary relocation Property blight Decline in property values Loss of property tax revenues	Access control Emergency structural and infrastructure stabilization measures Temporary transportation and infrastructure service provision Regional and local planning considerations, such as priority development areas and priority conservations areas in the "Plan Bay Area 2040" Community engagement in planning and rebuilding decisions Psychological and social service support Temporary building moratorium until planning is completed Site development and building code changes Land use and zoning changes Voluntary buyout program or land acquisition for replanning areas Funding for access control, emergency measures, planning and community engagement, property buyouts, and building, road, and infrastructure repairs and replacement
Areas with substantial transportation and infrastructure damage	Embarcadero Waterfront, San Francisco, 1989 Loma Prieta earthquake (King, 2004a) Hayes Valley, San Francisco, 1989 Loma Prieta earthquake (King, 2004b) West Oakland, 1989 Loma Prieta earthquake (Jackson, 1998)	Jones and others (this volume) investigated the exposure of five lifeline infrastructure systems (water, electric power, oil and gas, transportation, and telecommunications) to all the different hazards from the M_w 7.0 mainshock of the HayWired scenario (ground shaking, surface fault rupture, liquefaction, landslide, and fire) and identified an area of 178 km^2 that had four overlapping mainshock hazards as well as a small 0.2 km^2 area along the Hayward Fault trace where all five mainshock hazards overlap; see Jones and others, this volume. Areas where substantial damage patterns of both buildings and infrastructure offer opportunities for realignment, removal, or substantial reconfiguration and redesign of transportation, infrastructure, and the surrounding neighborhoods. Areas surrounding highway bridges and BART facilities with extended repair times. Areas surrounding San Francisco Bay with seaport, airport, wastewater treatment, and oil and gas processing facilities that may sustain substantial damage. Neighborhoods in these areas that also have populations vulnerable to displacement and may lack recovery resources or an ability to return.		

[1]Economic subareas are defined by Wein, Belzer, and others (this volume).

areas with examples from past disasters; general descriptions of potential communities at risk in the HayWired scenario; potential hazard, damage, and risk considerations; and potential governmental interventions and replanning actions that might be taken. The potential areas requiring governmental interventions and replanning in the HayWired scenario pertain to land damage from ground failure (Detweiler and Wein, 2017) and concentrated building and infrastructure damage (section A; Jones and others, this volume).

All of these areas are likely to sustain substantial damage to buildings and infrastructure from the M_w 7.0 mainshock of the HayWired scenario. They could also face additional damage from aftershocks and an increased vulnerability to other hazards, such as flooding and slope failures. These changes in risk may lead to uncertainty about the feasibility and affordability of land remediation and repairs to existing buildings and infrastructure. Ripple effects may include mortgage defaults by building and property owners, occupant displacement and (or) voluntary relocation, physical, social, and mental health issues for impacted residents, property blight, declining property values, and a loss of property tax revenues for local and State governments.

Many of these conditions were observed in past earthquakes. For example, in the 2010–11 Canterbury, New Zealand, earthquakes, properties were repeatedly damaged by liquefaction and also faced an increased vulnerability to flooding and uncertainty about the feasibility and affordability of repairs to existing buildings and infrastructure (van Ballegooy and others, 2014; Rogers and others, 2014; Johnson and Olshansky, 2017). After the 1994 Northridge earthquake, mortgage loan defaults, occupant displacement and voluntary relocation, health and safety issues, property blight, and the decrease in property values all occurred in the "ghost town" neighborhoods of Los Angeles (Comerio, 1998; Olshansky and others, 2005, 2006).

Governmental interventions and replanning actions that were undertaken to address these postdisaster conditions started with controls on access to the heavily damaged areas and emergency measures to stabilize damaged buildings and protect against other vulnerabilities (like flooding and slope failures). Rebuilding will also be subject to State and local planning and building regulations. Some of the heavily damaged areas are likely to be in the zones of required investigation for liquefaction and earthquake-generated landslide under the California Seismic Hazard Mapping Act (Public Resources Code, Chapter 7.8, Section 2690–2699.6) and active faulting under the Alquist-Priolo Earthquake Fault Zoning Act (California Code of Regulations, Section 3603(f)) (California Geological Survey, 2018).

There may also be areas where geologic hazard investigations on individual building sites may not provide an adequate understanding of future risks. This was the case in Santa Cruz County, California, after the 1989 Loma Prieta earthquake, where the potential risks caused by ground deformation in the mountains could not be assessed adequately through uncoordinated investigations on individual sites (Tyler, 1995). Santa Cruz County commissioned a technical study to determine the potential areawide risk to several hundred homes and adopted a moratorium on rebuilding in this "area of critical concern" until the study was completed. Finding a funding source for such studies can be difficult; in the case of Santa Cruz County, FEMA agreed to fund the study, which took two years to complete.

Such investigations may also reveal that areawide solutions are necessary to mitigate the hazards. Such solutions may need to involve land acquisition and the demolition of some structures. This was the case in the Canterbury region of New Zealand where areawide geologic-hazard investigations concluded that the structures in some liquefaction-damaged areas could not be adequately repaired to withstand future liquefaction hazards without major geotechnical engineering efforts to properly compact the ground and stabilize nearby riverbanks (van Ballegooy and others, 2014; Rogers and others, 2014; Johnson and Olshansky, 2017); see sidebar 3.

Funding for areawide solutions is also challenging, especially if impacted building owners are already facing significant repair costs. New Zealand's national government decided to offer a voluntary buyout to property owners in liquefaction and rockfall hazard areas to allow certainty for owners as soon as possible (see sidebar 3; Johnson and Olshansky, 2017). In the United States, voluntary buyout programs are most commonly applied in postflood events. Such programs were designed and implemented as part of major housing repair programs after the 2005 and 2012 hurricanes using HUD CDBG-DR and FEMA HMGP funds (Johnson and Olshansky, 2017).

Post-earthquake geologic hazard investigations also may need to consider the risks posed by other hazards, including current and future flood risks for liquefaction areas and winter storm and wildfire hazards for landslide areas. Earthquake damage may increase the vulnerability of land and structures to other hazards and there may be opportunities to mitigate the risks from multiple hazards as part of a repair or rebuilding solution. Community engagement, especially with affected property owners, would be essential throughout any post-earthquake hazard investigation as well as in the design of hazard mitigation solutions and rebuilding decisions.

In some areas, the earthquake damage in the HayWired scenario and subsequent ripple effects may be so significant that replanning of these areas may be required. Community engagement is always an essential part of any land use planning effort, but it can be especially challenging to design and implement a demographically representative and inclusive planning process if residents and businesses have been temporarily displaced by disasters (Olshansky and Johnson, 2010).

Local and regional planning considerations would also need to be taken into account. The strategies outlined in these plans may already call for changes in land use and occupancy. For example, some areas may be designated as priority development areas and priority conservations areas in the "Plan Bay Area 2040," which has the core strategy of focusing future growth in the region into existing communities

Sidebar 3—Residential Land Damage and Buyouts after the 2010–11 Earthquakes, Canterbury Region, New Zealand

The City of Christchurch and the Canterbury region of New Zealand were shaken by a series of earthquakes in 2010 and 2011. The first was a moment magnitude (M_w) 7.1 earthquake that struck 44 kilometers (km) west of the city center on September 4, 2010, and the second was a M_w 6.3 earthquake that struck on February 22, 2011, and was located only 6 km from the city center. The second killed 185 people, caused two dramatic building collapses, and rendered nearly half of the central business district buildings uninhabitable (Earthquake Engineering Research Institute, 2011). In total, there were thousands of aftershocks, including more than 30 M_w 5.0 or larger earthquakes and two more M_w 6.0 or larger earthquakes spaced about six months apart, and at least a dozen episodes of liquefaction in some neighborhoods.

New Zealand's national government, through its Earthquake Commission (EQC), offers natural disaster insurance for residential properties that includes coverage for land damage caused by earthquakes, landslides, and other natural hazards. Thus, the EQC conducts land damage assessments of insured properties as part of its claims process. Because of the scale and extent of land movements arising from the earthquakes, the EQC commissioned an areawide investigation to understand the extent and severity of land damages (van Ballegooy and others, 2014; Rogers and others, 2014). Nearly 65,000 residential properties experienced repetitive damage and multiple insurance claims from liquefaction, rockfall, and other ground failures that also heavily damaged surrounding roads, water, wastewater, and stormwater drainage systems (Johnson and Olshansky, 2017).

These studies, combined with the building damage inspection data, formed the basis of the national government's decision on June 23, 2011, to zone all residential properties in the Canterbury region as suitable or unsuitable for rebuilding and announce a package to buy more than 7,000 insured residential properties in the "red zone" area at a price based on the most recent property tax valuation (Canterbury Earthquake Recovery Authority, 2016). The red-zone offer was voluntary, and property owners were under no obligation to accept it, but it was unclear whether utility services would be continued to property owners who did not sell (New Zealand Human Rights Commission [HRC], 2013). By July 2013, nearly 95 percent (7,143) of red-zone property owners had agreed to sell, and most of the properties were cleared by 2016 (HRC, 2016). At the time of publication, planning for the reuse of the red-zone areas continues. The EQC has also assessed and made payments to more than 14,000 properties that had increased flood and liquefaction vulnerability, and thus a loss of property value, caused by the earthquake-induced land damage (Johnson and Olshansky, 2017).

The widespread damage to the region's residential building stock combined with the extensive buyout effort caused shortages; rental and for-sale housing costs rose by more than 30 percent on average during the first five years of recovery (Johnson and Olshansky, 2017). Affordable rental housing or government-owned public housing constituted a high proportion of the lost housing units, and the inhabitants have found it particularly difficult to find affordable housing (HRC, 2013). Homelessness rose and reconstruction of the public housing stock has been slow; concerns persist that more government intervention is needed to provide more affordable housing (Johnson and Olshansky, 2017). On-going monitoring of the well-being of the region's residents identified major individual and household stressors, including the anxiety caused by aftershocks, living in a damaged environment, insurance settlement issues, difficult transport, and additional work-related demands (Nielsen, 2015).



Home that subsided because of liquefaction damage, Christchurch, New Zealand. Photograph by Laurie Johnson, November 21, 2011.

and along the existing transportation network (Metropolitan Transportation Commission and Association of Bay Area Governments, 2017). Allowing additional dwelling units and providing for other development density bonuses are ways that local governments could help incentivize property owners to rebuild. Both the City of Santa Rosa and Sonoma County adopted new measures after the 2017 wildfires to encourage fire-damaged, single-family property owners to build additional dwelling units as part of the recovery (Mendoza, 2017). Temporary building moratoriums may also be needed in some areas until replanning is completed. Implementation for the replanned areas may ultimately involve site development and building code changes, land use and zoning changes, and voluntary buyout or land acquisition programs. Psychological and social service support may be especially important for impacted residents in affected areas.

Governmental interventions and replanning take community engagement, money, and time, and the demands would likely come at a point when populations are displaced and local government budgets may be very constrained because of tax base reductions and the additional costs of repairing publicly owned facilities and infrastructure. All properties that have been substantially damaged or destroyed in a State-proclaimed disaster are eligible for a property tax deferral and to have their property value reassessed, thereby reducing their overall property tax rate (California Revenue and Taxation Code section 170). The HayWired scenario could result in tremendous decline in property tax value in some communities with a commensurately large decrease in local and State property tax revenues for several years.

In general, community-scale land use changes and relocations are rare in the United States, since residents, and even governments, tend to seek to restore normalcy as quickly as possible after disasters (Olshansky and others, 2006; Johnson and Olshansky, 2017). However, disasters do provide an opportunity to relocate residents and communities away from hazard-prone areas as part of reconstruction, but there can be adverse economic, social, and psychological impacts, particularly for low-income households and the elderly, if the policies are not well designed and managed and if livelihoods are location specific (Nelson, 2014; Sapat and Esnard, 2017). Further implications related to businesses in areas of concentrated damage are considered by Wein, Belzer, and others (this volume). Complexity of property ownership and parcel characteristics, the availability and types of financing and funding requirements, preexisting plans and conditions, such as gentrification or blight, the history of natural disasters, level of disaster damage, and future risks, local cultural norms, and a sense of community and attachment to place are all factors influencing postdisaster land use changes and permanent relocation decisions (Green and Olshansky, 2012; Nelson, 2014; Binder and others, 2015; Johnson and Olshansky, 2017).

Discussion

This section of the communities-at-risk analysis builds on the foundational work performed in sections A and B to develop an integrated view of building damage from multiple earthquake hazards and fire, and identify areas of concentrated damage, as well as the numbers and characteristics of populations most at risk of displacement, in order to assess the long-term community recovery challenges that may result from a major earthquake in the San Francisco Bay region, like that in the HayWired earthquake scenario. The material is organized around three key issues that past disasters have shown to impede long-term community recovery: (1) assembling the financing resources for recovery, (2) repairing and rebuilding damaged housing, and (3) addressing areas that require substantial governmental interventions and replanning in order to recover.

In a major earthquake sequence like that in the HayWired scenario, it will be difficult for residents, businesses, and governmental and nongovernmental agencies to quickly assemble the substantial resources necessary to fund repairs and rebuilding. Total estimated losses for the HayWired scenario using Hazus sum to around $102 billion in damages (2016 U.S. dollars), with those losses split between residential (43.5 percent) and nonresidential (56.5 percent) occupancies. The actual cost of repairs and rebuilding could be substantially higher, however, because of the already high construction costs in the region and postdisaster construction cost inflation. CoreLogic, Inc. (2018) estimates $167.3 billion in potential losses resulting from the HayWired scenario (including $23.7 billion caused by the aftershock sequence), in the form of damages and disruption to commercial and residential property as well as automobiles caused by earthquake ground shaking, landslide, liquefaction, and fire hazards. More than 40 percent of the damage is incurred in Alameda County. Contra Costa and Santa Clara Counties also have high proportions of the total property damage, at 15 and 18 percent, respectively.

Though there are some significant discrepancies between the Hazus and CoreLogic building-related loss estimates, the important point to consider is the scale of loss—a loss that does not yet account for the longer term indirect and induced losses that are not directly related to property damage but caused by social and economic disruption.

In most areas of the United States, insurance is a foundational element of a community's disaster recovery. In the nine-county region, among all residential fire policyholders (comparable to general property insurance) only about 10 percent have an earthquake insurance policy. Most of the commercial earthquake insurance in the State covers large commercial buildings, whereas smaller commercial businesses do not typically buy earthquake insurance (owing to cost, short business time horizons, and small amounts of at-risk assets). CoreLogic, Inc. (2018) estimates $30.2 billion in insured losses for the HayWired earthquake sequence and fire, covering about

23 percent of commercial losses and 12 percent of residential losses. Approximately 87 percent of the total insured losses are incurred in Alameda, Contra Costa, and Santa Clara Counties—the three counties with the highest damage levels—but insurance covers at most 21 percent of the losses (in Alameda County) and less in the rest of the region.

A major earthquake like the mainshock of the HayWired scenario would almost certainly trigger State and Federal disaster assistance programs and activities. These programs help provide valuable financial resources to single-family homeowners, multifamily rental properties, and affordable housing construction. Studies from past disasters have shown, however, that race, ethnicity, gender, income, language fluency, cultural differences, and political connectedness can differentially influence the accessibility and distribution of formal disaster assistance, especially from government sources. For the HayWired scenario, some of the hardest hit communities also have high levels of social and economic vulnerability, and thus many individuals, households, and business owners in these areas may have difficulty obtaining formal disaster assistance. Funding delays, inflexible regulations, lengthy approval processes, and reduced state and local tax revenues also complicate and limit the effectiveness of government funding.

Financing housing repair and replacement depends on the extent of damage. Of the nearly 1 million residential buildings and 1.37 million housing units that sustain some level of damage from all hazards in the HayWired scenario, nearly 90 percent are single-family or duplex buildings in a slight to moderate damage state (most likely caused by ground shaking). In these cases, likely loss levels may not exceed insurance deductibles, but would be within the range of financing available with SBA disaster loans and FEMA Individual Assistance grants.

An estimated 97,397 residential buildings (housing 93,381 single-family and duplex units and as many as 78,445 multifamily units) are in an extensive or complete damage state because of ground shaking, fault rupture, liquefaction, landslides, and (or) fire. These losses may be partly covered by insurance, but may fall short because of underinsurance. Otherwise, SBA disaster loans, FEMA Individual Assistance grants, conventional loans, individual savings, or assistance from philanthropic or nonprofit funders would be needed to fund repairs and rebuilding (including temporarily increased construction costs). Some owners may sell their home and relocate. Financial challenges could involve low-income property owners, mortgage defaults, and affordable housing, in particular.

Household-level decisions to stay and rebuild depend on more than just housing damage and access to recovery resources. Other important factors include the speed, strength, and certainty of economic recovery; availability of jobs and businesses; speed with which water utilities, critical community services, and nearby businesses are restored; and regulatory changes to inspections, planning, construction, or zoning.

The potential areas requiring local governmental interventions and replanning in the HayWired scenario pertain to land damage from ground failure and concentrated building and infrastructure damage. Adverse effects of community-scale land use changes include economic, social, and psychological impacts, particularly for low-income households and the elderly, if the policies are not well designed and managed and if livelihoods are location specific.

Community engagement, especially with affected property owners, would be essential throughout any post-earthquake hazard investigation as well as in the design of hazard mitigation solutions and rebuilding decisions. Community engagement is always an essential part of any land use planning effort, but it can be especially challenging to design and implement a demographically representative and inclusive planning process if residents and businesses have been temporarily displaced by disasters. Local government budgets for community engagement, replanning, and other interventions to help stimulate community recovery may be very constrained because of tax base reductions and the additional costs of repairing public facilities and infrastructure.

Assumptions and approaches taken in this recovery analysis draw largely on past recovery experiences from earthquakes in California and New Zealand and hurricanes that struck the Atlantic and Gulf Coasts of the United States. Some areas of potential follow-up study to enhance our understanding of the potential recovery challenges that the San Francisco Bay region may face after a future earthquake include:

- Estimate likely Federal and State recovery funding needs and analyze different funding scenarios for the HayWired and other major earthquake scenarios for the San Francisco Bay region.
- Construct an incremental and measured depiction of how recovery in the HayWired scenario unfolds through time (for example, 6 months, 1 year, 2 years, 5 years, and 10 years) and some of the long-term recovery challenges that are likely to result from these impacts, perhaps on a neighborhood or community-specific level. Such detailed scenarios can offer added value and use in local recovery and hazard mitigation planning.

Research needs revealed by this analysis that would enhance the understanding of community recovery processes more broadly include:

- Systematic and longitudinal data collection and analysis of postdisaster recovery financing resources and gaps, the distribution of resources and potential redistribution of wealth from past disasters, and as part of future disaster research.
- Systematic and longitudinal data collection and analysis of the physical repair and recovery times of the built environment, especially housing, as well as the key social, economic, and political concerns and outcomes from past earthquakes and other disasters, and as part of future disaster research. This includes data collection and monitoring of postdisaster damage assessments, property tax assessments, permitting, occupancy certificates, sales, and land use changes to track recovery.

- Disaster-specific analyses of the physical (built and environmental, especially post-earthquake fires and geologic hazards, such as fault rupture, liquefaction, landslides, and other forms of ground failure), social, economic, and political factors that most strongly influence population, housing, and community-scale recovery and how certain policy and planning interventions and other external factors affect population displacement, as well as housing and community-scale recovery.
- Further examination of the effects of land use policy and comprehensive planning as contributions to community vulnerability to disasters, including population displacement and long-term housing and community recovery challenges.

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Chapter V1

Summary of Economic Impact Analyses and Policy Implications of the HayWired Scenario

By Stephen Levy[1], Anne M. Wein[2], and Cynthia Kroll[3]

Introduction

The HayWired scenario examines a hypothetical earthquake sequence with a moment magnitude (M_w) 7.0 mainshock occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region. Economic and community impact analyses for the HayWired earthquake scenario paint a bleak picture of the consequences of an earthquake centered in Alameda County and affecting much of the nine-county San Francisco Bay region, which is home to about 7.8 million people. In this scenario, hundreds of thousands of San Francisco Bay region residents are affected by disruption to their families, homes, and jobs, raising questions:

- Is the San Francisco Bay region economy strong enough to withstand an event of this magnitude?
- Would the region's economy recover? How quickly?
- What are the key factors in determining how resilient the economy would be?
- Where are businesses and the people living or working in the region affected?

This subchapter summarizes a series of technical subchapters that look at the level of economic impact that could be expected from the HayWired earthquake scenario, how that impact would be distributed among geographic areas and types of businesses in the region, and how individual and policy decisions made before or applied after the event can change the overall impact immediately and over time. The economic analyses convey that whereas the overall economic losses can be overcome at a regional scale, policy interventions can be most important for addressing human challenges and location-specific challenges.

[1]Center for Continuing Study of the California Economy.

[2]U.S. Geological Survey.

[3]Metropolitan Transportation Commission and Association of Bay Area Governments, retired.

Overview of the HayWired Economic Analysis

The HayWired scenario is a collaborative effort led by the U.S. Geological Survey. Five studies were commissioned to identify the economic impacts and related policy implications of the HayWired earthquake scenario (see table 1). The full technical subchapters are published separately in this volume. Two studies focused on macroeconomic impacts—impacts on the levels of output, employment, and associated population movements in the San Francisco Bay region after the earthquake. Two studies focused on impacts for industry groups, business types by size and ownership, small geographic areas, and employee workplaces and homes. The final study, commissioned to inform both the economic analyses and the communities-at-risk analysis, focused on insurance coverage and related policy issues. The aim of these efforts is to inform policies, mitigation approaches, and programs that could be helpful in the San Francisco Bay region before and after a large earthquake like that in the HayWired scenario.

The assessments of economic impact were derived from estimates of physical damage to structures and infrastructure, such as transportation and telecommunication networks. Output and employment losses are the result of business interruptions caused by business and residential damages, transportation (highway and mass transit) disruptions, and telecommunications, water, and electric power outages.

Damaged homes, businesses, public facilities, utilities, and transportation and telecommunications infrastructure would need to be rebuilt and the speed of rebuilding would affect the amount and duration of economic losses. Temporary housing, business relocation, and restoration of services can help to reduce these losses.

Impacts can be important for policy purposes either because they are large or because they fall on individuals and organizations with limited ability to respond. For example, small businesses are slightly more likely to be disrupted by building damages compared to very large businesses in the HayWired scenario. Of greater significance, small businesses are also less able to prepare for and respond to a large earthquake compared to larger firms and organizations with multiple locations.

Table 1. Analyses of economic outcomes of the HayWired scenario.

[ABAG, Association of Bay Area Governments; MTC, San Francisco Bay Area Metropolitan Transportation Commission; USC, University of Southern California; USGS, U.S. Geological Survey]

Study title	Authors and affiliations	Method	Commissioner	Location in HayWired volume 3
Economic consequences of the HayWired earthquake scenario—Cyber and electricity network linkages and resilience	Ian Sue Wing (Boston University), Dan Wei and Adam Rose (USC), and Anne Wein (USGS)	Macroeconomic model of Gross Domestic Product losses in San Francisco Bay counties, the region, and the State of California during the first 6 months	HayWired project	Subchapter V2
The economic effects of the HayWired scenario using the Association of Bay Area Governments regional growth forecast	Cynthia Kroll, Bobby Lu, and Aksel Olsen (MTC and ABAG), and Anne Wein (USGS)	Macroeconomic model of Gross Regional Product, job, and population losses in subregions and the nine-county region compared to growth forecast over the next two decades	HayWired project	Subchapter V3
Characteristics of businesses disrupted by building damages from the HayWired scenario mainshock	Anne Wein (USGS), Jon Haveman (Marin Economic Consulting), Cynthia Kroll (MTC and ABAG), and Jeff Peters (USGS)	Spatial analysis of business exposure to building damage throughout the region by business characteristics	HayWired project	Subchapter V4
Spatial analysis of industries, employment, and commute flows in areas of concentrated damage from the HayWired earthquake scenario	Anne Wein (USGS), Dena Belzer (Strategic Economics), Cynthia Kroll (MTC and ABAG), Carline Au (Strategic Economics), Jamie Jones (USGS), Laurie Johnson (Laurie Johnson Consulting), Aksel Olsen (MTC and ABAG), and Jeff Peters (USGS)	Subarea and industrial sector exposures to concentrated damage and work-home relations between these areas in the region	HayWired project	Subchapter V5
Financial implications of the HayWired scenario	CoreLogic, Inc.	Insurance models of damage and coverage	California Earthquake Authority	Discussed in chapter U; published separately by CoreLogic, Inc. (2018)

There is a time dimension to these findings. Some impacts are large and short lived. Other impacts may last for many months or years. Recovery would vary across different types of businesses and residents and geographic parts of the region. Recovery would also depend on the scope of insurance coverage and the ability of the public and private sectors to raise funds for rebuilding.

In addition to identifying and quantifying economic impacts, the goal of this research is to identify policy responses that can prevent damage, reduce some of the impacts, and facilitate the recovery process. These involve forward-looking community and regional planning, actions that can be taken beforehand, such as retrofitting buildings and new building designs, and policies that speed up recovery, such as business continuity and preparation, adequate insurance, and other reconstruction funding mechanisms.

This report is organized as follows: (1) an overview of high-level findings, (2) a summary of each individual report, (3) a list of the major policy implications, and (4) a closing statement.

High-Level Findings from the HayWired Scenario

This section identifies and summarizes the high-level findings of the four HayWired scenario economic analyses. These findings also include relevant insurance analysis findings.

Macroeconomic Analyses

- Damages to hundreds of thousands of vulnerable buildings (residential, commercial, and industrial) and months to years of disrupted transportation systems

(for example, major highways and transit) result in job and production (output) losses similar to a moderate to severe recession.

- Job and output losses are concentrated in the areas of strongest shaking and liquefaction in Alameda and Contra Costa Counties.
- The cumulative output loss effects from transportation network and commuting flow interruptions could spread economic losses throughout the San Francisco Bay region and be as large as the output loss associated with building damage.
- Most of the economic losses occur within the first 6 months to one year after the M_w 7.0 earthquake of the HayWired scenario, although the losses continue for a few years beyond, and it takes many more years to rebuild damaged buildings and infrastructure.
- Bottlenecks from labor, material, and funding shortages and higher construction costs could stretch recovery times for several additional years. Such delays were found in Santa Rosa and Sonoma County after extensive wildfire damage to homes in 2017 (Li, 2018).
- The amount of economic losses and the time for recovery and rebuilding can be reduced by implementing mitigation and resilience measures such as those discussed in the policy implications section.

Geographic and Business Analyses

- Risk of building damage that limits or restricts building use varies greatly depending on location, with the largest impacts in central Alameda County and parts of Contra Costa County.
- In addition to business location, the type of building an industry tends to occupy affects its risk of building damage. For example, production and distribution industries are more concentrated in older buildings with less modern reinforcement and seismic safety design, and thus face higher risk of building damage.
- Beyond individual building damage risks, concentrated building damage (defined as more than 20 percent of building square footage extensively or completely damaged within neighborhoods or business districts) complicates response and recovery in these areas. Concentrated building damage in more than 10 percent of San Francisco Bay region census tracts is largely attributable to damages to (likely older) industrial/warehouse, retail/commercial, and multifamily residential buildings.
- Almost 200,000 employees (7.6 percent of jobs in the nine-county region) may work in damaged buildings with limited or restricted use, but the lives of more than 500,000 employees (14 percent) are potentially affected by concentrated damage in their business districts or residential neighborhoods, even if their work or homes are undamaged.

Insurance Analysis

- About 95 percent of homeowners have basic (including fire) residential property insurance coverage, but only about 10 percent of general residential property insurance holders in the nine-county region have an earthquake insurance policy.
- Statewide, only 8.5 percent of insured commercial properties have earthquake insurance coverage. Large commercial properties are insured, raising the overall share of square footage covered by insurance, such that smaller and less-resourced businesses are less likely to have property insurance and more likely to face shortfalls in recovery financing.
- CoreLogic, Inc., estimates $170 billion in damages for the HayWired earthquake scenario, of which $30.2 billion are insured. About 18 percent of the total damage estimate is insured—9 percent of estimated residential damage and 20 percent of estimated commercial damage. Of the insured damages,
  - About $21.2 billion are for the M_w 7.0 earthquake damages from ground shaking, liquefaction, and landslide;
  - $4 billion are for fire and sprinkler damage; and
  - $5 billion are for aftershock damages.
- These estimates do not include the insured losses for damage to the region's infrastructure and government buildings (which may be covered by self-insurance funds set aside by jurisdictions), workers compensation exposures, automobile lines of business, and indirect business interruption of such a major disaster.

Human Considerations

- Whereas economic losses are comparable to the effects of the first few years of a recession, the human challenges (emotional trauma, population displacement, and job losses) to many residents and businesses would be severe and the degree of severity would depend on preparation and post-earthquake actions.

The San Francisco Bay Region Economy

The nine-county San Francisco Bay region accounts for a growing share of the U.S. economy, reaching almost 3 percent of the Nation's jobs and almost 4 percent of the Nation's output in 2017. The region has close to 4 million wage and salary jobs, of which 30 percent are in the east bay, where the HayWired scenario damages are concentrated. The region is home to Silicon Valley, which has seen several waves of industry innovation and expansion in high tech, multimedia, and social media over the past four decades, and the city of San Francisco, once the financial center of the west coast, is now a hub for high-tech services and social media and has played a key role in incubating new companies over the past two decades. Alameda and Contra Costa Counties, the two east bay counties, provide somewhat more affordable housing for many of the workers who commute to San Francisco and the south bay. One strength of the east bay economy has been its diversity, with some spillover of jobs from Silicon Valley and San Francisco, but also a concentration of regional and local serving and support services for residents and businesses. Oakland, the region's third largest city, is in the heart of the east bay and is a Federal job center for the region; the east bay also has a high concentration of trade and construction jobs. The San Francisco Bay region has a multiethnic, multilingual, and mobile population—more than 30 percent of the population is foreign born. With nine counties and 101 cities, the San Francisco Bay region has developed innovative ways to address the seismic risks faced daily, but also faces challenges in finding effective policies that can be adopted by small and large, rich and poor jurisdictions throughout the region.

Macroeconomic Impacts and Economic Resilience Analysis—The First 6 Months

The subchapter "Economic Consequences of the HayWired Earthquake Scenario" evaluates the economic impacts from the HayWired earthquake scenario on the economies of the San Francisco Bay region and California State using a computable general equilibrium (CGE) simulation model. A CGE model is commonly used for estimation of business interruption losses measured as Gross Domestic Product (GDP). It uses real-world sector purchasing data in a system of equations that describe the general equilibrium balance of different elements of an economy. As such, business interruption losses ripple through supply and customer chains.

In the 6-month period after the M_w 7.0 HayWired scenario earthquake, total GDP losses are estimated to be $43.2 billion (2014 U.S. dollars) for the State of California—that is, 4.2 percent of the State's baseline GDP for that period. The GDP losses are primarily caused by property damages; individual GDP losses from water, power, or telecommunication outages do not exceed $900 million.

However, this loss could be reduced by 42 percent to $25.3 billion if economic resilience measures are implemented after the damages and outages have occurred. Implementation of economic resilience measures after the disaster is in contrast to mitigation investments to reduce damages before a disaster. Evaluation of these resilience measures, which include business continuity planning, is a major contribution of this study. The sidebar below provides a summary of the types of measures evaluated.

Economic Resilience Measures

1. Resilience measures that speed restoration of services. These include:
    - A. Input substitution, such as fixed back-up power (batteries and generators) for telecommunications equipment and fuel management plans for water utilities in case of an electric power outage.
    - B. Inventories of portable telecommunication equipment to temporarily add capacity in telecommunications networks.
2. Resilience measures that work around the supplier disruption to maintain production of goods and services. These include:
    - A. Conservation of critical inputs (for example, recycling water).
    - B. Input substitution that replaces an unavailable good or service (for example, using a plain old telephone service in place of Voice over Internet Protocol service, or vice versa).
    - C. Resource isolation to allow the proportion of the production or sales processes that can continue without utility services. For example, much of agricultural production does not require electricity.
3. Resilience measures that use resources beyond normal use to serve more customers. Two examples are:
    - A. Production recapture (rescheduling) is the ability of businesses to recoup lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs and employees are available. This is a viable option for short-term disruptions, where customers are less likely to cancel orders from their standard suppliers.
    - B. Relocation of businesses, including teleworking from other locations (for example, shared workplaces or homes).

Table 2 illustrates resilience measures that reduce estimated unmet demand for telecommunication services. They may include

- fixed backup power (batteries and generators) to substitute for electric power supply disruption in the short term,
- user behavior management (including texting instead of talking) to temporarily conserve available bandwidth,
- longer lasting resilience measures when carriers truck in portable equipment and fuel to speed restoration.

For example, in Alameda County, the service disruption in the base case results in 5.1 percent unmet customer demand over 6 months. If the fixed back-up power measure alone is adopted, unmet demand drops to 4.4 percent. The table shows the impact of each resilience measure separately, but if all measures are adopted, unmet demand drops to 0.8 percent in Alameda County. In turn, the resilience measures reduce the GDP losses from telecommunication service outages from $350 million to $40 million.

Regarding property damages, the most effective resilience measure is shown to be catching up on lost production (38 percent reduction in GDP losses) followed by telework (6 percent reduction in GDP losses). Results of the modeling without and with resilience are shown in table 3. As shown below, the hardest hit county of Alameda has a decline of $12.7 billion (or 23.5 percent) with no resilience measures and a decline of $7.45 billion (or 13.8 percent) with all resilience measures. Both Alameda and Santa Clara Counties suffer from $7 billion GDP losses once resilience is incorporated. The study found that the overall economic impacts were smaller than the peak national percentage of GDP losses in two consecutive quarters of the Great Recession that began in 4th quarter of 2007, except for Alameda County alone, and smaller than the region's peak percentage of GDP losses, except for Alameda and Santa Clara Counties alone. Therefore, the predicted economic impacts of the HayWired scenario earthquake would result in a recession in the San Francisco Bay region, but not a multiyear global impact like the Great Depression of the 1930s.

Longer Term Macroeconomic Analysis—Effects of a Major Earthquake on the Region's Future

The subchapter "The Economic Effects of the HayWired Scenario Using the Association of Bay Area Governments Regional Growth Forecast" examines how the long-term trajectory of the region's economy could be altered by a major earthquake along the Hayward Fault for the nine-county San Francisco Bay region. In this analysis, the following subregions are defined:

- the east bay is Alameda and Contra Costa Counties,

Table 2. Summary of data and voice telecommunications disruptions resulting from the HayWired earthquake scenario for the base case and resilience cases on a 6-month basis for the five most disrupted counties in the San Francisco Bay region, California.

[Values are percentages of unmet customer service demand]

County	Base case (no resilience measures)	Supplier resilience measures		Customer resilience measures			All resilience measures
		Fixed back-up power	Fuel/portable equipment	User behavior management	Input substitution	Production and sale isolation	
Alameda	5.1	4.4	3.0	4.7	2.8	2.1	0.8
Contra Costa	3.6	3.1	1.7	2.8	1.9	1.1	0.3
San Francisco	1.9	1.6	1.5	1.7	1.3	1.0	0.5
San Mateo	2.3	1.9	1.6	2.2	1.4	1.1	0.4
Santa Clara	3.7	3.1	1.7	2.9	2.0	1.4	0.4

Table 3. Total Gross Domestic Product changes without and with all resilience measures in the 6 months after the HayWired earthquake scenario in the San Francisco Bay region and California.

[Values in billions of 2012 U.S. dollars. %, percent]

Loss category	Alameda County	Contra Costa County	San Francisco County	San Mateo County	Santa Clara County	Rest of San Francisco Bay region[1]	Rest of California	California total
No resilience	−12.7	−3.6	−2.5	−3.6	−13.1	−2.1	−6.5	−44.2
	−23.5%	−11.4%	−4.0%	−8.4%	−11.2%	−1.3%	−1.0%	−4.2%
With resilience	−7.45	−2.11	−1.31	−2.02	−7.23	−1.23	−3.94	−25.3
	−13.8%	−3.4%	−2.1%	−4.6%	−6.2%	−0.8%	−0.6%	−2.4%

[1]Marin, Napa, Sonoma, and Solano Counties.

- the north bay is Napa, Solano, and Sonoma Counties,
- the west bay is Marin, San Francisco, and San Mateo Counties, and
- the south bay is Santa Clara County.

The Association of Bay Area Governments (ABAG) and Metropolitan Transportation Commission analysis, using the Regional Economic Models, Inc. (REMI) model, translates sector output losses from building damage, commute flow interruption, and other factors into disruptions in business activity and then into estimates of the impact on the 2017 ABAG projection of jobs, regional output, and population. The analysis also considers sensitivities of effects to varying recovery times for trade and manufacturing sectors, housing cost increases, and population responses in terms of migration. Government disaster funds and insurance payouts counteract some of these effects.

The economic impacts are primarily caused by output losses from building damages and commute flow interruptions from transportation (Bay Area Rapid Transit [BART] and highways) disruptions that may last months to a few years. The analysis shows an economy that would experience substantial damages and losses in the short term. In the first year after the earthquake, assumed to occur in 2018, employment would drop by approximately half a million jobs (table 4) and Gross Regional Product would decline by 8 percent relative to the growth projected in 2017. The decline in output from commute flow interruption more than doubles the employment and population loss. Although building damage is the major contributor to employment loss from building damage in the east bay, where damage is greatest, commute flow interruptions in the west and south bay affect employment to a much greater degree than employment loss from building damages.

Government spending and new investments over a 9- to 10-year period have a stimulating effect on the economy that can counteract some of the job and population losses. If total impacts and stimulus effects are combined, the region's net employment loss in the first year is still more than 496,000 jobs—a 10 percent decrease compared to the regional baseline forecast. Results show a regional economy that could experience a deep recession with more severe effects in the most strongly affected area. Much of the economy could recover to the pre-earthquake growth path within a few years, but parts of the San Francisco Bay region do not recover to pre-earthquake employment levels until about 7 years later (2025). The region returns to within about 1 percent of the 2017 projected employment track by 2025 (fig. 1).

To put this in perspective, the HayWired economic impact analysis described here shows employment losses experienced in the east bay that are much sharper and deeper than during recent recessions, but with a faster rate of recovery than from either the dot-com recession of 2001 or the financial-crisis-related Great Recession that reached a trough in mid-2009. Figure 2 compares the effects of the HayWired scenario on employment with the effects of the last three recessions on east bay employment.

The speed of recovery would be helped by the continued economic strength of the Nation as a whole and other parts of the San Francisco Bay region, and by the assumption that individual firms recover rather than relocate. Employment losses in the San Francisco Bay region are of a magnitude similar to that experienced in the dot-com recession, but it ultimately took the region much longer to recover the jobs lost in the dot-com recession than the recovery illustrated in the HayWired scenario economic analysis drawn from the REMI model. In the dot-com bust, the region lost its main engine of growth. In contrast, effects from the HayWired scenario are more diversified among sectors, public money is invested in the recovery, and many businesses in undamaged parts of the region continue to operate.

All sectors experience jobs losses in the first few years after the HayWired earthquake scenario mainshock, relative to growth that would have occurred without the earthquake (fig. 3). The construction sector is one of the first to be stimulated by year three, as recovery spending picks up after initial delays (as were experienced after the Christchurch, New Zealand, earthquake in 2011), and other sectors return to normal. The accommodations and food services sector has the largest employment loss in 2018, at almost 59,000 lost jobs (19 percent), followed by the professional, scientific, and technical services sector (44,000 lost jobs, or 7 percent), the retail trade sector (43,000 lost jobs, or 10 percent), and the

Table 4. Total employment difference from all effects of the HayWired scenario mainshock relative to the undisrupted Association of Bay Area Governments' 2017 projection for the San Francisco Bay region, California.

[ABAG, Association of Bay Area Governments; %, percent]

Subregion	2018 (year of earthquake)	2019 (1 year after)	2022 (4 years after)	2027 (9 years after)	2040 (22 years after)
East bay	−238,518	−74,107	−48,398	−736	−3,149
North bay	−22,844	−10,136	−12,164	−780	−1,224
West bay	−145,844	−25,566	−25,422	−1,058	−3,619
South bay	−107,998	−22,300	−9,622	1,635	−2,380
San Francisco Bay region	−515,204	−132,108	−95,606	−940	−10,373
Regional percentage compared to ABAG 2017 projection	−10.1%	−2.6%	−1.9%	<0.1%	−0.2%

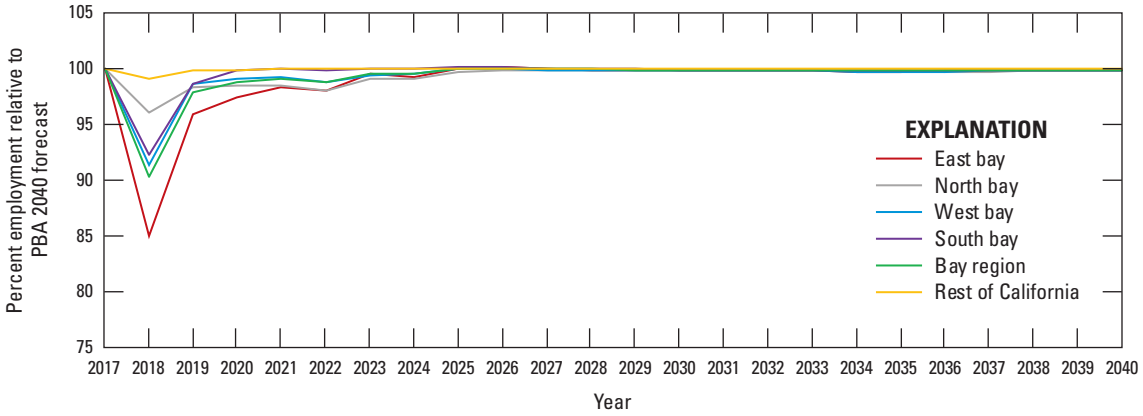


Figure 1. Line graph showing the percentage of employment difference resulting from the HayWired earthquake scenario in the San Francisco Bay region, California, by subregion compared to Association of Bay Area Governments (ABAG) regional and statewide projections. PBA 2040 is the ABAG Plan Bay Area 2040 forecast.

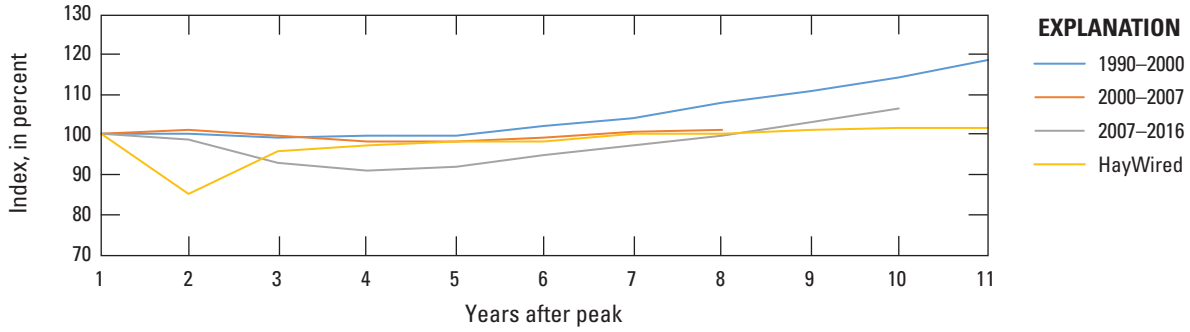


Figure 2. Line graph showing the recovery progression for the three most recent recessions from prerecession peak to peak of recovery or next upturn for the east bay subregion of the San Francisco Bay region, California, compared to job projection in the HayWired scenario. One hundred percent represents the peak before each downturn. Data from Kroll and others (this volume), based on California Employment Development Department data and, for HayWired projections through 2027, Association of Bay Area Governments Planning and Research Department REMI model version 1.7.8, adjusted control NC3RC1. REMI refers to models produced by Regional Economic Models, Inc.

administrative and waste management services sector (32,000 lost jobs, or 10 percent). Nevertheless, the region returns to a strong growth path within less than a decade, and by 2040, regionwide employment is only 10,000 below projections without the earthquake.

Although the initial net effect of the earthquake on population is smaller than employment effects relative to the regional growth projection, the population effects last longer in this analysis—the population in the region is below the ABAG projection without an earthquake for more than a decade. The population in the San Francisco Bay region decreases by about 145,000 in 2018 relative to projections, of which 83,000 occurs in the east and north bay. Population net loss in the east bay after the HayWired scenario earthquake includes those who move for economic reasons and those who retire, who are assumed in the analysis to choose not to rebuild but instead leave the area. These changes continue to have a small effect on the region's population throughout the forecast—the "economic" portion of the population returns as the jobs return, but the "noneconomic" departures (such as retirees) take longer to return, if ever. By 2040, the population in the San Francisco Bay region remains a net loss of about 21,000 people compared to the regional control forecast; see figure 4. These declines are small in percentage terms (around 4 percent at the peak in 2022, and only 0.2 percent compared to the 2040 forecast) compared to the 7.8 million regional residents in 2018 and projected 9.5 million residents in 2040, according to "Plan Bay Area 2040" (ABAG Planning and Research Department, 2016; Kroll and others, 2017).

Varying public spending and other assumptions affect the model results, and policies assumed before and after the earthquake may also determine the outcomes for individuals, communities, and the region as a whole. For example, sensitivity testing of an increase in postdisaster construction

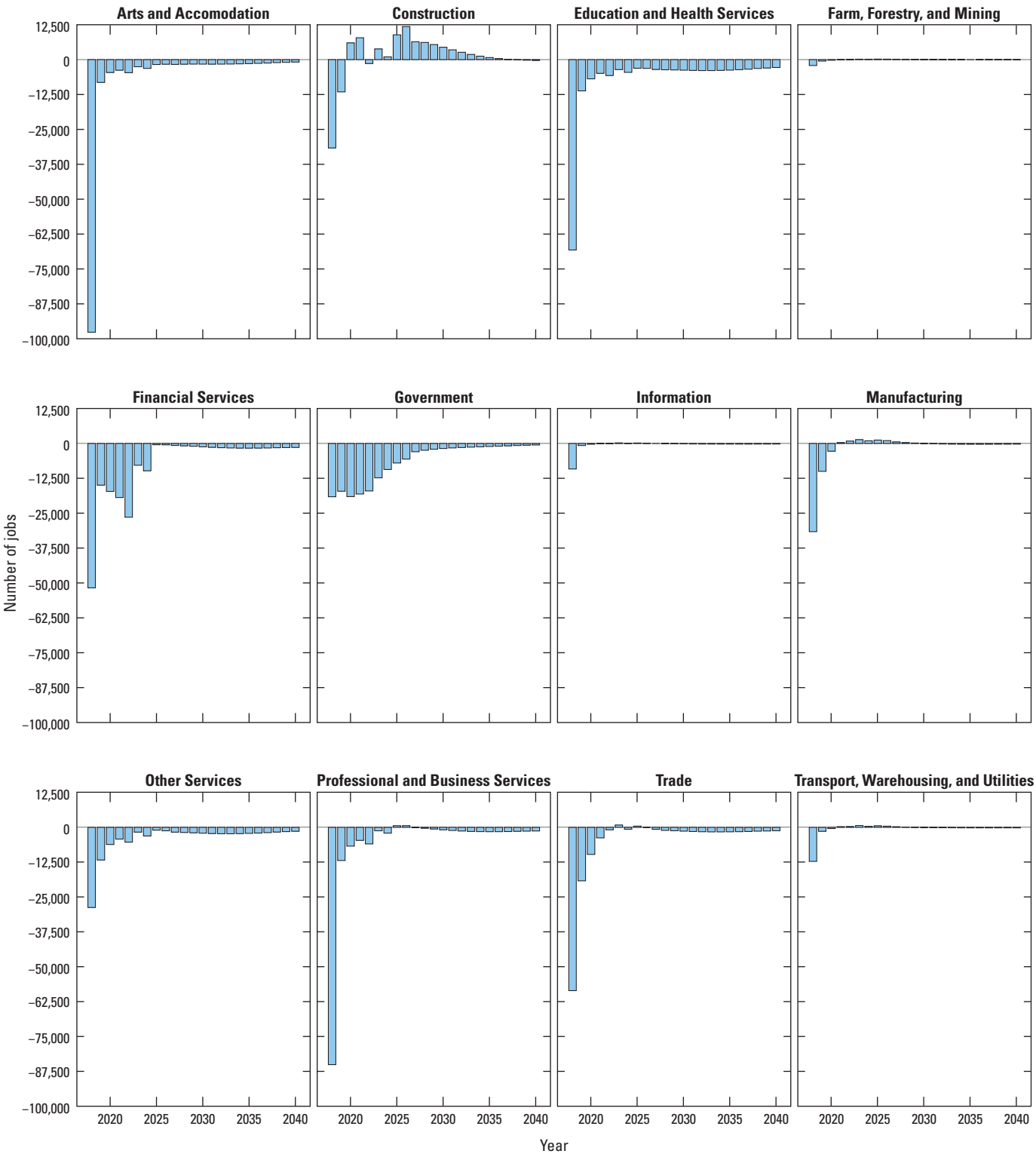


Figure 3. Bar graphs showing San Francisco Bay region, California, employment change projections after the HayWired scenario mainshock (in 2018) through 2040 by major North American Industry Classification System industrial sector. Employment is plotted relative to Association of Bay Area Governments regional growth projections.

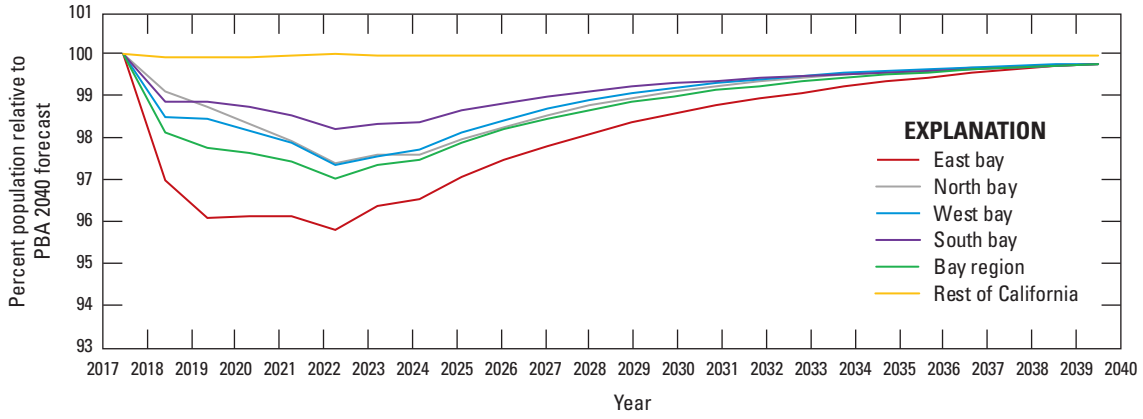


Figure 4. Line graph showing population curves in the HayWired scenario for the San Francisco Bay region, California, relative to the Association of Bay Area Governments (ABAG) regional and statewide projections. PBA 2040 is the ABAG Plan Bay Area 2040 forecast.

costs and an inadequate supply of construction workers significantly slows down recovery.[4] The pace and level of spending in response to the earthquake and the source of funds for rebuilding also influence the pace and level of recovery in the region.

How Business Characteristics and Location affect Vulnerability and Outcomes

The subchapter "Characteristics of Businesses Disrupted by Building Damages from the HayWired Scenario Mainshock" analyzes attributes of businesses vulnerable to limited or restricted use of their buildings as a result of extensive and complete damage (as determined by the Hazus-MH 2.1 loss-estimation software) from the HayWired scenario. The risk of disruptive building damage is estimated for business establishments by location, industry, size, structure, and ownership. For example, business establishment risk by location is the percentage of business establishments with disruptive building damage in a county divided by the total number of establishments in that county. Through a background review of past research, this chapter also recognized significant differences in the ability of various businesses and owners to prepare for and respond to an earthquake. Both the background research and the vulnerability findings suggested the value of exploring policies and programs to mitigate the impacts of an earthquake of the HayWired scenario magnitude for certain business characteristics.

Above average disruptive building damage risk for business establishment characteristics is shown in figure 5. The key finding is that location is the most distinctive attribute for this risk and a driver of other smaller risk differences.

- Alameda County establishments face the highest risk (25 percent of establishments), followed by Contra Costa County.
- Business establishments in the construction sector have a slightly higher risk resulting from greater concentration in the east bay and the building types occupied by construction firms. This is important in light of the current construction worker shortage, recovery challenges of small San Francisco Bay region construction businesses, and increased construction costs that delay overall recovery, as shown in the macroeconomic analysis.
- The largest businesses (with 500 or more employees) have a slightly lower level of risk of building damage, which could result from occupancy of modern buildings or location in less affected areas in this scenario. In contrast, smaller revenue (below $100,000) businesses appear more likely to suffer disruptive building damage and also have fewer resources to help in recovery.
- Minority-owned small businesses are slightly more likely to be in areas where buildings are at greater risk of disruptive damage—more than 9 percent, compared to the range of 6 to 8 percent for non-minority-owned establishments. This result reflects the presence of relatively more minority-owned establishments (4.6 percent of establishments and 7 percent of employment) in Alameda County, the most affected county, and

[4]The issue of construction worker availability is addressed more fully by Littlehale (2019).

in the sectors of manufacturing and wholesale trade, which have more disruptive building damage risk associated with location and building types. Some research has shown minority-owned establishments to be more vulnerable than other businesses for a variety of reasons relating to resources and networks. In this case, identifying these businesses as "vulnerable" is largely because of the vulnerability of the sectors and locations of these businesses. The situation for these establishments should not be confused with many of the most successful, well-capitalized, minority- or immigrant-owned businesses that started up in the San Francisco Bay region.

- If the risk to businesses is weighted by employment numbers at the establishments, manufacturing sector risk increases from 8.5 to 9.1 percent. Conversely, employment-weighted risk is less than establishment risk in Alameda County (22.9 percent) and the warehouse/transportation sector risk drops from 9.4 to 7.2 percent, meaning that fewer employees are in the riskier buildings for those characteristics.

- Fire hazard increases disruptive building damage risk most for businesses in Alameda County and for education and public administration sector businesses. The vulnerability of education and public administration sector businesses reflects the allocation of burned buildings to sectors based on the 1995 Northridge earthquake fire data—the distribution among building occupancy could be quite different in the San Francisco Bay region.

Geographic Concentrations of Impacts and their Interactions—A Spatial Analysis

Traditional macroeconomic impact analysis of building and infrastructure damage assessments provides an aggregate estimate of effects the HayWired scenario could have on the regional economy. Yet macroeconomic analysis does not adequately capture the fact that these effects are spread unevenly across counties and subregions nor the effects of the spatial relations between jobs and homes. The subchapter "Spatial Analysis of Industries, Employment, and Commute Flows in Areas of Concentrated Damage from the HayWired Earthquake Scenario" provides a geographical examination of potential disruption, focusing specifically on areas with concentrated building damage, and considers effects on both employee workplaces (by industry group) and homes (by single-family/duplex, multifamily, or group-living type).

Concentrated Building Damages

The total number of census tracts where the percentage of extensive or complete building damage is concentrated—greater than 20 percent from earthquake and fire hazards—is 173, out of a total of nearly 1,600. There are seven subareas in the region that contain these tracts (fig. 6), which make up about 11 percent of the total number of tracts in the nine-county San Francisco Bay region. The 173 tracts are primarily located in Alameda and Contra Costa Counties, with fire impacts also concentrated in Marin and Solano Counties. The cities of Hayward and San Leandro have older downtown cores with concentrations of vulnerable building

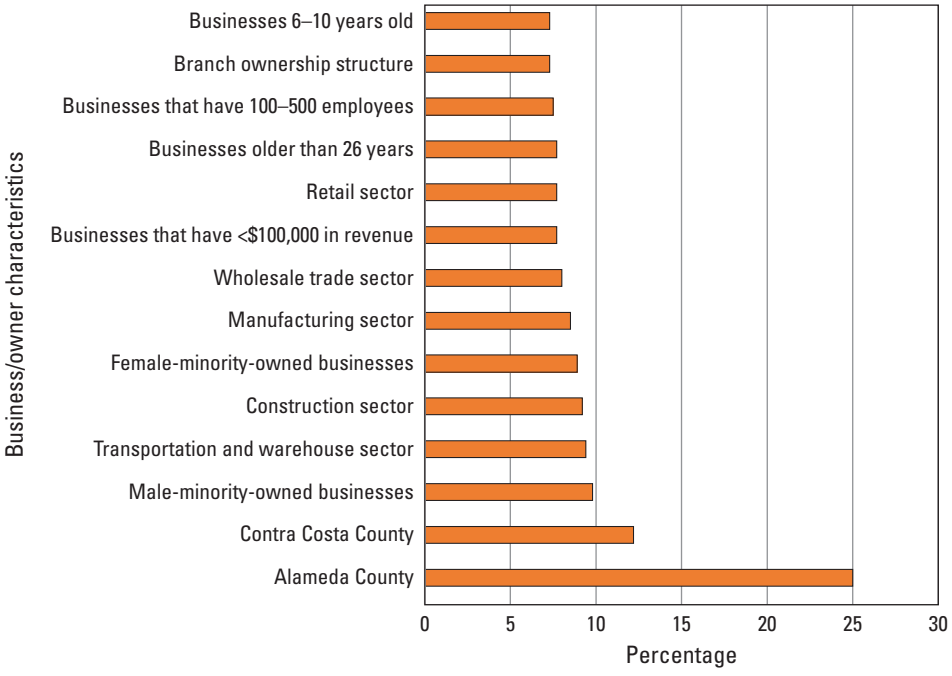


Figure 5. Plot showing business characteristics with average and larger risk of disruptive building damage from earthquake hazards in the HayWired scenario in the San Francisco Bay region, California.

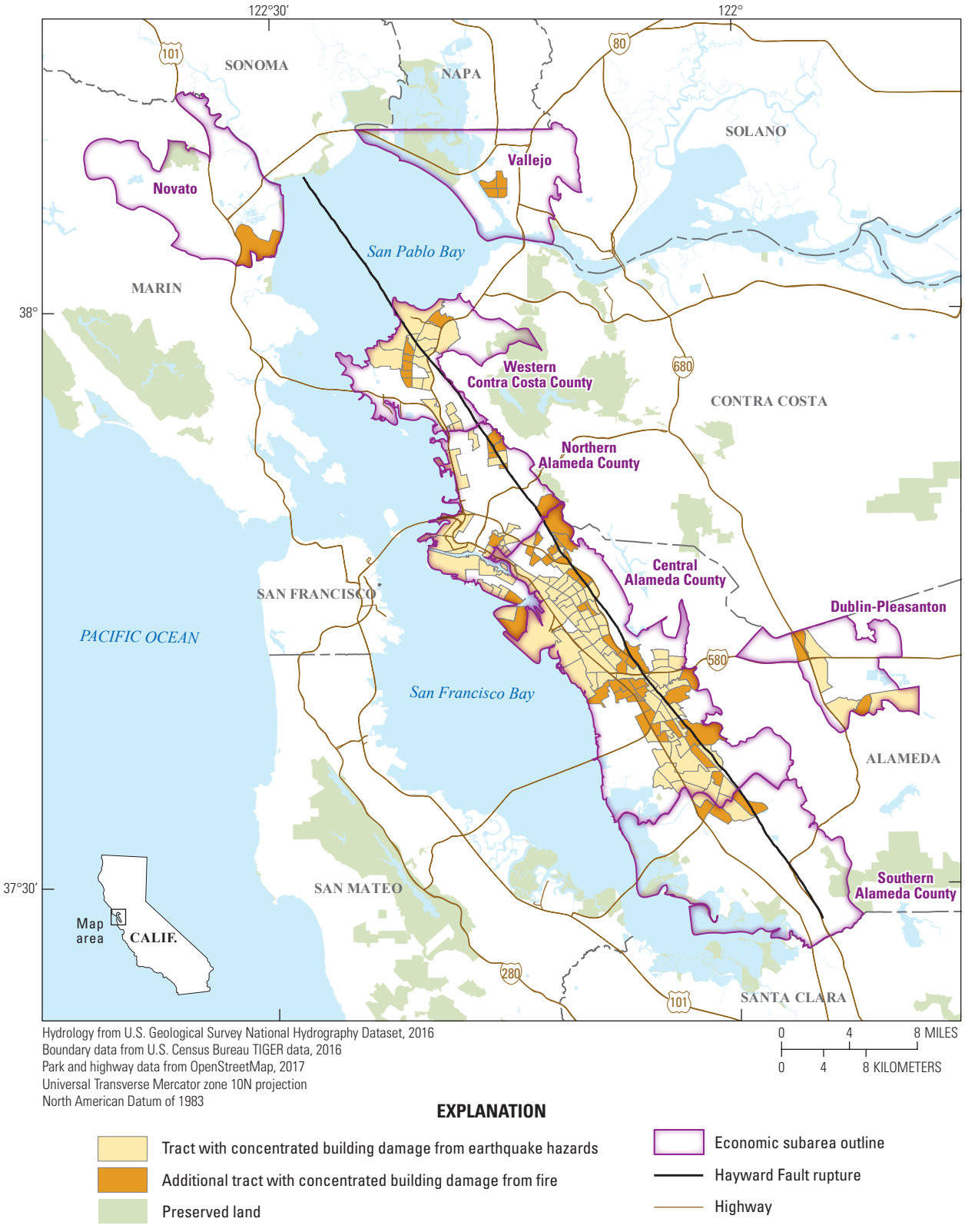


Figure 6. Map of the San Francisco Bay region, California, showing census tracts with concentrated damage in subareas as a result of hazards caused by the HayWired scenario mainshock on the Hayward Fault. Census tracts with concentrated damage are defined as tracts with 20 percent or more of their total building square footage in extensive or complete damage according to the Hazus analysis.

stock that are heavily damaged in the HayWired scenario. Downtown Oakland and San Francisco, which have some even older buildings are spared of the most intense shaking in the HayWired scenario (but could be highly vulnerable in a different earthquake scenario).

Concentrated Building Damages and Sectors

Industrial/warehouse, retail/commercial, and multifamily buildings (commonly low-cost rentals) largely affect neighborhood damage concentrations from all HayWired scenario hazards. Fire following earthquake is a primary cause of concentrated damage to multifamily buildings. Group-living occupancies, most prevalent in the northern Alameda County subarea, are also vulnerable to extensive or complete damage, but represent only a very small share of residential square footage. One item to note is that efforts by the University of California to strengthen their dormitories may have helped mitigate this vulnerability identified in the Hazus analysis; this would not address vulnerability in other types of older, privately owned group facilities or in correctional facilities. Office and single-family/duplex buildings generally perform well with respect to damage, but the businesses and households occupying these buildings may still be affected by their location in neighborhoods of more vulnerable, generally older, buildings.

Household serving industries are also affected by and are closely tied to the households that they serve. Predominantly single-family/duplex residential neighborhoods would have trouble reestablishing themselves without household services (for example, schools) available. Conversely, household serving industries could be affected if their customers—the households they serve—are displaced by significant multifamily residential damage.

Home and Workplace Relations

Home and workplace relations are defined as one of the following: employees (1) live and work in areas with concentrated damage, (2) live in areas with concentrated damage but work in areas with less-concentrated damage, (3) work in areas with concentrated damage but live in areas with less-concentrated damage, or (4) live and work in areas with less-concentrated damage (fig. 7). In the case of earthquake and fire hazards, about 15 percent of the nine-county San Francisco Bay region employees are affected by one of the first three relations. Of the 96,000 employees who live and work in tracts with concentrated damage, 70 percent do so in the same subarea, and 57 percent of employees that live and (or) work in the same subarea do so in central Alameda County.

With nearly 420,000 employees living and (or) working in at least one tract with concentrated damage in the nine-county region, job losses or relocation and employed resident displacement have the potential to geographically widen business impacts in addition to commuter interruption analyzed in the REMI model. Approximately 81,000 of these employees commuted to jobs in tracts with less-concentrated damage in Alameda County (Alameda County remainder in fig. 8). Further afield, around 50,500 employees commute to San Francisco and about 32,500 employees commute to Santa Clara County. Employment districts, such as downtown San Francisco and some cities in Santa Clara County, could be adversely affected if many of the people who work in these locations are stranded by the earthquake; lose their homes, utility services, and (or) community services (for example, schools are closed); are stressed by living conditions and home repairs; and (or) can no longer get to work because of transportation disruptions. Since the fire hazard disproportionately affects residences and concentrates damages in Marin and Solano Counties, some businesses could struggle to fill jobs, as their preexisting and potential workforce no longer has housing accessible to jobs, similar to the outcome of the 2017 Santa Rosa fires.

Conversely, of the 232,000 people working in areas with concentrated damage, half of these workers (114,000) are coming from less damaged residential neighborhoods in the remainder of Alameda and Contra Costa Counties (white areas within those counties in fig. 6). These workers could lose their jobs or be out of work for an extended period without a paycheck and could even relocate. Telework from home may be possible; office work generally has more flexibility for telework, but this is a less viable option for some of the 90,000 employees living in tracts with less-concentrated damage and working in the goods producing and trade, transportation, and utility industries located in tracts with concentrated damage.

These neighborhood impacts, along with extended transportation disruptions, could have consequences well beyond the direct effects to individual businesses and households. In addition to the direct loss of jobs from damage and commuting disruption, a large earthquake on the Hayward Fault could:

1. Accelerate the exit of declining industries;
2. Exacerbate the already precarious position of specialized industrial clusters in older manufacturing areas and move manufacturing to more affordable places, creating ripple effects to suppliers, customers, research and development, and headquarter operations; and
3. Accelerate the gradual conversion of industrial to higher uses in mixed land uses and the region's identified priority development areas, where concentrations of housing and office uses are planned, dislocating jobs.

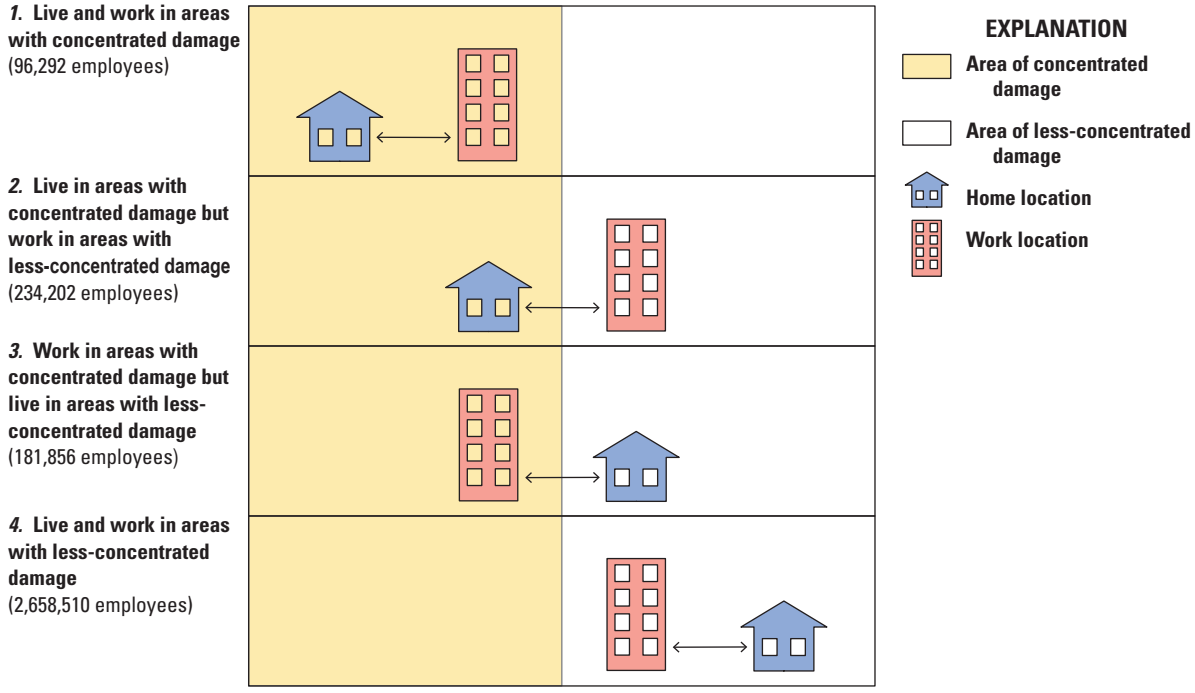


Figure 7. Cartoon showing possible home-workplace relations associated with areas of concentrated and less-concentrated damage resulting from the HayWired scenario mainshock in the San Francisco Bay region, California.

Construction Sector Stressors and Opportunities

Both the macroeconomic and business focused studies single out the unique situation of the construction industry before and after the HayWired scenario mainshock. The earthquake brings both stressors and opportunities in the sector.

- Many local construction firms are small businesses located in the east bay, in buildings that are at risk of extensive or complete damage, or in areas of concentrated damage.
- Demand for construction industry services will soar after the earthquake, after an initial slowdown, to repair and rebuild damaged structures, drawing new construction workers to the area.
- In 2018 (the year of the scenario earthquake), as well as in more recent years, the industry has already been dealing with a very tight labor market, unable to find all of the workers needed to fulfill demand for new housing construction. This labor shortage is exacerbated by rising demand for construction workers after the earthquake.
- The labor shortage and rising demand lead homeowners, businesses, and public agencies to face higher prices, with some effects on the pace of recovery. This may be further exacerbated by the transportation disruptions described above.
- Because of the damage to local businesses, the increased demand for construction work will not necessarily strengthen the existing base of smaller construction firms, which would be unable to quickly take advantage of new opportunities and, once recovered, could face extensive competition from outside firms.

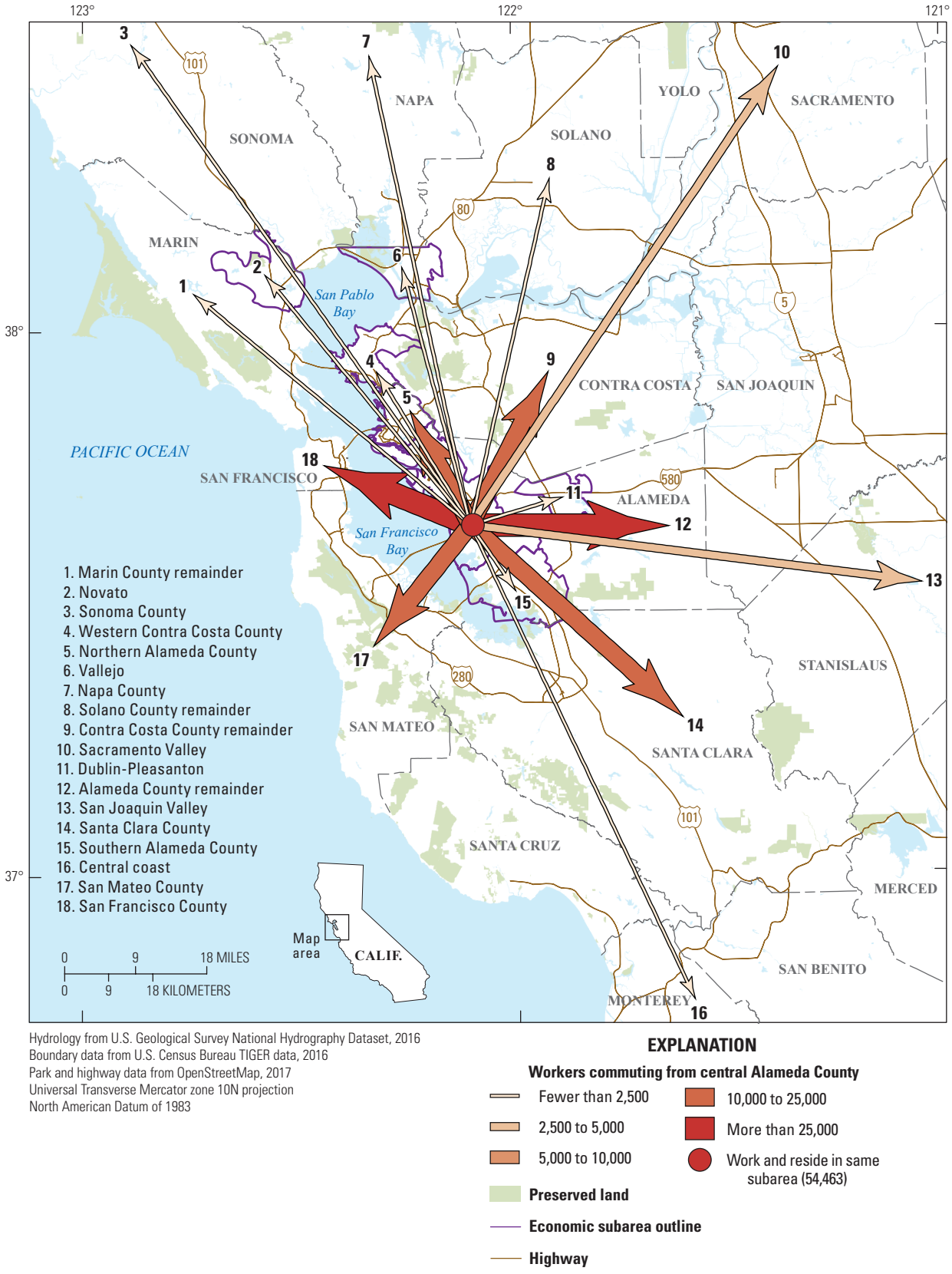


Figure 8. Map showing employed resident flow out of areas of concentrated damage resulting from the HayWired scenario mainshock for the central Alameda County subarea, California. Areas with "remainder" in the name are parts of counties outside the defined subareas, and other counties that do not have areas of concentrated damage are also included. More distant counties are aggregated into larger subregions: Sacramento Valley (Sacramento and Yolo Counties), San Joaquin Valley (Merced, San Joaquin, and Stanislaus Counties), and the central coast (Monterey, San Benito, and Santa Cruz Counties).

Policy Implications Related to the Economic Analyses

Public policy is a critical aspect of addressing the economic effects and the disruptions for workers and residents of an event like the HayWired scenario. Public policies include investments or planning that happen before a major event, as well as those that speed recovery and minimize disruptions after an earthquake occurs. Although the five reports identified critical vulnerabilities and causes, and in some cases, policies, the discussion that follows draws additionally on literature reviewed for the study and on the discussion during the HayWired Economic Consequences for Policy Interpretation workshop jointly hosted by the Association of Bay Area Governments and U.S. Geological Survey that was held on August 28, 2018.

Planning Ahead

- About $80 billion has already been invested in seismic strengthening of infrastructure and buildings since the 1989 Loma Prieta earthquake (Brocher and others, 2018). This money has likely reduced future economic impacts because HayWired economic analyses show the largest economic impacts are caused by building damage and transportation disruption. Continuing to retrofit or replace older structures and improve seismic building codes would continue to reduce potential economic impacts. Another study could use economic models developed for the HayWired scenario to quantify benefits of stronger structures.
- Designing and building to prevent fire ignitions and to be fire resistant would reduce not only earthquake-related hazards but also those related to wildland and urban wildfires. For example, 50 percent of buildings built using 2008 fire codes versus 18 percent of buildings built before 2008 survived the 2018 Camp Fire in Paradise, California. Impacts from fire spread can be further reduced if cities, regions, and the State have identified and planned for means of fighting fires in cases where water distribution has been interrupted.
- The advanced creation of policy and procedures about restricting access once damage occurs could anticipate potential tensions between keeping people safe versus allowing business owners into damaged buildings to get what they need, and efficiency of demolition behind a cordon versus business resumption in safe buildings in heavily damaged areas.
- The vulnerability of local household-serving businesses like food services, retail, and healthcare can have long-term effects on neighborhood resilience. Planning for neighborhood response and accommodating temporary business relocation needs in advance, as well as providing temporary facilities and support services for businesses and customers after the event, can help to mitigate the otherwise widespread losses that can be expected for businesses in these sectors.
- The impacts of building and inventory loss can be reduced by cooperative responses among businesses and neighbors and even between more and less heavily damaged areas. Efforts to build networking ties, including small business alliances, before the event can make it easier to develop these cooperative responses in a crisis period. Advance planning, including identification or development of communications and planning tools, can also improve the logistics of managing cooperative responses once an event occurs.
- In general, the points on inventory and supply chain issues raised in the previous two points could be addressed by reducing supply bottlenecks for responders and local businesses. As experienced after the north bay wildfires in 2017 and 2018, the increased demand for construction workers can be difficult to meet while the sector is experiencing challenges (such as labor shortages). There is already a current urgency for construction capability in the San Francisco Bay region to build more housing and for funded and approved transportation infrastructure projects. Loss of construction capacity or increases in construction costs because of high demand would slow the ability to recover, similar to the experience in Sonoma County after the 2017 wildfires. Long-term planning for resilience in the construction industry by major employers, trade organizations, educational institutions, and local, State, and Federal government can improve the industry's ability to respond to catastrophic events.[5] For example, preregistration of small construction firms within the region for disaster reconstruction could improve their participation. As the use of modular units in construction expands in the bay region, it would be useful to evaluate to what extent this approach eases delays and whether it would be an effective way of speeding reconstruction after a major earthquake.
- Even with a more robust regional construction sector, the scale of damage required by a major earthquake would tax the San Francisco Bay region's capacity to rebuild. Advanced planning for temporary expansion of the construction workforce can help to limit bottlenecks. Such approaches could include developing a national network of firms specialized in recovery, identifying in advance ways to provide housing and support services for the temporary construction workforce that would be needed, and planning for emergency measures, such as easing parking restrictions on mobile homes and recreational vehicles to house the temporary workforce as well as displaced residents and businesses.

[5]Recommendations for improving the availability of trades workers is addressed by Littlehale (2019); Li (2018) further discusses the rebuilding challenges in the San Francisco Bay region after a major earthquake.

- Expedited permitting would help enable rebuilding to happen in the time period shown in the San Francisco Bay region economic recovery model. In Sonoma County following the 2017 fires, for example, emergency ordinances eased physical and occupancy restrictions on temporary housing, extended existing permits, and included a simplified design review process.[6] Advanced planning for future contingencies (including draft ordinances outlining procedures for emergency situations) would better prepare jurisdictions to address rebuilding efforts from a comprehensive perspective, and effective retrofit programs could reduce the need in the first place.
- Regional and local jurisdictions would need to be prepared beforehand to launch a planning process that brings together local property owners and residents to discuss their needs as alternative travel patterns, land uses, and land use intensity are considered. Resources could be prepared in advance to instruct local jurisdictions on how best to document damage and register households and business owners needing or receiving assistance.
- State government and local jurisdictions may need to plan together to determine how the sales tax and property tax revenue losses of a widespread event could be shared and ensure that the local governments most in need of revenue for recovery have access to necessary resources. This could involve developing a reserve fund through contributions from State and local sources or an insurance program to cover lost revenues in affected areas.
- Similar to planning for sea level rise and fires, regional planners can take earthquake risk into account in land use and resilience planning. Land use decisions and earthquake planning can be integrated into regional responses to climate change. This approach could recognize the overlapping areas of projected sea level rise and geological risks of liquefaction during an earthquake.
- Major disruption of land use and routes may be an opportunity for improving planning, for example, to reduce greenhouse gas emissions and minimize risks from future earthquakes. Restored travel routes could be improved to address preexisting congestion and access concerns, and where appropriate, rebuilding could happen in some cases at higher densities to improve the viability of public transit use, especially in areas that already planned for this type of transition. In addition, future regional planning can examine reallocating planned land uses away from earthquake risk areas, as is being considered with regard to future building in high fire-risk areas.
- Policies for pre- and post-earthquake preparations can take into account opportunities presented by planning for the 21-county northern California megaregion. One opportunity is around goods movement. Megaregion goods movement studies by the regional agencies identify opportunities for expanding logistics and wholesale functions beyond the core San Francisco Bay region, and for diversifying the geographic location of tech-related manufacturing and services (Metropolitan Transportation Commission, 2019). Another opportunity is in expanding housing opportunities supported by new car-free commute options. For example, the San Francisco Bay Area Planning and Urban Research Association (SPUR) (www.spur.org) encourages a megaregional perspective on future growth, which would improve residential and business opportunities by building on growth generated by bay region businesses and connecting parts of the megaregion through new transportation investments.

The Role of Employers

The role of employers is also of key importance.

- Inclusion of major employers, such as those in the technology sector and in the health industries, at all stages—in advanced planning, initial responses, and recovery—can augment the resources available when most needed (such as emergency supplies and mental health services) and also ensure that employees, suppliers, and other linked sectors are informed about immediate and possible long-term effects as an event unfolds.
- Employers can prepare for neighborhood effects on their business operations and critical infrastructure, impacts on employee living situations, work relocation plans with respect to their customers and employee residences, particular vulnerabilities of their sector, and their role in neighborhood resilience and recovery. This preparation could benefit from being done cooperatively with similar types of businesses and within the context of city or regionwide resilience plans, to be able to address the differing needs of businesses of different sizes and sectors.
- Advanced planning in areas vulnerable to heavy damage can reduce the impacts of restricted access after an earthquake by locating critical assets (for example, emergency operations centers, police services, and fire services) and backing up business assets (for example, servers) outside these areas.

[6]See, for example, chapter 40 of the Sonoma County code of ordinances, titled Sonoma Complex Fire Disaster Recovery, available at https://library.municode.com/ca/sonoma_county/codes/code_of_ordinances?nodeId=CH40SOCOFIDIRE (last accessed September 11, 2020).

Policies Effective After the Earthquake

- Businesses can make up for output losses by implementing business continuity measures, including shifting production in time (to catch up on lost production) and space (to alternative locations), and having backup alternatives for power, water, and telecommunication services.
- A quick recovery in overall employment depends heavily on investment for rebuilding homes, nonresidential buildings, and infrastructure. The robust level of recovery spending assumed in the economic forecast analysis drops the east bay job deficit from 15 percent to below 3 percent in 2 years and brings the east bay to within 1 percent of projected employment levels within 5 years. The public sector plays a critical role in this, not only providing a portion of the funding, but also providing the means for clearance of debris, safety checks, issuance of new permits, and continuity of services (such as schools).
- Private lenders can work with local officials, regional representatives, business organizations, and their borrowers to provide ways of stabilizing businesses and homeowners through postponed loan payments and expedited new loans.
- Restoration of the telecommunications sector is also a major factor in allowing many economic sectors to restore their operations. As seen in the sensitivity tests, if telecommunications are not sufficiently repaired to provide for remote work, then the losses from transportation disruptions could be much more severe.
- The public sector would need to work cooperatively with private logistic firms to ensure the delivery of necessary emergency supplies at the outset, to ease supply bottlenecks for local producers during recovery, and to maintain pathways for distributing final products.

The Relation with Housing

- Temporary housing services would be crucial in maintaining the labor force needed to keep ongoing businesses in operation and support the labor force needed for reconstruction. Preparedness, response, and recovery plans would need to recognize population movements and long-term displacement as central components of earthquake resilience. Organizations would need to plan for emergency, interim, and temporary housing, as well as registering households in need, and also recognize the dynamics of these phenomena over time and space. Identification of successful efforts in previous disasters may make it easier to respond effectively after an event.
- The San Francisco Bay region is in a critical situation in 2018 and 2019 with respect to housing supply, as is much of urban California. Had the HayWired scenario actually occurred in April 2018, the housing losses and resulting rising prices could have been a drag on the economy for years. Recent experience with wildfires has shown that vulnerability to disaster does not discriminate by income or cultural group. However, the housing stock most vulnerable to earthquake damage—old multifamily units—is disproportionately occupied by households in the lower half of the income scale, as is discussed in a separate chapter in this volume that focuses on communities at risk. This emphasizes the importance of building more new housing for all income groups now, as well as being prepared with policies that support the replacement of the low-cost stock that is likely to be lost in a major earthquake event.

The Role of Insurance

- Investment in recovery is not only the responsibility of the public sector. In the sensitivity analysis, private insurance payments have a small effect on the outcome because these payments cover such a small share of the total damage. Were a larger share of homes and buildings covered by insurance, recovery would be better resourced, and displacement and outmigration could be less. Judging from past experience, close cooperation between assistance agencies, such as the Federal Emergency Management Agency and the California Governor's Office of Emergency Services, and private insurers may be needed to ensure the timely consideration and payment of claims.
- Regional agencies and local government could mount a campaign to educate public and private entities about earthquake insurance coverage and common issues, including underinsurance, interpreting insurance policy language, and policy changes, as well as recommend new approaches to insurance that might better meet the needs of households in risky locations. The context could be extended to fire and flood insurance and influences of sea level rise and climate change.
- Contingent business interruption insurance is important to cover losses from indirect causes, such as reduced patronage when business is inaccessible to customers because of cordons, checkpoints, or fear. Review of how existing policies supported businesses after disaster interruption in previous events would help to suggest modifications in the design of the product.
- Recovery funding for small businesses is an innovation opportunity in community development. Beyond suggestions to make changes to the Small Business

Administration's loan policy, cross-sector and (or) cross-agency collaboration can support and guide small businesses by providing individualized small business risk assessments and a small grant to help implement recommendations (for example, adequate insurance coverage, digitizing records, or adding a generator). Small businesses could be incentivized to become eligible for postdisaster funding that fits their needs during critical time periods by implementing preparedness actions. By the nature of many small businesses, needs also relate to family needs. The Federal Emergency Management Agency and the U.S. Economic Development Administration could be among the organizations collaborating with the Small Business Administration to provide support for small businesses with regional and subregional economic development organizations and to coordinate small businesses recovery with broader local, neighborhood, and regional needs.

- Resilience preparation, innovation, and entrepreneurship are action areas of the San Francisco Bay region's recently adopted Economic Action Plan—part of the Comprehensive Economic Development Strategy endorsed by the U.S. Economic Development Administration in fall 2018—and these action areas are likewise under discussion in the preparation of Plan Bay Area 2050. This provides a framework for linking actions in innovation and entrepreneurship with efforts to make the region's local economies recover quicker and stronger in the event of a major disaster.

Closing Statement

Macroeconomic analyses of the HayWired scenario focused on changes in employment and output levels in the San Francisco Bay region. Although these losses can be substantial, similar to a recession, the findings point to much larger and more challenging disruptions in the lives of residents who live near the Hayward Fault. The residents and communities with the highest levels of impact are expected to rebuild and recover slower than the recovery of a diverse and large economy, such as the nine-county San Francisco Bay region. The impacts on humans would be more devastating than the impacts on the economy.

Whether the focus is on the economy or the disruptions in the lives of residents, all of the studies identify effects that can be reduced by advanced planning, including actions that can be taken in advance of the earthquake and in post-earthquake recovery policies. Various policies imply actions by all levels of government but also stress the importance of business-led policies. Moreover, coordination among employers, governments, and neighborhood groups would minimize earthquake impacts.

The region now faces the challenge of planning for risks of sea level rise, wildfires, and other climate change effects, in addition to challenges posed by a large earthquake. This suggests that land use and transportation planning for the San Francisco Bay region and, indeed, the 21-county northern California megaregion, can help in minimizing human and economic disruptions by integrating all of these risks into future rounds of planning and policies.

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Reflections on the COVID-19 Pandemic, June 2020

By Cynthia Kroll, Stephen Levy, and Anne M. Wein

The Coronavirus Disease 2019 (COVID-19) pandemic began during the completion of the economic analysis of the HayWired scenario. Though the analysis is complete, there are a number of implications for the analysis, as well as policies towards earthquake preparedness, that might be learned from the COVID-19 pandemic experience in the San Francisco Bay region. In particular, we highlight the importance of earthquake preparedness and the opportunity to reduce our vulnerabilities to future earthquakes while recovering from this pandemic.

Pandemics and Earthquakes are Different Types of Disasters

It is important to keep in mind some of the differences between the COVID-19 pandemic and the effect of an earthquake or other spatially contained disaster. A disaster such as the HayWired scenario earthquake causes localized devastation to lives and livelihoods. The most vulnerable areas have higher shares of aged multifamily housing, industrial, and commercial buildings. These areas tend to be occupied by the households and businesses with the fewest resources for response and recovery, increasing the risk to both low- and middle-wage jobs and likely increasing the income gap between high- and low-income households. The HayWired scenario highlights a potential loss of more minority-owned businesses that have fewer resources available for recovery. From the regional, state, and national perspective, the HayWired event will stimulate additional economic activity as rebuilding occurs. Some of the lost economic output will be shifted geographically to other business, nonprofit, or government branches, shortening the duration of the aggregate effects, even as it creates short- and (or) long-term challenges for the recovery near the earthquake's epicenter—one area's loss may be another area's gain. Impacts on local and state government coffers will vary widely. A few jurisdictions may lose a very high share of revenue, but the effect is not universal across the state level, and even San Francisco Bay region jurisdictions more distant from the epicenter may remain fiscally sound.

The COVID-19 pandemic is a very different case, where much of the global economy was put into a policy-induced decline—a self-imposed "coma," as some have described (Krugman, 2020)—but there has been no physical damage to buildings, utilities, and transportation systems. In the pandemic, entire segments of the economy (for example, cultural events, sports, many personal services, and real estate) shut down almost completely, and any economic activity that depended on transportation, whether the airline or cruise ship industry or the oil industry, has been heavily dampened. Closures of schools and dependent care centers have affected the productivity of the workforce; this has also occurred after earthquakes, but the options for handling the situation differ. Sectors with large numbers of low-wage employees with minimal resources have experienced the greatest challenges. Furthermore, the social unrest that has emerged during the pandemic, sparked initially by the death of an unarmed black man at the hands of police, underlines the fragility of low-income and minority communities when economies become stressed.

During the pandemic, the lack of physical damage has made it easier for some types of local services (for example, restaurants and retail) to shift to other methods of delivery, including mail order, take-out, and pick-up options (McGrath, 2020). Yet sales have dropped sharply despite these efforts and some business have closed, although the experience varies widely depending on the type of business. If the effects of the pandemic on the economy and employment are long lasting, there may be excess commercial space rather than a loss of space as in an earthquake or wildland fire. In addition, residential rents may decrease, in contrast to expected rental increases and a construction boom in the HayWired scenario. This could occur from the pandemic because of the number of recently unemployed people, or because high-wage workers are given the option to telecommute from remote locations, easing the pressure on bay region housing markets. Housing prices may also drop if more homes go into forbearance or foreclosure. Revenue losses from the pandemic are expected to be much more universal for state and local governments, as tax revenues from sales, income, and capital gains decline.

In both the HayWired scenario and COVID-19 pandemic, the timeline for recovery is uncertain. History tells us that for a large earthquake, recovery takes years. Will COVID-19 be the same? Much of the uncertainty around HayWired scenario recovery is based on how quickly and how much funding is available for rebuilding, as well as around the frequency and level of damage of aftershocks over time—making recovery a moving target. With COVID-19, we face even greater uncertainty over the trajectory of impact (human, social, and economic) and recovery capacity and timelines, which are intertwined with health, behavioral, and political issues. Projections for loss of life from COVID-19 vary by factors of ten or more and depend in part on the results of health and safety guidelines ranging from shelter-in-place to social distancing and testing for exposure and spread. Uncertainty abounds as sectors of the economy are reopened on varying

timetables and under different guidelines throughout the country. When a new normal after COVID-19 will be reached and what that new normal will be are also unknown. Will telework continue, thus reducing transportation and fuel demand? Will development of successful treatments or a vaccine allow us to reduce social distancing and reopen additional segments of the economy? Will some industries, such as restaurants, entertainment/leisure, or either small or major retail outlets ever recover? Will the societal inequities exacerbated by the pandemic be addressed by changes in policy?

COVID-19 Pandemic Experience Can Inform the HayWired Scenario Analysis

The COVID-19 pandemic experience could inform both the HayWired scenario regional and spatial analyses of impacts. Sectors that rely primarily on knowledge workers have shown great versatility for continuing to operate, even as public transportation use dropped by 90 or 95 percent throughout the region as a whole (Bay Area Rapid Transit, 2020). Major San Francisco Bay region employers, like Google and Facebook, took early action to direct all employees to work from home (Elias, 2020; Eadicicco, 2020). Government offices have also continued to provide some professional services through telecommuting employees as well as keeping workers in critical positions, like maintenance, on the job. Work has continued via telework at a higher level compared to the assumptions made in the HayWired scenario analysis.

The resilience of some of these sectors even in the face of total shelter-in-place policies is consistent with the assumptions discussed in the macroeconomic analyses of the HayWired scenario. A longer run analysis of the effects of the pandemic over the next 2 years may help to highlight the resilience measures that could also operate after an earthquake across other sectors over time, such as production rescheduling, inventory management, conservation, and input substitution. Yet some repurposing of spaces for immediate business and housing needs, or adaptations of production processes and delivery services to meet changed demands, could be very different after an earthquake as compared to the broad pandemic, including the need to find new locations to accommodate for building damage and concentrated damages in business districts. Planning for and adjusting to spatial economic shifts around stranded assets (for example, underutilized commercial space with work from home) from the pandemic may also inform shifts from heavily damaged areas and their recovery.

At the same time, the COVID-19 situation raises supply chain questions that could affect the kinds of analyses done for the HayWired scenario. Even with no physical disruption to transportation, communications, production, or logistics facilities as in the case of a major earthquake, supply bottlenecks abound (for example, for personal protective equipment [Asian Development Bank, 2020] and ventilators [Ranney and others, 2020]). Distribution networks have been slow to adapt to shifts in the sources of demand—for example, although grocery shelves are sometimes empty of basic staples and food banks lack enough capacity to meet the growing demand, animals are being euthanized and crops plowed under because the normal distribution network has broken down (Yaffe-Bellany and Corkery, 2020; Blake and Walljasper, 2020). After an earthquake, supplies for personal hygiene, medical equipment, medication, and many types of grocery staples may suddenly be in increased demand. Companies that are still operating will continue to have a steady demand for inputs, but disrupted businesses will sharply decrease orders. Even households that did some advance preparation may find that the resupply of basic necessities recovers much more slowly than anticipated. The pace of recovery after an earthquake will be affected by how quickly logistics challenges, as well as physical damage, can be addressed for the supply chain.

Important Policy Lessons

Although mitigation investments have reduced seismic risk in the bay region, the impacts of the ongoing COVID-19 pandemic and the insights from the HayWired scenario economic analyses herein remind us that much more is needed to anticipate, plan, and prepare for earthquakes. The HayWired scenario volume 3 includes information and suggestions for actions that help prepare residents, businesses, nonprofit, and government organizations to reduce the potential severity and duration of economic impacts of a future earthquake. The experience of responding to the COVID-19 pandemic has lessons that could be used to inform policy about both preparing for a major earthquake and recovering from the pandemic itself.

Advance Preparedness and Mitigation

The pandemic has highlighted the importance of preparedness. The San Francisco Bay region and California have reacted quickly and transparently to the challenges faced by the COVID-19 pandemic. The global experience underlines the costs of being unprepared, and even the bay region was not fully ready for the types of unprecedented actions required to respond to the pandemic. With the gradual approach of the virus' spread to the bay region, counties had time to develop strategies and, to date, have deflected some potential impacts, particularly on the healthcare system (Ho, 2020; Kahn and Marinucci, 2020). In contrast, there will be no gradual onset of a major earthquake, and once it arrives, we will have lost the time needed to make preparations. We know with some certainty that the bay region will experience effects from a large earthquake, possibly in the not-so-distant future, which will challenge our healthcare systems, supply chains, and many economic sectors. Actions are needed to improve resilience before an event to lower potential damage, and advance planning for post-event response is needed to anticipate and avoid missteps that may otherwise characterize the implementation of well-intentioned responses (Federal Emergency Management Agency, 2016; M.C. Comerio, written commun., 2020). Taking steps to understand the needs and challenges of

low-income and minority communities now can better prepare these communities to plan for and provide recovery efforts that address the needs of all residents (Markhvida and others, 2020).

A COVID-19 Recovery Plan Can Spur Earthquake Preparedness

Another policy consideration is that recovery steps that will be taken to tighten supply chains and restore our economy during and after the pandemic can also become investments in physical improvements and strategic plans needed to strengthen our resilience to seismic risks. There are two main ways a COVID-19 recovery program can be helpful in earthquake preparedness.

1. Stimulus packages to spur economic recovery from the pandemic-induced recession can include support for infrastructure investments that also increase earthquake or fire resilience, such as retrofitting buildings, strengthening transportation and other infrastructure, and improving our telecommunications capacity.

2. The pandemic has increased the urgency for building housing to alleviate overcrowding and homelessness—two conditions that accelerate the spread of the virus but are also of critical concern to the region's economic health and its post-earthquake resilience. Building more housing, particularly affordable housing for low- and moderate-income and essential workers, is already a critical challenge in the bay region, and one that will increase with new regional housing-needs targets from the State that focus on reducing the number of cost-burdened and overcrowded households (Kirkeby, 2020).

A Final Thought

In the midst of the current human and economic pain from the COVID-19 crisis, it is tempting to address one crisis at a time, and to postpone preparing for the one that could happen tomorrow—or in 30 years. We believe that would be a lost opportunity if we do not tie the lessons of loss and resources for recovery from one event toward improving resilience in a later event.

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Chapter V2

Economic Consequences of the HayWired Scenario—Digital and Utility Network Linkages and Resilience

By Ian Sue Wing,[1] Dan Wei,[2] Adam Z. Rose,[2] and Anne M. Wein[3]

Abstract

The HayWired scenario examines a hypothetical earthquake (mainshock) with a moment magnitude (M_w) of 7.0 occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region. This study evaluates the economic impacts of the HayWired earthquake scenario on the greater San Francisco Bay region's economy using a detailed multiregional static computable general equilibrium model for 6 months following the event and a simpler, multiregional intertemporal partial equilibrium simulation model for the dynamic recovery in the 17 years thereafter. Economic impacts are measured by the estimated reduction in the bay region's gross regional product (GRP), the standard economic measure of the total value of final goods and services produced. The major hazards that cause property (buildings and contents) damages (or capital stock losses) are ground shaking, liquefaction, landslides, and fire following earthquake. Economic impacts in terms of GRP (or business interruption losses) caused by both capital stock losses and water and electricity utility and telecommunications-service disruptions from the HayWired earthquake sequence are estimated and are primarily caused by capital stock damages. The most vulnerable industry sectors are heavy manufacturing and service industries, such as education and healthcare. The hardest hit county (in absolute and relative terms) is Alameda County, followed by Santa Clara County. In the 6 months following the earthquake, total GRP losses are estimated to be $44.2 billion (4.2 percent of California's projected baseline gross state product [GSP] over the period), but this result could be reduced by about 43 percent to $25.3 billion after factoring in microeconomic resilience tactics, which promote the efficient use of remaining resources.

The most effective resilience tactic for businesses that experience property damages and power-service disruptions is production recapture (using overtime or extra shifts to catch up on lost production after necessary facilities and equipment have been repaired or replaced and power services have been restored). The most effective resilience tactic for water-service or data- and voice-service outages is production isolation (making greater use of processes that do not need these services). Production isolation combined with the use of portable equipment by telecommunication carriers to fast track data- and voice-service restoration can effectively reduce GRP losses below those imposed by power outages that are the greatest cause of data- and voice-service disruptions.

Information and communications technology (ICT) sectors, which are the core of the digital economy, include internet publishing and broadcasting; telecommunications; data- processing, hosting, and related services; and other information services. GRP losses (in percent) in the ICT sectors show a strong correspondence with property damages, although internet publishing and broadcasting show a consistent pattern of GRP losses exceeding capital losses in counties less directly affected by the earthquake (San Mateo and San Francisco Counties) and counties that export 80 percent of these services (Marin, Solano, and Santa Cruz Counties). Internet publishing not only suffers direct economic damage but also suffers from smaller supplies of data-processing and telecommunications inputs, whose prices increase significantly.

A simple, dynamic recovery model illustrates that initially, relative to "business as usual," capital stocks in the largely unaffected remainder of the bay region and the rest of California decrease owing to reallocation of investment toward the most severely damaged counties. Eventually, counties with less damage gain from picking up the slack of lost capacity in the core of the damaged region and also provide valuable inputs to all affected counties by producing their goods and services during the recovery process.

Introduction

Earthquakes and other natural disasters affect regional and national economies by disrupting inputs to the production of goods and services. These inputs include primary factors of production, such as land that provides natural resources,

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capital that provides productive capacity, and labor that provides human resources, as well as intermediate inputs such as processed goods and utility services.

The HayWired scenario examines a hypothetical earthquake (mainshock) with a moment magnitude (M_w) of 7.0 occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region. For such an urban earthquake, the primary economic concern is the damage to capital such as buildings and contents and critical infrastructure. Severely damaged buildings would be unavailable for use, and damages to critical infrastructure would cause utility-service outages (for example, electric, gas, water), interruptions to data and voice services, and disruption to transportation systems (for example, roadways, rail lines, airports, and seaports) (Porter, 2018; Jones and others, this volume; Wein, Witkowski, and others, this volume). Furthermore, damages to buildings and infrastructure could ignite fires that spread owing to limited fire-suppression resources, and damages to critical infrastructure (for example, communication systems, roadways, and water-supply systems) could increase emergency-response times (Scawthorn, 2018). This study focuses on the economic impacts from capital losses (property or building and content damages) and water-, power-, and data- and voice-service disruptions. The latter refers to a major theme of the HayWired scenario—today's wired and wirelessly connected world. Therefore, we also analyze the digital economy, centered around the information and communications technology (ICT) industry sectors, which play a vital role in the regional economy. For the HayWired scenario, economic impacts from earthquake damages to transportation infrastructure are considered in Kroll and others (this volume).

This study estimates the regional economic impacts of property damages and utility-service disruptions on the San Francisco Bay region economy from the HayWired scenario using a multiregional computable general equilibrium (CGE) model. The model consists of industrial sectors and institutions (for example, households and government sectors) and simulates their interaction through production functions and market linkages (for example, the output of one sector becomes an input to another sector or itself). This means that the effects of earthquake damages to one sector may be direct (production is affected by property damages and utility outages) or indirect (production is affected by disruptions to its supplier and customer chains). The latter are sometimes referred to as ripple, multiplier, or general equilibrium effects.

The equilibrium solution of the CGE model computes the prices and quantities of goods and production factors that equalize supply and demand in all markets in the economy. The economic impacts are measured by the estimated reduction in the bay region's gross regional product[4] (GRP), the standard economic measure of the total value of final goods and services produced. Within this model some sectors may lose, whereas others may gain. Where production decreases, prices increase owing to scarcity and thus drive a reallocation of scarce resources to highest marginal value uses. The analysis assumes capital to be fixed, but labor resources are somewhat mobile among sectors, and factors of production can substitute for each other. These flexibilities in the economy are a form of inherent economic resilience that effectively reduces GRP losses that otherwise would be incurred.

Economic resilience refers to the ability of the economy to use remaining resources efficiently and to recover from or adapt at an accelerated pace to damages and disruptions caused by adverse events. It can be measured as the capability to reduce potential negative effects on GRP (Rose, 2009, 2017). At the micro (business) and meso (sector/market) levels of the economy, resilience—sometimes termed "business continuity" practices—enables enterprises to reduce their revenue losses, typically termed "business interruption" (BI) losses. In this study, these practices are referred to as static inherent and adaptive resilience tactics and include conserving scarce resources, using existing inventories of materials, substituting for disrupted supplies and services, temporarily relocating business activities, telecommuting, and the ability to make up lost production time by people working overtime or extra shifts. Wein and Rose (2011) compiled and categorized (in economic resilience terms) many tactics that were identified as having the potential to reduce BI during the development of the 2008 ShakeOut southern San Andreas Fault earthquake scenario. In this study, the effectiveness of resilience tactics is evaluated by modifying inputs and outputs of the CGE model to demonstrate their relative potential effectiveness in reducing BI losses measured in terms of GRP.

We begin by reviewing literature on economic impact assessments of previous disasters and estimates of disaster scenarios. The scenario assessments include our own work

[4]In this report, we refer to several indicators of economic activity at the macroeconomic level. *Gross domestic product* (GDP) refers to the value of all final goods and services produced in an economy (less imports). It is the sum of consumption, investment, government spending, and exports, minus imports. *Gross regional product* (GRP) is the counterpart for subnational areas. Note that even though the term "gross" is used, it is only because the concept includes depreciation. It is otherwise considered a "net" concept, because it does not include intermediate goods (goods used to produce other goods). GRP is an indicator from the production side and is approximately equivalent to value added, which reflects the income and depreciation counterpart.

Gross output is also a production measure but one that includes the value of intermediate goods (which results in a great amount of double counting, so it is not as popular among economists). However, it is an indicator of significant interest to the business community because it is equivalent to sales revenue. In general, GRP is about 60 percent of gross output.

The term *direct gross output losses* refers to lost production at the sites of businesses directly affected by the HayWired mainshock (either through property damage or utility service disruptions). The term *total gross output losses* includes various "higher-order" effects. In input-output modeling this includes indirect and induced effects resulting from quantity interdependence through supply chains and in CGE modeling refers to general equilibrium effects (essentially indirect and induced effects but with the consideration of responses to prices and inclusion of input substitutions).

All of the above convey different aspects of the commonly used term *business interruption* (BI). The term BI is used at the levels of the individual business, sector, and economy as a whole, as is the term *gross output*. However, GRP is typically only used at the macroeconomic level, although its counterpart—value added—is used at all three levels. (See Rose [2004a] for more information.)

that has established techniques to model the economic impacts for the three previous U.S. Geological Survey (USGS) scenarios—the Southern California Shakeout earthquake (Rose and others, 2011), the California ARkStorm severe winter storm (Sue Wing and others, 2016), and a California tsunami generated by an earthquake offshore of the Alaska Peninsula (Rose and others, 2016). Next, we establish a foundation for this analysis with a description of the San Francisco Bay region economy and the composition of the largest industry sectors. We also define the ICT sectors, the core of the digital economy, and what sectors they depend on and serve. The detailed description of the CGE model is then provided, followed by the discussion of formal definitions and measures of economic resilience.

The analysis of economic impacts proceeds in several steps. First, estimates are constructed for the direct economic impacts to industry sectors resulting from physical damage to buildings and contents caused by the mainshock shaking, liquefaction and landslides, aftershocks, fire following the mainshock, and utility-service disruptions. Second, the total economic impacts (consisting of both direct and indirect effects) are estimated by simulating lost production in upstream and downstream sectors through market adjustments along the supply chain, using a multiregional CGE model. The economic impacts on sectors and the economy are first calculated without the consideration of microeconomic resilience tactics (apart from the resilience already incorporated in the CGE model's baseline structural representation of supply, demand, and market interactions[5]). The economic impacts are then estimated with various types of additional inherent and adaptive resilience tactics. The bottom-line measure of the economic impacts on the bay region economy of the HayWired earthquake scenario during the following 6 months are estimated as the reduction in GRP, in both absolute and percentage terms. To complement the short timeframe of the analysis, a simpler multiregional intertemporal partial equilibrium simulation model demonstrates a dynamic recovery for 17 years following the mainshock.

Literature Review of Economic Impact Analysis of Earthquake Events or Scenarios

The literature review focuses on the estimation of total economic impacts stemming from business interruption losses. The M_w 6.7 1994 Northridge, California, earthquake remains the costliest earthquake in U.S. history in terms of GRP reduction ($75 billion, in 2018 dollars) and property damage ($31 billion, in 2018 dollars). Based on empirical survey data collected from more than 1,000 firms in the cities of Los Angeles and Santa Monica, Tierney (1997) investigated the disaster preparedness, response, and recovery of businesses. Although structural and nonstructural damages caused substantial economic losses, a large number of firms suffered from extensive BI owing to other disaster-related problems, including utility service disruption, transportation network disruption, and a decrease in customer demand. The results also elucidate the cost-reducing potential of various resilience tactics adopted by businesses. For example, nearly 30 percent of the study respondents had stored fuel or batteries, and more than 35 percent had stored water prior to the earthquake. However, only 5.2 percent of respondents indicated that they had arrangements to move a business to an alternative location in case of a disaster. (See also Rose and Lim, 2002, and papers reviewed below for further analysis of resilience to electricity-service disruptions using Tierney's data.)

The series of earthquakes in 2010 and 2011 in Canterbury, New Zealand, resulted in an estimated $15 billion in rebuild costs, which is about 10 percent of New Zealand's annual gross domestic product (GDP) (Parker and Steenkamp, 2012). Insured losses, covering both property damage and business interruption losses, exceeded U.S. $25 billion (Parker and Steenkamp, 2012). The Canterbury economy exhibited reasonable resilience—agriculture and manufacturing sectors were only slightly affected, and merchandise exports remained strong owing to the rapid recovery of the capacity of seaports and airports. However, international tourism and student enrollment dropped significantly, which greatly affected service sectors such as retail, education, accommodation, and hospitality (Parker and Steenkamp, 2012).

Kajitani and others (2013) performed an economic impact analysis of the M_w 9.1 2011 Tohoku, Japan, earthquake, tsunami, and subsequent nuclear accident based on observed time-series data on economic activities before and after the disaster. The study revealed significant economic impacts beyond the direct damage of $211 billion. Indirect economic impacts include supply-chain disruptions, decrease in retail trade and tourism because of curtailed consumption, and fear of radiation. Japan's GDP decreased by 1.32 percent and 1.63 percent, respectively, in the first two quarters after the disaster. Despite these substantial losses, several resilience mechanisms were identified, including, for example, a collective energy conservation effort that successfully averted blackouts after the reduction of power generation capacity owing to nuclear power units being offline.

Using a time series-based input-output table for the City of Kobe, Okuyama (2014) applied a combined approach of structural-decomposition analysis (SDA) and shift-share analysis to analyze the long-term economic structural change and the corresponding economic impacts of the M_w 6.9 1995 Kobe earthquake. The four factors included in the SDA were changes in regional purchase coefficients, changes in production technological coefficients, changes in final demand, and changes in exports. Reduced final demand (caused by loss of lives and [or] out-migration) was found to be the largest contributor to total output losses. The study also identified how impacts varied across industries, with three service

[5]This includes inherent resilience of the economy through the price system in the form of input and locational substitution embedded in the CGE model's equations (see appendix 2 for details).

sectors (port-related transportation, other transportation, and public services) and the food and kindred products sector experiencing the largest negative effects.

Rose and Liao's (2005) pioneering study of economic resilience provided a rigorous definition of static economic resilience and demonstrated methods for incorporating key resilience tactics into a CGE modeling framework. The two tactics modeled were adaptive conservation (for example, recycling water) and adaptive input substitution (for example, finding new substitutes for piped water services, such as bottled or trucked water), and they were incorporated by altering constant elasticity of substitution (CES) production function productivity parameters and elasticities of substitution, respectively, based on Tierney's (1997) data. The model was applied to simulate a major Pacific subduction zone magnitude 6.1 earthquake affecting the Portland, Oregon, water system, resulting in a 48-percent reduction in service delivery over 4 weeks of recovery time, with direct and indirect losses of more than $1 billion (or 4.6 percent of gross output). The two resilience tactics described above yielded potential reductions in business interruption losses of 33 percent.

A CGE modeling study by Rose and others (2007a) of the resilience of the Los Angeles water system to a 2-week shutdown stemming from a terrorist attack indicated that these two resilience tactics could have a much smaller impact because of differences in the structure of the economies being modeled, the larger impacts to the water system, and the shorter period over which producers and consumers could engage in substitution. However, the additional resilience tactics of water storage, input isolation, and production recapture (see definitions below) increased the potential loss reductions to more than 90 percent. Rose and others (2007b) derived similar estimates for all of these resilience tactics combined to recover from a hypothetical shutdown of the Los Angeles electricity system caused by terrorist attack.

Rose and others (2011) simulated the economic impacts of an earthquake on the Verdugo Fault, north of Los Angeles, by coupling a CGE model with a water system fragility model. Base case results indicated a gross output loss of nearly $1 billion—or a nearly 5-percent loss of gross output over a 2-week recovery period, but resilience potential is estimated to be in excess of 90 percent. However, the authors cautioned that the moderation of losses in the real-world economy could be much smaller because of obstacles to implementation of the various resilience tactics (this applies to previous studies by the authors as well). A novel feature of that analysis relates to water prices, which are typically set by local government authorities rather than by the market and, therefore, do not adjust in the face of shortages. If water prices are allowed to rise with scarcity, curtailment of 24 percent of baseline supply triggers a 30-percent increase in the equilibrium price of water, but the consequent reallocation of water among users reduced business interruption losses by only 2 percent, in part because of the limited substitution possibilities among water and other inputs, even modeling the effect of additional measures that would have the effect of increasing the substitutability of other inputs for water.

Mackenzie and others (2012) used a multiregional input-output (I-O) model to estimate the total economic impacts of the 2011 Tohoku tsunami. As with the CGE framework, I-O models characterize the economy as a set of interconnected supply chains linking the activities of economic sectors. The key finding is that more than 90 percent of the potential BI losses could be avoided by a combination of inventories held by domestic producers and expanding input supplies through increased imports from abroad. Although the analysis did not explicitly consider issues of timing, some of this offset is implicitly contributed by production recapture.

In 2015, a multidisciplinary initiative was funded by the National Institute of Standards and Technology to develop a comprehensive set of modeling tools to better assess the likely impact of natural disasters on local communities, understand the factors affecting community resilience, and develop cost-effective strategies to optimize the recovery of communities (Ellingwood and others, 2016). A dynamic spatial CGE model was developed by Cutler and others (2016) to estimate the economic impact of damages to building stocks and transportation infrastructure caused by a simulated magnitude 7.8 earthquake in the Centerville Virtual Community, one of the community resilience testbeds of the initiative. The study also takes the dynamic impacts of changes in firm and household behavior into consideration. Alternative degrees of substitutability between capital and labor for the producing sectors and various rates of precautionary savings for households are analyzed to examine their effects on the long-run economic and social impacts of the disaster.

Thematically, the study that is closest to this report is the economic consequence analysis of the ShakeOut earthquake scenario—a hypothetical magnitude 7.8 southern San Andreas Fault earthquake centered near Palm Springs, California (Rose and others, 2011). That investigation used an I-O rather than a CGE model, which likely resulted in overstatement of the BI losses, because the former modeling approach omitted substitution among the various inputs to individual sectors and interregional substitution among the sources of supply of commodity inputs to production and consumption. Hazus and other geotechnical estimation methods were used to estimate property damage from ground shaking, supplemented by a fire-damage estimation methodology, yielding loss estimates of $113 billion—more than half accounted for by fire damage. The total BI losses (without resilience tactics) were estimated at $204 billion, stemming from as much as a 6-month disruption to the regional water system, which accounted for more than 35 percent of the total. The sole resilience option considered was production recapture, which was estimated to reduce BI losses by 67 percent to $68 billion.

San Francisco Bay Region Economy

The San Francisco Bay region consists of nine counties: Marin, Sonoma, Napa, Solano, San Francisco, San Mateo, Contra Costa, Alameda, and Santa Clara. In the past 15 years, the economy of the bay region experienced a 37-percent

growth in gross regional product (GRP)—the measure of the total value of final goods and services produced in a region, which for the bay region was about 14 percent greater than the average growth rate for the United States (Kroll and others, 2017).[6] Based on I-O data from IMPLAN (short for impact analysis for planning), of which we have aggregated the 9-county bay region economy into 46 industry sectors (see appendix 1 for details), the GRP for the bay region in 2012 was $579 billion (IMPLAN, 2014). This accounted for nearly 30 percent of the total gross State product (GSP) of California, which was $2,050 billion in 2012. Table 1 shows the top five industry sectors in terms of GRP, and table 2 shows the top five industry sectors in terms of employment (including both full- and part-time jobs).[7] The top five sectors listed in these two tables account for nearly 50 percent of the total GRP and total employment, respectively, of the economy of the bay region.[8]

One theme of the HayWired scenario is the effects of wired and wireless technology in today's world. Therefore, we focus on the digital economy through the ICT sectors that play a vital role in the bay region's economy. Based on the 9-county 46-sector bay region I-O table (see appendix 1 for details), the 3 sectors that provide ICT services in the model are (1) telecommunications (such as Verizon, AT&T, T-Mobile, Comcast, Spectrum); (2) internet publishing and broadcasting and web-search-portal services (such as Netflix and Amazon as video broadcast sites, Google and Yahoo as internet search portals, and Facebook and Twitter as internet social networking sites); and (3) data processing, hosting, and related services (such as Amazon, Microsoft, and Google for providing computer data-storage services and Google, Microsoft, and Apple for providing application hosting). The GRPs of these three sectors were $11.19, $7.39, and $4.26 billion, respectively, in 2012, and the employment in these sectors was 30,700, 30,400, and 15,900, respectively, in 2012.

Tables 3 to 5 show the top 10 sectors that depend on—that is, purchase the largest quantities of the outputs of—the three ICT service sectors in the bay region economy, both in total dollar terms and as a percentage of the purchasing sectors' gross output. The three ICT sectors themselves are major users of their own outputs as inputs in production. Apart from this, the top sectors using ICT are service sectors such as finance, insurance, real estate, and leasing; professional, scientific, and technical services; business services; and publishing, motion pictures, and broadcasting.

Tables 6 to 8 show the top 10 sectors from which the ICT service sectors purchase inputs to produce their services, both in total dollar terms and as a percentage of the respective ICT sectors' gross output. Consistent with that shown in tables 3 to 5, the three ICT services use large amounts of their own outputs as inputs in production. Apart from this, the top supplier sectors to ICT service sectors are professional, scientific, and technical services; finance, insurance, real estate, and leasing; business services; light industry; publishing, motion picture, and broadcasting; semiconductor and related device manufacturing; and computer systems design and related services.

Table 1. Five largest industry sectors (gross regional product basis) in the nine-county San Francisco Bay region, California (data from IMPLAN, 2014).

Computable general equilibrium model sector	Billions of 2012 dollars
33. Finance, insurance, real estate, and leasing	$86.45
36. Other professional, scientific, and technical services	$43.26
46. Government and non-NAICS[1]	$42.90
35. Computer systems design and related services	$36.27
16. Semiconductor and related device manufacturing	$28.74

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 2. Five largest industry sectors (employment basis) in the nine-county San Francisco Bay region, California (data from IMPLAN, 2014).

Computable general equilibrium model sector	Jobs
33. Finance, insurance, real estate, and leasing	560,300
46. Government and non-NAICS[1]	409,000
19. Retail trade	403,700
41. Arts, entertainment, and recreation	390,700
36. Other professional, scientific, and technical services	369,100

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

[6]This includes the five Metropolitan Statistical Areas defined by the U.S. Department of Commerce's Bureau of Economic Analysis in the San Francisco Bay region, which also includes San Benito County in addition to the nine counties listed above.

[7]The three major datasets used by IMPLAN for employment estimates are the Bureau of Labor Statistics (BLS) Census of Employment and Wages (CEW), the Census Bureau County Business Patterns (CBP), and the Bureau of Economic Analysis (BEA) Regional Economic Accounts (REA) data. IMPLAN employment estimates are usually larger than the employment data provided by government agencies (such as the California Employment Development Department [EDD]) because IMPLAN employment includes not only full-time and part-time wage and salary employment (typically small business and professional practices) but also proprietor employment. The latter is not included in the EDD employment estimates.

[8]The discussions of the San Francisco Bay region economy in this section and the economic impact model to be discussed in the next section are based on IMPLAN data for the year 2012. These represent the latest data that could be obtained when we started working on the HayWired economic impact study in 2014. Based on IMPLAN data obtained in 2018, the GRP and employment of the 9-county bay region were $804 billion and 5.293 million thousand jobs (full-time and part-time) in 2016. The top sectors in terms of GRP and employment remained the same as in 2012.

Table 3. Top industry-sector purchases of internet-publishing and broadcasting services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Internet publishing and broadcasting	1,219	Internet publishing and broadcasting	11.37
Food, drug, and chemicals	278	Other mining	6.13
Other professional, scientific, and technical services	267	Couriers and messengers	3.22
Other business services	220	Primary metal manufacturing	1.07
Light industry	216	Heavy industry	0.67
Heavy industry	157	Other business services	0.57
Finance, insurance, real estate, and leasing	148	Light industry	0.53
Publishing, motion pictures, and broadcasting	132	Food, drug, and chemicals	0.51
Telecommunications	83	Sightseeing transportation	0.48
Computer systems design and related services	75	Telecommunications	0.44

Table 4. Top industry-sector purchases of telecommunications in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Telecommunications	2,299	Telecommunications	12.28
Other professional, scientific, and technical services	936	Coal mining	4.95
Publishing, motion pictures, and broadcasting	795	Publishing, motion pictures and broadcasting	2.45
Finance, insurance, real estate, and leasing	673	Repair and maintenance	1.70
Other business services	390	Other professional, scientific, and technical services	1.53
Government and non-NAICS[1]	375	Electricity generation/transmission/distribution	1.23
Construction	299	Accommodations	1.08
Light industry	259	Rail transportation	1.02
Semiconductor and related device manufacturing	182	Other business services	1.01
Computer systems design and related services	175	Construction	0.97

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 5. Top industry-sector purchases of data processing, hosting, and related services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Other professional, scientific, and technical services	328	Other mining	1.56
Finance, insurance, real estate, and leasing	241	Telecommunications	1.21
Telecommunications	227	Other information services	0.90
Other business services	159	Accommodations	0.74
Publishing, motion picture, and broadcasting	127	Transit and ground passengers	0.55
Computer systems design and related services	95	Other professional, scientific, and technical services	0.54
Light industry	93	Air transportation	0.50
Government and non-NAICS[1]	44	Other business services	0.41
Arts, entertainment, and recreation	42	Publishing, motion picture, and broadcasting	0.39
Accommodations	35	Data processing, hosting, and related services	0.38

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 6. Top industry-supplier sectors to internet-publishing and broadcasting services in the San Francisco Bay region, California (data from IMPLAN 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of internet-publishing and broadcasting services
Internet publishing and broadcasting	1,219	11.37
Food, drug, and chemicals	278	2.59
Other professional, scientific, and technical services	267	2.49
Other business services	220	2.06
Light industry	216	2.02
Heavy industry	157	1.47
Finance, insurance, real estate, and leasing	148	1.38
Publishing, motion picture, and broadcasting	132	1.23
Telecommunications	83	0.78
Computer systems design and related services	75	0.70

Table 7. Top industry-supplier sectors to telecommunications in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of telecommunications
Telecommunications	2,299	12.28
Other professional, scientific, and technical services	936	5.00
Publishing, motion picture, and broadcasting	795	4.25
Finance, insurance, real estate, and leasing	673	3.60
Other business services	390	2.08
Government and non-NAICS[1]	375	2.00
Construction	299	1.60
Light industry	259	1.38
Semiconductor and related device manufacturing	182	0.97
Computer systems design and related services	175	0.93

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 8. Top industry-supplier sectors to data processing, hosting, and related services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of data processing, hosting, and related services
Other professional, scientific, and technical services	328	5.54
Finance, insurance, real estate, and leasing	241	4.06
Telecommunications	227	3.83
Other business services	159	2.68
Publishing, motion picture, and broadcasting	127	2.14
Computer systems design and related services	95	1.60
Light industry	93	1.57
Government and non-NAICS[1]	44	0.75
Arts, entertainment, and recreation	42	0.70
Accommodations	35	0.58

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Economic Impact Estimation Model—Computable General Equilibrium Modeling

A computable general equilibrium (CGE) model is a stylized computational representation of the circular flow of the economy (see, for example, Sue Wing, 2009, 2011; Sue Wing and Balistreri, 2018). It solves for the set of commodity and factor (intermediate inputs used to produce other goods and services rather than for final consumption, as well as labor and capital) prices and the set of activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy. The model developed for this study divides California's economy into 18 areas (the 17 counties in the region affected by the HayWired mainshock—Alameda, Contra Costa, Marin, Merced, Monterey, Napa, Sacramento, San Benito, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Stanislaus, and Yolo—and the remainder of the State). Each economy consists of 46 industry sectors and households in nine different income categories and is linked to the other regions through trade.

The industry aggregation (see appendix 1) is matched to the occupancy classes in Hazus, the Federal Emergency Management Agency's (FEMA) expert loss estimation system (Federal Emergency Management Agency, 2012), which was used by other HayWired team members to calculate the building and content losses caused by the earthquake's physical impacts (Seligson and others, 2018). Each sector is modeled as a representative firm that produces a single good or service using production technology characterized by a CES cost function denominated over combinations of intermediate commodity and primary factor inputs. The households in each income group are modeled as a single representative agent with a constant marginal propensity to save and invest out of income and preferences characterized by a CES expenditure function denominated over final consumption of commodities. Government is represented in a simplified fashion, because its role in the circular flow of the economy is passive—collecting taxes from industries and passing some of the resulting revenue to households as lump-sum transfers, in addition to purchasing commodities to create a composite government good that is consumed by households. Two primary factors of production are represented within the model—labor, whose endowment is fixed but whose allocation among sectors responds to changes in the wage rate, and capital, which is treated as sector-specific and immobile among industries or regions during the 6-month postearthquake recovery horizon. Factors are owned by the representative agents, who rent them out to the firms in the agents' county of residence in exchange for factor income. Each region is modeled as an open economy that engages in trade with the rest of California, the rest of the United States, and the rest of the world according to an assumption, whereby imports from other counties, States, and the rest of the world are imperfect substitutes for goods produced locally (Armington, 1969) and also modeled using CES functions.

The basic model is static, computing the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments, over a single period of 6 months duration.[9] The economic impacts of the earthquake are modeled as exogenous reductions in endowments of sector-specific capital in the sectors sustaining direct physical damage and negative shocks to the aggregate (that is, the sum of domestic and imported) supply of utility lifelines to each region. The model is formulated as a mixed complementary programming problem using the Mathematical Programming System for General Equilibrium analysis (MPSGE) subsystem for the General Algebraic Modeling System (GAMS) software (Brooke and others, 1988; Rutherford, 1999) and is solved using the PATH solver (Ferris and Munson, 2000). A more detailed and technical description of the model is given in appendix 2. The model is calibrated using an IMPLAN social accounting matrix for the State of California for the year 2012 (IMPLAN, 2014). The key parameters of the model are summarized in appendix 2. Earlier variants of the model were used to analyze the effects of other disaster scenarios, such as a San Francisco Bay region earthquake cutting off water supplies from the California Aqueduct to Los Angeles County (Rose and others, 2011), the USGS California ARkStorm severe winter storm scenario (Sue Wing and others, 2016), and the USGS Science Application for Risk Reduction project (SAFRR) tsunami scenario (Rose and others, 2016).

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[9]The shortest timeframe on which the assumptions of Walrasian general equilibrium (market clearance, zero profit, and income balance) that underpin the construction and operation of a CGE model can be said to hold is the timeframe of several weeks to months that corresponds to Alfred Marshall's "short-period" over which price signals bring supply and demand in line with one another but the endowment of productive factors does not adjust (see Helm, 2008). Intermediate and final goods markets clear on about the timeframe over which work-in-process and finished goods inventories are drawn down. However, labor markets can remain far out of full employment equilibrium for periods of several years. Our selection of a 6-month simulation horizon for our comparative statics CGE analysis attempts to strike a balance between the duration of damaging aftershocks and the shortest period on which Marshallian quasi-rents (above-normal profits generated by idiosyncrasies of location or specialized fixed factors such as human capital) are eroded by competitive entry firms into the economy's various markets and prices equilibrate in the postdisaster regime. Consumers tend to rapidly adjust the composition of expenditures if they experience appropriately weighted disequilibrium aggregate marginal expenditures that exceed their marginal utility (for example, shifting away from luxury goods and toward staple items in a postdisaster environment). However, the timeframe over which households can continue to undertake expenditures in excess of their income is determined by their pool of savings and (or) remittances, as well as borrowing constraints. These facilitating factors are unlikely to operate over periods longer than a few months, which will tend to bring households' spending into line with their income. Because most households' primary source of income is labor remuneration, but wages adjust slowly and job search and matching takes time, household adjustment is more likely to occur on the expenditure side rather than on the income side in the short run.

Economic Resilience

Researchers and decision makers in the disaster field are split on the definition of economic resilience. One group uses the concept to refer to any action taken to reduce disaster losses. This group, with a large representation of engineers, focuses primarily on mitigation to reduce the frequency and magnitude of disaster stimuli and strengthening property to reduce damage (see, for example, Bruneau and others, 2003). This broad definition has also been adopted and applied across the board by major panels of experts assessing resilience research and practice, such as the National Research Council, which defines resilience as "The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" (National Research Council, 2012, p. 16).

Another group, with a large representation of social scientists (Tierney, 2007; Rose, 2017; Cutter, 2016), but with increasing representation by engineers in relation to utility lifelines (National Research Council, 2017), focuses primarily on actions implemented after the disaster strikes. This group takes the meaning of resilience more literally, referring to its Latin language root, whose definition is "to rebound." They also acknowledge that resilience is a process, whereby steps can be taken before the disaster to build resilience capacity, but resilient actions do not take place until after a disaster. Examples would include emergency drills, purchase of back-up electricity generators, and lining up alternative suppliers of critical inputs. In each case, the action serves no benefit before a disaster takes place but lowers the interruption of key business services when a disaster takes place. Here the focus is not on property damage, which has already taken place, but rather the reduction in the loss of the flow of goods and services emanating from property or capital stock. The former is often measured in terms of GRP and employment and is typically referred to as business interruption (Tierney, 1997). BI begins at the point when the disaster strikes and continues until the system has recovered or reached a "new normal," which is typically considered a "sustainable" level of activity (meaning a healthy economy). Measuring BI losses is thus much more complicated, because it involves matters of the duration and time-path of recovery, both of which are strongly affected by the behavioral responses of public and private decision makers (Rose, 2015).

Defining Economic Resilience

There are many definitions of resilience, but Rose (2009) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them up with definitions that capture the essence of economic considerations. Following Rose (2004b, 2009), we distinguish two major categories of resilience.

In general, static resilience refers to the ability of the system to maintain a high level of functioning when shocked (Holling, 1973). Static economic resilience is the efficient use of remaining resources at a given point in time. It refers to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.

In general, dynamic resilience refers to the ability and speed of the system to recover (Pimm, 1984). Dynamic economic resilience is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to reestablish productivity in the future. Static economic resilience does not restore damaged capacity and is therefore not likely to lead to complete recovery.

Note that economic resilience can take place at three levels of analysis:

- Microeconomic (operation of individual businesses, households, and government agencies; for example, conservation of or substitution for critical inputs, use of inventories or excess capacity, relocation, and production rescheduling)
- Mesoeconomic (operation of industries and markets; for example, the resource-allocating mechanism of the price system)
- Macroeconomic (operation of the economy; for example, supply-chain adjustments, importation of critical inputs, and fiscal and monetary policy)

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Tierney, 2007; Cutter, 2016). Inherent resilience refers to resilience capacity already built into a system or capacity that can be enhanced before the disaster strikes, such as the ability to use more than one fuel in an electric-power generating unit, substituting domestically disrupted goods and services with imports, the workings of the market system in offering price signals to identify scarcity and value, and established government policy levers. Adaptive resilience is exemplified by normal or improvisational actions after a disaster strikes, such as undertaking conservation that was not previously thought possible, changing technology, devising market mechanisms where they might not have previously existed, and (or) devising new government postdisaster assistance programs. It is important to realize that a great deal of resilience is already embodied in the economy at various levels (for example, a firm's ability to substitute inputs and market signals for reallocating resources) and that policies could be designed to capitalize rather than obstruct or duplicate this capacity. At the same time, benefits can accrue from policy that is geared to rewarding both general categories of resilience.

Economic resilience can also be defined from both the customer-side and supplier-side (Rose, 2009, 2017). Customer-side resilience primarily refers to demand-side resilience tactics, by which the businesses and households cope with the disruption (quantity and timing) of the delivery of intermediate production inputs or final goods and services,

respectively, using resilience tactics such as conservation, input substitution, import substitution, use of inventories, and production recapture. In other words, it pertains to ways to use remaining resources available as effectively as possible (static resilience). In contrast, supplier-side resilience is concerned with delivering outputs to customers and could include the establishment of system redundancy in the production process (a form of static resilience); it also involves the repair or reconstruction of critical inputs (that is, dynamic resilience). Repair of the capital stock, or supplier-side efforts, are the domain of the sectors that provide production inputs (including services) to other (customer) sectors and are for the most part a separate matter from customer-side resilience.[10]

An Operational Economic Resilience Metric

The next step is to translate these definitions into something we can measure. For static resilience, this can be done in terms of the amount of BI losses prevented by the implementation of a given resilience tactic or set of tactics comprising a resilience strategy. For dynamic resilience, the metric would be the reduction in recovery time in addition to the reduction in BI losses, although the former influences the latter. In both cases, one needs to establish a reference point or baseline to perform the measurement. For static resilience, this would be the maximum potential BI losses in the absence of the resilience tactic, whereas for dynamic resilience it would be the duration and time-path of economic activity in the absence of resilience in relation to investment in repair and reconstruction.

Several studies have measured resilience using this and related metrics in addition to the studies reviewed above. Rose and others (2009) found that potential BI losses were reduced by 72 percent by the rapid relocation of businesses following the September 11, 2001, terrorist attacks on the World Trade Center. Rose and Wei (2013) found that a reduction in potential BI losses from a 3-month closure of a major U.S. seaport could be as great as 66 percent from the implementation of several types of static resilience, most notably ship rerouting, use of inventories, and production rescheduling. Xie and others (2018) estimated that dynamic resilience in the form of increase in and acceleration of the timing of investment funds in the aftermath of the M_w 7.9 2008 Sichuan (Wenchuan), China, earthquake reduced BI losses by 30 percent and recovery time by 1 year.

Other studies have found extensive potential of economic resilience. Kajitani and Tatano (2009) found extensive resilience possibilities among Japanese manufacturing firms in response to utility-service disruptions caused by disasters. Specialized studies have developed methodologies for examining the potential of specific resilience strategies, such as use of inventories (Barker and Santos, 2009).

[10]There are tradeoffs in the level of implementation of customer-side and supplier-side resilience in that an increase in resilience expenditures by one side reduces the need for expenditures by the other.

Inputs into the Economic Impact Model

There are three types of inputs into the HayWired scenario economic impact model. First, the percentage of property damages (capital stock losses) incurred in each sector are calculated by county. The direct economic impacts of these capital losses for each sector are expressed as a percentage of their baseline gross output. Second, digital and utility service disruptions are another source of business interruption and the percentage of baseline services provided are estimated by county. Third, resilience adjustments to these service disruptions are identified on both the supplier-side and customer-side. In addition to these resilience strategies on the input-side of the CGE analysis, we also explain how production recapture and relocation of production activities are applied to the CGE modeling output to ameliorate the impacts of property damage and digital- and utility-service disruptions.

Property Damage

The percentage of property damage (capital stock losses) incurred in each industry sector is calculated from building and content damages caused by the HayWired mainshock and aftershocks estimated using Hazus[11] (Seligson and others, 2018). Indirect, or ancillary, property damages from fire following earthquake are also estimated (see Scawthorn, 2018) and integrated with the Hazus damage assessment (see Johnson and others, this volume). Cumulative property damages are inputs to the CGE model for the evaluation of the total economic impacts of the HayWired scenario as follows:

1. Building and content exposure value (dollar) loss from HayWired mainshock shaking, liquefaction, and landslide hazards.
2. The above with additional building and content losses from fire following the mainshock.
3. The above with additional building and content losses from HayWired aftershocks.

Mainshock Earthquake Hazards

For building and content damages caused by the mainshock hazards, the following steps were followed to compute the percentage property damages for occupancy classes in each county:

1. Compute the percentage of building damage for each occupancy class in each county by dividing the

[11]One caveat is that the custom Hazus mapping schemes of construction used in the HayWired scenario were developed in 2006 to reflect the distribution across various vintages, and the building codes under which they were designed (vintage 2000). Although new buildings were constructed since then in the bay region, regional building stock is still dominated by older buildings, and "new" buildings represent only a small fraction of the current inventory. Since "new" buildings that comply with more current building codes are expected to perform better than "old" buildings, the property damage estimates generated by Hazus can be considered conservative.

Hazus "BldgLoss" of that occupancy class in the county by the corresponding Hazus "BldgVal"; and similarly, compute the percentage of content damage for each occupancy class in each county by dividing Hazus "ContentLoss" by Hazus "ContentsVal."

2. Determine the percentage of building damage and percentage of content damage for each CGE sector in each county based on the bridging table between the Hazus occupancy classes and the CGE sectors (see appendix 1, table 1.1).

3. In the case of one CGE sector corresponding to more than one Hazus occupancy class, we calculate the percentage of building damage (or percentage of content damage) for the CGE sector as a weighted average of the percentage of damage of all the relevant occupancy classes. The average is weighted by building value of the Hazus sectors.

The percentages of building damage and content damage are shown in appendix 3, tables 3.1 and 3.2, respectively. The county that suffers the greatest property damages, in percentage terms, is Alameda (ranging from 14.4 percent building and content damages of primary metal manufacturing to 44 percent for the mining sector and for the food, drug, and chemicals manufacturing sector), followed by Contra Costa (ranging from 7.2 percent for the imputed rental value for owner-occupied dwellings sector to 18.3 percent for the education services sector), Santa Clara (ranging from 3.7 percent for the imputed rental value for owner-occupied dwellings sector to 7.6 percent for the light industry), and San Mateo (ranging from 3.4 percent for the imputed rental value for owner-occupied dwellings sector to 6.5 percent for the mining sector and for the food, drug, and chemicals manufacturing sector).

Mainshock Earthquake and Fire Following Earthquake Hazards

Additional property damages are caused by fire following the HayWired mainshock. The additional percentage of buildings that are completely damaged from fire are computed, eliminating the potential double counting for the buildings that have already been completely damaged by shaking. (The integration of fire damage with direct earthquake hazard damages is described in section A of Johnson and others [this volume]). Appendix 1, table 1.1, is also used to map the percentage of this property damage by occupancy class to the corresponding CGE sectors. Appendix 3, table 3.3, shows the percentages of additional property damage (including both buildings and contents) caused by fire following the HayWired mainshock by county and by CGE sector. Appendix 3, table 3.4, shows the percentage of property damage caused by mainshock and fire combined. The three most damaged counties in terms of property damage are again Alameda (from 17 percent to 47 percent), Contra Costa (from 10.2 percent to 26.4 percent), and Santa Clara (from 5.1 percent to 9.7 percent).

Mainshock Earthquake Hazards, Fire Following Earthquake Hazards, and Aftershock Shaking Hazards

The property damage from aftershocks is also estimated. Appendix 3, table 3.5, shows the additional percentage of building and contents damages caused by aftershocks. It is assumed that the building and content losses for the mainshock and the aftershocks are additive. In other words, the total percentage of building and contents damage shown in appendix 3, table 3.6, represents a simple sum of the mainshock (including fire) losses and aftershock losses. Some of the damages could be double counted because Hazus assumes that the buildings are as they were before the mainshock in the simulations for each aftershock. Therefore, some of the buildings that have already been extensively or completely damaged by the mainshock may be "damaged" again by the aftershocks in the simulations. This leads to an overestimate of the building damages. Conversely, Hazus does not allow for structures that are slightly or moderately weakened by the mainshock to be more fragile to subsequent shaking, and this leads to an underestimation of damage to these buildings by aftershocks. The potential double counting (overestimation) of damages to buildings that are extensively or completely damaged by the mainshock and the underestimation of damages to weakened (slightly or moderately damaged) buildings by the mainshock offset each other to some extent when we compute the combined impacts of the mainshock and aftershocks. The total property damages for the three most impacted counties are 24.3 percent to 51.3 percent for Alameda, 10.5 percent to 26.9 percent for Contra Costa, and 8.8 percent to 16.6 percent for Santa Clara.

Gross Output Losses

To compare the baseline economy with direct economic impacts of property damages, the sector percentages of these capital losses are applied to baseline sector capital inputs in the model to obtain the direct impacts in terms of sector gross output. These are divided by baseline sector gross output to produce the percentages of gross output losses in figure 1. The figure summarizes the aggregate direct effects of the mainshock and aftershock shaking and fire at the level of sectors within each county. (The total economic impact result for this case is shown in table 18, line 4.) The figure indicates that, although direct adverse effects on the internet publishing and broadcasting sector are modest (losses on the order of 2–3 percent of baseline output), related and supporting sectors whose outputs are used intensively as inputs to that industry (for example, telecommunications, electric power, data processing, hosting and related services, computer storage device manufacturing, electronic computer manufacturing, and other information services) are on average among those that are most directly affected, with average losses of 5 to 10 percent of baseline output. However, these gross output reductions induce changes in the CGE model simulation which account for the price and substitution responses in markets throughout California's economy.

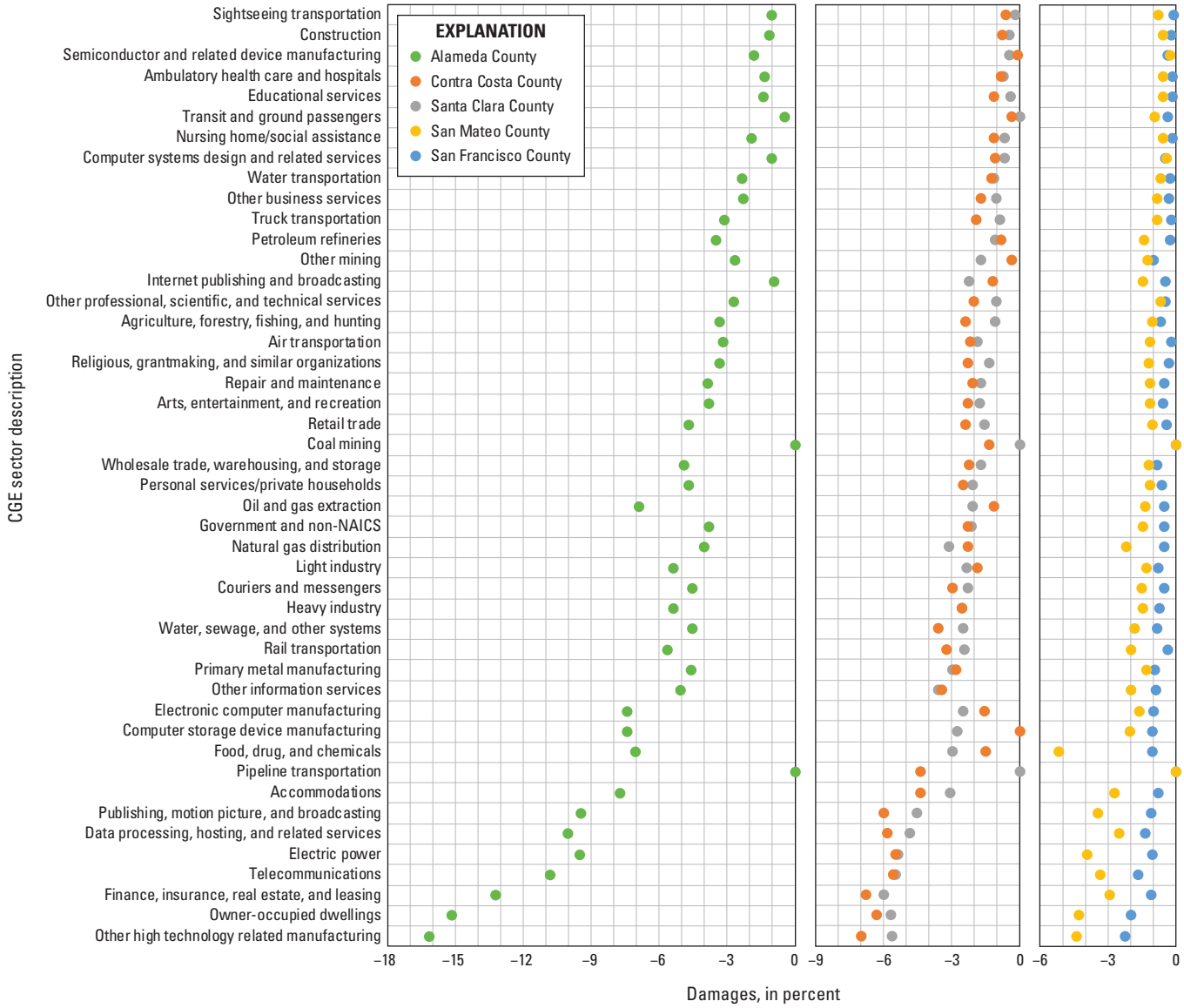


Figure 1. Aggregated mainshock, fire, and aftershock damages directly sustained by sectors in affected counties in the San Francisco Bay region, California, expressed as a percentage of a sector's gross output. CGE, computable general equilibrium.

Digital and Utility-Service Disruptions

Like all large urban earthquakes, the HayWired mainshock and aftershocks would damage the utility systems that supply water, electricity, and other essential services. To check equipment, repair damage, and reroute or restore service can take days to months. As recounted in Porter (2018) and Jones and others (this volume, appendix 3), all the water- and electricity-service damage envisioned in the HayWired scenario is eventually repaired and all the service is eventually restored. In San Francisco Bay region locations farthest from the mainshock epicenter these services are restored fastest or never disrupted at all. Closer to the mainshock, it would take days or weeks to restore electricity service and as long as 7 months to restore water service. Until service is restored, economic production in workplaces suffers as described in this chapter. Households also suffer from the significant inconvenience costs caused by the service disruptions detailed in appendix 7. CGE models, like nearly all macroeconomic models, focus on goods and services, and their value, transacted through market or delivered by governments. Therefore, household costs need to be evaluated outside the models by "nonmarket valuation" methods as presented in this section and appendix 4.

We summarize the base cases for the utility-service disruptions for water and electric power supply in the HayWired scenario. In the next section we will recognize resilience tactics that reduce the direct and total economic impacts of service disruptions. Inconvenience costs of water and power outages to households (that are not part of the larger economic impact analysis) are treated separately.

Water-Service Disruptions

Water service is evaluated in terms of a preplan scenario (as-is conditions) by Porter (2018) and is expected to be restored within 30 days in most counties. However, it is estimated that 100 percent restoration of water service in San Mateo County will take 90 days, and the full restoration in Alameda and Contra Costa Counties will take as long as 7 months. In table 9, utility-service disruption model inputs in percentage terms are shown by county and by 6-month period in the second through fourth columns. The percentage of water-service disruption is calculated for the first 6-month (or 182-day) horizon of the analysis using the CGE model. For example, if 50 percent of water service is disrupted for 7 days, the percentage of water-service disruption in the 182-day period is 50 percent × 7/182 = 1.92 percent. The same approach is used in the calculation of other utility-service disruptions.

However, for many households, loss of water service is an inconvenience that comes with a cost. In the HayWired scenario, almost 3 million people lose water service to their homes for more than 3 days. The average household in the study area loses water service for 16 days, and in Alameda and Contra Costa Counties, the average is 54 days. Between the mainshock and all the aftershocks of M_w 5.0 or greater, households lose just over 57 million service-days of water, that is each day of lost water supply to a household equates with one service day. Households without water service must rely on bottled water and portable toilets. To bathe, residents must travel to someplace outside the home that has a functioning water supply and shower facilities, all of which have inconvenience costs. The cost for bottled water, rental of portable toilets (assuming enough stock exists nationwide to supply the need), and the inconvenience cost of traveling for showers is estimated to cost $90 per household per day. The total inconvenience cost of disrupted water service to residences is conservatively estimated to be $5.2 billion (appendix 4). Using other sources examined in appendix 4, the figure could be as high as $33 billion.

Table 9. Percentage of customers experiencing utility-service disruptions in the first 6 months following the HayWired mainshock, by county in the San Francisco Bay region, California.

County	Water disruption	Electric power disruption	Data and voice disruption
	Percentage of customers		
Alameda	32.34	3.93	5.05
Contra Costa	32.34	2.52	3.60
Marin	0.54	0.74	1.39
Merced	0.20	0.29	0.60
Monterey	0.00	0.18	0.52
Napa	0.00	0.29	0.60
Sacramento	0.00	0.07	0.46
San Benito	0.05	1.02	1.16
San Francisco	3.68	1.31	1.86
San Joaquin	0.00	0.58	0.76
San Mateo	11.05	1.82	2.33
Santa Clara	2.80	2.69	3.67
Santa Cruz	0.00	0.41	0.67
Solano	0.11	0.60	1.27
Sonoma	0.00	0.09	0.99
Stanislaus	0.00	0.00	0.00
Yolo	0.00	0.00	0.00

Power-Service Disruptions

Power-service disruptions were estimated using Hazus (see appendix 3 in Jones and others, this volume). They are estimated to last a shorter duration than water-service disruptions in all counties. By Day 7, all counties are expected to have more than 90 percent of power service back. The only exception is Alameda County, which would have 83 percent power service restored. By Day 30, the only counties that still experience power-service disruptions are Alameda, Contra Costa, San Mateo, and Santa Clara, but the disruptions are all less than 4 percent of electric power services. Compared to water supply restoration, some counties initially have lower power than water services owing to the widespread nature of the electric power outage.

For households, while electricity is out, freezers thaw and refrigerators warm, food spoils, and people must rely on their emergency supplies. Approximately 1.4 million households lose power long enough that, once the electricity is restored, they must replace the spoiled food at a cost of approximately $325 per average household, for a total cost of $450 million (appendix 4). Other inconveniences, such as eating cold meals from emergency supplies and inability to charge devices, are real but not quantified here in dollar terms. Using a FEMA standard value, one can estimate the value lost as $3.9 billion.

Data- and Voice-Service Disruptions

In Wein, Witkowski, and others (this volume), data and voice service restoration curves are first derived for a base case that assumes full dependence on electric power such that service restoration lags behind power restoration. The base case also assumes a surge in demand, from customers communicating about the earthquake, that overloads networks. The surge decreases with time after the crisis subsides as the need to communicate with family, friends, and first responders and seek information lessens. The percentages of customer demand for data and voice services in the base case are in appendix 6, table 6.1.

Resilience Adjustments

As explained above, the CGE model implements economic resilience primarily at the meso (sector or market) and macro (entire regional economy) scale. At the micro scale, businesses

can take other actions to reduce business interruption. Many of these resilience tactics are beyond normal business and market behavior. Although resilience can be enhanced before the disaster strikes by investments that increase its capacity (for example, increasing stockpiles of critical inputs, purchasing backup generators), the various tactics are implemented only after the earthquake has occurred.

We model most of these effects by adjusting the inputs to the CGE model (discussed in detail in the subsection on Summary of Property Damage and Utility-Service Disruptions by Sectors) or by adjusting the GRP losses—the output of the CGE modeling (discussed in subsection on Resilience Adjustments). In particular, the resilience tactics are as follows:

1. Supplier-side resilience tactics that restore services faster:

D. Input substitution, such as fixed back-up power (batteries and generators) and fuel management plans in case of an electric power outage.

E. Inventories of portable equipment to temporarily replace power sources and add capacity.

These reductions in disruption are modeled by adjusting the restoration curves upward accordingly and then input into the CGE model.

2. Customer-side resilience tactics work around the supplier disruption to maintain production of goods and services. In general, these include the following:

A. Conservation is to produce goods or services using fewer critical inputs and to conserve critical inputs that could become scarce owing to indirect effects.

B. Input substitution replaces an unavailable good or service by a different available good or service.

C. Production isolation refers to the portions of a production process that are insulated from lifeline services, and hence are not affected by service disruptions (for example, much of agricultural production does not require electricity).

The reductions in disruptions are modeled as equivalent utility input (the base case utility-service disruption percentages adjusted downwards for each individual resilience tactic) to represent the production of goods and services that are attained by other means. The equivalent utility inputs are adjusted for each sector and used in the CGE model. However, we cannot account for the additional "upstream" effects to suppliers of the additional equivalent input.

3. Customer-side resilience tactics that use capacity of capital beyond normal use. Two examples are as follows:

B. Production recapture (rescheduling) is the ability of businesses to recoup lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs and employees are available. This is a viable option for short-run disruptions, where customers are less likely to cancel orders from their standard suppliers.

C. Relocation of businesses, including teleworking from other locations (for example, shared workplaces or homes).

These reductions in disruption are applied to the outputs of the CGE model to reduce total BI losses for sectors. However, the upstream effects from additional production are not accounted for.[12]

Resilience Adjustments on Input Side of CGE Modeling

Water-Service Disruptions with Resilience

Two customer-side resilience tactics applied to water supply restoration are

- Water conservation of 2 percent can be reasonably achieved by means such as water recycling.
- Production isolation from water inputs are derived from utility "Importance" factors by sector (Applied Technology Council, 1991) in appendix 5, table 5.1. The portion of production processes that can be isolated from water services is one minus the percentages shown in column 2.

Note that input substitution refers to the use of other products, such as bottled and trucked water, other beverages, and possibly even chemicals, in place of disrupted water input. Some of these substitutions are inherent in the economy and modeled through the ordinary elasticities of substitution between water and other inputs in the CES production functions in the CGE model. We lack information, however, on adaptive input substitution that could emerge under stressful conditions.

Note that Porter (2018) provided three cases: (1) base case ("no fuel management plan or mitigation" in Porter, 2018), (2) supplier-side fuel management plan to keep permanent generators running during power outages ("postplan" in Porter, 2018), and (3) both mitigation (brittle pipe replacement) and resilience (power source management plan for pumping) ("ideal world" in Porter, 2018). The effects of customer-side resilience (conservation, production isolation, or both) on the base case water-service disruption are shown in table 10. Table 11 shows water-service disruption percentages for the postplan and ideal-world scenarios.

Power-Service Disruptions with Resilience

Customer-side resilience tactics for power-service disruptions include 2-percent conservation and production isolation (similarly, derived from appendix 5, table 5.1). Again, input substitution is assumed to be already accounted for in the CGE model. Table 12 shows power-service disruptions by county for conservation and production isolation both separately and combined.

[12]We note that Porter (2018) also offers a water-disruption analysis for the mitigation action of replacing old brittle pipes that will reduce damages, and therefore disruption.

Table 10. Percentage of customers experiencing water-service disruptions in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics for preplan scenario in the San Francisco Bay region, California.

[Combined resilience is conservation and production isolation]

County	Water disruption with conservation	Water disruption with production isolation	Water disruption with combined resilience
	Percentage of customers		
Alameda	31.69	12.65	12.40
Contra Costa	31.69	13.11	12.85
Marin	0.53	0.16	0.15
Merced	0.19	0.09	0.09
Monterey	0.00	0.00	0.00
Napa	0.00	0.00	0.00
Sacramento	0.00	0.00	0.00
San Benito	0.05	0.02	0.02
San Francisco	3.61	1.04	1.02
San Joaquin	0.00	0.00	0.00
San Mateo	10.83	3.86	3.78
Santa Clara	2.75	1.49	1.46
Santa Cruz	0.00	0.00	0.00
Solano	0.11	0.05	0.05
Sonoma	0.00	0.00	0.00
Stanislaus	0.00	0.00	0.00
Yolo	0.00	0.00	0.00

Table 11. Percentage of customers experiencing water-service disruption in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics for postplan and ideal-world scenarios in the San Francisco Bay region, California.

[Postplan is conservation and production isolation; ideal world is conservation and production isolation]

County	Water disruption with resilience for postplan scenario	Water disruption with resilience for ideal world scenario
	Percentage of customers	
Alameda	10.59	5.11
Contra Costa	10.98	5.30
Marin	0.05	0.05
Merced	0.06	0.06
Monterey	0.00	0.00
Napa	0.00	0.00
Sacramento	0.00	0.00

Table 11—Continued.

County	Water disruption with resilience for postplan scenario	Water disruption with resilience for ideal world scenario
	Percentage of customers	
San Benito	0.02	0.02
San Francisco	0.34	0.34
San Joaquin	0.00	0.00
San Mateo	3.16	3.16
Santa Clara	1.46	0.89
Santa Cruz	0.00	0.00
Solano	0.01	0.01
Sonoma	0.00	0.00
Stanislaus	0.00	0.00
Yolo	0.00	0.00

Table 12. Percentage of customers experiencing power-service disruptions in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics in the San Francisco Bay region, California.

[Combined resilience is conservation and production isolation]

County	Power disruption with conservation	Power disruption with production isolation	Power disruption with combined resilience
	Percentage of customers		
Alameda	3.85	3.31	3.24
Contra Costa	2.47	2.29	2.24
Marin	0.73	0.62	0.61
Merced	0.28	0.22	0.21
Monterey	0.17	0.13	0.13
Napa	0.28	0.23	0.23
Sacramento	0.07	0.06	0.06
San Benito	1.00	0.84	0.82
San Francisco	1.29	1.10	1.07
San Joaquin	0.57	0.46	0.45
San Mateo	1.79	1.54	1.51
Santa Clara	2.63	2.45	2.41
Santa Cruz	0.40	0.33	0.33
Solano	0.59	0.51	0.50
Sonoma	0.09	0.07	0.07
Stanislaus	3.85	3.31	3.24
Yolo	2.47	2.29	2.24

Data- and Voice-Service Disruptions with Resilience

Resilience tactics for data and voice services are examined in Wein, Witkowski, and others (this volume). They include supplier- and customer-side tactics as well as customer behavior management.

Supplier-Side Resilience Tactics

Supplier-side resilience tactics for data and voice services include:

- Input substitution for power—using permanent backup batteries and generators—by the telecommunication providers to maintain the function of the residual data and voice infrastructure capacity that would otherwise depend on electric power. The assumption is that half the cellular sites are fitted with batteries that will drain on the first day and half the sites have a generator with fuel for three days.
- Inventories of portable gensets (for example, a diesel generator, which is a combination of diesel engine and electric generator) for cell sites lacking a functioning generator and mobile cell sites on wheels or light trucks (COWs or COLTs) to temporarily restore service capacity. Depending on the level of impact, the first trucks deliver and install portable equipment within a week after the earthquake.

The percentages of customer demand for data and voice services met for each of these resilience tactics with the base case are in appendix 6, tables 6.2 and 6.3. The service disruption estimates for customers during the first 6 months for these and subsequent resilience tactics are shown in table 13.

Customer Behavior Management

Wein, Witkowski, and others (this volume) suggest that data and voice bandwidth can be conserved through managing customer behavior on the supplier and (or) customer sides. Efficient use of bandwidth includes using text rather than voice and radio rather than news streaming to reduce the surge in demand for communication services immediately after the earthquake. Assuming the surge in customer demand is reduced by 10 percent, appendix 6, table 6.4, shows the percentages of demand for data and voice service met by county. The potential to benefit from customer behavior management decreases with reductions in demand as the crisis surge subsides.

Table 13. Percentage of customers experiencing data- and voice-service disruptions in the first 6 months following the HayWired mainshock for base case and after adjustment for resilience tactics, by county, in the San Francisco Bay region, California.

[Combined resilience is supplier permanent backup power and portable equipment, supplier and customer behavior management, and customer input substitution and production isolation]

County	Data and voice disruption in the base case	Data and voice disruption with supplier permanent backup power	Data and voice disruption with supplier portable equipment	Data and voice disruption with supplier/ customer behavior management	Data and voice disruption with customer input substitution	Data and voice disruption with customer production isolation	Data and voice disruption with combined resilience
	Percentage of customers						
Alameda	5.05	4.42	2.96	4.66	2.79	2.11	0.78
Contra Costa	3.60	3.06	1.68	2.79	1.91	1.12	0.29
Marin	1.39	1.27	1.25	1.17	0.91	0.77	0.37
Merced	0.60	0.52	0.56	0.59	0.46	0.20	0.14
Monterey	0.52	0.48	0.50	0.51	0.44	0.22	0.17
Napa	0.60	0.52	0.56	0.59	0.46	0.22	0.15
Sacramento	0.46	0.45	0.46	0.45	0.42	0.21	0.19
San Benito	1.16	1.26	0.82	1.16	0.69	0.37	0.18
San Francisco	1.86	1.62	1.48	1.67	1.25	1.03	0.47
San Joaquin	0.76	0.58	0.67	0.75	0.53	0.31	0.17
San Mateo	2.33	1.93	1.57	2.15	1.36	1.14	0.44
Santa Clara	3.67	3.08	1.73	2.88	1.99	1.36	0.36
Santa Cruz	0.67	0.55	0.61	0.67	0.47	0.29	0.18
Solano	1.27	1.15	1.16	1.04	0.79	0.42	0.19
Sonoma	0.99	0.97	0.98	0.73	0.58	0.42	0.20

Customer-Side Resilience

Customer-side resilience tactics to cope with the data and voice service disruptions include additional considerations that we describe in more detail below.

Input Substitution

Various input substitution options given in Rose and Miller (2017), including using paper records and people processes (personal conversations and couriers) rather than telecommunications, are estimated to prevent 20 percent to 35 percent of the loss of productivity from direct data- and voice-service disruptions. To be conservative, we increase the base case percentage of demand for data and voice services met (table 13, column 2) by 20 percent to represent an equivalent availability of data and voice service to customers who substitute inputs for the loss of data and voice services (see appendix 6, table 6.5).

Production Isolation

Production isolation refer to the portion of business operations that can continue without data and voice services. The "importance factors" of telephone services (Applied Technology Council, 1991) are shown in appendix 5, table 5.1, column 4. In appendix 6, table 6.6, we made further adjustments to the Applied Technology Council "importance factors" based on the dependence of individual sectors' operations on internet services. Appendix 6, table 6.7, shows the equivalent data and voice service availability after considering production isolation in the absence of data and voice service.

Combined Supplier-Side and Customer-Side Resilience

After simulating the effects of each of the supplier-side and customer-side resilience tactics to data- and voice-service disruption separately, we combine the effects of all of them together. The tactics are applied in a logical order of permanent backup power and use of portable equipment first; then customer behavior management followed by other customer-side resilience tactics (including input substitution and production isolation) (see estimates in appendix 6, table 6.8, which are in turn used as input to the CGE modeling).

Resilience Adjustments on the Output Side of CGE Modeling

To reflect unusual uses of capital after an earthquake, adjustments for production recapture and telework are applied to the CGE modeling results to reduce GRP losses by sector.[13]

Production Recapture

Production recapture entails employees working overtime and extra shifts after equipment and facilities have been repaired or replaced and employees and critical inputs become available. "Recapture factors" that lead to potential percent reductions in GRP losses for sectors have been used in economic analyses for 20 years (see, for example, FEMA, 2012; Rose and Lim, 2002). We adjust the factor values downward by 50 percent owing to obstacles to efficient implementation such as lack of excess capacity and customers cancelling their orders.[14] The adjusted production recapture factors in appendix 5, table 5.2, are applied directly to reduce GRP losses by sector.

The capability of the businesses to recapture lost productions diminishes over time, because more customers would cancel their orders and seek alternative suppliers as the length of disruption extends. Building recovery time increases with Hazus property damage states of slight, moderate, extensive, and complete damage. Therefore, using Hazus data, we computed the weighted average production recapture factor for each Hazus occupancy class in each county and applied it to the base case GRP losses.[15]

Relocation (Inter-County Shift in Economic Activity)

The multiregional CGE model automatically includes a form of business relocation through inherent substitution (shifts) of production across counties. This need not represent the actual physical move of a damaged operation to another location, but simply production entities in other counties picking up the slack if they have the capacity to do so. A related additional consideration, not taken into account by the CGE model (and discussed further below), is the potential for telework, relocation of good- and service-producing activities to other sites. The major source to estimate the telework potential is the Bureau of Labor Statistics (BLS) (2017) data on the percentage of workers working at least one day at home for different types of occupations. In appendix 6, we further adjusted the BLS data, with considerations of workers' readiness to go back to work after a major disaster, data- and voice-service restoration, and cloud-backup data availability.

[13]The evaluation of the effects of the various resilience tactics assumes that the businesses aim to return to "business as usual" conditions. In practice, businesses will reposition or redefine themselves and find new efficiency, as was reported after the Christchurch earthquakes (Chang and others, 2014; Stevenson and others, 2014; Brown and others, 2015).

[14]Note that most of these factors become more important as the disruption duration increases, but they are still pertinent in a short-run case.

[15]Note that for production recapture of BI losses stemming from property damages, we only have data on the distribution of property damages over damage states for the mainshock. For each occupancy class in each county, we assume that the weighted average recapture factor calculated based on the mainshock distribution of building damage states can be applied to aftershocks as well. The underlying assumption is that the distribution of building damage by severity state for each occupancy class for aftershocks is similar to the distribution for the mainshock. This would be a conservative assumption in terms of the potential of production recapture. This is because the aftershocks are less impactful than the mainshock except in a few localized areas. Since we assume that the damage distribution of the aftershocks is towards the more impactful category (as in the mainshock), on average the corresponding repair and reconstruction time of the buildings would be longer, so that the weighted average production recapture factor we calculate would be small.

Total Economic Impacts

Total economic impacts are estimated using the CGE model with inputs for the base case, with inputs for the various resilience cases, and by adjusting the outputs for production recapture and telework.

Base Case Without Resilience Tactics

Table 14 summarizes the total economic impacts of the HayWired scenario, elaborating on the effects on the bay region and broader California economies in terms of GRP losses resulting from business interruption caused by the HayWired scenario property damage and utility-service disruptions. The base case only includes inherent resilience in the CGE model relating to factor and locational substitution and price adjustments; it does not include the impacts of any other inherent or adaptive resilience tactics addressed subsequently.[16]

By far the greatest BI losses (measured in GRP losses) are caused by the initial mainshock, propagated via the destruction of structures (and, to a lesser extent, their contents) owing to shaking and ground failure. This impact pathway accounts for more than three quarters of the statewide economic loss in the 6-month postearthquake period, which totals $44.2 billion, or 4.2 percent of the State's projected baseline GSP over the period. In table 14 and other tables and figures to follow

[16]Note that the base case results presented in table 14 and the resilience results presented below are primarily based on CGE modeling results. However, adjustment needs to be made for the impacts of water and electricity service disruptions. The readers are referred to appendix 7 for detailed discussions on the adjustments we made.

Table 14. Base-case gross regional product (GRP) change in the first 6 months following the HayWired mainshock in San Francisco Bay region counties and the rest of California.

[Percent change with respect to 6-month benchmark GRP shown in parentheses]

Loss category	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Mainshock	−10.6	−3.4	−2.1	−2.1	−7.4	−1.7	−4.7	**−31.9**
	(−19.7)	(−10.7)	(−3.3)	(−4.8)	(−6.4)	(−1.3)	(−0.7)	**(−3.0)**
Shaking: buildings	−6.5	−2.2	−1.4	−1.3	−4.1	−0.9	−2.9	**−19.2**
	(−12.0)	(−6.9)	(−2.3)	(−3.0)	(−3.5)	(−0.7)	(−0.5)	**(−1.8)**
Shaking: contents	−2.4	−0.8	−0.5	−0.6	−2.0	−0.4	−1.2	**−7.9**
	(−4.3)	(−2.7)	(−0.9)	(−1.3)	(−1.7)	(−0.3)	(−0.2)	**(−0.7)**
Fire	−1.4	−0.32	−0.1	−0.2	−1.2	−0.3	−0.5	**−4.1**
	(−2.5)	(−1.0)	(−0.2)	(−0.5)	(−1.1)	(−0.3)	(−0.1)	**(−0.4)**
Aftershocks	−1.1	−0.16	−0.3	−1.5	−5.5	−0.4	−1.5	**−10.5**
	(−2.1)	(−0.5)	(−0.6)	(−3.3)	(−4.7)	(−0.3)	(−0.2)	**(−1.0)**
Shaking: buildings	−0.7	−0.1	−0.2	−0.9	−3.6	−0.2	−1.0	**−6.8**
	(−1.3)	(−0.3)	(−0.4)	(−2.1)	(−3.1)	(−0.2)	(−0.2)	**(−0.6)**
Shaking: contents	−0.4	−0.06	−0.1	−0.5	−1.9	−0.1	−0.5	**−3.7**
	(−0.8)	(−0.2)	(−0.2)	(−1.2)	(−1.6)	(−0.1)	(−0.1)	**(−0.3)**
Utility-service disruption	−0.7	−0.05	−0.06	−0.07	−0.2	−0.09	−0.2	**−1.4**
	(−1.4)	(−0.2)	(−0.1)	(−0.2)	(−0.1)	(-0.06)	(−0.04)	**(−0.1)**
Power	−0.02	−0.01	−0.01	−0.01	−0.04	−0.01	−0.03	**−0.1**
	(−0.04)	(-0.03)	(−0.02)	(-0.02)	(−0.03)	(−0.01)	(−0.01)	**(−0.01)**
Water[1]	−0.7	−0.02	−0.002	−0.03	−0.02	−0.05	−0.1	**−0.9**
	(−1.2)	(−0.07)	(−0.005)	(−0.08)	(−0.02)	(−0.04)	(−0.02)	**(−0.09)**
Data and voice[2]	−0.06	−0.02	-0.05	−0.03	−0.09	−0.03	−0.08	**−0.4**
	(−0.1)	(−0.06)	(-0.08)	(−0.07)	(-0.08)	(-0.02)	(-0.01)	**(−0.03)**
Total (mainshock, aftershocks, and utility-service disruption)	**−12.7**	**−3.6**	**−2.5**	**−3.6**	**−13.1**	**−2.1**	**−6.5**	**−44.2**
	(−23.5)	**(−11.4)**	**(−4.0)**	**(−8.4)**	**(−11.2)**	**(−1.3)**	**(−1.0)**	**(−4.2)**

[1]Results shown for the "preplan" scenario.

[2]Disruption of the inputs of digital and other information services to intermediate and final consumers in the various counties (internet publishing, telecommunications, data processing, and other information services).

the percentage of GRP losses are calculated with respect to the benchmark 6-month (as opposed to annual) value of the affected regions. Additional GRP losses caused by postmainshock fires are estimated to be $4.1 billion, or about 9 percent of GSP losses. Secondary business interruption, owing to disruption of utility services, leads to GSP losses of $1.4 billion, which is much lower than the BI losses from property damage. This is mainly because utility-service disruptions are largely confined to the three heavily impacted counties (Alameda, Santa Clara, and Contra Costa), and almost all of the counties restore more than 90 percent of power service within 7 days, with data and voice services following.

Water service takes the longest time to restore compared to power and data and voice services. Within 30 days, water service is fully restored in most counties. The two most affected counties, Alameda and Contra Costa, have 80 percent of their water service restored within 180 days. Economic losses from water-service disruptions for the HayWired earthquake scenario are much smaller than those found in the previous ShakeOut earthquake scenario. Four factors account for this divergence. First and foremost, the CGE model used in our analysis includes several possibilities to substitute other inputs for piped utility water services in production and consumption, less water-intensive products for those that use relatively more water, and commodity supplies in unaffected counties for production in damaged areas, as the latter become relatively scarce. By contrast, economic analysis of the ShakeOut scenario employed an input-output model whose fixed-coefficient representation of production and consumption activities precludes substitution behavior within activities; the only substitution that occurs is through differential changes in the levels of sectoral production. The additional margins of substitution in our analysis thus confer substantial cost-savings. Second, our analysis considers a broader array of resilience measures (including both additional inherent resilience tactics that are not already embedded in the CGE model and adaptive resilience tactics), all of which substantially lessen the magnitude of shock to water supplies that producers and consumers might actually experience. Similarly, a third factor is that the HayWired scenario water services are restored relatively faster than ShakeOut scenario water disruptions owing to the character of bay region infrastructure and the earthquake damage it sustains. Finally, in the ShakeOut analysis, water accounted for a larger part of the cost of production in industries in Southern California, with concomitantly larger increases in sectoral production costs associated with disruptions of water service.[17]

[17]Examination of the detailed input-output structure of the economies of Los Angeles County and Alameda County (which suffers the most damage in this study) reveals that, out of the 440 sectors in our 2012 IMPLAN database, water intensity (water and sewer utilities' share of total production cost) was higher for 269 industry groups in Los Angeles, compared to only 144 industries in Alameda. Additionally, the difference in the magnitude of economic output of the two sets of water-intensive sectors suggests that a given percentage disruption in water supply will likely incur absolute losses that are far larger in Los Angeles County, as the total gross output of sectors that were relatively more water-intensive in Los Angeles amounted to $553 billion, as compared with only $36 billion for those in Alameda.

Overall losses are concentrated in the five bay region counties that are most directly affected by the earthquake property damage, which together account for 80 percent of the overall reduction in GSP in the first 6 months (see the last row of table 14). Alameda and Santa Clara Counties are most severely impacted by destruction of buildings and their contents as a consequence of both the mainshock and aftershocks, and suffer reductions in economic output of $12.7 billion and $13.1 billion, or more than 23 percent and 11 percent of county-level baseline GRP, respectively. GRP of areas not directly damaged by the earthquake decreases by 1 percent ($6.5 billion). The percent decrease for the rest of the bay region is closer to the rest of California than the five most affected counties.

Figure 2 summarizes the effects of the earthquake at the sectoral level in the bay region and across the State. The "heatmaps" identify the sectors within each county that experience the ten largest reductions in gross output, and rank their losses shown in terms of percentages in figure 2*A*, and absolute dollars in figure 2*B*. The losses themselves are detailed in figure 2*C*. The figure highlights two clusters of activities that are most affected. The first encompasses manufacturing (food/drugs/chemicals, light and heavy industry, petroleum refining, computer/high tech manufacturing), trade (wholesale and retail trade, warehousing), and construction. Across the counties, manufacturing and construction generally show larger absolute and percentage effects, although percentage effects are most notable for device manufacturing, whereas trade sectors feature for absolute impacts. The second encompasses "brick and mortar" services (education, hospitals and nursing homes, arts/entertainment/recreation), information and hi-tech services (publishing/motion pictures/broadcasting, internet publishing, other business and scientific/technical services, computer systems design), as well as finance and real estate (finance/insurance/real estate, dwellings). These sectors feature across counties for absolute effects except for the percentage of effects on information and education. The latter do not show up in the ten largest reductions in Alameda and Santa Clara Counties where effects to the manufacturing sectors dominate.

Regarding the magnitude of sectoral effects, Santa Clara and Alameda Counties are hardest hit, experiencing similar aggregated net losses of gross output (on the order of $20 billion), whereas the effect on Contra Costa County's gross output is less than half as large and San Francisco's is less than a quarter as large. The aggregated reductions in gross output in figure 2*C* are considerably larger than the GRP losses in table 14, in both percentage and absolute terms. This result is unsurprising, however, given that the reductions in output of upstream sectors are a direct consequence of reduced demand owing to curtailment of production by downstream sectors. For this reason, summing gross output losses across the sectors in each region dramatically overstates the true economic effect. In earthquake-affected counties, building-, content-, and fire-related destruction of capital stocks triggers direct curtailment of the production and domestic supply of goods, with concomitant increases in their prices. Because the outputs

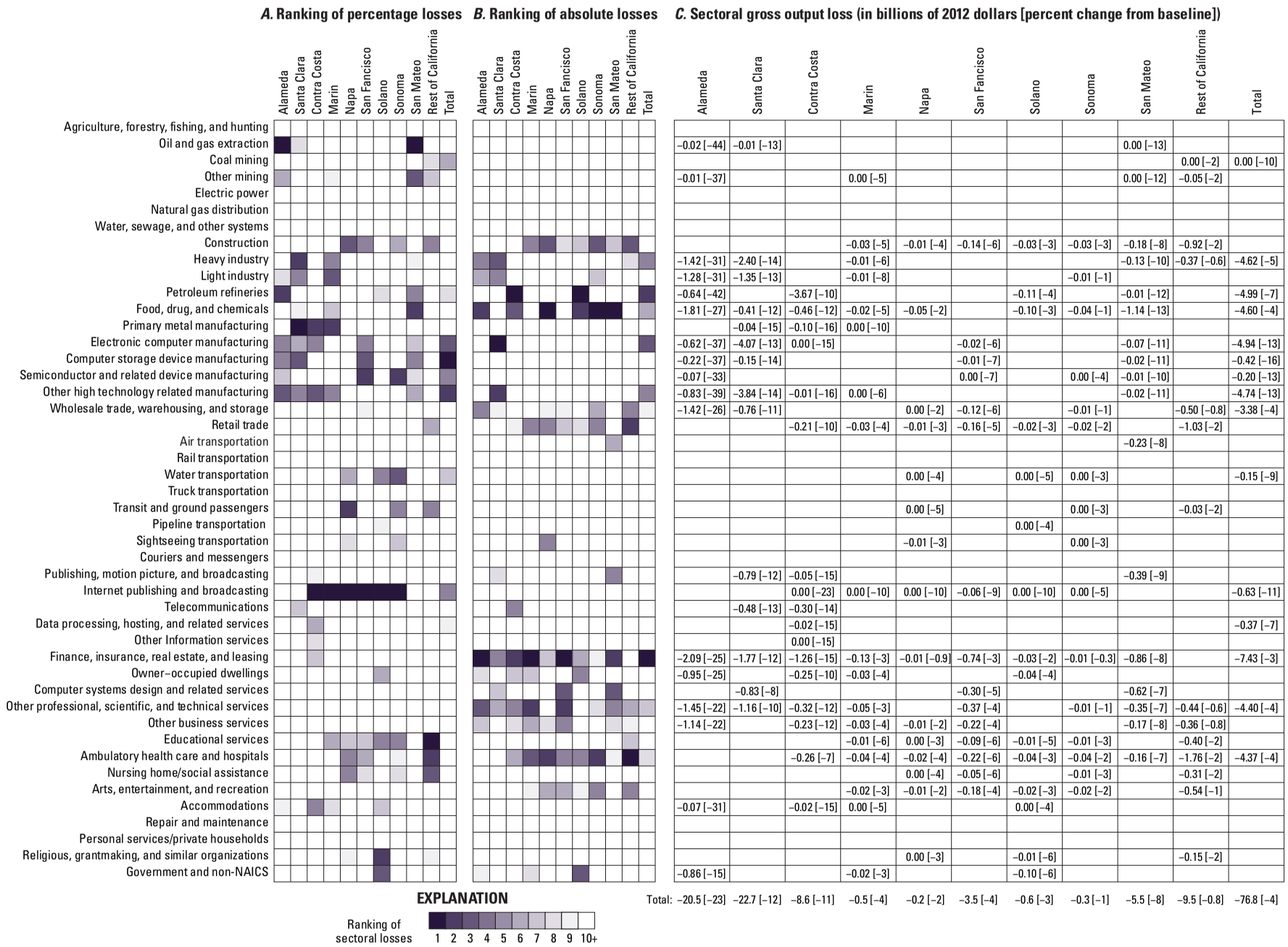


Figure 2. Top ten sectoral total gross output losses in San Francisco Bay region counties and the rest of California. NAICS, North American Industry Classification System (U.S. Census Bureau, 2017).

of producing sectors are used as intermediate inputs to production by other sectors, a crucial secondary effect of the initial damage is to reduce the quantity of intermediate inputs to producing sectors. The result is further reductions in sectoral output beyond those attributable solely to shrinkage in the economy's endowment of capital.

This multiplier effect is moderated by the inherent resilience of the economic system, in the form of substitution along two margins. The first is the producers' ability to substitute mobile factors (in our simulations, labor) for damaged capital and curtailed intermediate commodity inputs. The second margin is producer and consumer substitution of commodities imported from other counties, States, or world regions for domestically produced goods. But movement along the second margin is balanced by the income effects of earthquake damage on final consumers—by shrinking the endowment of, and the value of returns to, capital, the disaster reduces households' real income at the same time as their purchasing power is eroded by spiking goods prices, dampening their ability to increase imports. When the CGE model is simulated with all components of damage, the latter dampening effect outweighs the former propagating effect, resulting in a decrease in aggregate consumption and imports of commodities statewide (see fig. 4).

Within California, the concomitant reduction in the demand for commodity exports from unaffected counties induces a decrease in goods prices, domestic supply, and the returns to non-reproducible factors of production (labor and capital). It is for this reason that sectoral output and GRP decrease in both less affected bay region counties and unaffected counties in the remainder of the State. Even though the latter effect is very slight in intensity (percentage) terms, it is spread over a large swath of economic activity, and thus generates a more substantial aggregate impact.

Differences between parts *A* and *B* of figure 2 suggests that although internet publishing experiences some of the most acute gross output losses in percentage terms, that industry's comparatively small size relative to other industries means that its losses in absolute terms are dwarfed by those of less severely impacted, but economically much larger, sectors. Even so, out of all industries, the absolute losses sustained by the telecommunications and internet publishing sectors are ranked 14th and 15th in San Francisco County and 11th and 12th in Santa Clara County, respectively, and the telecommunications sector suffers the 5th largest output decrease of any sector in Contra Costa County.

Figure 3 suggests that capital stock damage owing to the mainshock and aftershocks is strongly predictive of the decrease in gross output experienced by telecommunications, data processing, other information services, and, for large losses, internet publishing.[18] The last of these sectors highlights the role of trade in the propagation of business interruption across the regional economy in counties such as Marin, Solano and Santa Cruz, that are geographically contiguous to the main disaster zone and export more than 80 percent of their internet publishing output. Internet publishing in these counties suffers slight damage (<5 percent of capital input), but experiences decreases in gross output that are two to three times as large. Because our CGE model's Armington (1969) structure does not explicitly model county-to-county bilateral trade in commodities and services, these decreases cannot be directly traced to the decrease in aggregate absorption by the bay region counties directly affected by the earthquake.[19] Notwithstanding this, figure 4 demonstrates that our simulations nonetheless capture the reduction in aggregate consumption of domestic and imported goods (fig. 4*A*) and aggregate intra-state exports (fig. 4*B*), which are the key drivers for this phenomenon.

[18]General equilibrium effects are the primary reason that some sectors' outputs do not decrease in lock-step with the direct damage to their capital stocks. For example, internet publishing not only suffers direct damage (on the x-axis) but also faces smaller supplies of data processing and telecommunications inputs, whose prices increase significantly.

[19] In the model, commodity exports from individual counties augment a statewide pool, from which individual counties' imports are then drawn. See appendix 3 for algebraic details.

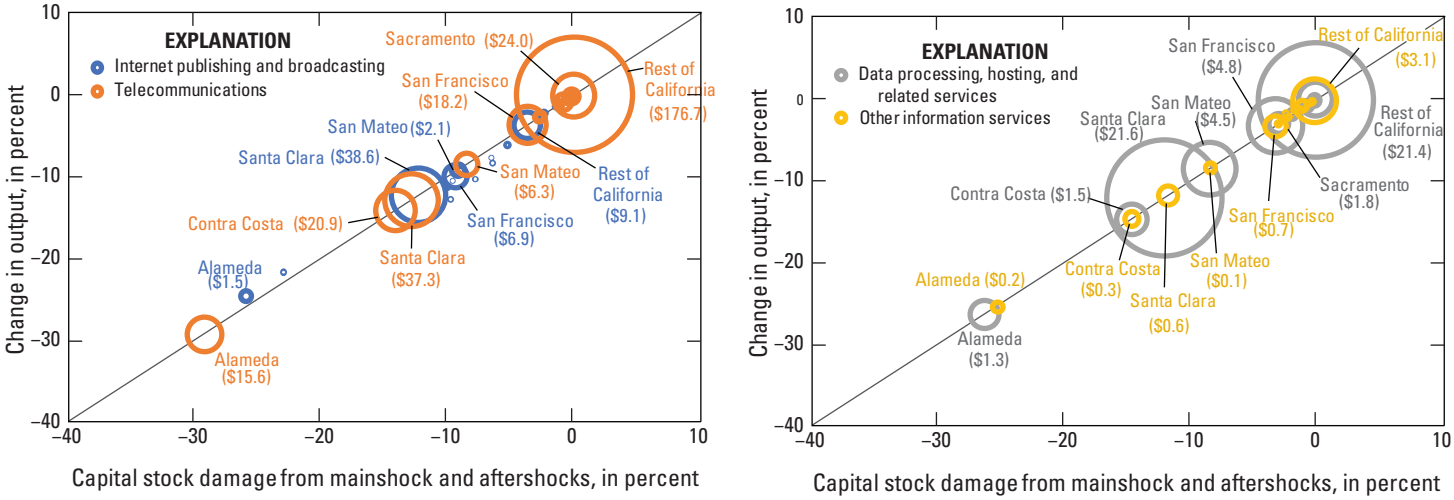


Figure 3. Damage and output impacts on information and communications technology service sectors.

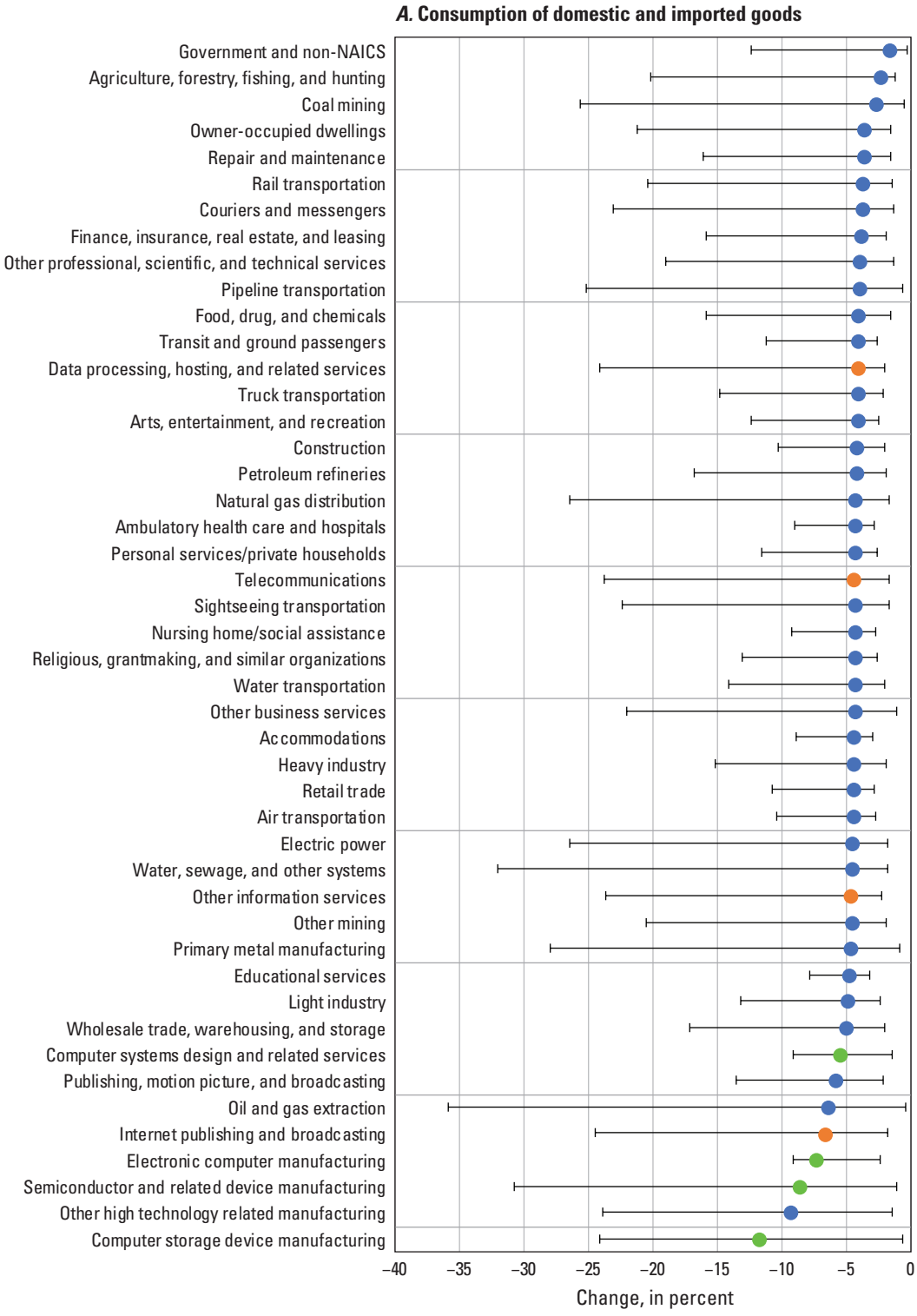


Figure 4 (pages 402–403). Statewide effects on goods and services trade and consumption, by commodity. In part *A*, error-bars show range across model regions of percentage changes in Armington aggregate use. Information and communications technology (ICT) and other information sectors in orange, ICT-supporting hi-tech service and durable goods sectors in green, all other sectors in blue. NAICS, North American Industry Classification System (U.S. Census Bureau, 2017).

***B.* Aggregate intrastate exports**

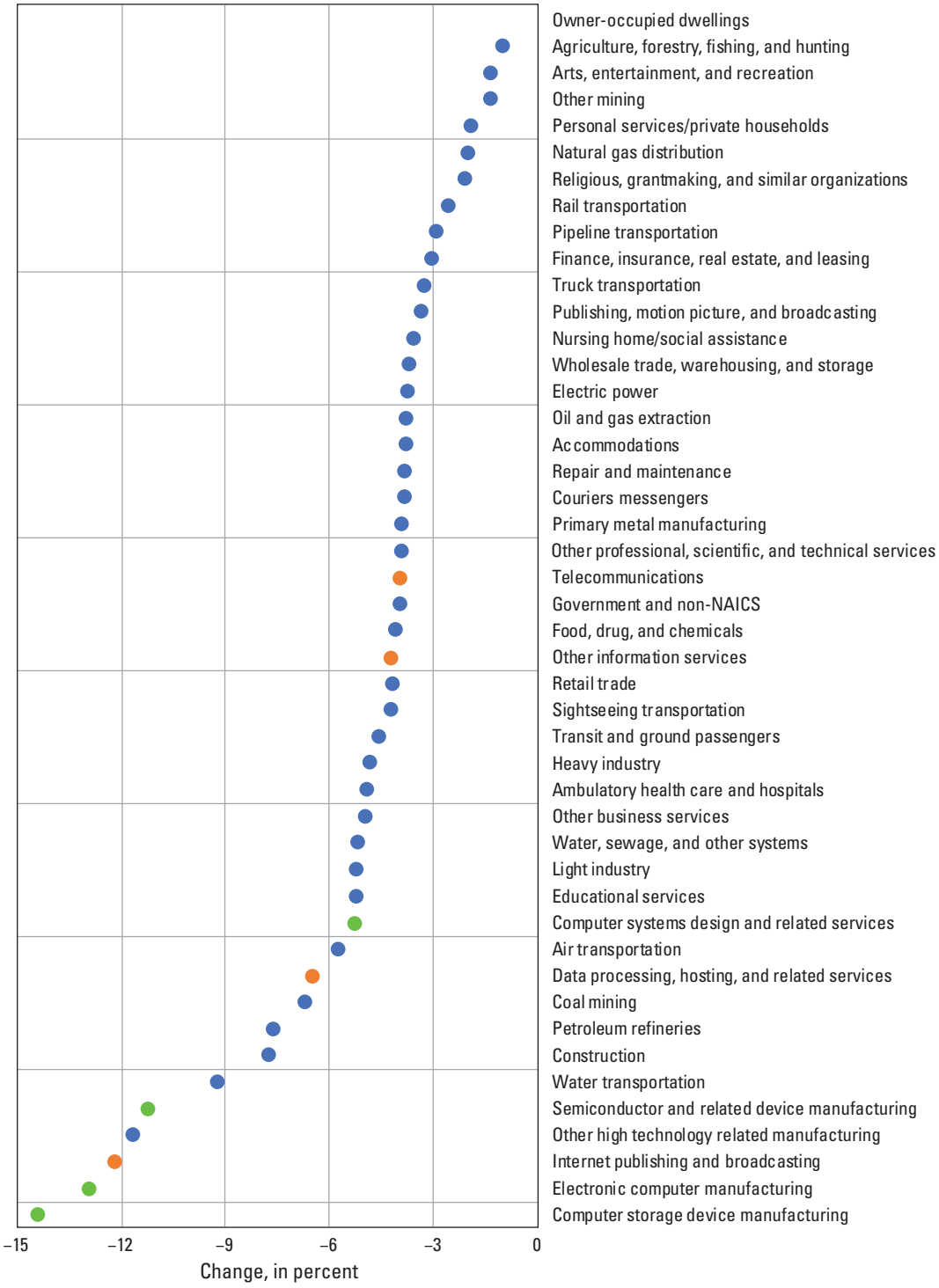


Figure 4 (pages 402–403).—Continued

Total Economic Impacts with Resilience Tactics

In this section, we discuss the total economic effects of various resilience tactics for different loss categories (property damages, water- and power-service disruptions). Next, the aggregate effects after combining all the resilience adjustments are discussed.

Economic Impacts from Property Damage with Resilience Tactics

BI losses from property damage are reduced by telework and production recapture (discussed in subsection on Resilience Adjustments). Table 15 shows GRP losses caused by property damage for the base case and adjusting for telework, production recapture, and combined resilience tactics. Property damages without and with fire are considered. Table 16 shows the potential for these resilience tactics to reduce BI losses stemming from property damage. Loss-reduction potential is calculated by dividing the avoided losses by the total losses for the base case. The results indicate that production recapture has a much higher loss-reduction potential than telework.

Table 16. Gross State product (GSP) loss-reduction potential of individual resilience tactics for property damage for California.

[Combined resilience is telework and production recapture. The combined reduction of GSP losses is not equal to sum of both entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by property damage, in percent
Mainshock (without fire) and aftershocks	
Telework	6.4
Production recapture	38.0
Combined resilience	44.7
Mainshock (with fire) and aftershocks	
Telework	6.3
Production recapture	36.9
Combined resilience	40.9

Table 15. Gross regional product (GRP) change caused by property damage in the first 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP shown in parentheses. Combined resilience is telework and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Mainshock (without fire) and aftershocks								
Base case	−10.0	−3.2	−2.3	−3.4	−11.6	−1.7	−5.5	**−37.6**
	(−18.5)	(−5.7)	(−3.7)	(−7.6)	(−10.0)	(−1.0)	(−0.9)	**(−3.5)**
Telework	−9.4	−2.9	−2.0	−3.1	−11.0	−1.6	−5.2	**−35.2**
	(−17.4)	(−5.4)	(−3.3)	(−6.9)	(−9.5)	(−1.0)	(−0.8)	**(−3.3)**
Production recapture	−6.5	−2.0	−1.4	−2.0	−6.7	−1.1	−3.6	**−23.3**
	(−12.1)	(−3.7)	(−2.2)	(−4.6)	(−5.7)	(−0.7)	(−0.6)	**(−2.2)**
Combined resilience	−6.2	−1.9	−1.2	−1.8	−6.3	−1.0	−2.4	**−20.8**
	(−11.4)	(−3.5)	(−2.0)	(−4.2)	(−5.4)	(−0.6)	(−0.4)	**(−2.0)**
Mainshock (with fire) and aftershocks								
Base case	−11.8	−3.5	−2.4	−3.6	−12.9	−2.1	−6.2	**−42.5**
	(−21.8)	(−6.4)	(−3.9)	(−8.1)	(−11.1)	(−1.3)	(−1.0)	**(−4.0)**
Telework	−11.1	−3.3	−2.1	−3.3	−12.2	−1.9	−5.9	**−39.8**
	(−20.5)	(−6.0)	(−3.5)	(−7.4)	(−10.5)	(−1.2)	(−0.9)	**(−3.7)**
Production recapture	−7.8	−2.3	−1.5	−2.2	−7.6	−1.3	−4.1	**−26.8**
	(−14.5)	(−4.2)	(−2.4)	(−5.0)	(−6.5)	(−0.8)	(−0.7)	**(−2.5)**
Combined resilience	−7.4	−2.1	−1.3	−2.0	−7.2	−1.2	−3.9	**−25.1**
	(−13.6)	(−3.9)	(−2.1)	(−4.5)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**

Economic Impacts of Water-Service Disruptions with Resilience

Table 17 shows GRP losses by region caused by water-service disruptions for both the base case and adjusting for various resilience tactics. The first three rows show the base case (no resilience tactics) for the three water-service-disruption scenarios: preplan (as-is conditions), postplan (fuel management plan), and ideal world (fuel management plan and pre-event mitigation). The next four rows show the results for the conservation, production isolation, production recapture, and combined resilience tactics (combining all three resilience tactics) for the preplan scenario, respectively. The last two rows show the results for the combined resilience tactics for the postplan and ideal-world scenarios.

Table 18 shows a summary of the loss-reduction potentials of each individual water resilience tactic for the preplan water-service-disruption scenario. The most effective resilience tactic is production isolation. The combined effect of all resilience tactics considered reduces the water-service disruption GSP losses for California by 91 percent, 86 percent, and 78 percent for the preplan (base case), postplan, and ideal-world water-service-disruption scenarios, respectively.

Table 18. Gross State product (GSP) loss-reduction potential of individual resilience tactics for water-service disruption for the preplan water disruption scenario for California.

[Combined resilience is conservation, production isolation, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by water disruption, in percent
Conservation	7.4
Production isolation	86.1
Production recapture	34.4
Combined resilience	91.0

Table 17. Gross regional product (GRP) change caused by water-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is production isolation and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case—preplan	−0.654	−0.022	−0.002	−0.030	−0.023	−0.052	−0.127	**−0.911**
	(−1.211)	(−0.071)	(−0.005)	(−0.075)	(−0.023)	(−0.037)	(−0.022)	**(−0.090)**
Base case—postplan	−0.309	−0.017	0.000	−0.022	−0.023	-0.037	−0.075	**−0.508**
	(−0.566)	(−0.052)	(0.000)	(−0.052)	(−0.019)	(−0.022)	(−0.015)	**(−0.045)**
Base case—ideal-world scenario	−0.053	−0.007	0.000	−0.015	−0.009	−0.015	−0.030	**−0.149**
	(−0.097)	(−0.019)	(0.000)	(-0.037)	(−0.009)	(−0.007)	(−0.007)	**(−0.015)**
Preplan and conservation	−0.592	−0.020	−0.002	−0.030	−0.023	−0.052	−0.119	**−0.844**
	(−1.087)	(−0.067)	(−0.005)	(−0.075)	(−0.019)	(−0.030)	(−0.015)	**(−0.082)**
Preplan and production isolation	−0.053	−0.005	0.000	−0.007	−0.009	−0.015	−0.022	**−0.127**
	(−0.088)	(−0.019)	(0.000)	(−0.022)	(−0.009)	(−0.007)	(−0.007)	**(−0.015)**
Preplan and production recapture	−0.433	-0.013	−0.002	−0.022	−0.019	−0.037	−0.082	**−0.597**
	(−0.795)	(−0.046)	(−0.004)	(−0.045)	(−0.014)	(−0.022)	(−0.015)	**(−0.060)**
Combined resilience—preplan	−0.035	−0.003	0.000	−0.007	−0.005	−0.007	−0.015	**−0.082**
	(−0.062)	(−0.012)	(0.000)	(−0.015)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Combined resilience—postplan	−0.027	−0.002	−0.001	0.000	−0.005	−0.015	−0.015	**-0.067**
	(−0.053)	(−0.007)	(−0.001)	(0.000)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Combined resilience—ideal-world	−0.009	−0.002	0.000	0.000	−0.005	0.000	−0.007	**−0.030**
	(−0.018)	(−0.005)	(0.000)	(-0.007)	(−0.005)	(0.000)	(0.000)	**(0.000)**

Economic Impacts of Power Disruptions with Resilience

Table 19 shows GRP losses by region caused by power-service disruptions for both the base case and adjusting for various resilience tactics. The resilience tactics analyzed include conservation, production isolation, and production recapture. The combined effects (after eliminating double counting) of these three resilience tactics are shown in the last row of table 19. The GSP losses in California stemming from power-service disruptions can be reduced from $100 to $50 million after adjusting for these three resilience tactics. Table 20 shows a summary of the loss-reduction potentials of each individual resilience tactic. Production recapture is the most effective resilience tactic for power-service disruption, and alone could reduce GSP losses in California by nearly 40 percent.

Economic Impacts of Data- and Voice-Service Disruption with Resilience

Table 21 shows GRP losses caused by data- and voice-service disruption for both the base case and adjusting for various resilience tactics. Table 22 shows a summary of the loss-reduction potentials of each individual ICT service-related resilience tactic. The loss-reduction potentials are calculated by dividing the avoided losses from each individual resilience tactic by the total losses calculated in the base case (without resilience tactics) for data- and voice-service disruption (see Rose, 2017).

Table 20. Gross State product (GSP) loss-reduction potential of individual resilience tactics for power-service disruption for California.

[Combined resilience is conservation, production isolation, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions.]

Resilience tactic	Potential reduction of base-case GSP losses caused by power disruption, in percent
Conservation	2.3
Production isolation	12.9
Production recapture	40.2
Combined resilience	49.2

Total Economic Impacts with Resilience

Table 23 shows the total economic impacts of the HayWired earthquake scenario after we consider all the resilience tactics we discussed above for the various conduits of shock to the economy. The base-case total GRP change are first shown, followed by the GRP change for various conduits of shock to the economy, property damage, and various types of utility service disruptions, adjusting for the combined resilience tactic cases discussed in the previous sections. The total economic impacts with resilience are shown in the last row of table 23. Combining all the resilience tactics we considered in this study, GSP losses in California decrease from $44.2 billion to $25.3 billion, a reduction of about 43 percent of the total losses.

Table 19. Gross regional product (GRP) change caused by power-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is conservation, production isolation, and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	SanFrancisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars percent change)							
Base case	−0.023	−0.009	−0.014	−0.009	−0.037	−0.011	−0.029	**−0.132**
	(−0.042)	(−0.026)	(−0.023)	(−0.021)	(−0.033)	(−0.007)	(−0.005)	**(−0.012)**
Conservation	−0.023	−0.008	−0.013	−0.009	−0.037	−0.011	−0.029	**−0.129**
	(−0.041)	(−0.026)	(−0.021)	(−0.021)	(−0.031)	(−0.007)	(−0.005)	**(−0.012)**
Production isolation	−0.019	−0.008	−0.011	−0.008	−0.034	−0.009	−0.026	**−0.115**
	(−0.035)	(−0.024)	(−0.019)	(−0.018)	(−0.030)	(−0.005)	(−0.004)	**(−0.011)**
Production recapture	−0.014	−0.005	−0.009	−0.005	−0.022	−0.007	−0.018	**−0.079**
	(−0.025)	(−0.016)	(−0.014)	(−0.013)	(−0.019)	(−0.004)	(−0.003)	**(−0.008)**
Combined resilience	−0.011	−0.004	−0.007	−0.005	−0.019	−0.005	−0.016	**−0.067**
	(−0.020)	(−0.014)	(−0.011)	(−0.011)	(−0.016)	(−0.003)	(−0.003)	**(−0.007)**

Table 21. Gross regional product (GRP) change caused by data- and voice-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is supplier backup power and portable equipment, user behavior management, and customer input substitution, production isolation, telework, and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case	−0.064	−0.020	−0.047	−0.030	−0.090	−0.028	−0.075	**−0.354**
	(−0.119)	(−0.063)	(−0.076)	(−0.067)	(−0.078)	(−0.017)	(−0.012)	**(−0.033)**
Supplier backup power	−0.056	−0.017	−0.041	−0.025	−0.076	−0.025	−0.064	**−0.302**
	(−0.103)	(−0.053)	(−0.066)	(−0.056)	(−0.065)	(−0.015)	(−0.010)	**(−0.028)**
Portable equipment	−0.037	−0.009	−0.034	−0.019	−0.044	−0.021	−0.044	**−0.208**
	(−0.069)	(−0.030)	(−0.056)	(−0.042)	(−0.037)	(−0.013)	(−0.007)	**(−0.020)**
User behavior management	−0.059	−0.015	−0.041	−0.026	−0.071	−0.025	−0.064	**−0.302**
	(−0.108)	(−0.049)	(−0.067)	(−0.060)	(−0.061)	(−0.015)	(−0.010)	**(−0.028)**
Customer input substitution	−0.035	−0.010	−0.030	−0.017	−0.049	−0.018	−0.043	**−0.202**
	(−0.065)	(−0.033)	(−0.048)	(−0.039)	(−0.042)	(−0.011)	(−0.007)	**(−0.019)**
Production isolation	−0.026	−0.006	−0.024	−0.013	−0.033	−0.012	−0.031	**−0.145**
	(−0.048)	(−0.020)	(−0.039)	(−0.030)	(−0.029)	(−0.007)	(−0.005)	**(−0.014)**
Telework	−0.063	−0.019	−0.045	−0.028	−0.089	−0.027	−0.073	**−0.345**
	(−0.117)	(−0.061)	(−0.073)	(−0.064)	(−0.076)	(−0.017)	(−0.012)	**(−0.032)**
Production recapture	−0.038	−0.012	−0.027	−0.017	−0.052	−0.017	−0.046	**−0.209**
	(−0.070)	(−0.038)	(−0.044)	(−0.038)	(−0.045)	(−0.011)	(−0.007)	**(−0.020)**
Combined resilience	−0.005	−0.001	−0.006	−0.003	−0.005	−0.010	−0.007	**−0.037**
	(−0.010)	(−0.003)	(−0.009)	(−0.006)	(−0.005)	(−0.006)	(−0.001)	**(−0.003)**

Table 22. Gross State product (GSP) loss-reduction potential of individual resilience tactics for voice and data service-related disruptions for California.

[Combined resilience is supplier backup power and portable equipment, user behavior management, customer input substitution, production isolation, telework, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by data and voice disruption, in percent
Supplier permanent backup power	14.7
Supplier portable equipment	41.3
User behavior management	14.8
Customer input substitution	43.0
Production isolation	59.0
Telework	2.7
Production recapture	40.9
Combined resilience	89.6

To place our economic impact estimates in perspective, we compare them with recessions that have affected the United States and the State of California since the end of World War II. The formal definition of a recession is a decrease in GDP in two successive calendar quarters. Until the "Great Recession" of 2008–09, these recessions generally resulted in a decrease in U.S. GDP of about 2 percent in at least one of the calendar quarters. On the other hand, the Great Recession resulted in a drop in GDP of about 8.4 percent, in the fourth quarter of 2008 and 4.4 percent in the first quarter of 2009. The annual rates of decrease were 0.1 percent in 2008 and 2.5 percent in 2009 for the Nation. The San Francisco-Oakland-Hayward Metropolitan Statistical Area suffered GRP decreases of 4.9 percent in 2008 and 2.8 percent in 2009. Our estimates of total economic impacts after factoring in resilience (see table 23) indicate the largest GRP decrease of 13.8 percent in Alameda County, a decrease of 2 to 6 percent in the other five most affected bay region counties, a decrease of 0.8 percent in the rest of the bay region, and a decrease of 0.6 percent in the rest of California in 6 months. The predicted economic effects of the HayWired scenario earthquake would result in a type of recession but would not have a multiyear effect like the Great Depression of the 1930s.

Table 23. Total gross regional product (GRP) change in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. BI, business interruption]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case (no resilience)	−12.7	−3.6	−2.5	−3.6	−13.1	−2.1	−6.5	**−44.2**
	(−23.5)	(−11.4)	(−4.0)	(−8.4)	(−11.2)	(−1.3)	(−1.0)	**(−4.2)**
BI from property damage (with resilience)	−7.4	−2.1	−1.3	−2	−7.2	−1.2	−3.9	**−25.1**
	(−13.6)	(−3.9)	(−2.1)	(−4.5)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**
Water-service disruption (with resilience)	−0.035	−0.003	0.000	−0.007	−0.005	−0.007	−0.015	**−0.082**
	(−0.062)	(−0.012)	(0.000)	(−0.015)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Power-service disruption (with resilience)	−0.011	−0.004	−0.007	−0.005	−0.019	−0.005	−0.016	**−0.067**
	(−0.020)	(−0.014)	(−0.011)	(−0.011)	(−0.016)	(−0.003)	(−0.003)	**(−0.007)**
Data- and voice-service disruption (with resilience)	−0.005	−0.001	−0.006	−0.003	−0.005	−0.010	−0.007	**−0.037**
	(−0.010)	(−0.003)	(−0.009)	(−0.006)	(−0.005)	(−0.006)	(−0.001)	**(−0.003)**
Total effects (with resilience)	−7.45	−2.11	−1.31	−2.02	−7.23	−1.23	−3.94	**−25.29**
	(−13.8)	(−3.4)	(−2.1)	(−4.6)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**

Dynamic Economic Recovery

In this section, we seek to understand how the differences in capital stock destruction across California drive reconstruction and thereby affect growth. The CGE model is limited in its suitability to analyze the effect of the earthquake on the dynamic path of California's economies, principally because its static formulation is set up to capture short-run economic effects, as opposed to forward-looking investment decisions that drive recovery. To address this shortcoming we construct a multiregional intertemporal partial equilibrium simulation that does not delve into the sectoral and regional details that underlie many of the results in the section on Direct Economic Impacts in order to place into sharp relief the impacts on, and consequences of, accumulation of capital. We adopt a simplified modeling approach to circumvent the substantial analytical and computational challenges required for the specification and solution of a multisector, multiregion, intertemporal model in which interregional productivity differences can be arbitraged by trade flows. The outcome is a multiregional model of the California economy that simulates aggregate investment, capital accumulation, production, consumption, and commodity trade in eight regional economies within the State over the 17-year (2018–2035) horizon on a semi-annual time-step. (A detailed description of the model is given in appendix 8.)

The main results, shown in figure 5, indicate that, with intertemporally optimizing economic agents, perfect markets, and an absence of frictions, California's economy will substantially recover over a period as short as a decade. Figure 5*A* shows that damage from shaking and fire reduce the size of the initial aggregate capital stock by nearly 30 percent in Alameda County, 14 percent in Santa Clara and Contra Costa Counties, and 10 percent in San Mateo County, whereas the remaining bay region counties sustain damage to their capital stocks of less than 5 percent. Interestingly, in the 6-month period immediately following this economic shock, capital stocks in the largely unaffected remainder of the bay region and the State also decrease relative to the baseline (business as usual). The reason is reallocation of investment toward the most severely damaged counties, shown in figure 5*B*. Statewide, the earthquake reduces initial capital by 4 percent. This in turn induces an increase in investment that initially covers the capital loss and then reverts slowly to the long-run baseline level over the course of the simulation horizon. This behavior arises from the fact that the quantity of investment is smaller than the capital stock, so that damage to the latter can only be offset by a sustained increase in the rate of accumulation of the former. Relative to baseline levels of investment, increases of 160 percent in Alameda County and 80 percent in Santa Clara and Contra Costa Counties drive rapid accumulation of capital, with stocks approaching 95 percent of their baseline levels less than 5 years after the earthquake, and 99 percent a decade postearthquake in these three counties. In the less-affected and unscathed areas of the State, investment and capital stocks—which are larger in magnitude—recover more slowly, attaining 98 percent and 99 percent of their baseline levels after 5 years and a decade, respectively.

In response to the departure of regional capital stocks from their baseline trajectories, gross output, value added, intermediate commodity uses, and final consumption all exhibit qualitatively similar dynamics (fig. 5*C*–*F*). The regions' initial declines and subsequent patterns of recovery mirror those of their respective capital stocks in figure 5*A*. This congruence is unsurprising given the small values of the elasticities of substitution, which limits the ability of regional

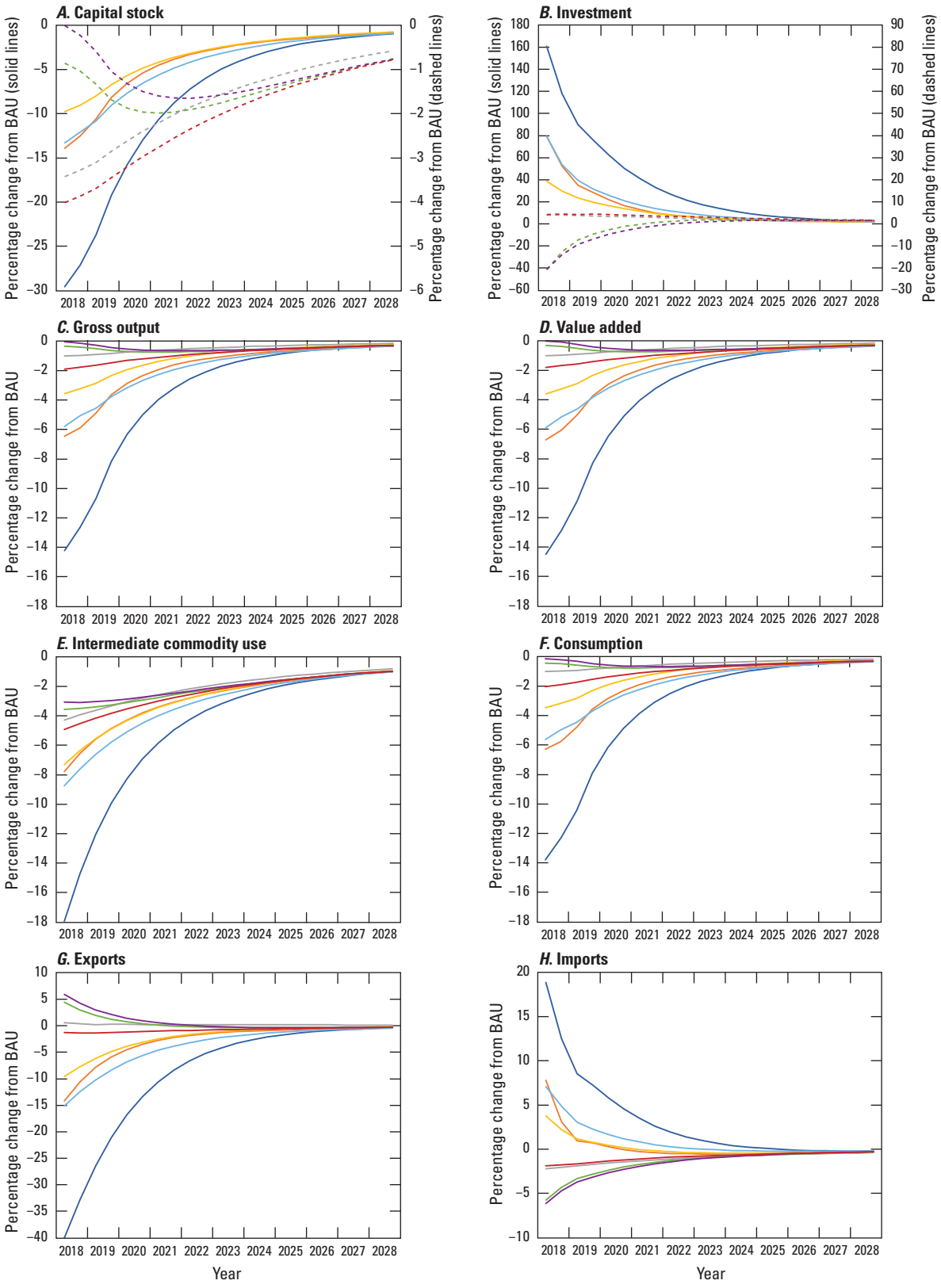


Figure 5. Plots showing percentage change from business as usual by semi-annual time steps following the HayWired mainshock for several economic factors, illustrating the dynamics of postearthquake recovery. BAU, business as usual.

producers to compensate for the impact of capital damage on production by increasing the quantity of intermediate commodity inputs. The consequent near-complementarity between capital and intermediate goods means that inputs of the latter decrease, albeit by a smaller amount than the shock to capital. The upshot is that the economy experiences a slightly larger reduction in value added than gross output, and both quantities decrease by a much smaller amount than capital. California's aggregate gross output and value added experience decrease by about 2 percent initially, after which they slowly increase to their long-run levels over the simulation horizon. The decrease in consumption is even smaller, as households attempt to preserve their level of utility, consistent with the model's objective function to maximize social welfare.[20] The magnitude of value-added losses is one-half to two-thirds as large as those computed by the CGE model. This result can be traced to the growth model's homogeneous representation of regional production, which implicitly assumes perfect substitutability among the outputs of, and the intermediate inputs to, different sectors, whereas the CGE model assumes far less elastic substitution among intermediate inputs to each sector, and among the contributions of the various sectors to regional consumption, investment, and exports.

Especially in the most affected counties, the need to allocate larger quantities of final goods to increased investment causes precipitous decreases in exports, coupled with increases in imports (fig. 5*G* and *H*). The result is a reorganization of commodity trade and a shift in counties' trade balances. Along the baseline dynamic trajectory, San Francisco County is a net exporter, Alameda County and the rest of the bay region are net importers, Contra Costa and San Mateo Counties and the rest of California are initially net importers that subsequently transition to net exporters, and Santa Clara County is initially a net exporter that becomes a net importer. Overall, the shock induces severely impacted counties to increase imports, accentuating baseline patterns of trade—in the counterfactual solution to the model, Alameda, Contra Costa, Santa Clara, and San Mateo Counties all remain net importers throughout the simulation horizon, and increase their consumption of goods and services exported by San Francisco County, other bay region counties, and the remainder of the State.

The results have several important implications for the interregional nature of recovery from a major shock such as the HayWired earthquake scenario. They indicate that, as in the case of the direct and indirect consequences themselves, the pattern of recovery reveals further departures from simple direct assessments of investment in repair and reconstruction, after considering various types of dynamic interregional general equilibrium effects. Those counties implementing the higher levels of repair and reconstruction investment benefit the most, but these effects spill over onto neighboring counties as well. The spillover effect is greater than in ordinary circumstances because the less-affected counties have greater productive capacity relative to directly affected counties than in the base case, and they are relied upon as the sources of supplies of direct and indirect inputs into recovery. Thus, the lightly damaged counties gain from picking up the slack of lost capacity in the core of the damaged region and also provide valuable inputs to all affected counties during the recovery process.

[20]Counties in figure 5 experience sizeable negative shocks to both their capital stocks and domestic output. The representative agent within each county reallocates the disposition of this smaller quantity of output preferentially to investment, as a way of quickly rebuilding lost capital, while simultaneously cutting back on other components of domestic expenditure (as consumption, exports, and intermediate commodity uses) and increasing imports. Rather than being allocated to producers, the larger quantity of imports is consumed. This, combined with reduced exports of domestic product, serves to sustain the level of consumption.

Study Limitations

There are limitations to both the CGE analysis of economic consequences during the first 6 months and the simple dynamic recovery model over 17 years.

CGE Model Limitations

In the CGE model analysis we have excluded sources of disruption such as transportation. We do not consider the effects from damages to roads, bridges, or railroads, although we expect that the delays to goods and people movement during repairs and reconstruction will be costly. The Regional Economic Models, Inc. (REMI) model analysis conducted by Kroll and others (this volume) estimates that close to half of the region's output losses come from transportation network and commuting disruptions, rather than directly from building damage.

Several key assumptions about resilience tactics are based on the best data we could obtain at the time of this work. For example, the percentage production isolation factors in the voice- and data-service resilience analysis are calculated by scaling down the telephone production isolation factors in order to factor in the large use of internet (not just telephone) by sector. The telework potentials by sector and by county are calculated based on the BLS (2017) data on telework potential by job type, and factoring the considerations of readiness of employees to go back to work after the major disaster, internet access, and the availability of backup data. Future studies can benefit from better sectoral and region-specific data on these resilience tactic assumptions.

Another limitation of the CGE model analysis of economic impact and resilience is the assumption that businesses aim to return to business-as-usual conditions. In practice, businesses will reposition or redefine themselves and find new efficiencies, as was reported after the Christchurch earthquakes (Chang and others, 2014; Stevenson and others, 2014; Brown and others, 2015). The recovery of an economy affected by a major disaster is inherently a transitory disequilibrium phenomenon that is influenced by a multitude of non-economic forces. However, the non-economic factors often tend to be subject to large uncertainties, making them very challenging to characterize and to model in a tractable way. Our analytical approach sidesteps some of these difficulties by taking as given many of the details of the recovery trajectory, in order

to focus squarely on the equilibrium to which the economy converges during the (Keynesian) "short-period." over which prices are determined and bring supply and demand into balance. The benefit of such analytical clarity can only be obtained at the expense of realism and detail, not the least of which are potential differences in the behavioral responses of economic factors to the main earthquake as opposed to decreasingly punctuated and less intense aftershocks. The 6-month horizon selected for our analysis thus represents a compromise between capturing the effects of most aftershocks and having the increasingly long intervening periods of normal economic functioning dampen their apparent effects. More detailed elaboration of the effects of these and other fine temporal-scale forces can be accomplished using modeling approaches other than CGE, but these are beyond the scope of our study.

We have also not explored dynamic economic resilience that would accelerate the pace of recovery (to jumpstart and [or] reduce the duration of recovery) in relation to a standard recovery path. Accelerating the recovery path is based on numerous decisions by government officials, businesses, and households for which we did not have data, and hence were not able to provide any reasonable estimates. For an analysis of longer term impacts of the HayWired scenario the gold standard is an intertemporal CGE model that simulates the dynamic impacts of the foregoing decisions on postdisaster regional economic growth. Given the dearth of relevant input data, our contingency was a highly stylized partial equilibrium intertemporal simulation discussed in the section on Dynamic Economic Recovery and appendix 8. The reader is also referred to the regional economic modeling in the accompanying report by Kroll and others (this volume).[21] For CGE modeling of dynamic resilience, the reader is referred to papers such as Xie and others (2018).

We offer the following additional caveats about population effects. First, we emphasize that it would be wrong to think of substitution of labor for destroyed capital as resulting from an increase in the labor supply. On the contrary, depending on the scenario being simulated, labor endowments in all counties, and statewide, decrease by 2–7 percent in 6 months.[22] Crucially, however, in the most severely affected counties earthquake damage reduces the amount of capital by a larger amount. The result is a relative increase in labor intensity that reflects substitution, whereby the resulting smaller pool of labor moves among producing sectors, and is used in place of lost capital to different degrees, until the equilibrium condition of the marginal productivity of labor being equalized across production activities is satisfied. Such reallocation of labor to its highest marginal-value use is a key mechanism of inherent resilience (Rose and Liao, 2005; Rose, 2017).

Given this, the main limitation of our analysis is insufficient detail in modeling the earthquake's effects on the supply side of the labor market. Destruction of capital in the private dwellings, real estate, and accommodation sectors is likely to render a nontrivial fraction of the bay region housing stock uninhabitable, and in turn trigger large-scale short-term displacement of local populations. A key question that we leave unanswered is the degree to which initial population displacement persists over the long term, which is a particular concern given the preexisting shortage of housing in the region. To address this issue it is necessary to undertake additional dedicated modeling of the microeconomic forces that determine, initially, the likely geographic dispersal of evacuees based on intercounty differences in postdisaster housing market conditions, and, subsequently, population return based on the pace of State and Federal provision of temporary housing, and local governments' proclivity to intervene in housing markets to enable alternative shelter arrangements.

The experience of New Orleans, Louisiana's, labor supply in the aftermath of Hurricane Katrina points to the importance of such modeling. Figure 6*A* illustrates that the key unknown is whether evacuees return. Although half of the housing units in Orleans Parish were destroyed, displaced populations were able to secure temporary or permanent shelter in neighboring, less-affected counties and States relatively quickly. A Gompertz recovery curve fit to FEMA data (Department of Homeland Security Office of Inspector General, 2008) suggests that the number of households in hotels and motels decreased to half its peak after 4.5 months, and after 6 months would have fallen to the initial level of prestorm evacuation.[23] But many of the workers in these households did not return, causing the New Orleans metro area to lose 23 percent of its labor supply—a shock from which New Orleans has not yet fully recovered after more than a decade.

Even so, several features of the HayWired scenario raise the possibility that the pattern of recovery might be very different in the bay region. The first is simply the character of the hazard: in the HayWired scenario, affected areas do not experience the prolonged inundation that was responsible for further capital stock destruction as well as delaying the return of displaced households by more than 1.5 months. Second, the magnitude of capital stock losses is less severe; figure 6*B* shows that building damage owing to the mainshock, fires following the mainshock, and aftershocks amounts to 20 percent of the capital stock in the accommodation sector, 17 percent of the capital stock in the private dwellings sector in Alameda, and less than 11 percent in the accommodation sector and 6 percent in the private dwellings sector for the next three most impacted counties. The result is that there

[21]Kroll and others (this volume) indicate that the majority of economic losses (including output losses caused by building damages, transportation network and commuting flow disruptions, and amenity loss of the region) of the HayWired scenario will take place in the first year after the mainshock. If the stimulus effects of government response and recovery investment are taken into consideration, the net output effects in the bay region are projected to turn positive starting from year 2 (assuming 3/4 of the government aid is exogenous Federal spending, and thus is additive to the regional economy).

[22]We emphasize that the CGE model neither represents nor measures labor in terms of employment (that is, jobs or workers), but rather the aggregate quantity of hours supplied by all households.

[23]The function is *Displacement Population* $(t) = ae^{-b(t-t_0)}e^{-ce^{-b(t-t_0)}}(1+c(1-e^{-b(t-t_0)}))$, in which t is time, t_0=8/25/2005 is the date of Katrina landfall, a = 120,000, b = 0.175 and c = 2.3 are parameters selected to match estimates of displaced individuals taken from Department of Homeland Security Office of Inspector General (2008).

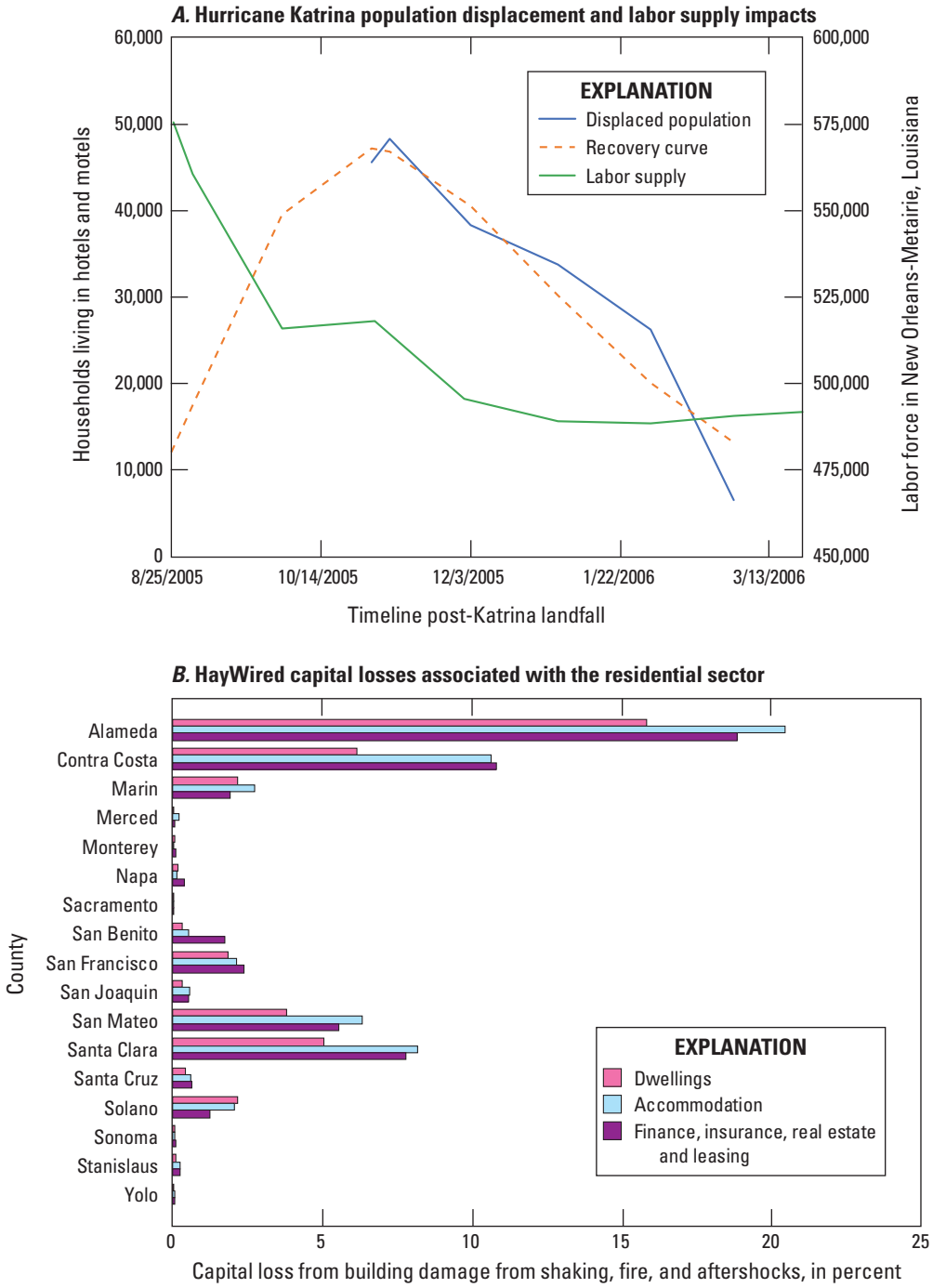


Figure 6. Charts showing postdisaster evacuation and return, illustrating implications for bay region labor supply. *A*, Plot showing Federal Emergency Management Agency estimates (Department of Homeland Security Office of Inspector General, 2008), and our own simulation, of the number of households displaced by Hurricane Katrina across the Gulf Coast and living in hotels and motels and evolution of the labor force in the New Orleans-Metaire, Louisiana, area over time following Hurricane Katrina's landfall. *B*, Percentage of capital loss by housing-related sector owing to building damage from the HayWired mainshock, fire following the mainshock, and aftershocks, in the San Francisco Bay region counties, California.

will likely be a much higher percentage of structures that are sufficiently undamaged compared to the case in New Orleans in the aftermath of Hurricane Katrina, and that they can provide temporary housing, further hastening individuals' ability to return and resume work over a 6-month horizon.[24] Third, the restoration of telecommunications within a few weeks, and the concomitant facilitation of telework, suggests the need to carefully distinguish between population return and recovery of the labor supply, especially in information sectors. Finally, the dynamics of population return may be much more consequential for "brick and mortar" industries that rely on low-wage occupations and require workers to be physically present to supply labor (for example, service sectors such as wholesale, retail, accommodation, repair, health, and education). However, under prevailing baseline economic conditions there is concern that workers in these occupations are being priced out of bay region housing markets and reside increasingly far away from the region's major employment centers. The crucial question is whether existing drivers of households' geographic dispersal already push such workers out of the zone of maximum earthquake damage. If this is indeed the case, the magnitude of worker displacement is likely to be much smaller, and the reduction in labor supply will primarily be a function of the extent of commuting disruption and the pace of restoration of transport links.

Johnson and others (this volume) examine population displacement. For the purposes of this report, and in the face of the substantial uncertainties we opt to generate loss estimates using the standard Keynsian labor market closure rule of a fixed wage and flexible labor supply. Elaboration of additional supply-side dynamics and their potential implications for labor-market equilibrium over the recovery period is beyond the scope of this report and is left to future research.

Simple Dynamic Recovery Model Limitations

Our stylized analysis of dynamic recovery is subject to several caveats. The dynamic model is notable for its lack of frictions, particularly capital adjustment costs that have the potential to introduce divergence between the resources allocated to investment and the consequent formation of new capital. In severely affected counties, such as Alameda, the massive rebuilding efforts across a broad range of sectors would require substantial coordination and involve temporary inefficiencies in investment. The extent to which this might increase the contemporaneous costs of investment is an open question and beyond the scope of this study. Future analysis of this issue would have to determine the extent to which investment in repair and reconstruction would displace investment in ordinary plant and equipment, and it would also determine how much of an injection there would be externally from government assistance, philanthropy, and insurance payments (see Xie and others, 2018). This would also require consideration of factors such as "demand surge." which refers to the likely increase in the cost of construction activity and materials in the aftermath of a disaster (see Olsen and Porter, 2011; Kroll and others, this volume).[25]

As with the CGE impact analysis, a key influence on the dynamics of recovery that remains unmodeled is population displacement and return, and their impacts on regional production, consumption, and capital accumulation in the 1–3 year postdisaster period. Workers emigrating from the most affected counties would further reduce production, consumption, and utility there, but would increase all three variables in the rest of the bay region and other parts of California that would likely receive migrants. Fundamental empirical analysis of spatial and temporal patterns of population displacement and return was outside the scope of the project—we eschew such analysis as being too speculative at this time, and instead leave the definition of the consequent shocks to labor supply and the simulation of their impacts as topics for future research.

More realistic modeling of the recovery of California's regional economies would require differentiating production into multiple sectors, trade into multiple commodities, and investment into a vector of sector-specific investment goods that would be allocated to bring the marginal products of capital across different production activities into equilibrium. In addition to this there would likely be layered non-market policies that direct investment to specific sectors (for example, attempts by State and local governments to restore infrastructure or other public components of the capital stock), which would have additional effects on the relative rates of sectoral capital accumulation, and, ultimately, structural change. Such a model is at the forefront of economic modeling research and is unfortunately outside the scope of our analysis.

We offer some suggestions for future research that emanate from the discussion above. First is a county by county elaboration of the effects on long-run trajectories of economic growth. This would be most effective if it included

[24]However, at the same time, we do note two factors that may delay the process of population return in the HayWired scenario: (1) some of the areas that are severely damaged by fire are likely to be more difficult than flood inundated areas to get repaired and reconstructed; (2) there is a virtually zero vacancy rate for housing in the bay region. The already very high costs of housing will become even higher with the shortage of housing supply after the disaster, which may prohibit the immediate return of the evacuated population.

[25]The dynamic translation of capital investment in one sector at time t into units of new capital stock in another sector in the subsequent time period t+1 involves conceptual and empirical modeling difficulties. The Bureau of Economic Analysis (BEA) records data on capital flow according to industry demand (irregularly and at the national level, which, thus, may not reflect the particular structure of California's economy). Most consequentially, a key unknown is whether, in the aftermath of a disaster, the coefficients of such a matrix of sectoral shares of the mix of investment goods will remain constant, especially on the brief 6-month timestep necessary to capture the short-run consequences of an earthquake. In the initial chaotic postdisaster period, it is plausible that localized shortages, and (or) firm resilience tactics, such as bartering intermediate inputs or cooperating to share salvaged plants, equipment, or structures, might lead to localized deviations from the investment shares that would otherwise prevail under normal conditions. However, in the absence of well-founded representations of the microeconomic details of these processes, predicting the deviations in capital flow that might arise would be highly speculative.

the dynamics of county- and sector-level capital-labor substitution that accompany population return, reconstruction, and economic recovery over the long run of one or more decades postdisaster. However, the ability to address this question is complicated by the need to develop a model of short-run evacuation and long-run population repatriation (or decline), ideally endogenously linked to the employment demand shock triggered by firms' loss of productive capacity owing to capital stock destruction. Another area of future research would be to validate the IMPLAN capital stock data that we have used. For example, Cutler and others (2017) have used county assessor data that describes the use of each parcel of land, including data on the size of the parcel, value of the land, and value of the structure on the land (building value or other capital stock), and also distinguishes these data by sector.

Conclusion

In this study, we estimated total regional economic effects (in terms of gross regional product [GRP] losses caused by business interruption) of the HayWired scenario earthquake on the San Francisco Bay region economy. The study follows from the analysis of the physical damages of the earthquake, including property damage caused by mainshock shaking, liquefaction and landslides, fire following earthquake, and aftershocks. Business interruption losses flow from the direct property damage to producing sectors, and are also caused by disruption of water, power, and data and voice services. A multiregional computable general equilibrium model was used to analyze the total regional economic effects of the HayWired earthquake scenario. The basic simulations indicate how the economy is affected, including how it adjusts to damages and disruptions transmitted through price changes, which spur the reallocation of resource use, primarily through substitutions of inputs and geographical redistributions. The capability to undertake such substitutions is an important measure of the inherent resilience of the macroeconomy. The study also evaluates the potential effectiveness of various additional inherent and adaptive microeconomic resilience tactics that can greatly reduce the business interruption losses from the disaster.

The dominant cause of economic losses in the bay region and California is found to be business interruption (BI) from property damage. Without additional resilience tactics, total potential BI losses for California, measured in gross State product (GSP) reduction in the 6-month period after the HayWired mainshock, are estimated to be $44.2 billion (or 4.2 percent of the State's projected baseline GSP during the period). About $42.5 billion in GSP reduction is BI losses caused by property damage (among which $32 billion is caused by the mainshock [including fire] and $10.5 billion is caused by aftershocks). Overall, losses are concentrated in the five bay region counties that are most directly affected by earthquake property damage in absolute terms (Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco), which together account for 80 percent of the overall reduction in GSP. Alameda and Santa Clara Counties are the most affected counties, which suffer reductions in economic output of about $12.7 and $13.1 billion, or more than 23 percent and 11 percent, respectively, of the counties' baseline GRPs. Contra Costa County also suffers an 11 percent reduction in economic output, followed by an 8 percent reduction in San Mateo County and a 4 percent reduction in San Francisco County.

In terms of the sectoral distribution of the total effects, sectors with the largest reductions in gross output statewide include finance, insurance, real estate (FIRE) and owner-occupied dwellings, manufacturing (petroleum refining, light and heavy industry, food, drug, and chemical manufacturing), ambulatory healthcare and hospitals, and professional, scientific, and technical services. The greatest reductions in output are in high-tech device manufacturing and internet publishing and broadcasting. These sectors suffer relatively more intensive property damage (building and content losses) than other sectors, and thus experience greater reductions in the endowments of sector-specific capital.

Information and communications technology (ICT) sectors that are central to the digital economy include internet publishing and broadcasting; telecommunications; data processing, hosting, and related services; and other information services. Both telecommunications and internet publishing and broadcasting are their own top suppliers and customers. Telecommunications and data processing, hosting, and related services purchase from professional services and FIRE sectors. Industry, manufacturing, and mining sectors are top purchasers of the internet publishing and broadcasting sectors. GRP losses in the ICT sectors show a strong correspondence with capital stock (property) losses, although internet publishing and broadcasting show a consistent pattern of percentage of GRP losses exceeding capital losses in counties less directly impacted by the earthquake (San Mateo and San Francisco) and the rest of California. Internet publishing not only suffers direct economic damage but also suffers from smaller supplies of data-processing and telecommunications inputs, whose prices increase significantly.

Our results illustrate how interregional trade in goods and services performs the dual role of a mechanism for broader transmission of the economic consequences and a margin of economic adjustment to the disaster-related business interruption. Firms in directly affected counties can substitute intermediate inputs imported from undamaged counties for curtailed supplies of such inputs that might have been produced locally. This helps moderate the reduction in the former producers' outputs—production still decreases, but by a smaller fraction than would be predicted by the shock to the economy from capital stock destruction and curtailment of utility-service supplies. However, at the same time, counties that are geographically contiguous with the main disaster zone and export a large fraction of their output to firms and households that sustain direct damage incur losses that are far greater than their direct damage would predict. The latter arises because over the short period of our analysis, the disaster has the effect of causing a reduction in the demand

for their output. In this way, import and export markets throughout the bay region are responsible for the earthquake's direct effects rippling through the broader California economy.

Economic resilience tactics can potentially greatly reduce the total economic effect on the California economy. The GSP losses could be reduced from $43.5 billion to $25.2 billion (a reduction of 42 percent) if various microeconomic resilience tactics are taken into account. Based on assumptions about the effectiveness of resilience tactics over time, the tactic that has the greatest potential effect on reducing BI losses from property damages is production recapture in which businesses make up for their lost production through employees working overtime or extra shifts after their necessary facilities and equipment have been repaired or replaced and critical inputs become accessible. Production recapture is an effective resilience tactic in the short run (for example, within 3 months)—it is unlikely that most customers will cancel their orders within this timeframe. However, the effectiveness of production recapture decreases over time as customers grow impatient when their orders are not filled and, therefore, seek other suppliers. In this study, we found that, even in the counties that are most directly affected by the earthquake, a large percentage of damaged buildings in commercial and industrial sectors take less than 3 months to repair or recover. Therefore, production recapture has great potential in reducing BI losses stemming from property damage.

The most effective resilience tactic for utility-service disruptions differs across service types. For water-service disruption, production isolation (referring to those parts of a production process that can continue without using water inputs) emerged as the most effective tactic. For power-service disruption, production recapture has the greatest effect on reducing the BI losses. For data- and voice-service disruptions, production isolation is the single most effective tactic, followed by input substitution and production recapture, in accordance with our assumptions. The supplier implemented equipment strategies of back-up power (permanent batteries and generators) and portable equipment (for example, generator on a truck, cell on wheels), implemented in recent disasters, collectively reduce the percentage of BI losses from data and voice service disruption by 90 percent.

In summary, GRP losses are concentrated in the five bay region counties that are most directly affected by earthquake property damage in absolute terms (Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco), which together account for 80 percent of the overall reduction in GSP. Sectors with the greatest reductions in gross output statewide include real estate (finance, insurance, real estate, and owner-occupied dwellings), manufacturing (petroleum refining, light and heavy industry, food, drug, and chemical manufacturing), ambulatory healthcare and hospitals, and professional, scientific, and technical services. Microeconomic resilience tactics could potentially greatly reduce the total economic effect on the California economy. The GSP losses could be reduced from $44.2 billion to $25.3 billion (a reduction of 43 percent) if various resilience tactics are implemented. The tactic that has the greatest potential effect on reducing BI losses from property damages and power-service disruption is rescheduling production to catch up; the most effective resilience tactic for water-service disruption and data- and voice-service disruptions is production that can continue without these inputs.

A special focus in this HayWired scenario analysis was a study of the core of the digital economy made up of the telecommunications, data hosting and processing, internet publishing and broadcasting, and other services sectors. These sectors are subjected to infrastructure damage, power outages, and business interruption, which are aggravated by their dependence on each other. Their importance in recovery is illustrated by assumptions about telework in sectors that reduce economic impacts (most recently seen during the 2020 COVID-19 pandemic); telework reduces estimated GSP losses from property damage by a few billion dollars (6 percent of baseline GSP). Every resilience tactic, or business continuity practice, implemented by businesses, sector alliances, and governments—including utility and digital economy sectors—preserves economic activity for their organizations, as well as that of others, through sectoral and geographic economic linkages, after this potentially devastating scenario earthquake strikes.

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Appendixes 1–8

Appendix 1. Sectoring Scheme

This appendix summarizes how we determine the sectoring scheme used in the economic impact modeling of the USGS HayWired Scenario. We follow the seven steps below when we consider the sectoring scheme to be used:

1. Start with the 3-digit NAICS sectoring scheme, which divides the whole regional economy into 86 sectors.
2. Disaggregate the utility sector into water and sewage system, natural gas distribution, and electricity generation and distribution.
3. Based on the 440-sector IMPLAN (short for impact analysis for planning) data, identify the top five sectors in terms of gross output in the 9-county study region, and include them as separate sectors. We also examined the top five sectors in terms of gross output for the three most heavily affected counties (Alameda, Santa Clara, and Contra Costa). The data indicate that the top five sectors in terms of gross output are identical in the 9-county region and in the three most affected counties.
4. Retain two major telecommunication and internet-related sectors at the most disaggregated level in IMPLAN. These include (1) IMPLAN 350, internet publishing and broadcasting (NAICS 519130); (2) IMPLAN 351, telecommunications (NAICS 517); and (3) IMPLAN 352, data processing, hosting, and related services (NAICS 518).
5. Examine the IMPLAN input-output matrix and import matrix, identify major customer sectors of the telecommunication and internet-related sectors, and retain key sectors at the most disaggregated level in IMPLAN.
6. Examine the top upstream supplying sectors to electricity generation, computer manufacturing, and telecommunication and internet services, and retain key sectors at the most disaggregated level in IMPLAN.
7. Aggregate other sectors to arrive at a reasonable total number of sectors to be used in the CGE model. The aggregation of the sectors should also align with Hazus occupancy classes. A major aggregation pertains to the manufacturing sectors. Except for the key sectors we keep disaggregated as noted above, we combine the other manufacturing sectors in line with the Hazus occupancy classes for industrial sectors (IND 1 for heavy industries, IND 2 for light industries, IND 3 for food, drugs, chemicals, and so on)

The final sectoring scheme and its correspondence to IMPLAN sectors, NAICS codes, and Hazus occupancy classes are shown in table 1.1.

Table 1.1. Sectoring scheme for computable general equilibrium (CGE) modeling.

[IMPLAN, impact analysis for planning; NAICS, North American Industry Classification System. No., CGE sector number]

No.	Sector description	IMPLAN sector	NAICS code[1]	Hazus occupancy class
1	Agriculture, forestry, fishing, and hunting	1–19	11	AGR1
2	Oil and gas extraction	20	211	IND4
3	Coal mining	21	2121	IND4
4	Other mining	22–30	212-213 except for 2121	IND4
5	Electric power generation, transmission, and distribution	31, 428, 431	2211	COM4
6	Natural gas distribution	32	2212	COM4
7	Water, sewage, and other systems	33	2213	COM4
8	Construction	34–40	23	IND6
9	Heavy industry	75–81, 95–112, 153–169, 181–233, 276–294	313, 321, 322, 327, 332, 333, 336	IND1
10	Light industry	82–94, 113–114, 142–152, 236–240, 244–275, 295–318	314, 315, 316, 323, 326, part of 334 (except for 334111, 334112, 334411, 334412, 334413), 335, 337, 339, 511, 516	IND2
11	Petroleum refineries	115	32411	IND3

Table 1.1.—Continued

No.	Sector description	IMPLAN sector	NAICS code[1]	Hazus occupancy class
12	Food, drug, and chemicals	41–74, 116–141	311, 312, 324 except for 32411, 325	IND3
13	Primary metal manufacturing	170–180	331	IND4
14	Electronic computer manufacturing	234	334111	IND5
15	Computer storage device manufacturing	235	334112	IND5
16	Semiconductor and related device manufacturing	243	334413	IND5
17	Other high technology related manufacturing	241, 242	334411, 334412	IND5
18	Wholesale trade, warehousing, and storage	319, 340	42	COM2
19	Retail trade	320–331	44-45	COM1
20	Air transportation	332	481	COM4
21	Rail transportation	333	482	COM4
22	Water transportation	334	483	COM4
23	Truck transportation	335	484	COM2
24	Transit and ground passengers	336	485	COM4
25	Pipeline transportation	337	486	COM4
26	Sightseeing transportation	338	487 and 488	COM4
27	Couriers and messengers	339	492	COM4
28	Publishing, motion picture, and broadcasting	341–349	511, 512, 515	IND2, COM4
29	Internet publishing and broadcasting	350	51913	COM4
30	Telecommunications	351	517	COM8
31	Data processing, hosting, and related services	352	518	COM4
32	Other information services	353	51911-2	COM4
33	Finance, insurance, real estate, and leasing	354–360, 362–366	52, 53	COM4, COM5
34	Imputed rental value for owner-occupied dwellings	361	n.a.	RES1-RES3
35	Computer systems design and related services	371–373	5415	COM4
36	Other professional, scientific, and technical services	367–370, 374–380	54 except for 5415	COM4
37	Other business services	381–390	55, 56	COM4
38	Educational services	391–393	6111, 6112-3, 6114-7	EDU1, EDU2
39	Ambulatory health care and hospitals	394–397	621, 622	COM6, COM7
40	Nursing home/social assistance	398–401	623, 624	RES6, COM3
41	Arts, entertainment, and recreation	402–410, 413	711-713, 722	COM8
42	Accommodations	411–412	721	RES4
43	Repair and maintenance	414–418	811	COM3
44	Personal services/private households	419–422, 426	812, 814	COM3
45	Religious, grantmaking, and similar organizations	423–425	813	REL1
46	Government and non-NAICS	427, 429–430, 432–440	n.a.	GOV1, GOV2

[1]See the website of North American Industry Classification System (NAICS) (https://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2017) for example establishments for the various NAICS sectors.

Appendix 2. Technical Description of the CGE Model

Introduction

This appendix summarizes the design, construction, and application of a static computable general-equilibrium (CGE) simulation model of the California economy. The application is over a time horizon of a single 6-month period from the onset of an earthquake.

The CGE model is a stylized computational representation of the circular flow of the economy. It solves for the set of commodity and factor prices and activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy (Sue Wing, 2009, 2011; Sue Wing and Balistreri, 2018). Our model divides California's economy into 18 regions, the 17-county earthquake impacted region (Alameda, Contra Costa, Marin, Merced, Monterey, Napa, Sacramento, San Benito, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Stanislaus, and Yolo) and an aggregate of the rest of the State, and 46 industry sectors (appendix 1, table 1.1), each of which is modeled as a representative firm characterized by a constant elasticity of substitution (CES) technology to produce a single good or service. Households are modeled by a representative agent with CES preferences and a constant marginal propensity to save and invest out of income. The government is also represented in a simplified fashion. Its role in the circular flow of the economy is passive: collecting taxes from industries and passing some of the resulting revenue to the households as a lump-sum transfer, in addition to purchasing commodities to create a composite government good which is consumed by the households. Three factors of production are represented within the model: labor, intersectorally mobile capital, and sector-specific capital, all of which are owned by the representative agent and rented out to the firms in exchange for factor income. California is modeled as an open economy which engages in trade with the rest of the United States and the rest of the world using the Armington (1969) specification (imports from other States and the rest of the world are imperfect substitutes for goods produced in the State).

The model computes the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments. The impacts of an earthquake are modeled as exogenous shocks to the productivity of industries, reductions in house-hold consumption and investment, and contemporaneous destruction of capital stock, with concomitant reductions in the economy's endowments of capital input.

Production

The supply side of the model employs a hierarchical nested CES production structure. In each region r and sector j (see table 2.1), the quantity and price of output are given by $QY_{j,r}$ and $PY_{j,r}$. At the top level of the hierarchy, output is produced by combining a bundle of capital, labor, and lifeline inputs ($QKLV_{j,r}$, with price $PKLV_{j,r}$) with a bundle of intermediate inputs ($QZ_{j,r}$, with price $PZ_{j,r}$). This production relationship is represented in dual form by the unit cost function:

$$PY_{j,r} \leq [\alpha_{KLV,j,r}^{\sigma_Y} PKLV_{j,r}^{1-\sigma_Y} + \alpha_{Z,j,r}^{\sigma_Y} PZ_{j,r}^{1-\sigma_Y}]^{1/(1-\sigma_Y)}. \quad (1a)$$

Here, σ_Y denotes the top-level the elasticity of substitution between intermediate inputs and the value-added-lifelines composite, and α_{KLV} and α_z are the CES distribution parameters, or technical coefficients.

Table 2.1. Values of the elasticities of substitution and transformation in the computable general equilibrium (CGE) model.

Elasticities	Symbol	Values
Elasticities of substitution		
Between a value-added lifelines composite and intermediate input composite in production	σ_Y	0.1
Between a value-added composite and lifeline input composite in production	σ_{KLV}	0.1
Between capital and labor in production	σ_{KL}	0.25
Among lifeline intermediate inputs to production	σ_V	0.1
Among intermediate inputs to production	σ_Z	0.1
Among counties' outputs of a particular good in aggregate commodity supply	$\sigma_{YY,i}$	[1]4.0
Between domestic (California) and imported (rest of world) varieties of each good in county Armington composite	$\sigma_{DM,i}$	[1]2.0
Among inputs to household consumption	σ_C	0.25
Among inputs to investment	σ_I	0.25
Among inputs to government	σ_G	0.25
Elasticities of transformation		
Between California aggregate supply and rest of world exports in California-wide sectoral supply composite	η_X	[1]2.0

[1]0.1 in utility lifeline sectors (electric power, water and wastewater, telecommunications).

At the second level of the hierarchy, the bundle *QKLV* is produced from a value-added composite of labor and capital ($QKL_{j,r}$, with price $PKL_{j,r}$) and a bundle of intermediate lifeline commodity inputs ($QV_{j,r}$, with price $PV_{j,r}$) according to the unit cost function:

$$PKLV_{j,r} \leq [\alpha_{KL,j,r}^{\sigma_{KLV}} PKL_{j,r}^{1-\sigma_{KLV}} + \alpha_{v,j,r}^{\sigma_{KLV}} PV_{j,r}^{1-\sigma_{KLV}}]^{1/(1-\sigma_{KLV})}, \quad (1b)$$

in which σ_{KLV} is the elasticity of substitution between lifelines and value-added, α_{KL} and α_{V} are technical coefficients.

At the third level, the value-added composite is produced from sector-specific capital ($QK_{j,r}$, with price $PK_{j,r}$) and intersectorally mobile labor ($QL_{j,r}$, with average wage PL) according to the unit cost function:

$$PKL_{j,r} \leq [\alpha_{K,j,r}^{\sigma_{KL}} PK_{j,r}^{1-\sigma_{KL}} + \alpha_{L,j,r}^{\sigma_{KL}} PL^{1-\sigma_{KL}}]^{1/(1-\sigma_{KL})}, \quad (1c)$$

where σ_{KL}, α_{K}, and α_{L} denote the capital-labor elasticity of substitution and associated technical coefficients. The composite of lifeline inputs is modeled by a CES aggregation of intermediate inputs of a subset of the *i* distinct commodities (of which sector *j* consumes a vector of quantities, $q_{i,j,,r}$, with "Armington" user prices $PA_{i,r}$) according to the unit cost function

$$PV_{j,r} \leq [\Sigma_{i \in Lifelines} \alpha_{i,j,r}^{\sigma_V} PA_{i,r}^{1-\sigma_V}]^{1/(1-\sigma_V)}, \quad (1d)$$

with elasticity of substitution, σ_{V}, and associated technical coefficients α_{i}. The bundle of intermediate inputs (*QZ*) at the second level of the production hierarchy is modeled in a similar way:

$$PZ_{j,r} \leq [\Sigma_{i' \in Lifelines} \alpha_{i',j,r}^{\sigma_Z} PA_{i',r}^{1-\sigma_Z}]^{1/(1-\sigma_Z)}. \quad (1e)$$

with elasticity of substitution, σ_{Z}, and associated technical coefficients, $\alpha_{i'}$.

Trade and Commodity Supply

Trade is modeled according to an Armington (1969) formulation, in which the output of a sector in a particular region is allocated between consumption of locally produced goods and exports. In turn, exports are divided between goods destined for other regions within the United States and goods that satisfy foreign demand. Symmetrically, on the demand side, each consumed commodity is a composite of domestic and imported varieties, where the latter is an amalgam of imports from other U.S. regions and from abroad.

The calibration dataset does not record bilateral trade among counties or county aggregates. We use $QXUS_{i,r}$ to denote units of the i^{th} commodity exported by region *r* to U.S. consumers in other locales, and model these quantities as feeding into an aggregate national pool at a commodity-specific nationwide price (PUS_i). Similarly, we use $QXF_{i,r}$ to denote units of commodity *i* exported to consumers abroad. These quantities are treated as feeding an international pool at a single price (the generalized price of foreign exchange, *PFX*). Using $PYT_{i,r} = (1+\tau_{i,r}^{Y})PY_{i,r}$ to represent the gross-of-tax price of commodity *i* in region *r* (where $\tau_{i,r}^{Y}$ denotes the production tax rate), the transformation of regional output into exports (quantity $QX_{i,r}$) is specified in terms of the dual by the following constant elasticity of transformation (CET) equation:

$$PYT_{i,r} \geq [\beta_{XCA,i}^{\eta_{X,i}} PUS_i^{1+\eta_{X,i}} + \beta_{XF,i}^{\eta_{X,i}} PFX^{1+\eta_{X,i}}]^{1/(1+\eta_{X,i})}, \quad (2a)$$

where (suppressing the commodity subscript for the sake of brevity) η_{x} is the commodity-specific elasticity of transformation between domestic and international export destinations, and β_{XCA} and β_{XF} are commodity-specific technical coefficients. Symmetrically, region *r* imports $QMUS_{i,r}$ units of *i* from other U.S. regions and $QMF_{i,r}$ units from abroad. Its aggregate imports of each commodity (quantity $QM_{i,r}$ with price $PM_{i,r}$) are modeled as a CES composite of these quantities, given in terms of the dual by

$$PM_{i,r} \leq [\beta_{MUS,i,r}^{\sigma_{MM,i}} PUS_i^{1-\sigma_{MM,i}} + \beta_{MF,i,r}^{\sigma_{MM,i}} PFX^{1-\sigma_{MM,i}}]^{1/(1-\sigma_{MM,i})}, \quad (2b)$$

in which (suppressing the commodity subscript) σ_{DM} is the elasticity of substitution among import origins, and β_{MUS} and β_{MF} are commodity-specific technical coefficients. In turn, within each region, sectors' intermediate demands and households' final demands for a particular commodity are satisfied by the Armington total supply of that good ($QA_{i,r}$, with price $PA_{i,r}$). Armington total supply is modeled as a CES composite of domestic and imported varieties of the good, given in dual form by

$$PA_{i,r} \leq (1-\Phi_{A,i,r})^{-1} \cdot [\beta_{D,i,r}^{\sigma_{DM,i}} PY_i^{1-\sigma_{DM,i}} + \beta_{M,i,r}^{\sigma_{DM,i}} PM^{1-\sigma_{DM,i}}]^{1/(1-\sigma_{DM,i})}, \quad (2c)$$

where (suppressing the commodity subscript) σ_{DM} is the commodity-specific elasticity of substitution, β_{D} and β_{M} are commodity-specific technical coefficients, and the parameter $\Phi_{A,i,r}$ captures the disaster's adverse shock to the aggregate supply of each commodity.

A simple trade closure is adopted for the model. Each county is treated as a small open economy which cannot affect the price of foreign exchange. Following open-economy modeling convention, foreign exchange is treated as the unit of account; accordingly, the price of foreign exchange (*PFX*) is designated as the numeraire price by fixing its value at unity. The model only resolves regions within the state of California, and not elsewhere in the United States, so in general trade flows of a particular good recorded by the benchmark input-output accounts will not balance. California's net export position vis-a-vis the rest of the United States is calculated by applying Shephard's lemma (for example, Varian, 1992), yielding the supply-demand balance condition:

$$\begin{aligned} &\Sigma_r QXUS_{i,r} \geq \Sigma_r QMUS_{i,r} + QBUS_i \Rightarrow \\ &\Sigma_r \frac{\partial PYT_{i,r}}{\partial PUS_i} QX_{i,r} \geq \Sigma_r \frac{\partial PM_{i,r}}{\partial PUS_i} QM_{i,r} + QBUS_i \end{aligned} \quad (2d)$$

where $QBUS_i$ is introduced as an exogenous balancing quantity of net exports of good *i*. The corresponding expression for trade supply-demand balance with foreign countries is

$$\Sigma_r QXF_{i,r} \geq \Sigma_r QMF_{i,r} + QBF_i \Rightarrow \quad (2e)$$
$$\Sigma_r \frac{\partial PYT_{i,r}}{\partial PFX} QX_{i,r} \geq \Sigma_r \frac{\partial PM_{i,r}}{\partial PFX} QM_{i,r} + QBF_i$$

with exogenous balancing quantity QBF_i.

Final Demands and Commodity Market Closures

In each county there are *h* household archetypes, each of which is modeled as a representative agent who with CES preferences overconsumption of commodities ($q_{i,C,h,r}$, at price $PA_{i,r}$). The associated dual expenditure functions are given by

$$PU_{h,r} \leq [\Sigma_i \gamma_{i,C,h,r}^{\sigma_C} PA_{i,r}^{1-\sigma_C}]^{1/(1-\sigma_C)}, \quad (3a)$$

where $PU_{h,r}$ is the households' unit expenditure index, and, suppressing subscripts for brevity, σ_C denotes households' consumption elasticity of substitution, and $\gamma_{i,C}$ are technical coefficients. There are also *g* levels of government, each of which consumes commodity inputs ($q_{i,G,g,r}$ at price $PA_{i,r}$) for the purpose of producing a government good (quantity $QG_{g,r}$, at price $PG_{g,r}$) with CES technology. The associated cost functions are

$$PG_{g,r} \leq [\Sigma_i \gamma_{i,G,g,r}^{\sigma_G} PA_{i,r}^{1-\sigma_G}]^{1/(1-\sigma_G)}, \quad (3b)$$

in which σ_G denotes the elasticity of substitution, and (suppressing subscripts) $\gamma_{i,G}$ are technical coefficients. As well, each region produces an investment good (QI_r, at price PI_r) from a CES aggregation of commodities ($q_{i,I,r}$ at price $PA_{i,r}$), given in dual form by

$$PI_r \leq [\Sigma_i \gamma_{i,I,r}^{\sigma_I} PA_{i,r}^{1-\sigma_I}]^{1/(1-\sigma_I)}, \quad (3c)$$

where σ_I denotes the elasticity of substitution, and (suppressing subscripts) $\gamma_{i,I}$ are technical coefficients. It is assumed that each representative agent exhibits a fixed marginal propensity to save (MPS) and invests out of income. Supply-demand balance for households' savings ($QS_{h,r}$) requires

$$QI_r \leq \Sigma_h QS_{h,r}, \quad (3d)$$

while a fixed MPS implies a constant of proportionality, $\mu_{h,r}$, which allows savings to scale with changes in activity (consumption) levels:

$$QS_{h,r} = \mu_{h,r} U_{h,r}. \quad (3e)$$

Government consumption is financed out of tax revenue and transfers. Government *g* is modeled as claiming a fraction $\xi_{g,r}$ of the total tax revenue raised within region *r*, as well as receiving a net transfer, $GXFER_{g,r}$ (which for convenience is denominated in units of the numeraire). The activity level of public provision is then given by:

$$QG_{g,r} \leq (\xi_{g,r} \Sigma_j \tau_{j,r}^{Y} PY_{j,r} QY_{j,r} + PFX \cdot GXFER_{g,r}) / PG_{g,r}. \quad (3f)$$

The supply-demand balance for domestic output is given by

$$QY_{i,r} \geq QD_{i,r} + QX_{i,r} \quad (3g)$$

where the unconditional demand for domestic uses is given by Shephard's lemma: $QD_{i,r} = \frac{\partial PA_{i,r}}{\partial PY_{i,r}} QA_{i,r}$.

The supply-demand balance for imports is given by Shephard's lemma:

$$QM_{i,r} \geq \frac{\partial PA_{i,r}}{\partial PM_{i,r}} QA_{i,r}. \quad (3h)$$

Finally, the supply-demand balance for Armington commodities is closed via the condition

$$QA_{i,r} \geq \Sigma_j q_{i,j,r} + \Sigma_h q_{i,C,h,r} + q_{i,I,r} + \Sigma_g q_{i,G,g,r} \quad (3i)$$

in which the unconditional demands on the right-hand side are given by

$$q_{i,j,r} = \frac{\partial PY_{j,r}}{\partial PA_{i,r}} QY_{j,r},\ q_{i,C,h,r} = \frac{\partial PU_{h,r}}{\partial PA_{i,r}} U_{h,r},\ q_{i,I,r} = \frac{\partial PI_r}{\partial PA_{i,r}},$$
$$\text{and}\ \ q_{i,G,g,r} = \frac{\partial PG_{g,r}}{\partial PA_{i,r}} QG_{g,r}.$$

Inter-Sectoral Factor Mobility and Static Income Closures

Given the brief duration of the period over which the equilibrium represented by the model is established, the assumption of frictionless inter-sectoral reallocation of capital commonly made by CGE models is unlikely to accurately capture the behavior of factor markets. Although the authors continue to treat labor as mobile across industries and counties, capital is modeled as a sectorally and geographically fixed factor at each timestep, with instantaneous supply-demand balance determined by the county- and sector-specific supply of capital input ($\varepsilon_{K,j,r}$):

$$(1 - \Phi_{K,j,r}) \cdot \varepsilon_{K,j,r} \geq \frac{\partial PKL_{j,r}}{\partial PK_{j,r}} QKL_{j,r}. \quad (4a)$$

Disaster-related capital-stock destruction on the left-hand side of this expression is the primary driver of economic impact. Traditional CGE models close the labor market either through the "neoclassical" assumption of full employment (perfectly inelastic supply) or "Keynesian" variable employment (perfectly elastic supply at a fixed wage). Although neither of these extremes adequately captures the effect of a large transitory shock (which typically induces simultaneous adjustments in both employment and wages), for the sake of simplicity and computational tractability we employ the latter, Keynesian closure. This is achieved by scaling counties labor endowments relative to their benchmark levels ($\varepsilon_{L,r}$), with the supply-demand balance condition:

$$\Upsilon_L \cdot \Sigma_r \varepsilon_{L,r} \geq \Sigma_j \Sigma_r \frac{\partial PKL_{j,r}}{\partial PL} QKL_{j,r} \quad (4b)$$

in which the value of the scaling factor, Y_L, is endogenously chosen to hold the wage constant

$$PL = 1. \tag{4c}$$

County-level household, investment, and government activities are bound together by an income-expenditure balance condition that constrains the value of expenditure and saving to equal the value of factor returns plus net household transfers ($HXFER_{h,r}$, also denominated in units of the numeraire). Thus, using $\zeta_{K,h,r}$ and $\zeta_{L,h,r}$ to denote the shares of labor and capital remuneration going to the various household income groups within each county, income balance is given by

$$\begin{aligned}&\zeta_{K,h,r} \cdot \Sigma_j PK_{j,r} \cdot \varepsilon_{K,j,r} + \zeta_{L,h,r} \Upsilon_L \cdot PL \cdot \varepsilon_{L,r} + PFX \cdot HXFER_{h,r} \\ &\geq PU_{h,r} U_{h,r} + PI_r QS_{h,r} + \Sigma_i PCA_i SA_{i,h,r}.\end{aligned} \tag{4d}$$

The final closure rule is the statewide balance of payments constraint, which balances the net supply of foreign exchange against the demands for transfer payments that make up the idiosyncratic components of household and government income:

$$\begin{aligned}&\Sigma_i PUS_i \left(QBUS_i + \Sigma_r PUS_i \left(QXUS_{i,r} - QMUS_{i,r}\right)\right) + \\ &\Sigma_i PFX \left(QBF_i + \Sigma_r \left(QXF_{i,r} - QMF_{i,r}\right)\right) + \\ &\Sigma_g \Sigma_r GXFER_{g,r} + \Sigma_h \Sigma_r HXFER_{h,r} = 0.\end{aligned} \tag{4e}$$

California's exports to, and counties' imports from, international (U.S.) markets are both valued at the numeraire foreign exchange price (U.S. average commodity-specific domestic prices), with quantities given by the application of Shepard's lemma to equations 2a and 2b:

$$QXUS_{i,r} = \frac{\partial PYT_{i,r}}{\partial PUS_i},\ QMUS_{i,r} = \frac{\partial PM_{i,r}}{\partial PUS_i}, \text{ and}$$

$$QXF_{i,r} = \frac{\partial PYT_{i,r}}{\partial PFX},\ QMF_{i,r} = \frac{\partial PM_{i,r}}{\partial PFX}.$$

Modeling the Impacts of an Earthquake

The static equilibrium model made up of equations 1 through 4 is subjected to the shock of economic damage caused by the earthquake event. Damage to sectoral capital stocks are modeled as secular reductions in sectors' endowments of capital input, $\Phi_{K,j,r} \in (0,1)$, whereas lifeline outages are modeled as secular reductions in the productivity of delivery of Armington lifeline commodities to their intermediate and final uses, $\Phi_{A,i,r} \in (0,1)$ for $i \in Lifelines$. In the economy's baseline state, these shock parameters are set to zero, whereas in the various loss scenarios they take on values between zero and one, reflecting different components of damage.

Model Calibration, Formulation, Solution, and Application

The vectors of technical coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ in equations 1 through 4 are calibrated using an IMPLAN social accounting matrix for the State of California for the year 2012 (IMPLAN, 2014) in conjunction with values of the elasticities of substitution, transformation, and supply in appendix 3, table 3.2. The model is formulated as a mixed complementarity problem using the MPSGE subsystem for GAMS (Rutherford, 1999; Brooke and others, 1988) and is solved using the PATH solver (Ferris and Munson, 2000).

Table 3.1. Percentage of buildings damaged by HayWired mainshock shaking, liquefaction, and landslide, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	16.69	9.45	1.37	0.09	0.18	0.11	0.05	0.55	2.60	0.32	2.39	3.45	0.60	0.42	0.12	0.19	0.06
Oil and gas extraction	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Coal mining	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Other mining	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Electric power generation, transmission, and distribution	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Natural gas distribution	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Water, sewage, and other systems	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Construction	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Heavy industry	14.25	8.45	1.93	0.06	0.27	0.55	0.04	1.33	3.02	0.72	3.77	4.56	0.54	0.85	0.14	0.35	0.09
Light industry	18.70	9.07	1.92	0.07	0.14	0.75	0.06	1.52	3.15	0.73	3.89	4.92	0.55	0.80	0.18	0.40	0.12
Petroleum refineries	19.11	6.65	2.20	0.11	0.20	0.26	0.03	1.41	2.84	0.57	3.48	4.38	0.67	0.74	0.13	0.53	0.12
Food, drug, and chemicals	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Primary metal manufacturing	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Electronic computer manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Computer storage device manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Semiconductor and related device manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Other high-tech manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Wholesale trade, warehousing, and storage	19.80	9.00	1.85	0.09	0.17	0.48	0.02	0.91	3.28	0.59	3.50	4.52	0.52	0.77	0.15	0.27	0.06
Retail trade	20.49	11.56	1.42	0.09	0.11	0.28	0.02	0.83	2.31	0.52	3.02	3.68	0.41	0.82	0.10	0.25	0.06
Air transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07

Table 3.1.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Rail transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Water transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Truck transportation	19.80	9.00	1.85	0.09	0.17	0.48	0.02	0.91	3.28	0.59	3.50	4.52	0.52	0.77	0.15	0.27	0.06
Transit and ground passengers	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Pipeline transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Sightseeing transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Couriers and messengers	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Publishing, motion picture, and broadcasting	16.96	9.84	1.44	0.08	0.10	0.38	0.02	1.67	2.35	0.57	3.28	3.97	0.42	0.78	0.11	0.26	0.08
Internet publishing and broadcasting	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Telecommunications	18.83	9.35	1.42	0.14	0.08	0.25	0.03	0.86	2.32	0.55	3.15	3.76	0.45	0.86	0.11	0.27	0.09
Data processing, hosting, and related services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other information services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Finance, insurance, real estate, and leasing	16.69	10.03	1.39	0.08	0.10	0.31	0.02	1.71	2.26	0.53	3.21	3.77	0.41	0.77	0.10	0.24	0.07
Imputed rental value for owner-occupied dwellings	10.09	4.51	0.98	0.04	0.05	0.15	0.01	0.32	1.58	0.33	2.17	2.22	0.27	0.45	0.05	0.12	0.03
Computer systems design and related services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other professional, scientific, and technical services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other business services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Educational services	16.33	13.24	1.15	0.07	0.11	0.23	0.02	0.51	1.96	0.47	2.48	3.21	0.36	0.80	0.07	0.21	0.06

Table 3.1.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Ambulatory health care and hospitals	15.69	8.96	1.37	0.05	0.12	0.30	0.02	0.75	1.92	0.57	2.64	3.27	0.37	0.72	0.10	0.21	0.08
Nursing home/ social assistance	19.64	10.38	1.52	0.09	0.11	0.40	0.02	1.05	2.39	0.55	3.07	3.70	0.45	0.90	0.10	0.26	0.08
Arts, entertainment, and recreation	18.83	9.35	1.42	0.14	0.08	0.25	0.03	0.86	2.32	0.55	3.15	3.76	0.45	0.86	0.11	0.27	0.09
Accommodations	15.31	9.38	1.12	0.21	0.03	0.12	0.04	0.51	2.01	0.55	3.70	3.39	0.35	0.66	0.06	0.24	0.08
Repair and maintenance	19.73	10.53	1.52	0.09	0.12	0.40	0.02	1.07	2.40	0.56	3.09	3.74	0.45	0.93	0.10	0.27	0.08
Personal services/ private households	19.73	10.53	1.52	0.09	0.12	0.40	0.02	1.07	2.40	0.56	3.09	3.74	0.45	0.93	0.10	0.27	0.08
Religious, grantmaking, and similar organizations	17.91	10.20	1.29	0.10	0.09	0.25	0.02	0.77	2.02	0.47	3.08	3.31	0.46	1.04	0.09	0.20	0.06
Government and non-NAICS	14.91	9.05	2.12	0.16	0.06	0.37	0.02	2.07	2.26	0.67	2.95	4.53	0.43	0.86	0.09	0.31	0.07

Table 3.2. Percentage of contents damaged by HayWired mainshock shaking, liquefaction, and landslide, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	6.79	3.82	0.66	0.06	0.11	0.07	0.03	0.34	1.17	0.19	1.15	1.63	0.33	0.24	0.07	0.12	0.05
Oil and gas extraction	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Coal mining	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Other mining	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Electric power generation, transmission, and distribution	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Natural gas distribution	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Water, sewage, and other systems	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Construction	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Heavy industry	6.17	3.40	0.84	0.03	0.14	0.26	0.02	0.64	1.31	0.34	1.61	2.56	0.25	0.40	0.07	0.17	0.05
Light industry	7.52	3.55	0.82	0.03	0.06	0.34	0.03	0.73	1.32	0.32	1.64	2.64	0.26	0.36	0.08	0.18	0.06
Petroleum refineries	7.39	2.63	0.97	0.05	0.09	0.12	0.02	0.56	1.20	0.26	1.49	2.09	0.30	0.34	0.06	0.24	0.06
Food, drug, and chemicals	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Primary metal manufacturing	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Electronic computer manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Computer storage device manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Semiconductor and related device manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Other high-tech manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Wholesale trade, warehousing, and storage	7.46	3.46	0.88	0.06	0.11	0.29	0.02	0.54	1.39	0.34	1.53	2.55	0.30	0.43	0.08	0.17	0.05
Retail trade	7.18	4.27	0.67	0.06	0.07	0.17	0.01	0.45	1.00	0.30	1.40	1.78	0.25	0.45	0.06	0.15	0.05
Air transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Rail transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Water transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Truck transportation	7.46	3.46	0.88	0.06	0.11	0.29	0.02	0.54	1.39	0.34	1.53	2.55	0.30	0.43	0.08	0.17	0.05
Transit and ground passengers	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Pipeline transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Sightseeing transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Couriers and messengers	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Publishing, motion picture, and broadcasting	6.19	3.71	0.67	0.04	0.05	0.22	0.01	0.63	0.87	0.30	1.51	2.12	0.24	0.41	0.06	0.15	0.05
Internet publishing and broadcasting	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Telecommunications	5.90	3.51	0.64	0.08	0.04	0.13	0.02	0.42	1.02	0.28	1.45	1.91	0.24	0.44	0.06	0.15	0.05
Data processing, hosting, and related services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other information services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Finance, insurance, real estate, and leasing	5.82	3.77	0.65	0.05	0.05	0.18	0.01	0.60	0.80	0.29	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Imputed rental value for owner-occupied dwellings	4.93	2.64	0.48	0.03	0.04	0.10	0.01	0.25	0.88	0.21	1.26	1.43	0.18	0.28	0.03	0.08	0.03
Computer systems design and related services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other professional, scientific, and technical services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other business services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Educational services	5.12	5.11	0.61	0.06	0.08	0.15	0.02	0.38	0.91	0.29	1.26	1.63	0.24	0.49	0.05	0.16	0.05
Ambulatory health care and hospitals	5.42	3.41	0.59	0.02	0.06	0.17	0.01	0.40	0.83	0.29	1.25	1.51	0.22	0.40	0.05	0.12	0.05
Nursing home/social assistance	6.96	4.03	0.70	0.05	0.07	0.23	0.01	0.56	1.08	0.31	1.46	1.94	0.26	0.49	0.06	0.15	0.05
Arts, entertainment, and recreation	5.90	3.51	0.64	0.08	0.04	0.13	0.02	0.42	1.02	0.28	1.45	1.91	0.24	0.44	0.06	0.15	0.05
Accommodations	5.49	3.74	0.53	0.14	0.02	0.07	0.03	0.32	0.63	0.28	1.76	1.72	0.22	0.36	0.03	0.14	0.05
Repair and maintenance	6.97	4.05	0.70	0.06	0.07	0.23	0.01	0.56	1.08	0.31	1.47	1.94	0.26	0.50	0.06	0.16	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Personal services/ private households	6.97	4.05	0.70	0.06	0.07	0.23	0.01	0.56	1.08	0.31	1.47	1.94	0.26	0.50	0.06	0.16	0.05
Religious, grantmaking, and similar organizations	6.43	4.06	0.61	0.07	0.05	0.16	0.02	0.49	0.97	0.28	1.50	1.78	0.28	0.58	0.05	0.12	0.04
Government and non-NAICS	4.60	3.27	1.02	0.10	0.03	0.20	0.01	0.79	0.87	0.36	1.45	1.95	0.24	0.44	0.05	0.15	0.04

Table 3.3. Percentage of buildings and contents damaged by fire following the HayWired mainshock, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oil and gas extraction	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Coal mining	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Other mining	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Electric power generation, transmission, and distribution	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Natural gas distribution	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Water, sewage, and other systems	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Construction	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Heavy industry	2.37	0.80	2.23	0.00	0.00	0.01	0.00	0.00	0.13	0.00	0.48	0.78	0.00	1.04	0.01	0.00	0.00
Light industry	3.93	1.38	3.84	0.00	0.00	0.03	0.00	0.00	0.04	0.00	0.74	1.34	0.00	0.80	0.03	0.00	0.00
Petroleum refineries	4.48	1.23	4.88	0.00	0.00	0.01	0.00	0.00	0.21	0.00	0.80	1.49	0.00	0.01	0.01	0.00	0.00
Food, drug, and chemicals	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Primary metal manufacturing	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00

Table 3.3.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Electronic computer manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Computer storage device manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Semiconductor and related device manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Other high-tech manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Wholesale trade, warehousing, and storage	1.55	0.45	0.85	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.23	0.40	0.00	0.30	0.00	0.00	0.00
Retail trade	2.87	1.18	0.70	0.00	0.00	0.02	0.00	0.00	0.06	0.00	0.43	0.68	0.00	1.01	0.02	0.00	0.00
Air transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Rail transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Water transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Truck transportation	1.55	0.45	0.85	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.23	0.40	0.00	0.30	0.00	0.00	0.00
Transit and ground passengers	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Pipeline transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Sightseeing transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Couriers and messengers	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Publishing, motion picture, and broadcasting	2.47	1.26	1.31	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.42	0.82	0.00	0.70	0.02	0.00	0.00
Internet publishing and broadcasting	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Telecommunications	2.50	0.99	0.65	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.43	0.78	0.00	1.20	0.02	0.00	0.00
Data processing, hosting, and related services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other information services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00

Table 3.3.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Finance, insurance, real estate, and leasing	2.03	1.27	0.95	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.36	0.65	0.00	0.68	0.01	0.00	0.00
Imputed rental value for owner-occupied dwellings	10.18	3.08	2.32	0.00	0.00	0.03	0.00	0.00	0.37	0.00	1.11	1.78	0.00	3.36	0.04	0.00	0.00
Computer systems design and related services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other professional, scientific, and technical services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other business services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Educational services	23.28	8.00	8.01	0.00	0.00	0.05	0.00	0.00	0.77	0.00	3.17	4.87	0.00	14.13	0.10	0.00	0.00
Ambulatory health care and hospitals	3.37	1.06	0.75	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.46	0.53	0.00	0.64	0.03	0.00	0.00
Nursing home/social assistance	2.75	0.87	0.81	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.69	0.00	1.97	0.02	0.00	0.00
Arts, entertainment, and recreation	2.50	0.99	0.65	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.43	0.78	0.00	1.20	0.02	0.00	0.00
Accommodations	8.77	2.20	3.20	0.00	0.00	0.00	0.00	0.00	0.12	0.00	1.33	2.47	0.00	2.37	0.02	0.00	0.00
Repair and maintenance	2.63	0.82	0.76	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.67	0.00	2.00	0.01	0.00	0.00
Personal services/ private households	2.63	0.82	0.76	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.67	0.00	2.00	0.01	0.00	0.00
Religious, grantmaking, and similar organizations	6.11	1.93	2.78	0.00	0.00	0.01	0.00	0.00	0.12	0.00	0.89	1.42	0.00	9.91	0.04	0.00	0.00
Government and non-NAICS	7.18	2.55	2.35	0.00	0.00	0.01	0.00	0.00	0.02	0.00	1.16	2.00	0.00	8.67	0.01	0.00	0.00

Table 3.4. Percentage of buildings and contents damaged by the HayWired mainshock and fire following the mainshock, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	23.48	13.27	2.02	0.15	0.30	0.18	0.08	0.88	3.76	0.51	3.54	5.08	0.94	0.67	0.19	0.31	0.11
Oil and gas extraction	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Coal mining	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Other mining	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Electric power generation, transmission, and distribution	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Natural gas distribution	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Water, sewage, and other systems	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Construction	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Heavy industry	22.78	12.65	5.00	0.09	0.41	0.83	0.05	1.97	4.46	1.06	5.86	7.91	0.79	2.30	0.22	0.52	0.14
Light industry	30.14	14.01	6.58	0.10	0.20	1.12	0.08	2.26	4.51	1.06	6.28	8.91	0.81	1.97	0.29	0.58	0.18
Petroleum refineries	30.98	10.51	8.05	0.16	0.29	0.38	0.05	1.97	4.25	0.82	5.77	7.97	0.96	1.09	0.20	0.77	0.18
Food, drug, and chemicals	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Primary metal manufacturing	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Electronic computer manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Computer storage device manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Semiconductor and related device manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Other high-tech manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Wholesale trade, warehousing, and storage	28.82	12.90	3.58	0.14	0.28	0.78	0.04	1.45	4.70	0.93	5.26	7.47	0.82	1.50	0.24	0.44	0.11
Retail trade	30.54	17.01	2.79	0.14	0.17	0.47	0.04	1.28	3.37	0.82	4.85	6.14	0.66	2.28	0.17	0.40	0.11
Air transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12

Table 3.4.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Rail transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Water transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Truck transportation	28.82	12.90	3.58	0.14	0.28	0.78	0.04	1.45	4.70	0.93	5.26	7.47	0.82	1.50	0.24	0.44	0.11
Transit and ground passengers	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Pipeline transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Sightseeing transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Couriers and messengers	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Publishing, motion picture, and broadcasting	25.62	14.81	3.42	0.12	0.15	0.61	0.04	2.29	3.24	0.87	5.22	6.91	0.66	1.89	0.19	0.41	0.12
Internet publishing and broadcasting	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Telecommunications	27.22	13.84	2.71	0.21	0.12	0.39	0.04	1.28	3.37	0.83	5.03	6.46	0.69	2.50	0.19	0.42	0.14
Data processing, hosting, and related services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other information services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Finance, insurance, real estate, and leasing	24.54	15.07	2.99	0.13	0.15	0.49	0.03	2.31	3.08	0.82	5.05	6.37	0.64	1.86	0.16	0.38	0.12
Imputed rental value for owner-occupied dwellings	25.21	10.23	3.78	0.08	0.09	0.28	0.02	0.58	2.83	0.54	4.54	5.43	0.45	4.09	0.12	0.20	0.06
Computer systems design and related services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other professional, scientific, and technical services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other business services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Educational services	44.73	26.35	9.77	0.13	0.19	0.43	0.04	0.90	3.64	0.77	6.90	9.70	0.60	15.42	0.22	0.37	0.12

Table 3.4.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Ambulatory health care and hospitals	24.48	13.42	2.71	0.07	0.18	0.47	0.03	1.16	2.82	0.86	4.35	5.31	0.59	1.76	0.18	0.33	0.13
Nursing home/social assistance	29.36	15.28	3.03	0.14	0.18	0.64	0.04	1.61	3.52	0.86	4.95	6.33	0.71	3.36	0.18	0.42	0.13
Arts, entertainment, and recreation	27.22	13.84	2.71	0.21	0.12	0.39	0.04	1.28	3.37	0.83	5.03	6.46	0.69	2.50	0.19	0.42	0.14
Accommodations	29.57	15.31	4.85	0.36	0.04	0.19	0.07	0.83	2.76	0.83	6.80	7.58	0.57	3.39	0.11	0.37	0.13
Repair and maintenance	29.32	15.40	2.97	0.15	0.18	0.65	0.04	1.64	3.53	0.86	4.97	6.35	0.72	3.43	0.18	0.42	0.14
Personal services/ private households	29.32	15.40	2.97	0.15	0.18	0.65	0.04	1.64	3.53	0.86	4.97	6.35	0.72	3.43	0.18	0.42	0.14
Religious, grantmaking, and similar organizations	30.46	16.20	4.68	0.17	0.14	0.41	0.04	1.27	3.11	0.75	5.47	6.51	0.74	11.53	0.18	0.33	0.11
Government and non-NAICS	26.68	14.88	5.48	0.25	0.09	0.58	0.03	2.86	3.15	1.03	5.56	8.48	0.67	9.97	0.14	0.46	0.11

Table 3.5. Percentage of buildings and contents damaged by HayWired aftershocks, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	2.19	0.29	0.08	0.01	0.04	0.05	0.01	0.02	0.34	0.02	3.71	4.41	0.22	0.17	0.01	0.01	0.02
Oil and gas extraction	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Coal mining	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Other mining	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Electric power generation, transmission, and distribution	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Natural gas distribution	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Water, sewage, and other systems	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Construction	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Heavy industry	6.16	0.60	0.14	0.02	0.06	0.18	0.02	0.04	0.75	0.04	7.12	5.76	0.50	0.25	0.01	0.02	0.04

Table 3.5.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Light industry	4.67	0.58	0.14	0.01	0.04	0.21	0.02	0.04	0.60	0.04	5.39	7.53	0.60	0.47	0.01	0.02	0.03
Petroleum refineries	4.45	0.44	0.15	0.01	0.06	0.09	0.01	0.05	0.57	0.03	3.99	7.25	0.40	0.34	0.03	0.02	0.04
Food, drug, and chemicals	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Primary metal manufacturing	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Electronic computer manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Computer storage device manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Semiconductor and related device manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Other high-tech manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Wholesale trade, warehousing, and storage	3.62	0.36	0.11	0.01	0.05	0.13	0.01	0.03	0.50	0.03	2.60	5.24	0.35	0.29	0.02	0.02	0.02
Retail trade	2.16	0.43	0.09	0.01	0.03	0.10	0.01	0.03	0.32	0.02	3.19	5.38	0.43	0.16	0.01	0.02	0.02
Air transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Rail transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Water transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Truck transportation	3.62	0.36	0.11	0.01	0.05	0.13	0.01	0.03	0.50	0.03	2.60	5.24	0.35	0.29	0.02	0.02	0.02
Transit and ground passengers	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Pipeline transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Sightseeing transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Couriers and messengers	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Publishing, motion picture, and broadcasting	2.39	0.31	0.09	0.01	0.03	0.12	0.01	0.03	0.25	0.02	3.88	6.11	0.44	0.26	0.01	0.02	0.02
Internet publishing and broadcasting	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Telecommunications	2.12	0.32	0.10	0.01	0.03	0.09	0.02	0.03	0.36	0.03	3.59	6.53	0.51	0.17	0.01	0.02	0.03

Table 3.5.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Data processing, hosting, and related services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other information services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Finance, insurance, real estate, and leasing	1.99	0.30	0.08	0.01	0.02	0.10	0.01	0.03	0.20	0.02	3.61	5.80	0.42	0.22	0.01	0.02	0.02
Imputed rental value for owner-occupied dwellings	1.26	0.24	0.03	0.00	0.01	0.04	0.00	0.01	0.19	0.01	2.08	3.41	0.27	0.08	0.00	0.01	0.01
Computer systems design and related services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other professional, scientific, and technical services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other business services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Educational services	1.46	0.55	0.07	0.01	0.03	0.08	0.01	0.02	0.28	0.02	2.41	5.49	0.38	0.21	0.01	0.02	0.02
Ambulatory health care and hospitals	1.53	0.31	0.08	0.01	0.03	0.11	0.01	0.03	0.34	0.03	3.59	6.35	0.41	0.16	0.01	0.02	0.02
Nursing home/social assistance	2.20	0.43	0.09	0.01	0.03	0.12	0.01	0.03	0.34	0.03	3.50	5.92	0.46	0.18	0.01	0.02	0.02
Arts, entertainment, and recreation	2.12	0.32	0.10	0.01	0.03	0.09	0.02	0.03	0.36	0.03	3.59	6.53	0.51	0.17	0.01	0.02	0.03
Accommodations	1.34	0.31	0.06	0.01	0.01	0.05	0.01	0.02	0.13	0.02	3.25	5.27	0.46	0.37	0.01	0.01	0.02
Repair and maintenance	2.21	0.44	0.09	0.01	0.03	0.12	0.01	0.03	0.35	0.03	3.48	5.95	0.46	0.18	0.01	0.02	0.02
Personal services/ private households	2.21	0.44	0.09	0.01	0.03	0.12	0.01	0.03	0.35	0.03	3.48	5.95	0.46	0.18	0.01	0.02	0.02
Religious, grantmaking, and similar organizations	1.76	0.45	0.07	0.01	0.03	0.08	0.01	0.03	0.29	0.02	3.80	5.35	0.46	0.16	0.01	0.02	0.02
Government and non-NAICS	1.41	0.28	0.12	0.01	0.02	0.13	0.01	0.03	0.22	0.03	4.38	5.41	0.47	0.20	0.01	0.02	0.02

Table 3.6. Percentage of buildings and contents damaged by the HayWired mainshock, fire following the mainshock, and aftershocks, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	25.67	13.56	2.10	0.16	0.34	0.22	0.09	0.91	4.10	0.53	7.25	9.48	1.15	0.84	0.20	0.32	0.13
Oil and gas extraction	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Coal mining	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Other mining	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Electric power generation, transmission, and distribution	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Natural gas distribution	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Water, sewage, and other systems	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Construction	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Heavy industry	28.94	13.25	5.15	0.10	0.47	1.01	0.07	2.01	5.20	1.10	12.98	13.66	1.29	2.55	0.23	0.54	0.17
Light industry	34.81	14.59	6.72	0.11	0.24	1.33	0.11	2.30	5.11	1.10	11.67	16.44	1.40	2.44	0.31	0.61	0.22
Petroleum refineries	35.43	10.95	8.21	0.18	0.35	0.47	0.06	2.01	4.81	0.86	9.76	15.22	1.36	1.43	0.23	0.79	0.21
Food, drug, and chemicals	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Primary metal manufacturing	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Electronic computer manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Computer storage device manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Semiconductor and related device manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Other high-tech manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Wholesale trade, warehousing, and storage	32.44	13.26	3.69	0.16	0.33	0.91	0.05	1.48	5.20	0.96	7.86	12.71	1.16	1.79	0.25	0.45	0.13

Table 3.6.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Retail trade	32.70	17.44	2.88	0.15	0.20	0.57	0.05	1.31	3.69	0.85	8.04	11.52	1.09	2.44	0.18	0.42	0.13
Air transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Rail transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Water transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Truck transportation	32.44	13.26	3.69	0.16	0.33	0.91	0.05	1.48	5.20	0.96	7.86	12.71	1.16	1.79	0.25	0.45	0.13
Transit and ground passengers	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Pipeline transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Sightseeing transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Couriers and messengers	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Publishing, motion picture, and broadcasting	28.01	15.12	3.51	0.13	0.18	0.73	0.05	2.33	3.50	0.89	9.10	13.02	1.10	2.15	0.20	0.43	0.15
Internet publishing and broadcasting	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Telecommunications	29.34	14.17	2.81	0.23	0.14	0.48	0.06	1.31	3.73	0.86	8.62	12.99	1.20	2.68	0.20	0.44	0.16
Data processing, hosting, and related services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Other information services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Finance, insurance, real estate, and leasing	26.53	15.37	3.07	0.14	0.17	0.60	0.04	2.34	3.28	0.84	8.66	12.18	1.06	2.08	0.17	0.40	0.14
Imputed rental value for owner-occupied dwellings	26.47	10.47	3.81	0.08	0.10	0.32	0.02	0.59	3.02	0.55	6.63	8.84	0.72	4.17	0.12	0.21	0.07
Computer systems design and related services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Other professional, scientific, and technical services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14

Table 3.6.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Other business services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Educational services	46.19	26.89	9.84	0.14	0.22	0.50	0.05	0.92	3.92	0.79	9.32	15.19	0.98	15.63	0.22	0.39	0.14
Ambulatory health care and hospitals	26.02	13.73	2.78	0.08	0.21	0.59	0.04	1.18	3.16	0.89	7.94	11.66	1.00	1.92	0.18	0.35	0.15
Nursing home/social assistance	31.56	15.70	3.12	0.15	0.21	0.76	0.05	1.65	3.87	0.88	8.45	12.25	1.16	3.55	0.18	0.43	0.16
Arts, entertainment, and recreation	29.34	14.17	2.81	0.23	0.14	0.48	0.06	1.31	3.73	0.86	8.62	12.99	1.20	2.68	0.20	0.44	0.16
Accommodations	30.92	15.62	4.91	0.37	0.05	0.24	0.08	0.85	2.89	0.85	10.05	12.84	1.03	3.75	0.12	0.38	0.15
Repair and maintenance	31.53	15.83	3.06	0.16	0.22	0.77	0.05	1.67	3.88	0.89	8.45	12.29	1.18	3.61	0.18	0.44	0.16
Personal services/ private households	31.53	15.83	3.06	0.16	0.22	0.77	0.05	1.67	3.88	0.89	8.45	12.29	1.18	3.61	0.18	0.44	0.16
Religious, grantmaking, and similar organizations	32.22	16.65	4.74	0.18	0.17	0.49	0.05	1.30	3.40	0.77	9.26	11.86	1.19	11.69	0.19	0.34	0.13
Government and non-NAICS	28.10	15.16	5.60	0.27	0.11	0.71	0.04	2.89	3.37	1.06	9.94	13.89	1.15	10.17	0.15	0.48	0.14

Appendix 4. Household Inconvenience Costs of Electricity and Water Service Disruptions

By Keith Porter[1]

Inconvenience Cost for Loss of Water

Loss of Water Service

Porter (2018, table 30) presented estimates of the fraction of customers receiving water service at several points in time after the HayWired mainshock. The data in the table can be charted as restoration curves: time on the horizontal axis and fraction of customers receiving water on the vertical axis. The area above the curves and below 100 percent represents the average number of days a customer in each county is without water service, referred to here as the average service-days lost per household. Bruneau and others (2003) refer to that area as the loss of resilience; many other authors refer to it as the loss triangle, though it need not have a triangular shape (National Research Council, 2011). One can use the trapezoidal rule to estimate the average service-days lost per household in each county:

$$L = \sum_{i=1}^{n} (t_i - t_{i-1}) \cdot \left(1 - \frac{y_i + y_{i-1}}{2}\right). \quad (1)$$

[1]University of Colorado Boulder.

One can then estimate the total service-days lost, that is, the product of service connections and days without service, as

$$S = L \cdot C \quad (2)$$

where

- L average service-days lost per household, in days
- i an index to count the number of time increments (for example, 0 to 1 day, 1 to 3 days, and so on)
- n number of time increments shown in the table ($n = 6$)
- t_i time at the end of increment i, for example, $t_1 = 1$ day after the mainshock
- y_i fraction of customers receiving water at time t_i
- S total service-days lost and
- C number of service connections, taken here as 1.0 times the number of households.

Table 4.1 shows the results of the foregoing calculation. In the table households and total service days lost are displayed only to two significant figures to reduce the appearance of excessive accuracy.

Table 4.1. Loss of water service by county, San Francisco Bay region, California.

County	Households without service[1]	Average service-days lost per household, days	Total service-days lost
Alameda	520,000	54	**28,000,000**
Contra Costa	340,000	54	**18,000,000**
Marin	100,000	1	**100,000**
Merced	64,000	0	**24,000**
Monterey	120,000	0	--
Napa	45,000	0	--
Sacramento	450,000	0	--
San Benito	16,000	0	**1,600**
San Francisco	330,000	7	**2,300,000**
San Joaquin	180,000	0	--
San Mateo	250,000	20	**5,200,000**
Santa Clara	570,000	5	**3,000,000**
Santa Cruz	91,000	0	--
Solano	130,000	0	**27,000**
Sonoma	170,000	0	--
Stanislaus	150,000	0	--
Yolo	59,000	0	--
Total	**3,600,000**	**16**	**57,000,000**

[1]Data from Porter (2018), table 30.

Loss of water service to homes does not affect economic production but it does have a real cost, especially if it exceeds people's emergency supplies, requires a change in habits that people would prefer not to make, or requires purchases that they would otherwise avoid.

Many Californians do stockpile water at the advice of the Red Cross, Earthquake Country Alliance, and others. Emergency managers have been asking Californians to keep 3 to 7 days of water in their homes. It seems likely that people's actual supplies are at the lower end and only provide enough water for drinking, not other household uses such as toilets and showers.

Loss of water service throughout much of the study area lasts far longer than the time people can reasonably go without toilets and showers. The average East Bay Municipal Utility District customer loses water for 6 weeks, which is a long time to have to find substitutes for showers, drinking water, toilets, and so on. What will the loss of water service cost households?

Literature on the Inconvenience Cost of Lost Residential Potable Water

The Federal Emergency Management Agency's (FEMA's) [undated] benefit-cost analysis tool offers a default value of potable water service of $103.00 per person, per day, "calculated based on residential and regional economic impact from national statistics." Elsewhere, FEMA (2009, p. A-5) states, without reference to a source, that its standard values for loss of potable water service is $88 per person per day, which in 2018 would equate with $104 per person per day and $260 per household per day for a household size of 2.5.

Heflin and others (2013) conducted three focus-group studies and collected 162 in-person surveys of people affected by loss of water service. The elicited costs of extra bottled water, boiling or bleaching, replacing water filters, extra costs associated with cooking and eating, effects on work and school schedules, and travel costs, produced an average added expense of $102 per household per day in 2018 dollars.

Aubuchon and Morley (2013) estimate the economic value associated with loss of water service between $67 and $457 per person per day and suggest an average value of $208 per person per day (2011 dollars), approximately equivalent to $231 per person per day (2018 dollars) or $580 per household per day.

Several authors have estimated the hedonic value of potable water in the developing world (for example, in Ghana: Twerefou and others, 2015; in the Philippines: North and Griffin, 1993; in Rwanda: Kolowe, 2014). The present author could find no analogous studies for the United States.

The range suggested by the three U.S. sources is large: $102 to $580 per household per day in 2018 dollars. Let us revisit the question in the context of the HayWired scenario.

A New Estimate of the Daily Household Value of Potable Water

Bottled water will realistically be provided for free on street corners to residences and businesses, as it was in New Orleans after Katrina, but not at zero cost. Bulk bottled water seems to cost about $0.50 per gallon at the wholesaler, implying something like $0.75 per gallon delivered to street corners all over the east bay. At 1 gallon per person per day, and average household size of around 2.5, the cost to provide drinking water is about $2 per household per day.

Portable toilets will also be necessary. The national average rental and service cost is $260 per month and is up to 50 percent higher in San Francisco. (There may not be enough portable toilets in the entire national market to meet the need.) Assuming availability, at $260 per month, and assuming one portable toilet per household, portable toilet rental adds $9 per household per day.

The $11 direct cost seems small compared with the hedonic value of living like that for several weeks—how much people would pay not to have to use a portable toilet. There is no obvious market to use to assess the value of having to rely on the bottled water and to substitute portable toilets for internal plumbing. Short of a survey, we are forced to estimate a realistic number. The author estimates that a typical middle-class household would value the convenience of tap water and toilets at least $10−20 per household per day.

For showers, there is no market-based value of the effort of traveling to a Red Cross shelter. One can at least price the time, using the value that Independent Sector (2020) places on volunteer labor: about $25 per hour. Supposing a shower at the Red Cross shelter adds about an hour of effort per person in terms of travel, lines, and so on, at 2.5 occupants per household, showers add another $65 per household per day (in round numbers).

The foregoing items total $80 to $100 per household per day. That figure is exceeded by the cost of staying in short-term temporary accommodations (hotel and motel) and exceeds the cost of an apartment. It seems reasonable to assume, however, that there are insufficient temporary accommodations of either kind available because of people displaced by shaking damage to their homes. We use the median of the foregoing range to value the inconvenience of lost water service: $90 per household per day. This estimate is consistent with those in the literature on the subject (see, for example, Federal Emergency Management Agency, 2010; Heflin and others, 2013; and Aubuchon and others, 2014).

The total inconvenience cost of lost water service to residences can therefore be conservatively estimated to be $90 per household per day times 57.3 million service-days, totalling $5.2 billion. Using the values suggested by Heflin and others (2013), FEMA (2009), and Aubuchon and Morley (2013), the loss can be estimated as high as $5.8 billion, $14.9 billion, or $33 billion (2018 dollars), respectively.

Total Water Inconvenience Cost

It is conservatively estimated here that the inconvenience cost of the loss of water service to residential water customers is $5.2 billion.

Inconvenience Cost for Loss of Electricity

Loss of Electricity Service

The economic analysis relied on Hazus-MH estimates of the number of households without electric service across the study region (out of 3.6 million households) at days 1, 3, 7, 30, and 90, as shown in table 4.2.

Table 4.2. Number of households without electric service in days after the HayWired mainshock in the San Francisco Bay region, California, estimated using Hazus.

Day	Number of households without service
1	1,373,301
3	606,834
7	195,422
30	46,067
90	3,597

Let Q denote the total number of households (3.60 million) and let H_i denote the number of households without service on day t_i, from table 4.2. A large San Francisco Bay region earthquake would almost certainly cause temporary loss of electricity service to the entire region to protect equipment. Power would then be restored to locations where it was safe to do so, leaving 1.4 million households without electricity 24 hours later, as shown in table 4.2. For purposes of completing the numerical integration then, one can take $t_0 = 0$, $H_0 = 3.60$ million, and assume electricity is restored to the last customer by $t_6 = 180$ days (that is, $H_6 = 0$). Then one can estimate the average service-days lost per household L with equation 1, where

$$y_i = \frac{Q - H_i}{Q}. \quad (3)$$

Evaluating equation 1, $L = 2.9$ days, that is, the average customer is without electricity for about three days. (The average service-days lost per household remains the same to two significant figures whether one takes t_6 to be 91 days, 180 days, or 365 days.)

Literature on the Inconvenience Cost of Lost Residential Electric Service

FEMA [undated] offers a standard value of electric service of $131 per person per day. FEMA (2009, p. A-5) states without reference to the source that its standard values for loss of electric service is $126 per person per day, which in 2018 would equate with $150 per person per day and $375 per household per day for a household size of 2.5, or a total value lost of $3.9 billion. Again, let us revisit the question in the context of the HayWired scenario.

A New Estimate of the Daily Household Value of Residential Electric Services

Obvious sources of inconvenience costs include the following:

- *Food spoilage*.—After about 24–48 hours, one's freezer and refrigerator warm up and one must replace all the food. The Chicago Tribune recently estimated the average family refrigerator costs $250 to stock from scratch (O'Connell, 2017). It takes about 3 hours to replace all the food, with an associated inconvenience cost of $25 per hour, or $75 per household. The total labor and material cost sums to $325 per household that loses electricity for more than 1 day.

- *Inability to cook*.—One generally cannot dine outside of the house because restaurants would also be without power. Californians would therefore use emergency supplies, barbeque, or eat cold meals in the home. No obvious method presents itself to estimate the value of this inconvenience.

- *Inability to charge devices*.—And although some businesses will provide places to charge devices, presumably most people would charge a few devices in their automobile at negligible cost.

Only the inconvenience cost of food spoilage is estimated here, and thus represents a lower bound. Per table 4.2, 1.4 million households in the study area must replace their food at a cost of $325 per household, for a total cost of $450 million. However, using the FEMA (2009) figure, the total value lost could be estimated as high as $3.9 billion.

Appendix 5. Resource Isolation Resilience Factors

Table 5.1. Utility service importance factors by sector.

[Data from Applied Technology Council (1991). No., CGE sector number]

No.	Sector description	Water	Electricity	Telephone	Data and voice
		Importance factor			
1	Agriculture, forestry, fishing, and hunting	53	50	20	24
2	Oil and gas extraction	15	90	10	12
3	Coal mining	15	90	10	12
4	Other mining	15	90	10	12
5	Electric power generation/transmission/distribution	40	80	30	36
6	Natural gas distribution	40	80	30	36
7	Water, sewage, and other systems	40	80	30	36
8	Construction	50	40	10	12
9	Heavy industry	64	98	13	14
10	Light industry	64	99	17	16
11	Petroleum refineries	50	100	10	11
12	Food, drug, and chemicals	75	90	15	18
13	Primary metal manufacturing	90	90	15	19
14	Electronic computer manufacturing	90	100	15	18
15	Computer storage device manufacturing	90	100	15	17
16	Semiconductor and related device manufacturing	90	100	15	18
17	Other high-tech manufacturing	90	100	15	18
18	Wholesale trade, warehousing, and storage	20	90	50	60
19	Retail trade	20	90	50	60
20	Air transportation	20	30	30	36
21	Rail transportation	20	30	30	36
22	Water transportation	20	30	30	36
23	Truck transportation	20	30	30	36
24	Transit and ground passengers	20	30	30	36
25	Pipeline transportation	20	30	30	36
26	Sightseeing transportation	20	30	30	36
27	Couriers and messengers	20	30	30	36
28	Publishing, motion picture, and broadcasting	20	90	40	60
29	Internet publishing and broadcasting	20	90	40	60
30	Telecommunications	20	90	40	60
31	Data processing, hosting, and related services	20	90	40	60
32	Other information services	20	90	40	60
33	Finance, insurance, real estate, and leasing	20	90	60	80
34	Imputed rental value for owner-occupied dwellings	20	90	60	72
35	Computer systems design and related services	20	90	40	60
36	Other professional, scientific, and technical services	20	90	40	60
37	Other business services	20	90	40	60
38	Educational services	40	80	15	18

Table 5.1.—Continued

No.	Sector description	Water	Electricity	Telephone	Data and voice
		Importance factor			
39	Ambulatory health care and hospitals	40	80	15	23
40	Nursing home/social assistance	40	80	15	23
41	Arts, entertainment, and recreation	80	80	40	48
42	Accommodations	80	80	40	48
43	Repair and maintenance	20	90	40	48
44	Personal services/private households	20	90	40	48
45	Religious, grantmaking, and similar organizations	20	90	40	48
46	Government and non-NAICS	25	60	20	24

Table 5.2. Production recapture factors by sector.

[Data from FEMA (2012). Recapture is zero after 1 year. No., CGE sector number]

No.	Sector description	Days 1–90	Days 91–180	Days 181–270	Days 271–360
		Production recapture factor			
1	Agriculture, forestry, fishing, and hunting	0.38	0.28	0.19	0.09
2	Oil and gas extraction	0.49	0.37	0.25	0.12
3	Coal mining	0.49	0.37	0.25	0.12
4	Other mining	0.49	0.37	0.25	0.12
5	Electric power generation/transmission/distribution	0.45	0.34	0.23	0.11
6	Natural gas distribution	0.45	0.34	0.23	0.11
7	Water, sewage, and other systems	0.45	0.34	0.23	0.11
8	Construction	0.48	0.36	0.24	0.12
9	Heavy industry	0.49	0.37	0.25	0.12
10	Light industry	0.49	0.37	0.25	0.12
11	Petroleum refineries	0.49	0.37	0.25	0.12
12	Food, drug, and chemicals	0.49	0.37	0.25	0.12
13	Primary metal manufacturing	0.49	0.37	0.25	0.12
14	Electronic computer manufacturing	0.49	0.37	0.25	0.12
15	Computer storage device manufacturing	0.49	0.37	0.25	0.12
16	Semiconductor and related device manufacturing	0.49	0.37	0.25	0.12
17	Other high-tech manufacturing	0.49	0.37	0.25	0.12
18	Wholesale trade, warehousing, and storage	0.44	0.33	0.22	0.11
19	Retail trade	0.44	0.33	0.22	0.11
20	Air transportation	0.45	0.34	0.23	0.11
21	Rail transportation	0.45	0.34	0.23	0.11
22	Water transportation	0.45	0.34	0.23	0.11
23	Truck transportation	0.45	0.34	0.23	0.11
24	Transit and ground passengers	0.45	0.34	0.23	0.11
25	Pipeline transportation	0.45	0.34	0.23	0.11

Table 5.2.—Continued

No.	Sector description	Days 1–90	Days 91–180	Days 181–270	Days 271–360
		Production recapture factor			
26	Sightseeing transportation	0.45	0.34	0.23	0.11
27	Couriers and messengers	0.45	0.34	0.23	0.11
28	Publishing, motion picture, and broadcasting	0.45	0.34	0.23	0.11
29	Internet publishing and broadcasting	0.45	0.34	0.23	0.11
30	Telecommunications	0.30	0.23	0.15	0.08
31	Data processing, hosting, and related services	0.45	0.34	0.23	0.11
32	Other information services	0.45	0.34	0.23	0.11
33	Finance, insurance, real estate, and leasing	0.45	0.34	0.23	0.11
34	Imputed rental value for owner-occupied dwellings	0.30	0.23	0.15	0.08
35	Computer systems design and related services	0.45	0.34	0.23	0.11
36	Other professional, scientific, and technical services	0.45	0.34	0.23	0.11
37	Other business services	0.45	0.34	0.23	0.11
38	Educational services	0.30	0.23	0.15	0.08
39	Ambulatory health care and hospitals	0.30	0.23	0.15	0.08
40	Nursing home/social assistance	0.30	0.23	0.15	0.08
41	Arts, entertainment, and recreation	0.30	0.23	0.15	0.08
42	Accommodations	0.30	0.23	0.15	0.08
43	Repair and maintenance	0.26	0.19	0.13	0.06
44	Personal services/private households	0.26	0.19	0.13	0.06
45	Religious, grantmaking, and similar organizations	0.30	0.23	0.15	0.08
46	Government and non-NAICS	0.40	0.30	0.20	0.10

Appendix 6. Data- and Voice-Service Tables for Resilience Adjustment Cases

Data- and Voice-Services for the Base Case and Three Resilience Cases

Data and voice service restoration is modeled in Wein, Witkowski, and others, this volume. There are results for the percentage of customer demand met for a base case and three resilience cases: (1) use of permanent backup batteries and generators on telecommunications equipment; (2) use of portable equipment (such as cells on light trucks [COLTS] and cells on wheels [COWS]); and (3) implementation of user behavior management. Tables 6.1 to 6.4 show the percentage of customer demand for data and voice services met by county and by day for the base case and after each of the above three resilience tactics are applied. Table 6.5 shows the percentage of customer demand for data and voice services met by county and by day for the input substitution resilience case.

Table 6.1 Percentage of customer demand for data and voice service met by county and by day in the base case, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.5	8.5	16.8	30.8	41.4	53.4	63.3	73.9	79.8	96.0	100.0
Contra Costa	1.2	18.3	31.6	45.8	56.0	65.2	75.0	85.5	87.4	98.0	100.0
Marin	5.4	50.6	64.1	75.8	82.4	87.7	93.2	98.7	99.1	100.0	100.0
Merced	14.0	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Monterey	17.0	94.0	96.5	99.0	99.3	99.5	99.8	100.0	100.0	100.0	100.0
Napa	13.6	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Sacramento	19.0	98.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.0	63.0	76.0	89.0	91.3	93.5	95.8	98.0	98.0	100.0	100.0
San Francisco	2.2	33.2	51.0	66.6	75.6	82.2	89.0	96.1	97.2	100.0	100.0
San Joaquin	8.0	78.0	87.0	96.0	97.0	98.0	99.0	99.0	100.0	100.0	100.0
San Mateo	2.3	30.5	46.9	62.7	71.8	78.9	86.3	94.1	95.3	99.0	100.0
Santa Clara	0.8	16.0	29.0	43.5	53.8	63.6	74.2	85.5	87.4	98.0	100.0
Santa Cruz	12.0	83.0	90.0	97.0	97.8	98.5	99.3	100.0	100.0	100.0	100.0
Solano	7.9	58.4	68.6	78.9	84.0	88.9	93.9	99.0	99.1	100.0	100.0
Sonoma	13.0	71.8	77.5	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.2. Percentage of customer demand for data and voice service met by county and by day after adjustment for use of supplier batteries and generators, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	4.8	16.5	24.2	31.2	42.9	56.5	67.6	77.8	83.4	97.0	100.0
Contra Costa	7.0	28.1	32.6	48.7	60.8	70.1	79.1	88.5	90.1	98.7	100.0
Marin	11.4	57.9	64.7	76.9	83.9	89.0	94.0	99.1	99.4	100.0	100.0
Merced	19.4	94.0	93.9	98.9	99.2	99.5	99.7	100.0	100.0	100.0	100.0
Monterey	19.7	96.7	98.1	99.5	99.6	99.7	99.9	100.0	100.0	100.0	100.0
Napa	18.8	93.8	96.3	98.9	99.2	99.4	99.7	100.0	100.0	100.0	100.0
Sacramento	19.9	98.9	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	13.9	59.7	68.7	78.3	83.3	88.4	93.6	98.9	98.8	100.0	100.0
San Francisco	10.2	44.9	52.0	68.8	78.8	85.1	91.0	97.1	98.1	100.0	100.0
San Joaquin	18.8	87.9	92.9	97.8	98.3	98.9	99.4	100.0	100.0	100.0	100.0

Table 6.2.—Continued

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
San Mateo	10.5	44.1	48.1	65.7	76.3	83.0	89.3	95.8	96.9	99.3	100.0
Santa Clara	7.4	27.5	30.2	47.1	59.6	69.3	78.7	88.6	90.3	98.7	100.0
Santa Cruz	19.2	90.6	94.5	98.3	98.8	99.2	99.6	100.0	100.0	100.0	100.0
Solano	13.7	65.2	69.1	79.8	85.3	90.1	94.7	99.4	99.5	100.0	100.0
Sonoma	14.3	73.1	77.6	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.3. Percentage of customer demand for data and voice service met by county and by day after adjustment for use of portable equipment, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.5	8.5	16.8	32.8	48.8	67.0	83.6	92.9	93.9	99.6	100.0
Contra Costa	1.7	27.4	47.5	69.8	83.3	90.0	94.5	99.0	99.2	99.8	100.0
Marin	5.4	50.6	65.8	79.2	86.4	91.3	95.6	99.9	99.9	100.0	100.0
Merced	14.0	89.0	96.4	99.8	99.9	99.9	100.0	100.0	100.0	100.0	100.0
Monterey	17.0	94.0	98.1	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0
Napa	13.6	89.0	96.4	99.8	99.9	99.9	100.0	100.0	100.0	100.0	100.0
Sacramento	19.0	98.0	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.0	63.0	86.8	98.9	99.1	99.4	99.6	99.8	99.8	100.0	100.0
San Francisco	2.2	33.2	54.2	74.1	85.0	90.7	95.2	99.6	99.7	100.0	100.0
San Joaquin	8.0	78.0	92.9	99.6	99.7	99.8	99.9	100.0	100.0	100.0	100.0
San Mateo	2.3	30.5	50.5	72.0	84.2	90.4	94.9	99.4	99.5	99.9	100.0
Santa Clara	1.2	23.9	44.3	68.2	82.7	89.8	94.4	99.0	99.2	99.8	100.0
Santa Cruz	12.0	83.0	94.5	99.7	99.8	99.9	99.9	100.0	100.0	100.0	100.0
Solano	7.9	58.4	69.8	80.9	86.7	91.4	95.6	99.9	99.9	100.0	100.0
Sonoma	13.0	71.8	77.7	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.4. Percentage of customer demand for data and voice service met by county and by day after adjustment for customer behavior management, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.6	9.3	18.5	33.8	45.5	58.8	69.6	77.8	83.6	96.0	100.0
Contra Costa	1.9	30.1	47.8	64.5	74.4	81.5	85.8	90.0	91.5	98.0	100.0
Marin	5.9	55.6	70.5	83.4	90.7	95.7	97.2	98.7	99.1	100.0	100.0
Merced	15.4	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Monterey	18.7	94.0	96.5	99.0	99.3	99.5	99.8	100.0	100.0	100.0	100.0
Napa	14.9	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Sacramento	20.9	98.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.6	63.0	76.0	89.0	91.3	93.5	95.8	98.0	98.0	100.0	100.0
San Francisco	2.4	36.5	56.1	73.3	83.2	89.6	92.9	96.1	97.2	100.0	100.0
San Joaquin	8.8	78.0	87.0	96.0	97.0	98.0	99.0	100.0	100.0	100.0	100.0
San Mateo	2.5	33.5	51.6	68.9	79.0	86.1	90.1	94.1	95.3	99.0	100.0
Santa Clara	1.3	26.3	43.9	61.3	71.5	79.5	84.8	90.0	91.6	98.0	100.0
Santa Cruz	13.2	83.0	90.0	97.0	97.8	98.5	99.3	100.0	100.0	100.0	100.0

Table 6.4.—Continued

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Solano	8.7	64.3	75.5	86.8	92.4	97.0	98.0	99.0	99.1	100.0	100.0
Sonoma	14.3	79.0	85.3	91.6	96.3	100.0	100.0	100.0	100.0	100.0	100.0

Table 6.5. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for input substitution, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.6	10.1	20.2	36.9	49.6	64.1	75.9	88.7	95.7	100.0	100.0
Contra Costa	1.4	21.9	37.9	54.9	67.2	78.3	90.1	100.0	100.0	100.0	100.0
Marin	6.5	60.7	77.0	91.0	98.9	100.0	100.0	100.0	100.0	100.0	100.0
Merced	16.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Monterey	20.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Napa	16.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sacramento	22.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	7.2	75.6	91.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Francisco	2.7	39.9	61.2	79.9	90.7	98.6	100.0	100.0	100.0	100.0	100.0
San Joaquin	9.6	93.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Mateo	2.7	36.6	56.3	75.2	86.2	94.7	100.0	100.0	100.0	100.0	100.0
Santa Clara	1.0	19.2	34.8	52.2	64.6	76.3	89.0	100.0	100.0	100.0	100.0
Santa Cruz	14.4	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Solano	9.5	70.1	82.3	94.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sonoma	15.6	86.2	93.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Resilience Adjustment of Production Isolation

Production isolation refers to the portion of business operation that can continue without data and voice services. The "importance factors" of telephone service (Applied Technology Council, 1991) are shown in appendix 5, table 5.1, column 5. Based on the review of businesses that are mostly dependent on internet (Mushroom Networks, 2017), we scale the importance factors up by 50 percent for the following sectors (but cap the importance factors at 80 percent) to account for the large use of internet (not just telephone) for these sectors: publishing, motion picture, and broadcasting; internet publishing and broadcasting; telecommunications; data processing, hosting, and related services; other information services; finance, insurance, real estate, and leasing; computer systems design and related services; other professional, scientific, and technical services; other business services; ambulatory health care and hospitals; nursing home/social assistance. For the remaining sectors, we scale up the importance factors by 20 percent for all non-manufacturing sectors in appendix 5, table 5.1 to account for the important role of internet in every aspect of economic activities.

For manufacturing sectors, we adjust the scale-up factor of 20 percent up or down based on the U.S. Census Bureau's e-commerce data for individual manufacturing sectors relative to the manufacturing average dependence on e-commerce (U.S. Census Bureau, 2017).[1] For example, the average percentage of total shipments through e-commerce for the aggregated manufacturing sector was 63 percent in 2015. The percentage for fabricated metal product manufacturing is 50 percent. Therefore, we adjust the 20 percent scale-up factor downwards to 15.8 percent (20 percent × 50/63). Note that the e-commerce data are also available for wholesale trade, retail trade, and selected service sectors. However, we do not use these data to further adjust the data and voice importance factors for these sectors for two reasons. First, the e-commerce data for these sectors are significantly lower than those that are indicated by the telephone importance factors. The primary reason is that the e-commerce data pertain to the proportion of sale of goods and services that are achieved through online systems, rather than the proportion of business operations and production process (other than sale) that rely on information

[1]The Census e-commerce data report the percentage of sales of goods or services for which the orders are placed (or the price or terms of the sale are negotiated) through any online systems, including internet, mobile device, extranet, email, and so on (U.S. Census Bureau, 2017).

and communications technology (ICT) services. Second, we have already scaled up the telephone importance factors by 50 percent for the top service sectors that depend on ICT services, and 20 percent for all the other trade and service sectors as described above. We consider these adjustments have reasonably incorporated the information on the relative importance of ICT services on business operation across sectors. The production isolation percentages of data and voice service are calculated as 100 minus the importance factors shown appendix 5, table 5.1, column 6.

Based on the gross output by sector for each county, we calculated the weighted average production isolation factor for each county (see table 6.6). The smaller isolation factor value for a county reflects a profile of industries in the county that include more of the industries that have higher dependence on ICT services. For example, finance, insurance, and real estate (FIRE) are disproportionately more present in San Francisco.

> Equivalent voice and data service = Base case availability + (100 − Base case availability) × Production Isolation Factor.

Table 6.7 shows the percentage of availability of data and voice service by county and by day for the production isolation resilience case.

Table 6.6. Weighted average production-isolation factor of telecommunication by county, San Francisco Bay region, California.

County	Weighted average telecommunication isolation factor
Alameda	58.3
Contra Costa	69.0
Marin	44.8
Merced	66.7
Monterey	57.9
Napa	63.2
Sacramento	54.2
San Benito	68.3
San Francisco	44.6
San Joaquin	58.6
San Mateo	51.3
Santa Clara	63.0
Santa Cruz	56.6
Solano	67.3
Sonoma	57.5

Table 6.7. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for production isolation of telecommunication, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	58.5	61.8	65.3	71.1	75.6	80.6	84.7	89.1	91.6	98.3	100.0
Contra Costa	69.3	74.6	78.8	83.2	86.4	89.2	92.3	95.5	96.1	99.4	100.0
Marin	47.8	72.7	80.2	86.7	90.3	93.2	96.2	99.3	99.5	100.0	100.0
Merced	71.4	96.3	97.8	99.3	99.5	99.7	99.8	100.0	100.0	100.0	100.0
Monterey	65.1	97.5	98.5	99.6	99.7	99.8	99.9	100.0	100.0	100.0	100.0
Napa	68.2	96.0	97.6	99.3	99.4	99.6	99.8	100.0	100.0	100.0	100.0
Sacramento	62.9	99.1	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	70.2	88.3	92.4	96.5	97.2	97.9	98.7	99.4	99.4	100.0	100.0
San Francisco	45.8	63.0	72.8	81.5	86.5	90.1	93.9	97.9	98.5	100.0	100.0
San Joaquin	62.0	90.9	94.6	98.3	98.8	99.2	99.6	99.6	100.0	100.0	100.0
San Mateo	52.4	66.1	74.1	81.8	86.3	89.7	93.3	97.1	97.7	99.5	100.0
Santa Clara	63.3	68.9	73.7	79.1	82.9	86.5	90.4	94.6	95.3	99.3	100.0
Santa Cruz	61.8	92.6	95.7	98.7	99.0	99.3	99.7	100.0	100.0	100.0	100.0
Solano	69.9	86.4	89.7	93.1	94.8	96.4	98.0	99.7	99.7	100.0	100.0
Sonoma	63.0	88.0	90.5	92.9	94.7	96.5	98.2	100.0	100.0	100.0	100.0

Table 6.8. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for use of batteries/generators, use of cell sites on wheels or light trucks (COWs/COLTs), user behavior management tactics, input substitution, and production isolation, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	60.9	67.4	71.6	76.6	85.8	96.0	100.0	100.0	100.0	100.0	100.0
Contra Costa	73.3	86.2	88.9	98.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Marin	53.1	87.0	93.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Merced	75.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Monterey	68.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Napa	72.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sacramento	66.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	74.1	93.3	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Francisco	52.0	77.4	84.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Joaquin	68.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Mateo	58.0	79.6	84.5	98.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Santa Clara	68.4	83.1	85.4	97.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Santa Cruz	67.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Solano	73.2	95.5	97.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sonoma	65.5	98.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 6.8 shows the percentage availability of data and voice service by county and by day for all the above resilience cases combined.

Resilience Adjustment of Telework

Table 6.9 shows the percent of workers doing some or all of their work at home by major occupations in the United States in 2015. On average 24.1 percent of the workers across different economic sectors worked at least one day a week from home. We assume that this translates to 12 percent of full-time equivalent work from home (half of the 24.1 percent) because some workers worked less than 5 days a week from home. After the earthquake, we assume that the workers that ordinarily work less than full-time from home could have the capability of doing so from home or at an alternative location (such as hotel) when data and voice services become available. Based on the sectoral employment data by county and the Bureau of Labor Statistics telework data as shown in table 6.9, we computed the employment-weighted average telework percentage for each county in the first numerical column in table 6.11. Based on the assumption above, we assume that only half of these levels represent an incremental amount of telework potential after the earthquake.

Telework capacity will be affected as people deal with the physical and emotional effects of the earthquake. Therefore, we next adjust the incremental telework potential by the percentage of readiness of employees to go back to work, though remotely. A survey study following the Christchurch earthquake indicated that 35 percent of workers were ready to work within the first week. This percentage increased to 82 percent within 30 days and 96 percent within 12 weeks (Donnelly and Proctor-Thomson, 2013). We also adjusted the Christchurch worker-readiness percentages up and down depending on how hard the counties are hit by the earthquake. Specifically, we assume 50 percent lower readiness for the hardest hit counties (Alameda, Contra Costa, and Santa Clara); use the Christchurch percentages for San Francisco, San Mateo, and San Benito; and assume 50 percent higher readiness for all the other counties. This telework potential in the third column of table 6.11 can, in general, be applied to reduce the gross regional product (GRP) losses from property damages.

Two additional factors that affect the feasibility of telework when data and voice services are necessary are analyzed next. First, we assume that telework is only possible when people have internet access. Second, telework may depend on the availability of backup data if the local data are destroyed by the earthquake. For the first factor, we adjust incremental telework percentages by the percentage of data and voice service demand met for the base case. For the second factor, we

- Assume the percentage of loss of local data equals the percentage of content damages by sector and by county.
- Use data on the level of adoption of cloud technologies by major industries (see table 16). For other industries, we assume the level of adoption is half of the lowest average adoption percentage of the top 10 industries (that is, 25 percent).
- Calculate the further decreases in telework potential as: Percentage content damage × (1 – Percentage adoption of cloud technologies).

Columns 4 to 9 in table 6.10 show the increased telework potential after the adjustment for worker readiness, data and voice service restoration, and cloud backup data. These percentages are used to lower the GRP loss estimates from the base case computable general equilibrium (CGE) simulation results.

Table 6.9. Percentage of workers doing some or all of their work on their main job at home in 2015.

[Data from Bureau of Labor Statistics (2017)]

Management, business, and financial operations occupations	Professional and related occupations	Service occupations	Sales and related occupations	Office and administrative support occupations	Construction and extraction occupations	Installation, maintenance, and repair occupations	Production occupations	Transportation and material moving occupations	Total
37.8	34.6	10.5	22.1	11.2	16.2	9.6	5.5	7.7	**24.1**

Table 6.10. Percentage of top industries adopting cloud technologies.

[Data from Kerrest (2016)]

Industry	Cloud document storage	Cloud mail	Cloud developer tools	Average
	Percentage of industry			
Internet and software		90	60	75
Marketing and advertising	70	80	70	73
Biotechnology and pharmaceuticals	60	81		71
Real estate	60	80	27	56
Not-for-profit		90	30	60
Retail	30	70		50
Construction	64	64	18	49
Hospitals and healthcare		72	41	57
Education	40	87	24	50
Finance	70		32	51

Table 6.11. Estimated percentage increase of employee telework, by day and by county, San Francisco Bay region, California.

County	Weighted-average telework potential (percent)	Incremental telework potential (percent)	Increased telework after adjusting for worker readiness, data- and voice-service restoration, and cloud data backup adoption (percent)										
			Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
Alameda	19.7	9.8	0.0	0.1	0.3	0.5	0.7	0.9	1.0	1.2	1.5	3.7	4.5
Contra Costa	21.3	10.7	0.0	0.3	0.6	0.8	1.0	1.2	1.4	1.6	1.8	4.2	5.0
Marin	22.7	11.3	0.3	3.0	3.8	4.5	4.9	5.2	5.5	5.8	6.3	11.3	11.3
Merced	14.0	7.0	0.5	3.3	3.4	3.6	3.6	3.6	3.7	3.7	4.0	7.0	7.0
Monterey	15.3	7.6	0.7	3.8	3.9	4.0	4.0	4.0	4.0	4.0	4.3	7.6	7.6
Napa	16.7	8.4	0.6	3.9	4.1	4.3	4.3	4.3	4.4	4.4	4.7	8.4	8.4
Sacramento	19.3	9.7	1.0	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.5	9.7	9.7
San Benito	15.1	7.6	0.2	1.7	2.0	2.3	2.4	2.5	2.5	2.6	2.9	6.2	7.2
San Francisco	22.6	11.3	0.1	1.3	2.0	2.6	3.0	3.2	3.5	3.8	4.3	9.2	10.8
San Joaquin	17.4	8.7	0.4	3.6	4.0	4.4	4.4	4.5	4.5	4.5	4.9	8.7	8.7
San Mateo	22.2	11.1	0.1	1.2	1.8	2.4	2.8	3.0	3.3	3.6	4.1	8.9	10.6
Santa Clara	20.5	10.3	0.0	0.3	0.5	0.8	1.0	1.1	1.3	1.5	1.7	4.1	4.8
Santa Cruz	18.3	9.2	0.6	4.0	4.3	4.7	4.7	4.7	4.8	4.8	5.2	9.1	9.1
Solano	17.0	8.5	0.3	2.6	3.0	3.5	3.7	3.9	4.2	4.4	4.7	8.4	8.4
Sonoma	18.8	9.4	0.6	3.5	3.8	4.1	4.3	4.5	4.7	4.9	5.3	9.4	9.4

Appendix 7. Adjustments on the Economic Impacts for Electricity and Water Service Disruptions

The input-output table and social accounting matrix of IMPLAN (short for impact analysis for planning) are the most widely used sources of data for constructing computable general equilibrium (CGE) models in the United States today. However, they do have some limitations. One of them is a lack of disaggregation of the State and local government enterprises sector of the final demand quadrant. A major example pertains to government provision of water services, which is not separately identified. IMPLAN databases do, however, include this sector explicitly in the transactions table (intermediate goods and services production) quadrant for local private sector water service providers. The second issue is that, even where public sector utilities are separated out, the data are considered sub-standard, because they are downscaled from national and State economic production structures that do not accurately reflect local conditions. This is especially problematic for the case of electric utilities, where the national structure is dominated by large-scale operations. Hence, we did not choose to use the disaggregated State and local government electricity sector in our analysis.

To compensate for the inadequacy of data on public utilities in IMPLAN, analysts have two choices. One is to undertake some disaggregation or refinement of the State and local government enterprises sector to identify each of these sectors individually by use of supplementary data and data transfer methods or some combination of the two. This requires adding more sectors to the CGE model and can be a cumbersome process. The other is to adjust the results by some ratios of aggregate economic activity between private sector and public sector versions of each type of utility.[1] We have chosen this second, more straightforward, approach.

Tables 7.1 and 7.2 present the adjustment factors on government provision of water and electricity in the four main counties affected by the HayWired scenario earthquake (Alameda, Contra Costa, San Francisco, and Santa Clara) and their effect on gross regional product (GRP) in those counties, the rest of the bay region, and the rest of the State. This appendix also presents the method and data sources we used to calculate the adjustment factors. These factors for the four main counties in the bay region are calculated separately based on the data on private and public provisions of water and power services in each county. We then applied a weighted average of the adjustment factors of the four counties to the other regions. For the rest of the bay region, this weighted average adjustment factor is intended to factor in the public and private sector adjustment for this region, as well as for the adjustment in the interregional multiplier effects of the four main counties on other counties in the bay region. For the rest of California, the factor is applied to take into consideration the adjustment in the interregional multiplier effects of the earthquake in directly affected counties on other counties in the State.

Alameda County has a very high adjustment factor because the majority of the water supply in this county comes from public providers. The IMPLAN private water sector only has an output of $35.5 million. Additional calculations indicate that Alameda County customers received $202.2 million worth of water from the East Bay Municipal Utility District (EBMUD) and another $76.1 million from the San Francisco Public Utility (SFPU).

Essentially, for California as a whole, there is only a 32.1 percent increase in the gross State product (GSP) losses from electricity disruptions, but the increase in GSP losses from water disruptions is nearly 650 percent. The reason for this very large difference in adjustments is due to the very large difference in State and local provision of electricity and water services, which were not separately identified in the underlying IMPLAN data. Only a relatively small proportion of electricity in the affected areas is provided by State and local government electricity generators, whereas a major proportion of water services are provided by the East Bay Municipal Utility District.[2]

We have applied the same adjustment factors presented in column 3 of tables 7.1 and 7.2 to the GRP change results of water and electricity service disruptions for the various resilience cases by region to obtain the final results presented in tables 17 and 19.

[1]Note that there are no government-provided data or voice services, so the adjustment need only be made for electricity and water.

[2]Our adjustment methodology is applicable to all States in which there is a significant proportion of either or both electricity or water services provided by Sstate and local government sources. Note also that this adjustment method will become less necessary as more electricity becomes generated by distributed sources in private hands (such as rooftop solar and smaller windfarms), both because the services are not part of the State and local government sector and also because they are less vulnerable to network outages.

Table 7.1. Gross regional product (GRP) change caused by electricity-service disruptions in the 6 months following the HayWired mainshock by county, in the San Francisco Bay region, California.

Area	GRP change before adjustment (in billions of 2012 dollars)	Adjustment factor	Difference in GRP change from applying adjustment factors (in billions of 2012 dollars)	GRP change after adjustment (in billions of 2012 dollars)
Alameda	−0.020	1.1371	−0.0027	−0.0227
San Francisco	−0.010	1.4273	−0.0043	−0.0143
Contra Costa	−0.008	1.0947	−0.0008	−0.0088
Santa Clara	−0.025	1.4981	−0.0125	−0.0375
4-county total	−0.063	1.3210	−0.0202	−0.0832
Rest of bay region	−0.015	1.3210	−0.0048	−0.0198
Bay region total	−0.078	1.3210	−0.0250	−0.1030
Rest of California	−0.022	1.3210	−0.0071	−0.0291
California total	**−0.100**	**1.3210**	**−0.0321**	**−0.1321**

Table 7.2. Gross regional product (GRP) change caused by water-service disruptions in the 6 months following the HayWired mainshock by county, in the San Francisco Bay region, California.

Area	GRP change before adjustment (in billions of 2012 dollars)	Adjustment factor	Difference in GRP change from applying adjustment factors (in billions of 2012 dollars)	GRP change after adjustment (in billions of 2012 dollars)
Alameda	−0.074	8.8386	−0.5801	−0.6541
San Francisco	−0.002	1.2407	−0.0005	−0.0025
Contra Costa	−0.013	1.6864	−0.0089	−0.0219
Santa Clara	−0.005	4.6711	−0.0184	−0.0234
4-county total	−0.094	7.4661	−0.6078	−0.7018
Rest of bay region	−0.011	7.4661	−0.0711	−0.0821
Bay region total	−0.105	7.4661	−0.6789	−0.7839
Rest of California	−0.017	7.4661	−0.1099	−0.1269
California total	**−0.122**	**7.4661**	**−0.7889**	**−0.9109**

Method and Data Sources for Calculating the Adjustment Factors of Public Versus Private Power and Water Provisions

Electricity

We took the following steps to separate total electricity demand in Alameda, Contra Costa, San Francisco, and Santa Clara Counties between services provided by Pacific Gas and Electric (PG&E) and municipal providers using the data in table 7.3:

1. Obtain data on total electricity consumption for the residential and nonresidential sector for each county in 2012 from the California Energy Commission (CEC) consumption database (CEC, 2020).
2. Obtain 2012 data on electricity generation at the state level for all major power producing entities, including municipal utilities.
3. For each county, subtract the amount of electricity produced by utilities other than PG&E and that was self-generated, from total electricity consumption reported by the CEC to arrive at the total amount produced by PG&E. For example, for San Francisco County, we subtracted electricity produced by the Power Enterprise of the San Francisco Public Utilities Commission and self-generation from the total annual electricity consumption of San Francisco County.
4. Differentiate between production from PG&E versus self-generated by calculating the share of self-generation within the entire area in which PG&E operates as reported by CEC; since the data is not available for specific counties, we assumed that the proportion is the same for all four counties.

5. Use the above calculations as an input for estimating annual sales of electricity. We multiply the amount estimated by utility providers in each county by the average annual electricity price in California in 2012 as reported by the U.S. Energy Information Administration (2020). Our method implicitly assumes that the price of electricity in different counties and produced by different utilities is the same across the State, which is a simplification. For each utility, however, we calculated a different price for nonresidential electricity based on a weighted average of electricity prices for commercial and industrial use and that utility's supply to those sectors as reported by the CEC for 2012. Industrial clients, for example, make up a larger share of total electricity sold for PG&E than for the Power Enterprise of the San Francisco Public Utilities Commission, which sells primarily to commercial clients. Therefore, its average electricity price for the nonresidential sector is more heavily weighted toward average prices for industrial supply.
6. In PG&E service area, calculate that 92.6 percent of self-generation is by nonresidential sectors.
7. For each county, calculate the ratio of total electricity (private plus public) to private electricity provision by dividing total electricity supply by the supply from PG&E in each county. These ratios are used as the adjustment factors to the GRP changes in the original HayWired report.

Table 7.3. Estimation of electricity supply by power producing entities in 2012 in Alameda, Contra Costa, San Francisco, and Santa Clara Counties, California.

[Data from 2012. kWh, kilowatthour]

Utility	County	Residential usage (in millions of kWh)[1]	Nonresidential usage (in millions of kWh)[1]	Residential price (in cents per kWh)[2]	Nonresidential price (in cents per kWh)[2]	Residential annual sales (dollars)	Nonresidential annual sales (dollars)	Total sales (dollars)
Alameda Municipal Power	Alameda	140	234	15.34	13.14	21,424,611	30,762,068	**52,186,679**
Hercules Municipal Utility	Contra Costa	4	12	15.34	12.39	595,652	1,505,228	**2,100,880**
Port of Oakland	Alameda	0	47	15.34	13.10	0	6,192,615	**6,192,615**
Power Enterprise, San Francisco Public Utilities Commission	San Francisco	22	966	15.34	13.34	3,375,268	128,922,280	**132,297,548**
Silicon Valley Power	Santa Clara	244	2,659	15.34	12.15	37,460,280	323,077,587	**360,537,867**
Palo Alto Utilities Department	Santa Clara	158	778	15.34	12.74	24,222,627	99,084,901	**123,307,528**
Self-generation	Alameda	46	749	15.34	11.10	7,121,249	83,150,149	**90,271,398**
Self-generation	San Francisco	24	348	15.34	11.10	3,709,060	38,583,498	**42,292,558**
Self-generation	Contra Costa	45	646	15.34	11.10	6,884,937	71,694,184	**78,579,122**
Self-generation	Santa Clara	57	940	15.34	11.10	8,680,578	104,288,598	**112,969,177**
Pacific Gas and Electric	Alameda	2,815	6,571	15.34	12.63	431,787,854	830,198,119	**1,261,985,974**
Pacific Gas and Electric	San Francisco	1,466	3,049	15.34	12.63	224,894,130	385,230,187	**610,124,317**
Pacific Gas and Electric	Contra Costa	2,721	5,666	15.34	12.63	417,459,383	715,818,046	**1,133,277,429**
Pacific Gas and Electric	Santa Clara	3,431	8,242	15.34	12.63	526,335,782	1,041,251,272	**1,567,587,054**

[1]Data from California Energy Commission (2020).

[2]Data from U.S. Energy Information Administration (2020).

Water

Water sales from three major public water suppliers to Alameda, Contra Costa, San Francisco, and Santa Clara are calculated below.

East Bay Municipal Utility District (EBMUD)

The total revenues of EBMUD from water sales in 2012 was $306.2 million (EBMUD, 2015). EBMUD's service area encompasses cities in northern Alameda County and western and central Contra Costa County. In order to calculate the proportions of EBMUD's water that is sold to customers in Alameda and Contra Costa, we looked up the largest cities that are fully served by the EBMUD. These cities make up 77 percent of the overall population served by EBMUD. We then calculate that 66 percent of the population is in Alameda and 34 percent is in Contra Costa. These percentages are used to split the water sales of EBMUD between Alameda and Contra Costa.

San Francisco Public Utilities Commission (SFPUC)

The total revenues of SFPUC from charges of water services in 2012 was $356.6 million (SFPUC, 2013). One third of SFPUC's delivered water goes to San Francisco, another two-thirds delivered to customers in Alameda, Santa Clara, and San Mateo counties. Table 7.4 presents SFPUC water sales to wholesale water districts outside of San Francisco. We use the percentage estimates in table 7.4 to calculate the water sales from SFPUC to San Francisco, Alameda, and Santa Clara.

Santa Clara Valley Water District (SCVWD)

In 2012, water sales from SCVWD to Santa Clara County was $62.1 million (SCVWD, 2013).

In table 7.5 we summarize the water sales from private and public providers for the four counties.

Table 7.4. San Francisco Public Utilities Commission water sales in 2012, San Francisco Bay region and rest of California.

[Data from San Francisco Public Utilities Commission (2013). n/a, not applicable]

Customer	County	Sales (hundred cubic feet)	Percentage of total water sales
California Water Service	n/a	16,081,887	15.54
Hayward Municipal Water	Alameda	7,610,980	7.36
City of Palo Alto	Santa Clara	5,561,559	5.38
City of Sunnyvale	Santa Clara	4,406,804	4.26
City of Redwood City	San Mateo	4,420,594	4.27
City of Mountain View	Santa Clara	4,273,100	4.13
Alameda County Water District	Alameda	3,953,054	3.82
City of Milpitas	Santa Clara	3,027,111	2.93
City of Daly City	San Mateo	1,766,549	1.71
Estero Municipal Improvement District	San Mateo	1,982,291	1.92
All other wholesale customers	n/a	17,549,128	16.96
Wholesale water sales	n/a	70,633,057	68.27
Total water sales	n/a	**103,455,390**	**100.00**

Table 7.5. Water sales from private and public providers and adjustment factors for Alameda, San Francisco, Contra Costa, and Santa Clara Counties, California.

County	Water sales from private sector[1]	Water sales from public sector	Total water sales	Adjustment factor (ratio of total to private water sales)
	(in millions of 2012 dollars)			
Alameda	35.5	[2,4]278.3	313.8	8.839
San Francisco	493.8	[4]118.9	612.7	1.241
Contra Costa	151.5	[2]104.0	255.5	1.686
Santa Clara	47.9	[3,4]175.7	223.6	4.671

[1]Data from IMPLAN (2014).

[2]Data from East Bay Municipal Utility District (2015).

[3]Data from Santa Clara Valley Water District (2013).

[4]Data from San Francisco Public Utilities Commission (2013).

Appendix 8. Technical Description of the Dynamic Economic Model

Introduction

We specify a multiregional dynamic model of the California economy that simulates the effect of the earthquake on capital accumulation and growth in affected and unaffected regions of the State over the 17-year (2018–2035) horizon on a semi-annual timestep.

Algebraic Structure

Table 8.1 outlines the model's variables and their parameterization. The model follows the standard multiregional Ramsey growth model formulation (Acemoglu, 2009), in which a social planner allocates consumption, investment, exports, and imports to maximize social welfare (W) defined as the weighted sum of regional consumers' present discounted value of utility. We assume that consumers in each region have a logarithmic utility function denominated over per-capita consumption, which permits specification of the objective function as:

$$\max_{\widetilde{QC}_{r,t},\widetilde{QI}_{r,t},\widetilde{QX}_{r,t},\widetilde{QM}_{r,t},\widetilde{QZ}_{r,t}} W = \Sigma_r \omega_r \Sigma_{t=0}^{T} \vartheta_t \widetilde{QL}_{r,t} \log\left(\widetilde{QC}_{r,t} / \widetilde{QL}_{r,t}\right). \quad (5a)$$

In this expression r and $t=\{0, \ldots, T\}$ index counties and time periods, ω_r is a vector of welfare weights, ϑ_t is a discount factor, and $\widetilde{QC}_{r,t}$ and $\widetilde{QL}_{r,t}$ denote the quantities of consumption and labor supply. For simplicity, employment is assumed to be synonymous with the working population and is treated as exogenous. Throughout, the variables used in this model are aggregate analogues of the corresponding primal quantity variables defined in appendix 2, which we identify using a tilde (~).

The objective in equation 5a is maximized subject to several constraints. The first is the primal definition of production analogous to equations 1a through 1e, in which firms in each county produce a homogeneous final good from a constant elasticity of substitution (CES) composite of capital and labor that substitutes for an aggregate of intermediate inputs. We specify this nested production function in "calibrated share" form:

$$\widetilde{QY}_{r,t} = \overline{QY}_r \left(\begin{array}{l} \tilde{\alpha}_{KL,r} \left(\widetilde{QKL}_{r,t} / \overline{QKL}_r \right)^{(\tilde{\sigma}_Y - 1)/\tilde{\sigma}_Y} + \\ \tilde{\alpha}_{Z,r} \left(\widetilde{QZ}_{r,t} / \overline{QZ}_r \right)^{(\tilde{\sigma}_Y - 1)/\tilde{\sigma}_Y} \end{array} \right)^{\tilde{\sigma}_Y/(\tilde{\sigma}_Y - 1)} \text{ and, } \quad (5b)$$

$$\widetilde{QKL}_{r,t} = \overline{QKL}_r \left(\begin{array}{l} \tilde{\alpha}_{K,r} \left(K_{r,t} / \bar{K}_r \right)^{(\tilde{\sigma}_{KL} - 1)/\tilde{\sigma}_{KL}} + \\ \tilde{\alpha}_{L,r} \left(\widetilde{QL}_{r,t} / \overline{QL}_r \right)^{(\tilde{\sigma}_{KL} - 1)/\tilde{\sigma}_{KL}} \end{array} \right)^{\tilde{\sigma}_{KL}/(\tilde{\sigma}_{KL} - 1)}, \quad (5c)$$

where $\overline{QY}_r$, $\overline{QKL}_r$, $\overline{QZ}_r$, and $\overline{QL}_r$ are parameters that denote sectoral aggregations of benchmark quantities from the IMPLAN social accounting matrix that are consistent with the computable general equilibrium (CGE) model's baseline equilibrium, the CES distribution parameters, $\tilde{\alpha}_{KL,r}$, $\tilde{\alpha}_{Z,r}$, $\tilde{\alpha}_{K,r}$, and $\tilde{\alpha}_{L,r}$ are the aggregate analogues of the sectoral input coefficients, and the elasticities of substitution, $\tilde{\sigma}_Y$ and $\tilde{\sigma}_{KL}$, quantify the degree of fungibility between factor inputs and intermediate use of commodities by producers, and between capital and labor, respectively. Compared to the detailed representation of production in the CGE model, the present two-level formulation is simplified and aggregated for the purpose of computational tractability in capturing the economy's dynamics. It does not resolve differences among sectors' production or the supply and use of their intermediate inputs. Note that $K_{r,t}$ and $\bar{K}_r$ indicate the county-specific capital stock as opposed to the value of capital input (that is, the services that flow from the stock). Second, analogous to equation 3g, production of the final good satisfies county-specific demands for domestic uses and exports, where for simplicity the latter aggregate together goods that are destined for other counties, the rest of the United States, and foreign countries:

$$\widetilde{QY}_{r,t} \geq \widetilde{QD}_{r,t} + \widetilde{QX}_{r,t}. \quad (5d)$$

Third, we develop an aggregate approximation to the CGE model's Armington (1969) formulation of intermediate goods trade. As in equations 2a through 2e, counties' exports are treated as imperfect substitutes that feed into an aggregate supply pool, which in turn satisfies all counties' import demands. The former is modeled as a CES aggregation technology, specified according to the calibrated share form, that yields the supply-demand balance condition:

$$\bar{X} \left(\Sigma_r \tilde{\beta}_{X,r} \left(\widetilde{QX}_{r,t} / \overline{QX}_r \right)^{(\tilde{\sigma}_X - 1)/\tilde{\sigma}_X} \right)^{\tilde{\sigma}_X/(\tilde{\sigma}_X - 1)} \geq \Sigma_r \widetilde{QM}_{r,t}, \quad (5e)$$

in which $\tilde{\sigma}_X$ is the elasticity of substitution among exporters, the CES distribution parameters, $\tilde{\beta}_{X,r}$ are region-specific technical coefficients, and $\bar{X} = \Sigma_r \overline{QX}_r$ denotes the aggregate quantity of exports from all California regions. In turn, each county's total supply of the final good is an Armington composite of domestic and imported varieties:

$$\widetilde{QA}_{r,t} = \overline{QA}_r \left(\begin{array}{l} \beta_{D,r} (\widetilde{QD}_{r,t} / \overline{QD}_r)^{(\tilde{\sigma}_A - 1)/\tilde{\sigma}_A} + \\ \beta_{M,r} \left(\widetilde{QM}_{r,t} / \overline{QM}_r \right)^{(\tilde{\sigma}_A - 1)/\tilde{\sigma}_A} \end{array} \right)^{\tilde{\sigma}_A/(\tilde{\sigma}_A - 1)} \quad (5f)$$

where $\tilde{\sigma}_A$ is the Armington domestic-import elasticity of substitution, and $\tilde{\beta}_{D,r}$ and $\tilde{\beta}_{M,r}$ are CES distribution parameters.

Fourth, as in equation 3i, each county's Armington composite satisfies domestic demands for consumption, investment and intermediate commodity uses:

$$\widetilde{QA}_{r,t} \geq \widetilde{QC}_{r,t} + \widetilde{QI}_{r,t} + \widetilde{QZ}_{r,t}. \quad (5g)$$

Fifth, the dynamics of the economy are determined by two forces. Growth is fundamentally determined by the exogenous increase in each county's aggregate supply of labor with population expansion (given by growth rates, $\tilde{g}_r$):

$$\widetilde{QL}_{r,t} = \widetilde{QL}_{r,0}\left(1+\tilde{g}_r\right)^t \quad (5h)$$

and endogenous accumulation of capital that follows the perpetual inventory equation:

$$\tilde{K}_{r,t+1} = \kappa_0 \widetilde{QI}_{r,t} + \kappa_1 \widetilde{QI}_{r,t-1} + \kappa_2 \widetilde{QI}_{r,t-2} + \left(1-\delta\right)\tilde{K}_{r,t}, \quad (5i)$$

where δ denotes the rate of depreciation. Time-to-build lags in new capital formation have a significant economic impact at the fine temporal resolution of our analysis, with the duration of construction exceeding 12 months for multi-unit residential buildings. Accordingly, we model investment as maturing into new capital over three periods, controlled by the parameters κ_0, κ_1, and κ_2, whose values are all set to 1/3. Initial capital stocks ($\tilde{K}_{r,0}$) are fixed and are subjected to exogenous perturbations that represent aggregate capital stock destruction from shaking and fires. Finally, we close the model by mandating consistency between investment in the terminal period and balanced growth over the postterminal infinite horizon

$$\widetilde{QI}_{r,T} \geq \left(\tilde{g}_r + \delta\right)\tilde{K}_{r,T}. \quad (5j)$$

Model Calibration, Formulation, Solution, and Application

For computational tractability, and to facilitate detailed understanding of the long-run impacts on the hardest hit counties, we collapse the geographic dimension of the economy into the seven aggregate regions in table 23 (Alameda, Contra Costa, San Francisco, San Mateo, Santa Clara, rest of the San Francisco Bay region, and rest of California). The parameter vectors $\tilde{\boldsymbol{\alpha}}$ and $\tilde{\boldsymbol{\beta}}$ are calibrated using the benchmark quantities in the IMPLAN social accounts, which are also used to initialize the growth model, as shown in table 8.1. We use a depreciation rate of 5 percent, an interest rate of 2.65 percent (equivalent to the average yield on 10-year treasury bonds), and average rates of growth of the labor supply based on California Department of Finance (2017) population projections,[1] consistent with our 6-month timestep (δ=0.025, ρ=0.0133, $\tilde{g}_r$=0.7–1.1 percent). Each county's welfare weight is approximated by its fraction of statewide initial period utility, $\omega_r = \log\left(\widetilde{QC}_{r,0} / \widetilde{QL}_{r,0}\right) / \Sigma_{r'} \log\left(\widetilde{QC}_{r',0} / \widetilde{QL}_{r',0}\right)$. The elasticities of substitution were unchanged from their CGE model counterparts ($\tilde{\sigma}_Y$=0.1, $\tilde{\sigma}_{KL}$=0.25, $\tilde{\sigma}_A$=0.5,$\tilde{\sigma}_X$ =2). The model is formulated as a nonlinear program in GAMS and solved using the CONOPT solver (Drud, 1994; GAMS, 2018).

[1]Total estimated and projected population for California and counties: July 1, 2010, to July 1, 2060, in 1-year increments.

Table 8.1. Parameterization of the dynamic economic model.

A. Set indexes

Index	Explanation
i	Commodity
j	Sector
r	County
t	Time period
h	Household income class
g	Level of government

B. Key parameters and benchmark quantities from the IMPLAN social accounting matrix

Quantity	Explanation
ρ	Interest rate
$\bar{q}_{i,C,h,r}$	Private consumption by commodity, county, and household income class
$\bar{q}_{i,I,r}$	Private investment by commodity and county
$\overline{QXUS}_{i,r}$	Exports to U.S. markets by commodity and county
$\overline{QMUS}_{i,r}$	Imports from U.S. markets by commodity and county
$\overline{QD}_{r}$	Aggregate domestic use by county
$\overline{QL}_{j,r}$	Labor input by sector and county
$\overline{QY}_{j,r}$	Output by sector and county
δ	Depreciation rate
$\bar{q}_{i,G,g,r}$	Government consumption by commodity, county, and level of government
$\bar{q}_{i,j,r}$	Intermediate use by commodity, using sector and county
$\overline{QXF}_{i,r}$	Exports to foreign markets by commodity and county
$\overline{QXM}_{i,r}$	Imports from foreign markets by commodity and county
$\overline{QA}_{r}$	Aggregate Armington commodity use by county
$\overline{QK}_{i,r}$	Capital input by sector and county

C. Dynamic model variables and their initialization

Variable	Initialization	Explanation
$\widetilde{QC}_{r,t}$	$\widetilde{QC}_{r,0} = \overline{QC}_{r} = \Sigma_i \Sigma_h \bar{q}_{i,C,h,r} + \Sigma_i \Sigma_g \bar{q}_{i,G,g,r}$	Quantity of aggregate consumption (private and government)
$\widetilde{QI}_{r,t}$	$\widetilde{QI}_{r,0} = \overline{QI}_{r} = \Sigma_i \bar{q}_{i,I,r}$	Quantity of aggregate investment
$\widetilde{QZ}_{r,t}$	$\widetilde{QZ}_{r,0} = \overline{QZ}_{r} = \Sigma_j \bar{q}_{i,j,r}$	Quantity of intermediate commodity use
$\widetilde{QX}_{r,t}$	$\widetilde{QX}_{r,0} = \overline{QX}_{r} = \Sigma_i \left(\overline{QXUS}_{i,r} + \overline{QXF}_{i,r} \right)$	Quantity of aggregate exports
$\widetilde{QM}_{r,t}$	$\widetilde{QM}_{r,0} = \overline{QM}_{r} = \Sigma_i \left(\overline{QMUS}_{i,r} + \overline{QMF}_{i,r} \right)$	Quantity of aggregate imports
$\widetilde{QD}_{r,t}$	$\widetilde{QD}_{r,0} = \overline{QD}_{r} = \Sigma_j \overline{QY}_{j,r} - \overline{QX}_{r}$	Quantity of aggregate domestic use
$\widetilde{QA}_{r,t}$	$\widetilde{QA}_{r,0} = \overline{QA}_{r} = \overline{QD}_{r} + \overline{QM}_{r}$	Quantity of Armington aggregate commodity use
$\widetilde{QL}_{r,t}$	$\widetilde{QL}_{r,0} = \overline{QL}_{r} = \Sigma_j \overline{QL}_{j,r}$	Labor supply
$\tilde{K}_{r,t}$	$\tilde{K}_{r,0} = \bar{K}_{r} = \Sigma_j \overline{QK}_{j,r} / \left(\rho + \delta \right)$	Capital stock

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Chapter V3

The Economic Effects of the HayWired Scenario Using the Association of Bay Area Governments Regional Growth Forecast

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Abstract

This chapter uses existing modeling techniques that underlie the 2015 regional economic forecast of the San Francisco Bay region, California, to estimate how a major earthquake along the Hayward Fault would change the trajectory of that forecast. The Association of Bay Area Governments (ABAG) creates long-term regional forecasts of employment, population, and households that span a period of two to three decades. The forecast released in January 2015 is built on the framework of a Regional Economic Models, Inc. (REMI) model for the San Francisco Bay region and projects growth in the bay region through 2040. This chapter uses the simulation tools in the REMI model to apply the HayWired building damages from the HayWired scenario capital and output losses estimated using the Federal Emergency Management Agency's Hazus model to ABAG's economic and demographic 2015 regional forecast.

We apply Hazus estimates of direct output losses from a moment magnitude (M_w) 7.0 earthquake along the Hayward Fault to the REMI model, to examine direct, indirect, and induced effects on gross regional product (GRP), employment, and population. The analysis shows an economy that would experience substantial damages and losses in the short term. In the first year, employment would drop by almost half a million jobs, whereas GRP would decrease by 8 percent. The two counties near the epicenter of the earthquake would be greatly affected, with a 15 percent loss in jobs and 13 percent loss in GRP. Population losses because of the economic effect would be smaller—on the order of 150,000 (or 2 percent) in the first year, although previously reported analyses suggest that displacement within the region could be much higher, and social effects could lead to a larger outmigration than is indicated by the model. Much of the economy could recover within a few years, but a full return to the previous trajectory could take more than five years for the region and closer to a decade for the most severely affected counties. Recovery and rebuilding investments will be crucial to repairing the economic base of the region and returning it to its projected growth trajectory.

Sensitivity analyses using the model identify some of the critical factors that would lead to different levels of change. For example, a shortage of construction workers could lead to a deeper, longer recession as rebuilding is postponed. Should major technology employers decide to relocate substantial portions of their operations and later expansion outside of the region, the recovery period from the earthquake-induced recession could stretch to 6 or 7 years and the region's trajectory could be permanently damped relative to the ABAG 2015 forecast for 2040.

State and local policies, as well as business and personal preparedness can reduce the length and severity of effects. The model has substantial inbuilt resilience, whereas some of the sensitivity tests reduce that resilience and indicate how lack of advanced preparation and absence of relief spending and insurance after the fact could slow the region's trajectory in the long term.

Introduction

This chapter is a contribution to a broader set of analyses on the potential economic and social effects from a major earthquake on the Hayward Fault in the east bay subregion of the San Francisco Bay region, California. The chapter has a narrow purpose—to use existing modeling techniques that underlie the regional forecast of the San Francisco Bay region economy and population to estimate how a major earthquake would alter that forecast. Other chapters in this volume address community vulnerability (through application of past experience to existing demographic and social conditions; Johnson and others, this volume), the effects of the earthquake on the region's economic output during the first 6 months after the earthquake (a computable general equilibrium analysis; Sue Wing and others, this volume), a detailed assessment of

[1]Metropolitan Transportation Commission and Association of Bay Area Governments, retired.

[2]Metropolitan Transportation Commission and Association of Bay Area Governments.

[3]Metropolitan Transportation Commission.

[4]U.S. Geological Survey.

characteristics of businesses in vulnerable parts of the region (based on the National Establishment Time Series dataset; Wein, Haveman, and others, this volume), and an analysis of economic vulnerabilities at the neighborhood level in severely affected areas and the spread across neighborhoods related to commute flows within the most affected areas, between those areas, and in less-affected parts of the region (Wein, Belzer, and others, this volume).

This study applies the building damages from the HayWired scenario capital and output losses that are estimated from the Federal Emergency Management Agency's (FEMA) Hazus model to the Association of Bay Area Governments (ABAG) Regional Control Forecast using the Regional Economic Models, Inc. (REMI) model 1.7.8. The ABAG Regional Control Forecast is a forecast for the San Francisco Bay region created using the framework of the REMI model and adopted by the ABAG Executive Board in January 2015 as the basis for creating the projections used in Plan Bay Area 2040 (described by Kroll and others, 2017). The purpose of examining how an earthquake would change the REMI ABAG regional control outcome is to address several long-term questions on the economy that are not fully fleshed out in the short-term computable general equilibrium analysis (Sue Wing and others, this volume), which focuses on immediate effects during the first six months. These long-term questions include:

1. What are the overall effects on economic output from the earthquake, taking into account the direct output losses from damage to buildings and contents (defined as furniture, equipment that is not integral with the structure, computers, and other supplies)? What are the effects on economic output from second-order multiplier effects from interrupted firms, capturing both upstream and downstream losses in output?

2. How do these losses in output affect employment by sector?

3. What are the population effects caused by changing workforce demand, changing price levels, and changing amenities in the region?

4. How does public and insurance spending affect the outcome of the earthquake recovery?

5. Would an earthquake of this magnitude be expected to change the long-term economic trajectory for the region in the future? Given uncertainties of predicting such effects, what types, levels, and duration of effects could lead to long-term negative or positive changes in the region?

The chapter begins with a brief discussion of the most relevant research on the long-term effects of natural disasters, especially research focused on urbanized areas in developed countries. A more in-depth review of disaster research is provided by Johnson and others (this volume). We then lay the framework by briefly describing the REMI model, which is the basis for the San Francisco Bay regional forecast, and the Hazus model, which underlies the estimates of physical damage and direct output loss. We describe the analysis of the earthquake's economic effects by defining sequentially the measures of effect factors applied to the model and the results of each factor, followed by the measures of mitigation and policy approaches and the effects of those measures. We test the sensitivity of the results to the level of public spending, insurance coverage, construction costs, and potential relocation decisions of major employers. We conclude with an overview of findings, a discussion of how shifts in assumptions could change the results, and some policy observations.

What Past Experience Tells Us about Long-Term Effects of Natural Disasters

The past decade has seen an expansion of literature that focuses on the long-term effects of disaster. One such analysis is Hsiang and Jina (2014) that outlines four trajectories described in the literature of how a disaster may affect an economy in the long run. These trajectories are: "creative destruction," where the economy is stimulated by aid dollars and replacement investment; "build back better," where a short-term downturn is followed by a long-term "strengthening" and replacement capital is an improvement over older outmoded damaged capital; "recovery to trend," where economies converge back to the predisaster growth trend; and "no recovery," where the long-term growth is permanently reduced by diverted investment (Hsiang and Jina, 2014).

Research results to date offer mixed evidence on which of these trajectories an economy experiencing a natural disaster will follow and how effects may vary by geography, community, or country. DuPont and Noy (2015) conclude in a literature review that, "To summarize, the literature on the long-term impact of economic shocks is inconclusive, but the weight of the evidence suggests no long-term impact of even catastrophic shocks at the national level." They go on to note that, "Several papers, however, do point to some potentially long-term impacts at the local/regional level."

Methods of analysis to understand the long-term effects include statistical analyses across countries or within countries, across counties or metropolitan areas, case studies, and even more disaggregated analysis of the effects across individual households, establishments, or across simulation exercises of the type we conduct in this chapter. Economic effects examined include those on output (gross domestic or regional product) or income (total personal income), on employment, and effects on population movements. The widely diverse scales of inquiry, depth of detail, and indicators analyzed all lead to ambiguity in understanding the long-term implications of a natural disaster.

Cavallo and others (2013) constructed what they called "counterfactuals" to compare how economies experiencing

natural disasters would have grown absent the event. They found that even economies experiencing large disasters (defined by lives lost relative to population size) have not experienced long-term lags in output growth relative to the estimations based on comparable areas of growth in a scenario without the event's occurrence. Their research covered diverse disasters ("hydrometeorological," geophysical, or biological), whereas Hsiang and Jina (2014) studied the effects of cyclones alone across countries. They conducted a statistical analysis based on number, timing, and size of events and found that, although an individual event has a marginally small effect on long-term output and income trajectory, because cyclones can occur in a single economy with some frequency, "…repeatedly exposing the same population to frequent storms results in an accumulation of income losses over time…" relative to what the economy would experience without cyclones (Hsiang and Jina, 2014).

Boustan and others (2017) investigated disaster effects on migration, poverty rates, and home prices in a study of all types of disasters across U.S. counties over a 90-year period. The results of the study suggest a direct relation between the level of outmigration and the number of disasters experienced, with a "super-severe" disaster doubling the overall average effect. Some variation of effects occurred by type of disaster. Poverty rates also increased, suggesting that wealthier households were better able to move after a disaster than were poorer households. Relief spending did not mitigate this effect and may have actually exacerbated outmigration by making it easier for households to move, whereas outmigration was particularly high where a severe event occurred in an area prone to disaster. Nevertheless, there was a great deal of variation in the propensity to migrate after a disaster. For example, higher outmigration occurred from rural areas than from productive urban areas. Earthquakes were not found to induce migration, in contrast to volcanoes, landslides, and fires (although it is not clear how landslides and fires induced by earthquakes affected the results). Housing prices were not sensitive to the frequency of disasters but did drop after a severe disaster.

Cavallo and Noy (2010), in their review of disaster research, note a differential level of impact between large and small countries. "Therefore, while direct losses may be high in large countries because of the wealth exposure, the greater capacity to absorb shocks means that indirect losses may be lower, and/or that the size of the damage may be lower relative to the size of the country" (Cavallo and Noy, 2010 p. 13). They also comment on "poverty traps," which are related to restricted ability to recover owing to the lack of resources in poorer countries. A similar divide is found between rural and urban counties in recent research by Boustan and others (2017).

Retrospective studies of the case of Kobe, Japan, after the 1995 earthquake argue that, although the economy "recovered" (in the sense that would be applied to bouncing back from a recession, eventually exceeding pre-earthquake output and population), there were long-term changes in the level of growth and the structure of the economy after the earthquake. DuPont and Noy (2015) estimated how Kobe's economy and population size would have grown had it maintained the same levels of these factors relative to other Japanese metropolitan areas in the post-earthquake period. Their analysis indicated that although the population returned to pre-earthquake trends within five years, gross domestic product (GDP) per capita, despite early fiscal stimulus spending, lagged by 13 percent of the synthetically constructed estimates of GDP for the metropolitan area absent an earthquake 15 years later.

Okuyama (2014) highlighted the variability of each disaster event and its effects on the economy. The author disaggregated elements of the Kobe economy before and after the earthquake and used a shift-share analysis to identify structural changes in the distribution of economic activity. Results indicated a decline in regional competitiveness, especially in final demand, more than ten years after the Kobe earthquake, attributed largely to the population decline that followed the earthquake. However, at the aggregate input-output level, many differences level out, suggesting that negative effects in one sector or one geographic area may be offset by positive effects elsewhere in the economy or country.

Simulation models are another approach to analyzing the potential or actual effects of a disaster and are generally applied to a single case study. Common analytic tools in these studies include computable general equilibrium (CGE) models, input-output (I-O) models, or, in some cases, the REMI model, which uses aspects of I-O, CGE, and other tools. Many are used for short-term analysis, as by Sue Wing and others (this volume). Xie and others (2014) used a CGE model to examine long-term effects of the 2008 Wenchuan earthquake in China. Their findings highlight the dependence of the outcome on what aspects of the disaster are included. Analyzing costs alone, without taking into account recovery investments, gives an unrealistic view of the outcome. Including recovery investment in the analysis brings long-term growth much closer to the expected trajectory absent the earthquake.

Several authors describe redistribution of activity in the absence of measurable long-term effects on a national or regional economy. The unevenness of effects may be geographic, with locational shifts in patterns of development, or through unevenness in the experience and recovery of different population groups within the region. Peacock and others (2014) examined long-term housing recovery after hurricanes in 1992 and 2008. They discovered that low-income areas (and, in one case, areas with high shares of minority populations) were more vulnerable to the initial-level damage experienced and recovered more slowly. In one case, the recovery differential disappeared after two years, whereas, in the second case, the differential continued for a longer time period. If effects are separated by owner-occupied and rental property, rental values continue to lag in recovery compared to homeowner values and compared to the prestorm values for at least four years. Tierney (1997) found that after the 1994 earthquake in Northridge, California, businesses in the most heavily damaged areas were less likely to have recovered to pre-earthquake levels, even if the business itself experienced

no building damage, suggesting that there could be long-term effects on the affected area beyond any short-term effects of damage.

The historical literature, then, points to four possible areas of effect that should be considered in the analysis:

1. How quickly does recovery occur in the regional economy and population base?
2. What are the possible long-term outcomes to the economy—does growth (or decline) occur at the same rate as before the earthquake?
3. Would the internal composition of the economy change relative to expected trends?
4. Would the geographic patterns of growth change as a result of the earthquake?

The HayWired Scenario

The HayWired earthquake scenario examines a hypothetical moment magnitude (M_w) 7.0 earthquake on the Hayward Fault, centered along the urban corridor of the eastern San Francisco Bay region (see Seligson and others, 2018, for a detailed description of the HayWired scenario). The mainshock triggers liquefaction and landslides, and is followed by fires, further slip of the fault, and a series of aftershocks. Seligson and others (2018) calculated building damage of multiple hazards of ground shaking, landslide, and liquefaction for the mainshock and aftershock sequence of the HayWired scenario using the Hazus model, which we refer to as the Hazus analysis hereafter when discussing results. Scawthorn (2018) estimated the potential addition of building damage (outside of the Hazus model) caused by post-earthquake fires. Using the integrated building damage data from Hazus by Seligson and others (2018) and the fire analysis by Scawthorn (2018), Johnson and others (this volume) estimated that the earthquake could result in extensive or complete damage to more than 103,000 buildings (both residential and nonresidential) in the San Francisco Bay region, as well as to a much smaller number of structures in other parts of California. The most severe damage would be in Alameda County, where 16 percent of all residential buildings and 29 percent of nonresidential buildings would experience extensive or complete damage, and where approximately 82 percent of residential and 85 percent nonresidential building square footage would sustain some type of damage, ranging from slight to complete. In addition to structural, nonstructural, and contents damage to buildings, roadways, rail service, and power, water, gas, and communications utilities would also be damaged, and critical life-support services (health and education) housed in the buildings would be impeded as well. The time frame for restoration of these facilities and services could range from a few days to nearly a year for some roadways and as much as three years for the most severely damaged parts of the Bay Area Rapid Transit (BART) system. These damages and delays, in turn, may have ripple effects on the economy through disruption to households, commute flows, and operating capacity within businesses.

The Hazus model estimates the level of physical damage from multi-hazards caused by an earthquake, identifying different levels of damages and loss for distinct types of residential and nonresidential buildings, as discussed in more detail elsewhere in the report by Seligson and others (2018). In financial terms, direct building and contents losses resulting from the mainshock, aftershocks, liquefaction, and landslides in the Hazus analysis are estimated to be $72 billion in 2016 dollars (table 1). Fire-caused building and content losses approach an additional $30 billion in 2016 dollars (Scawthorn, 2018). Fire damage would likely be covered by insurance rather than the damage directly related to seismic causes, although there would still be cases of underinsurance. Until these capital losses are repaired or replaced, these direct effects to buildings and contents mean considerable disruption to economic activity.

Taking into account building cleanup, repair, and recovery time, and the probability of recapturing some business-related loss after the event, as defined in the Hazus technical manual (see FEMA [2003] and Sue Wing and others [this volume] for a more detailed discussion), integrated building damage data from the mainshock, landslides, liquefaction, aftershocks, and fire effects translates into direct output loss estimates of $27.0 billion (2016 U.S. dollars) for all affected counties. Output loss estimated for Alameda County amounts to $17.5 billion and for the nine-county bay region to $26.9 billion, or 8 and 3 percent of total output, respectively. Effects from fire following the mainshock alone account for $2.2 billion of the loss to the bay region, whereas $500 million of the output loss results from aftershocks. Of aftershock-related output losses, 80 percent ($397 million) is concentrated in Santa Clara County (table 2).

On the basis of estimates of residential building damage from ground shaking and liquefaction, Seligson and others (2018) estimate that the displacement from the mainshock is about 153,000 households, and the population seeking short-term shelter would exceed 48,000 people. Building damage from aftershock ground shaking adds more than 2,800 displaced households, and 1,600 people seeking shelter. Johnson and others (this volume) argue that the potential population displacement and sheltering needs caused by damage from landslide, fire, lifeline infrastructure damage, and utility outages or environmental threats are not included in these estimates, and that displacement could be as high as 268,000 households and 720,000 people. According to Johnson and others (this volume), the methodology used by Seligson and others (2018) for calculating short-term shelter requirements recognizes that only a portion of those displaced from their homes will seek public shelter, and some will seek shelter even though their residence may have low levels of damage.

Table 1. Hazus-estimated direct building and contents value effects from the HayWired scenario in the San Francisco Bay region, California.

[Amounts are in billions of 2016 U.S. dollars for damages from the mainshock, aftershocks, liquefaction, and landslides. Loss data generated from Seligson and others (2018). Note that these numbers do not include the additional loss caused by fire]

County	Nonresidential buildings	Residential buildings	Building contents	Total direct loss
Alameda	11.3	15.4	7.0	33.7
Contra Costa	2.7	5.1	2.0	9.8
Marin	0.3	0.8	0.3	1.4
Napa	0.03	0.05	0.03	0.11
San Francisco	1.2	1.4	0.7	3.3
San Mateo	1.5	2.8	1.4	5.7
Santa Clara	5.1	7.6	4.3	17
Solano	0.1	0.2	0.1	0.4
Sonoma	0.03	0.18	0.05	0.26
San Francisco Bay region total	22.3	33.5	15.8	71.6
Other areas	0.22	0.41	0.21	0.84

Table 2. Direct output loss for the HayWired scenario in the San Francisco Bay region, California.

[Values in millions of 2016 U.S. dollars]

County	Mainshock, landslides, liquefaction	Mainshock, landslides, liquefaction, and fire after earthquake	Mainshock, landslides, liquefaction, fire after earthquake, and aftershocks
Alameda	16,136	17,447	17,489
Contra Costa	2,764	2,949	2,951
Marin	115	220	220
Merced	1	1	1
Monterey	6	6	6
Napa	9	10	10
Sacramento	2	2	2
San Benito	7	7	7
San Francisco	726	743	746
San Joaquin	47	47	47
San Mateo	759	854	910
Santa Clara	3,533	3,994	4,391
Santa Cruz	18	18	19
Solano	58	129	129
Sonoma	8	10	10
Stanislaus	14	14	14
Yolo	1	1	1
Total[1]	24,206	26,452	26,956
San Francisco Bay region total[1]	24,110	26,356	26,858

[1]Because of rounding, sum totals may not be exact.

The Hazus calculation for the HayWired scenario is based on a 2005–2006 inventory of buildings. Housing stock expanded by 9.8 percent in Alameda County and 7.4 percent region-wide between 2005 and 2017. New construction is more likely to be resistant to shaking and liquefaction and possibly less vulnerable to fire as well, potentially reducing the share of buildings and contents vulnerable to damage and displacement effects.

Table 3. California's San Francisco Bay subregions and the counties that compose them.

Subregions	Counties
North bay	Napa, Solano, and Sonoma
East bay	Alameda and Contra Costa
South bay	Santa Clara
West bay	Marin, San Francisco, and San Mateo

The ABAG Regional Control Forecast and the REMI Model

Beginning in the fall of 2014, ABAG used a REMI model as a framework for producing a regional forecast for the nine counties that compose the San Francisco Bay region (Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Sonoma, and Solano). The model divides the San Francisco Bay region into four subregions, as shown in table 3 and figure 1. A final regional forecast adopted by the ABAG executive board in February 2016 (Association of Bay Area Governments Planning and Research Department, 2016) serves as the benchmark comparison forecast for the HayWired REMI analysis (see Kroll and others, 2017, for an explanation of the regional forecast; appendixes 1–5 describe the methodology for producing the ABAG Regional Control Forecast). Absent a major earthquake or other disruptive event, the region is projected to experience a slowdown of growth compared to the very rapid post-recession expansion of 2010–2015, and to maintain its competitive advantage in such sectors as professional and business services and some aspects of the information sector. To do so, the region will need to add almost 700,000 jobs and almost 2 million people between 2015 and 2040. The forecast—9.6 million people and 4.7 million jobs in the region by 2040—has a policy or visionary aspect because it assumes the region's housing needs are successfully addressed, so that existing and in-migrating workers will be able to find housing in the region and in-commuting would be kept to a minimum. A major earthquake would certainly disrupt the housing expectations implied in the ABAG Regional Control Forecast in the short run because the model measures relative real estate prices rather than number of units. The pace of the housing market and transportation network recovery could have long-term effects depending on how both businesses and individuals react to this disruption.

Regional Economic Models, Inc. (2015) describes the version of the model used in this analysis (p. 3):

> PI+ is a structural economic forecasting and policy analysis model. It integrates input-output, computable general equilibrium, econometric, and economic geography methodologies. The model is dynamic, with forecasts and simulations generated on an annual basis and behavioral responses to compensation, price, and other economic factors.
>
> The model consists of thousands of simultaneous equations with a structure that is relatively straightforward. The exact number of equations used varies depending on the extent of industry, demographic, demand, and other detail in the specific model being used. The overall structure of the model can be summarized in five major blocks: (1) Output and Demand, (2) Labor and Capital Demand, (3) Population and Labor Supply, (4) Compensation, Prices, and Costs, and (5) Market Shares.

The model captures economically significant relations, such as that between productivity in an industry and associated demand for labor, while taking into account the available labor supply in the region and its cost relative to other regions. The population, in turn, grows through natural increase as well as through economic migration when earnings rise to compensate for the cost-of-living differential. With the basic parameters of the economy and its responses estimated, the model allows the analyst to test the effects of specific occurrences to see how the system responds given the change. Direct, and some indirect, effects of an event (such as an earthquake) are added in the policy change part of the model to evaluate how the event affects different aspects of the economy, including the direct and indirect effects on output, employment, population, and labor force. The flexible aspects of the model allow sensitivity testing on the level of effects, some aspects of mitigation and resilience (such as telework), alternative government actions (such as imposed outmigration), and social effects (such as changing perceptions toward the attractiveness of the region). Some of these are included in our application of the model. One caveat is that the level of the effects result from assumptions about factors such as the degree of outmigration or government spending, which ultimately rely on judgment calls by the analyst. Furthermore, to the degree that the model is built for times of ordinary



Figure 1. Map showing the four subregions in the Association of Bay Area Governments (ABAG) REMI model version 1.78 of the San Francisco Bay region, California. REMI refers to models produced by Regional Economic Models, Inc.

economic relations rather than prolonged crisis, such as long-term recovery stresses from a major earthquake, it could underestimate or misallocate the level or location of the effect.

The ABAG REMI model includes four subregions: the east, north, west, and south bay (table 3) as well as a fifth "region," the rest of California. The strongest effects are felt in the east bay, with some effects spreading to the other bay subregions. Some neighboring counties to the east also experience small effects (capital and output losses) according to the Hazus results, but these are difficult to discern in the San Francisco Bay region REMI model v. 1.7.8 because of the aggregation with the rest of the State. Therefore, discussion of the REMI model results will focus on the four subregions within the larger San Francisco Bay region. Rather than basing the analysis on the standard regional control built into the model, employment and population effects are examined relative to the ABAG Regional Control Forecast, which becomes the baseline forecast absent an earthquake.

Hypothetical Sequence of Effects and Their Incorporation into REMI

We follow the approach adopted by Rose and others (2009; a study of border closure effects on the U.S. economy), where a set of possible drivers of change is identified, the effect of each driver is examined separately, and then a combination of factors is used to examine cumulative and interactive effects. We first describe conceptually the factors causing economic change. We then identify factors in the REMI model that represent these changes. We follow with independent application of the different types of change and finally with the combination of some of these factors to look at overall effects. For some factors, the absolute measure of change is a straightforward application of Hazus results. For other factors, the level of change requires judgment informed by past experience. We include some analyses at the end of the chapter to test the sensitivity of results to some of these assumptions.

A major earthquake will disrupt the economy through the initial physical losses, human casualties inflicted on the region, and the disruption to business output and employment from the damage, which we refer to as direct effects. However, the effects quickly become more complex, because indirect effects, listed below, arise and may continue even as recovery efforts begin.

- As production halts in damaged space, suppliers to affected businesses experience drops in demand, whereas those dependent on the output of damaged businesses will face shortages or rising costs.
- Damage to utilities, such as power and water, may cause business operations to cease temporarily, even in undamaged buildings.
- Damage to road and transit networks can disrupt supply chains and employee commutes between work and home, as well as tourism, business-related travel, and shipments (including supply chains) from within and beyond the region.
- Seaport and airport damage can disrupt supply and customer networks.
- Housing damage may incapacitate employees and customers in the short term and can lead to an outmigration of workers and customers in the long term.
- Shortages in supplies and available labor may lead to higher production costs.
- Coping with loss and disruption may decrease productivity of workers.
- "Reputation" effects can spread beyond the immediate effects of damage, as visitors or potential new residents avoid the region because of expectations of problems.

Yet there are stimulating effects as well:

- The rebuilding period can bring a boom to some industries and occupations, and rebuilding can leave behind a newer capital stock than what was damaged.
- Insurance payments and government spending can cover some of the costs of response, repair, and recovery.
- The influx of rescue and recovery workers can fill hospitality services that would otherwise have declined because of loss of business and leisure travel caused by the earthquake and its aftermath.

There are additional responses that may bring either positive effects, leading to resilience, or enhance negative effects:

- The high level of technological sophistication in the local economy can have both short-term resilience effects and long-term depressing effects on growth.
    - Businesses that make heavy use of portable computers, cloud-based files and services, and wireless communications may be able to continue operating despite displacing effects of local building damage. Demand for their services may even increase if they can substitute for more location-bound operations.
    - However, these operating characteristics may enable the business to be footloose, and to move divisions to other locations outside the region. Given anticipated temporary cost spikes and attendant operational disadvantages, temporary relocation from the region could evolve into permanent relocation of operations beyond the bay region.
- Insurance and government payments need to be paid for. The effects on the region will vary depending on whether the cost is tied directly to the affected area, the bay region, or spread more widely to the State or Nation.
- Businesses, government, and nonprofit organizations may be able to relocate to space that is still usable and also to provide help to one another, mitigating the effects of damage and displacement. For example, temporary agreements to share space can keep businesses in operation, reduce operating costs from displacement, and provide continuity of services, making the economy more resilient.

The next section describes how these effects and response measures are included in the REMI model.

Assumptions and Simulated Effects within the REMI Model—Part 1

To estimate how the effects of the HayWired scenario would affect the San Francisco Bay region's economy, we used the regional control scenario in the REMI model from the Plan Bay Area 2040 regional forecast and then entered measures of effects into the model. The model reports the effects of these changes over the forecast period. The model forecast goes from 2010 through 2040 in annual increments, with the HayWired scenario effects examined between 2018 and 2040.

The major earthquake effects applied to the bay region REMI model regional forecast consisted of output loss from building damage, output loss from transportation disruption, changes in housing prices, and migration decisions. After applying the effects that create losses in the economy (described in detail below), we also added the stimulating effects of recovery efforts to the model. Response, repair, and reinvestment in capital stock stimulates new economic activity to counterbalance some of the losses and to support a return to predisaster levels. We looked at government spending in the analysis to assess the overall effects of the earthquake on the economy after the expenditure of resources for rebuilding and recovery. The effects of the earthquake are reported in terms of total output change (the direct effects from damage plus secondary and tertiary effects from supply-chain disruption and business and population relocation), employment, and population change.

Direct Output Loss from Building Damage

Whereas the REMI model includes residential and nonresidential capital stock and capital investment variables, the stock variables are not directly related to output in the model. Thus, entering a loss in capital stock becomes only stimulating as the model accounts for rebuilding, without accounting for the output loss tied to the capital stock. For this reason, we began with entering output losses estimated directly from Hazus into the REMI model.

Direct output loss occurs when building damage disrupts economic activity. In the Hazus model, this is the product of floor area, output realized per square foot, and the expected days of loss of function for each damage state. Recapture factors, factors discounting the business-related output loss from earthquakes owing to the possibility that some of the loss could be recouped to some extent by working overtime after the event, are also taken into account in the Hazus output calculations (see Sue Wing and others, this volume, for a more disaggregated analysis of direct and recaptured effects). Total Hazus-estimated output loss (table 2) was disaggregated into loss for a 3-year time period to reflect the time needed for rebuilding that causes output loss to last longer than 1 year. In the HayWired scenario, a series of aftershocks follow the mainshock over the course of 2 years. Although the largest four aftershocks hypothetically happen in 2018, two of which occur 2 weeks after the mainshock and the other two occur about 6 months later, direct output loss from all sequences of aftershocks in this analysis were added into the second-year total. This captures the spread through time of effects of larger aftershocks that occur near the end of 2018, so that most of the output loss occurs in 2019.

Overall, the estimated direct output loss from building damage (from the mainshock, aftershocks, and fire following earthquake effects) for the bay region is around $26 billion in the first year, $580 million in the second year, and $22 million in the third year (in 2016 dollars) after the earthquake (table 4). The east bay subregion of the San Francisco Bay region accounts for the majority of the loss: $20 billion in the first year, and $105 million and $18 million in the following two years, respectively.

Table 4. Direct output loss estimates from Hazus as defined in the REMI Association of Bay Area Governments model for the HayWired scenario shown by subregion of the San Francisco Bay region, California.

[Subregions are defined in table 3. REMI refers to the models produced by Regional Economic Models, Inc. Data sourced from the Association of Bay Area Governments and Metropolitan Transportation Commission from Hazus results. There is no estimate for total output for the State of California from Hazus. n.a., not applicable]

Subregion	1st year, in millions of 2016 dollars	2d year, in millions of 2016 dollars	3d year, in millions of 2016 dollars	1st year loss of area's output, in percent
East bay	20,317	105	18	7.1
North bay	147	2	1	0.1
West bay	1,809	67	1	0.7
South bay	3,984	405	2	1.8
San Francisco Bay region total[1]	26,257	579	22	3.0
Rest of California	96	2	0	0.0
California total[1]	26,354	581	22	n.a.

[1]Because of rounding, sum totals may not be exact.

The level of loss by sector was determined by the type of building the sector occupies, the degree of damage to that occupancy type, and total employment and output levels of the industry. We calculated the share of output loss for each industry using Hazus output loss results by occupancy class through the North American Industry Classification System (NAICS) (appendix 1, table 1.1) and the crosswalk between Hazus occupancy class and REMI industry (table 1.2) and applied those shares to the total output estimates in 2018 of the REMI regional control scenario in the version of the model used for Plan Bay Area 2040. This leads to slightly different total output loss estimates, because the baseline in the two models are different. We also found that five industry sectors—telecommunications; performing arts and spectator sports; museum, historical sites, zoos and parks; amusement, gambling, and recreation; and food services and drinking places—belong to the same occupancy class. However, utility providers report shorter estimated recovery times than the Hazus default value. Therefore, for the telecommunication sector, we revised the loss of function time for damage state and recaptured factor for damage state to recalculate a lower level of output loss. The results are shown in appendix 1.

Among all 66 private nonfarm industries, the petroleum and coal products manufacturing industry experienced the largest value of output loss ($2 billion, 4 percent of the industry's total output) in the San Francisco Bay region in the first year, followed by food services and drinking places ($1.9 billion, 9 percent), ambulatory health care services ($1.8 billion, 6 percent), machinery manufacturing ($1.6 billion, 12 percent), real estate ($1.3 billion, 1 percent), and professional, scientific, and technical services ($1.2 billion, 1 percent). Several manufacturing sectors sustained the largest share of industry output loss, including 22 percent of motor vehicles, bodies and trailers, and parts manufacturing; 16 percent of paper manufacturing, and 12 percent of machinery manufacturing. In the second year, total output loss declined for the bay region. The largest amount of output loss was in ambulatory health services ($90 million), food services and drinking places ($77 million), and private hospitals ($72 million). In the third year, output loss, although very small, only remained in the social assistance and nursing and the residential care facilities sectors, because they are more dependent upon the reconstruction of buildings (table 1.3). Loss by occupancy class is translated to loss by REMI industry sector. See appendix 1 for further discussion regarding translation methodology.

Jobs, as reported by REMI, are measured by the Bureau of Economic Analysis (BEA) and represent an annual total, which includes not only wage employment but also self-employment, rather than a monthly average of wage and salaried employment only, as reported by the Bureau of Labor Statistics (BLS). The BEA employment total is about 26 percent higher than the BLS total for the San Francisco Bay region. Percentages are reported here to show the relative effects, whatever employment base is used. We reduced the forecast industry output in the REMI model Plan Bay Area 2040 regional control by the industry-specific loss and examined the cumulative effects of how such reductions reverberated throughout the economy. Direct output loss from building damage led to a loss of 232,000 jobs in 2018, and a 50,000 person decline in population related to job loss, or 4.6 percent of total jobs and 0.6 percent of population. Population displacement related to damage to residential buildings was almost 15 times this level, according to Seligson and others (2018) and Johnson and others (this volume). However, displacement from a home does not necessarily mean displacement from the region. The population analysis is discussed as a separate category below.

Job losses in the east bay subregion of the San Francisco Bay region are estimated to be 160,000, more than two thirds of the region's total loss, and 10.5 percent of total jobs in the east bay subregion (table 5). The north bay, west bay, and south bay subregions of the San Francisco Bay region experience reductions of 8,000, 33,000 and 33,000 in employment (1.4, 2.0, and 2.5 percent), respectively. The direct population effects of job loss for the east bay subregion are a drop of 1.3 percent in 2018, accounting for more than

Table 5. Estimate of 2018 employment and population effects in the San Francisco Bay region, California, relative to Association of Bay Area Governments forecast levels from Hazus-estimated output loss related to HayWired scenario building damage.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	Employment loss	Employment loss as a percent of subregion's job base	Employment loss as a percent of total loss	Population loss attributed to job loss	Population loss as a percent of area population	Population loss as a percent of total loss
East bay	158,872	10.5	68	36,243	1.3	72
North bay	7,623	1.3	3	2,856	0.3	6
West bay	32,585	2.0	14	5,527	0.3	11
South bay	33,212	2.5	14	5,495	0.3	11
San Francisco Bay region total[1]	232,293	4.6	100	50,121	0.6	100

[1]Because of rounding, sum totals may not be exact.

70 percent of the region's direct job-related loss in population (table 6). The other three subregions are estimated to lose 14,000 people in the first year related to job loss, a much smaller share of their populations. In the second year, bay region job levels are 19,000 less than the projected levels without the earthquake, and population is lower by 41,000 people, which are 0.4 percent of employment level projected for the region in REMI and 0.5 percent of the projected population level.

The industry with the largest employment loss in the first year is food services and drinking places, with a loss of about 34,000 jobs (11 percent). The construction sector loses approximately 19,000 jobs (7 percent), which would create challenges for the region as construction activities will be needed for the recovery of communities. Large losses in employment in critical neighborhood-serving retail trade and ambulatory health care services sectors would also make the recovery work harder for cities and communities (table 7). Because of multiplier effects, total output loss of all private nonfarm sectors is approximately $46 billion in 2018 (2016 dollars), compared with the $27 billion direct output loss estimated by Hazus. The real estate sector has the largest output loss ($4 billion), followed by professional services and construction sectors, both of which sustain a loss of more than $3 billion in industry output in year 2018 (table 8; appendix 2).

Table 6. Estimate of 2019 employment and population effects in the San Francisco Bay region, California, relative to Association of Bay Area Governments forecast levels from Hazus-estimated output loss related to HayWired scenario building damage.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	Employment loss	Employment loss, in percent	Employment loss as a percent of total loss	Population loss	Population loss as a percent of area population	Population loss as a percent of total loss
East bay	8,850	0.6	47	29,192	1.1	71
North bay	1,195	0.2	6	2,547	0.2	6
West bay	2,982	0.2	16	4,627	0.2	11
South bay	5,500	0.4	30	4,746	0.2	12
San Francisco Bay region	18,527	0.4	100	41,112	0.5	100

Table 7. Ten industries with the largest estimated reduction of employment from the HayWired scenario owing to building, population, and other output losses identified in linked industries in the San Francisco Bay region, California, in 2018, relative to the Association of Bay Area Governments forecast.

[Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis from 2018 (this study)]

Category	Job loss	Share of job loss, in percent
Food services and drinking places	33,603	10.90
Construction	18,576	7.30
Retail trade	17,555	4.20
Professional, scientific, and technical services	16,643	2.50
Ambulatory health care services	14,464	8.10
Administrative and support services	12,984	4.20
Social assistance	9,775	4.50
Performing arts and spectator sports	8,225	13.60
Real estate	7,564	3.00
Hospitals	7,370	6.80

Table 8. Ten industries with the largest estimated total cumulative output loss from the HayWired scenario owing to building, population, and other output losses identified in linked industries in the San Francisco Bay region, California, in 2018, relative to the Association of Bay Area Governments forecast.

[Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis from 2018 (this study)]

Category	Output loss	Share of output loss, in percent
Real estate	4,095.15	2.9
Professional, scientific, and technical services	3,304.39	2.3
Construction	3,053.06	7.5
Ambulatory health care services	2,625.5	8.5
Petroleum and coal products manufacturing	2,485.79	5.2
Food services and drinking places	2,315.74	10.4
Retail trade	1,958.74	4.0
Wholesale trade	1,897.34	4.0
Machinery manufacturing	1,830.1	13.9
Monetary authorities and other credit institutions	1,694.08	3.8

Transportation Network and Commuting Flows

The transportation network provides important lifeline support to a functional economy. After an earthquake, recovery of the region's economy, housing, and communities depends on the restoration of the transportation system. Even if buildings are relatively intact, as long as the workers cannot get to their place of work, business activities will not be able to recover. Jones and others (this volume) identify the potential damages to major transportation systems in the region, including the road network and regional transit systems, such as the BART system. Figure 2 shows the range of repair times for shaking damage to the California Department of Transportation (Caltrans) roadway bridges and BART facilities.

Roadway damage would occur on major freeways and State highways, most of which require 2 to 3 weeks to repair. Severe damage is expected to happen along Interstates 880 and 580 near San Leandro and Hayward, along Interstate 680 in the Dublin-Pleasanton area, along Highway 24 in northern Oakland, and along Highway 37 near Sears Point between Novato and Vallejo, for which the repair time ranges from 4 to 10 months.

The effects on commuter flow, in addition to worksite buildings being damaged, can lead to further adverse effects on the regional economy. Wein, Belzer, and others (this volume), in an analysis of commuter flows within the region from or to areas with concentrated damage (census tracts with 20 percent or more extensive or complete damage to overall building square footage), found that commuting flows could affect the regional economy beyond the immediate damages from the earthquake. We examined commuting flow effects for both the areas with concentrated damage and those outside of heavily affected areas, which we refer to as "less-affected areas" hereafter (figs. 2, 3).

Damage to the transportation infrastructure system interrupts worker commute patterns and can increase the business output loss. After the 1989 Loma Prieta, Calif., earthquake, commuter transportation disruption (caused by a one-month closure of the San Francisco-Oakland Bay Bridge, in particular) was largely averted by alternative roadway routes and switching modes to the BART system and ferries (Deakin, 1991). Commutes were as much as 15 minutes longer, and limited relief was obtained from changes in work schedules or alternate workplaces (including home). After the 1994 Northridge earthquake damaged four major freeways in the Los Angeles area, Boarnet (1998) reported that 31 percent of employees (in surveyed businesses) endured longer commutes for 1 or 2 months on average (depending on the level of effect). Gordon and others (1998) estimated that increased travel time cost commuters at least $33 million. The most common employer policy allowed employees to change their work hours (Boarnet, 1998). More than twenty years later, San Francisco Bay region commuters are able to leverage technological advancements and are already responding to everyday traffic congestion with work-at-home options. However, the damage to the system is likely to be much greater than from the 1989 Loma Prieta earthquake, and repairs may last much longer. To incorporate the effects of transportation network and commute flow disruptions in the REMI analysis, we looked at where workers work and live by industry at the detailed census-tract level and at where roadway and freeway bridge damage would heavily affect workers' commutes. We differentiate the level of effect by the type of economic activity, to the extent such information is available, recognizing that flexibility to work at home varies by sector and occupation.

The U.S. Geological Survey (USGS), using Hazus, estimated that extensively or completely damaged buildings in commercial and industrial occupancy classes could lose functionality from a week to a year (FEMA, 2003). Regional roadways and bridges experiencing downtime could be repaired within 2 to 40 weeks (on the basis of calculations by Werner and others, 2000). Given the uncertainty of repair times for extensively or completely damaged buildings and roadways, we assume that the direct output loss for the heavily affected areas calculated using the Hazus methodology by USGS has accounted for the commuting flow effects in these areas, since those who work in heavily affected areas would not be commuting to buildings and areas that are nonfunctional. On the other hand, in less-affected areas, building repair times would be shorter. Likewise, if the transportation network is still broken, regardless of residence locations, commuters would not be able to get to buildings in these areas, leading to additional business output losses.

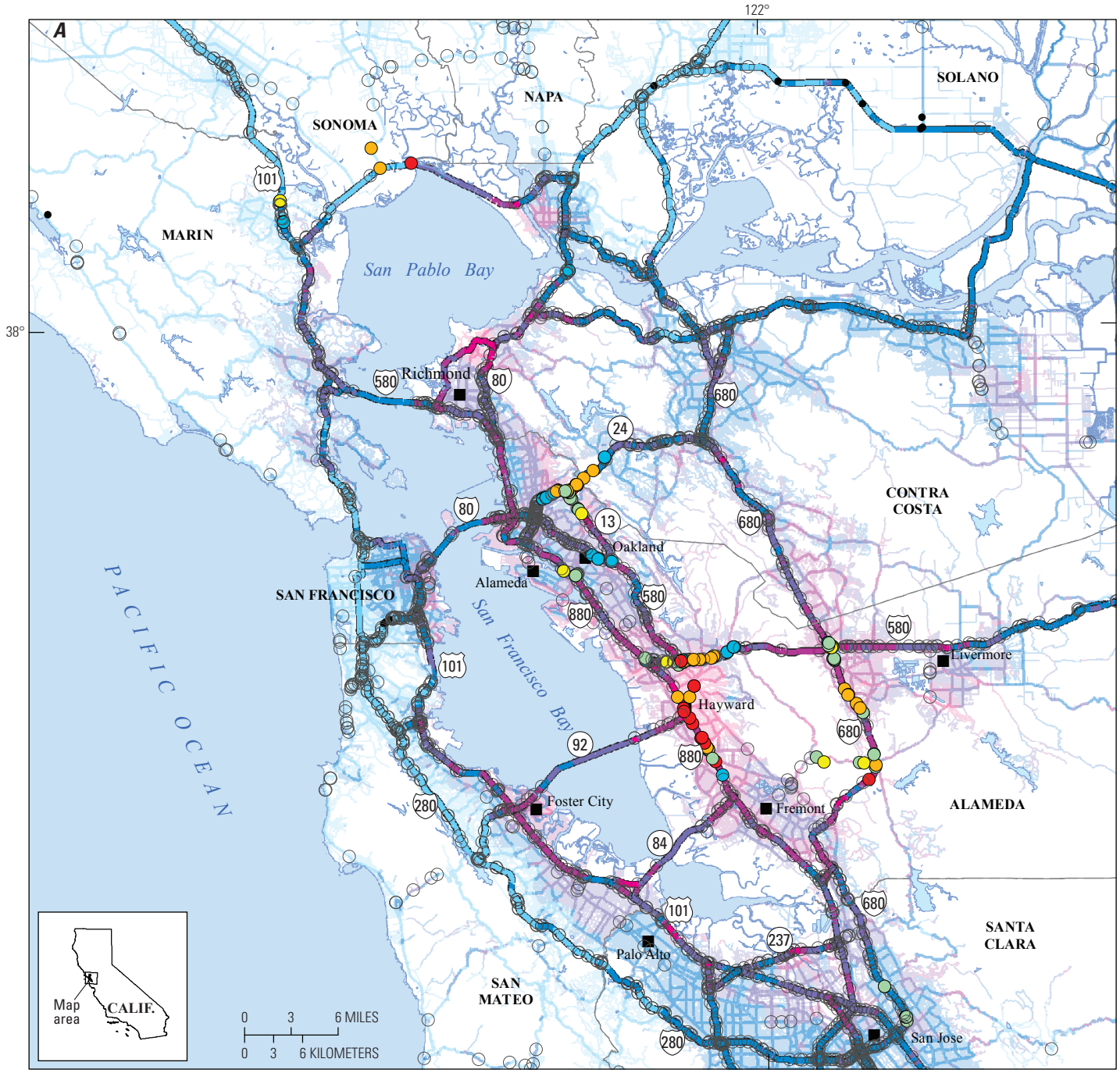
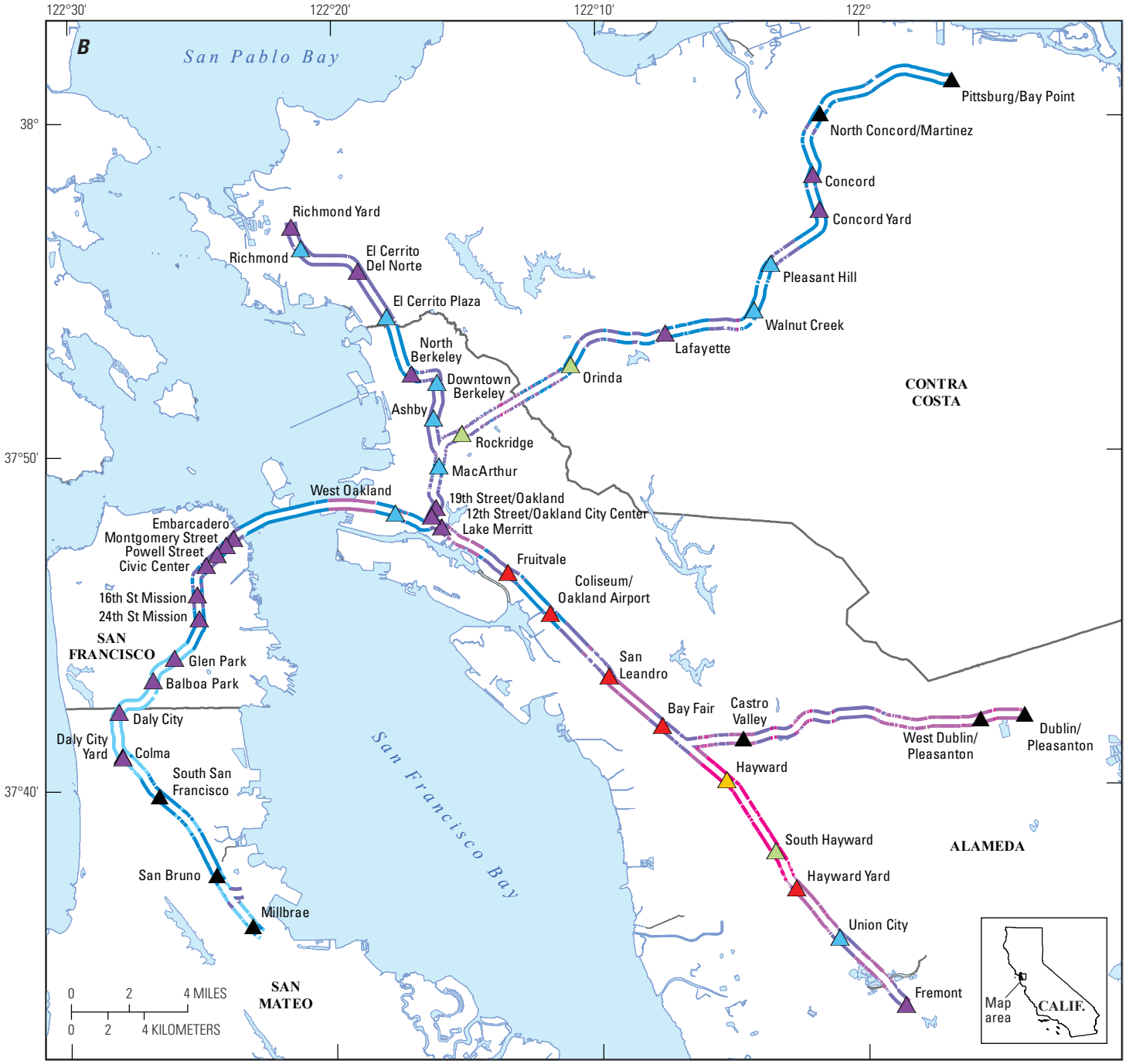


Figure 2 (pages 475–476). Maps of the San Francisco Bay region, California, showing the multi-hazard exposure of roadways (*A*) and the Bay Area Rapid Transit (BART) system rail lines (*B*), including the estimated repair times for California Department of Transportation bridges and BART facilities in the HayWired scenario. Multi-hazard exposure refers to the combined shaking, landslide, liquefaction, slip, and fire hazards that follow the hypothetical earthquake of the HayWired scenario. Map modified from Jones and others (this volume).



Hydrology from U.S. Geological Survey National Hydrography Dataset, 2016
Boundary data from U.S. Census Bureau TIGER data, 2016
Universal Transverse Mercator zone 10 north projection
North American Datum of 1983

EXPLANATION

BART rail multi-hazard exposure

- Low
- Moderate
- Moderate-high
- High
- Very high

BART station repair time range

- 1 to 3 years
- 9 to 12 months
- 2 to 36 weeks
- 1 to 14 days
- <1 day
- New station; not analyzed

Figure 2 (pages 475–476).—Continued.

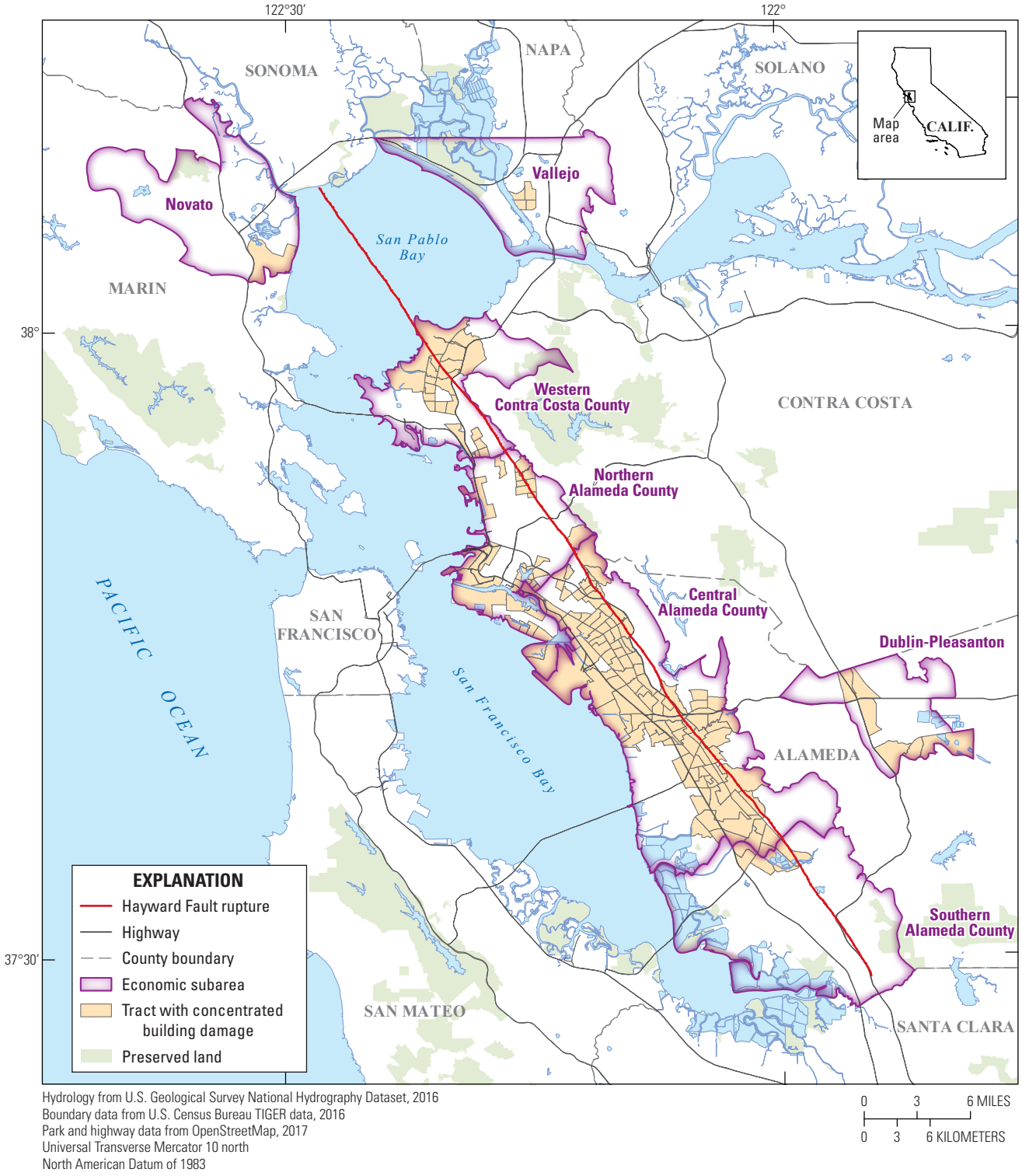


Figure 3. Map of the San Francisco Bay region, California, showing economic subareas and census tracts with concentrated damage in the HayWired scenario. Modified from Wein, Belzer, and others (this volume).

Therefore, in addition to the direct output loss estimated by USGS from building damages for less-affected areas, we need to account for how commute flow (table 9) and the transportation network affects businesses.

Less-affected areas in Alameda County employ about 452,000 workers, of which 72 percent commute from other parts of the bay region, including the heavily affected areas in Alameda, Contra Costa, Marin, and Solano Counties, as well as from counties outside the bay region. San Francisco, with a job base of about 695,000, is an example of a county with no heavily affected areas, but where 59 percent commute from areas outside San Francisco. For these types of less-affected areas, we added the loss from commute flow interruption to the loss from damaged buildings to get a total for output loss.

To translate commuting flow interruption from roadway and highway bridge damage into an output loss estimate (for less-affected areas) that is entered into the REMI model, we assumed that the percentage of output loss equals the percentage of all workers' working weeks lost in a year while commuters wait for repairs of roadways and bridges. We considered that commuters using these disrupted routes would seek alternative unblocked travel routes or modes (for example, ferry to avoid damaged bridges) if they think the new commuting time is still reasonable. Recall that in this scenario, bridges across San Francisco Bay are not estimated to sustain severe structural damages. Such outcomes would substantially disrupt commuters and increase business effects. We used Google Maps as our reference to select the optimal routes—routes that take the shortest time according to Google Maps—and to determine (somewhat subjectively) alternative commuting routes and the time it takes to use these routes. We then compared the new commute time with the shortest time suggested by Google Maps to decide whether commuters (as a group instead of individuals) would be willing to adopt the new routes given the marginal increase in commute time. We assumed those unable or unwilling to take alternative routes would have to wait for 7 months—midrange value of repair time for the most severely damaged roadways based on figure 2*A*—before they resume working. This would be time lost with regard to producing industry output.

We combined, for the less-affected areas in each county, the weeks lost by commuters waiting for roadways and bridges to reopen (table 10) and then divided the total lost commuter weeks by total commuter weeks (equal to the total number of commuters multiplied by 52) to get the share of lost commuter weeks. In order to calculate the share of total worker weeks lost for our model, we then multiplied the share of lost commuter weeks by the share of commuters calculated in table 9.

$$\textit{Commute share of output loss} = \frac{\textit{Lost commuter weeks}}{\textit{Number of commuters} \times 52} \times \frac{\textit{Number of commuters}}{\textit{Number of workers}} \quad (1)$$

For example, in San Francisco County (where the whole county is a less-affected area) for all sectors, 12 percent of the working weeks are lost because of transportation network damage. Therefore, we assume an additional 12 percent of total output loss for the county. In Alameda County, commuters are 72 percent of workers in less-affected areas, so the share of work weeks lost for this part of the county are $0.24 \times 0.72 = 0.17$ (or 17 percent; see the fourth column in the first row of table 10).

Based on the approach described above, table 10 shows that Alameda County is the most highly affected county, in regard to percentage of work time lost, with 17 percent of total workers' weeks lost. Although San Francisco and San

Table 9. Commuters in less-affected areas for the HayWired scenario in each county of the San Francisco Bay region, California.

[Data generated using an Association of Bay Area Governments analysis from 2018 (this study) of U.S. Census Bureau (2015) Longitudinal Employer-Household Dynamics (LEHD) data. LEHD job data is based on company payroll data, which might inflate the total number of commuters where company payroll data reporting location is different from actual workplace]

County	Total workers employed in less-affected areas	Total commuters to less-affected areas	Share of commuters, in percent
Alameda	451,877	323,221	72
Contra Costa	333,926	169,275	51
Marin	106,018	66,801	63
Napa	72,803	36,553	50
San Francisco	695,298	412,119	59
San Mateo	385,083	238,095	62
Santa Clara	1,001,412	385,077	38
Solano	139,565	76,004	54
Sonoma	191,411	56,271	29
Other Areas	1,802,175	785,233	44

Table 10. Percentage of weeks lost during the HayWired scenario because of transportation network interruption for all industry sectors for less-affected areas in each county of the San Francisco Bay region, California.

[Data generated using an Association of Bay Area Governments analysis from 2018 (this study) of U.S. Census Bureau (2015) Longitudinal Employer-Household Dynamics (LEHD) data and Jones and others (this volume). LEHD job data is based on company payroll data, which might inflate the total number of commuters where company payroll data reporting location is different from actual workplace]

County	Total commuter weeks	Total lost commuter weeks	Commuter weeks lost, in percent	Total worker weeks lost, in percent
Alameda	16,807,492	4,088,725	24	17
Contra Costa	8,802,300	1,638,960	19	9
Marin	3,473,652	339,518	10	6
Napa	1,900,756	93,944	5	2
San Francisco	21,430,188	4,245,934	20	12
San Mateo	12,380,940	2,105,963	17	11
Santa Clara	20,024,004	3,428,082	17	7
Solano	3,952,208	311,476	8	4
Sonoma	2,926,092	131,547	4	1
Other Areas	23,078,536	1,382,194	6	2

Mateo Counties experience less severe building damage than Alameda and Contra Costa Counties, commuters in these counties lose around 10 percent of their working time as the cross-boundary commute flow is interrupted.

There are some minor variations in vulnerability to commute flow interruption by industry type, as shown in table 11. We calculated the share of total worker weeks lost by three industry groupings, defined and discussed by Wein, Belzer and others (this volume), who separate out commute activity by industry grouping. In general, trade, transportation, and utilities jobs tend to have a slightly higher share of workers vulnerable to commute interruption than either goods-producing or services industries.

These percentages do not translate directly into output loss shares. Businesses and workers are very flexible and resilient in commuting and working. For example, telecommuting and working from home, an option 6 percent of workers in the region chose in 2016 (U.S. Census Bureau, 2016 [American Community Survey, 1 year]), could help keep businesses running, even more so for services industries rather than the goods producing, trade, transportation, and utilities industries. In addition, some commuters facing difficult or impossible commutes may choose to stay in hotels, with colleagues or friends, or in temporary living quarters near their offices during the week, particularly in places where buildings serving accommodation functions are not severely damaged. Taking into account these resiliency enablers, we applied factors to discount business output loss. In this analysis, we assumed one-third output loss from the effect of commuting in the goods producing, trade, transportation, and utilities industries, and one-fourth output loss in the services industry would occur. A method did not exist at the time of this study to objectively calculate how commute solutions would reduce the level of the commute disruption effect. However, fairly small shares were used in order to avoid exaggerating the effect.

For each REMI model subregion, we summed up the direct output loss from building damage of heavily affected areas and the combined output loss from building damage and transportation network interruption of less-affected areas to use as inputs to the REMI model. Among all 66

Table 11. Share of weeks lost because of transportation network interruption in the HayWired scenario by industry group for less-affected areas in each county of the San Francisco Bay region, California.

[Data generated using an Association of Bay Area Governments analysis from 2018 (this study) of U.S. Census (2015) longitudinal employer-household dynamics (LEHD) data; and Jones and other, this volume. LEHD job data is based on company payroll data, which might inflate the total number of commuters when company payroll data reporting location is different from actual workplace]

County	Goods producing	Trade, transportation, and utilities	Services
	Share of weeks lost, in percent		
Alameda	17	18	17
Contra Costa	8	12	9
Marin	6	8	6
Napa	2	3	2
San Francisco	12	13	12
San Mateo	12	12	10
Santa Clara	7	9	6
Solano	4	6	4
Sonoma	1	2	1
Other areas	2	3	1

private nonfarm industries, the professional, scientific, and technical services industry would experience the largest value of output loss in the San Francisco Bay region in the first year, approximately $4.4 billion, 3 percent of the industry's total output, followed by real estate ($4.3 billion, 3 percent), computer and electronic product manufacturing ($3.7 billion, 3 percent), food services and drinking places ($3.1 billion, 14 percent), and ambulatory health services ($2.6 billion, 9 percent). In the second year, total output loss is much smaller for the bay region (appendix 3). We again reduced the ABAG Regional Control Forecast output by this modified industry-specific loss in the REMI model.

Even with these conservative assumptions, the cumulative output loss effects from transportation network and commute flow interruption calculated in the model are as large as the output loss associated with building damage for the bay region. Employment loss increases from 232,000 to 498,000 jobs, and population decline expands from 50,000 to 105,000 people. As shown in table 12 and figure 4, loss of employment in the east bay subregion of the bay region rises from 159,000 to 228,000 jobs. The additional job losses in the west bay and south bay subregions are greater than the estimates from output losses from building damages alone in those areas. The west bay subregion loses 33,000 jobs because of building and contents damage, but an additional 108,000 jobs from commuting effects. Employment loss in the south bay subregion also increases by more than twofold.

In the San Francisco Bay region, the industry with the largest employment loss in the first year is food services and drinking places, with a loss of about 59,000 jobs (19 percent), followed by professional services (44,000 jobs, 7 percent) and retail trade (43,000 job, 10 percent). The construction sector loses 41,000 jobs (table 13). Total output loss approaches $106 billion in 2018 (2016 dollars) and increases by 120 percent from $48 billion if only output loss from direct building damage is considered. The real estate sector has the largest output loss ($11 billion), followed by professional services ($10 billion) and construction ($7 billion) (table 14 and appendix 4).

Table 12. Total employment and population effects in the HayWired scenario from building and transportation damage in 2018, San Francisco Bay region, California.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	Employment loss	Employment loss as a percent of subregion jobs	Employment loss as a percent of total loss	Population loss[1]	Population loss,[1] in percent	Population loss[1,2] as a percent of total loss
East bay	228,106	14.54	46	55,436	2.0	53
North bay	20,467	3.53	4	6,996	0.7	7
West bay	141,229	8.22	28	23,680	1.2	23
South bay	107,776	7.64	22	18,555	0.9	18
San Francisco Bay region	497,578	9.8	100	104,668	1.3	100

[1]Population loss relates only to the population effects of the output and employment loss, not the losses because of outmigration as a result of residential building damage or loss of community services.

[2]Because of rounding, percentages may not be exact.

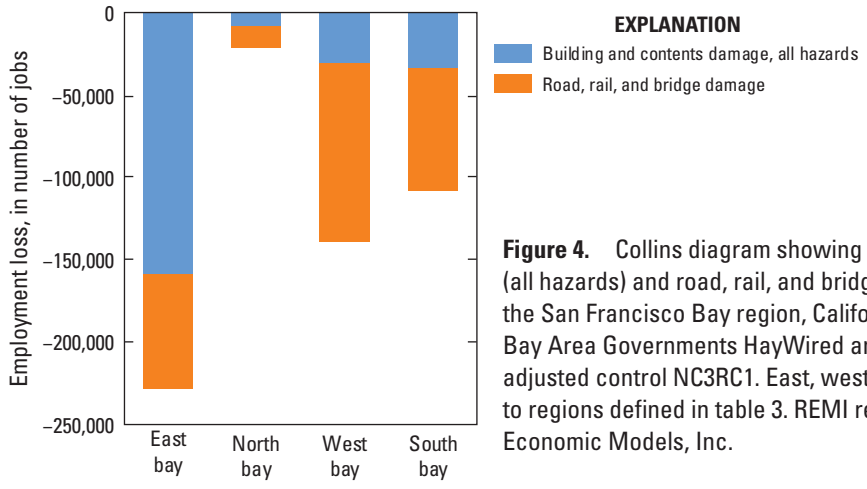


Figure 4. Collins diagram showing the HayWired scenario effects of building (all hazards) and road, rail, and bridge damage output loss on employment in the San Francisco Bay region, California. Data comes from the Association of Bay Area Governments HayWired analysis, using REMI model version 1.7.8, adjusted control NC3RC1. East, west, north, and south bay subregions refer to regions defined in table 3. REMI refers to models produced by Regional Economic Models, Inc.

Table 13. Ten industries with the largest employment loss from combined building and transportation effects in the San Francisco Bay region, California, in 2018.

[Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Sector category	Job loss	Job loss as a percent of sector jobs
Food services and drinking places	58,654	19.0
Professional, scientific, and technical services	44,174	6.6
Retail trade	43,011	10.2
Construction	41,434	16.2
Administrative and support services	31,846	10.3
Ambulatory health care services	25,735	14.3
Social assistance	20,220	9.2
Real estate	18,753	7.5
Wholesale trade	15,096	9.4
Performing arts and spectator sports	14,698	24.3

Table 14. Ten industries with the largest HayWired scenario total cumulative output loss from combined building and transportation effects in the San Francisco Bay region, California, in 2018.

[Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Sector category	Total output loss, in millions of dollars[1]	Output loss as a percent of sector output
Real estate	10,934.9	7.6
Professional, scientific, and technical services	9,531.9	6.5
Construction	6,772.3	16.5
Retail trade	4,993.2	10.3
Monetary authorities and other credit institutions	4,652.9	10.4
Ambulatory health care services	4,623.2	14.9
Wholesale trade	4,517.2	9.4
Food services and drinking places	4,174.5	18.7
Computer and electronic product manufacturing	4,091.2	3.2
Petroleum and coal products manufacturing	3,562.9	7.4

[1]2016 U.S. dollars.

Recovery Time Adjustment for Trade and Manufacturing Sectors

Empirical studies on business recovery for a range of crisis events, including hurricanes, earthquakes, and floods, have suggested that the more vulnerable businesses tend to be those that: are small; are reliant on discretionary income, such as retailers; are tenants rather than building owners; experience more severe damage; and (or) are closed for a longer period of time (Powell and Harding, 2007; Wein, Haveman, and others, this volume). In the HayWired scenario, manufacturing and mining companies are found to be more vulnerable because of direct output losses from building damages and effects of concentrated damages in their districts or neighborhoods (Wein, Belzer and others, this volume). Based on these findings we assumed an increase in the recovery time for retail trade, wholesale trade, mining, and selected manufacturing sectors. These manufacturing sectors consist of: wood product manufacturing; nonmetallic mineral product manufacturing; primary metal manufacturing; fabricated metal product manufacturing; machinery manufacturing; computer and electronic product manufacturing; electrical equipment and appliance manufacturing; motor vehicles, bodies and trailers, and parts manufacturing; other transportation equipment manufacturing; furniture and related product manufacturing; miscellaneous manufacturing; food manufacturing; beverage and tobacco product manufacturing; apparel manufacturing; leather and allied product manufacturing; paper manufacturing; petroleum and coal products manufacturing; chemical manufacturing; and plastics and rubber product manufacturing, which are based on data from Jon Haveman (Marin Economics Consultant, written commun., 2018). Specifically, we added 80 percent of the first-year direct output loss to the second-year direct output loss, 60 percent to the third year, and 40 percent to the fourth year for the retail sector in the east bay subregion. For nonretail sectors in the east bay subregion, we added 60 percent of the direct output loss estimated for 2018 to the second-year loss, 30 percent to the third year, and 10 percent to the fourth year. And for all sectors mentioned above in other subregions, we added 25 percent of the first-year direct output into the second-year loss and 5 percent to the third year. Assumptions of additional output loss for these sectors are shown in table 15. The differences reflect the degree of building damage in each of the REMI-defined subregions.

Table 15. Additional output loss as share of first year (2018) estimated output loss for the HayWired scenario in the San Francisco Bay region, California.

[Industry sectors of output loss considered are listed in parentheses. Subregions are defined in table 3]

Subregion	Output loss, in percent		
	2019	2020	2021
East bay (retail)	80	60	40
East bay (nonretail)	60	30	10
North bay (all)	25	5	0
West bay (all)	25	5	0
South bay (all)	25	5	0
Rest of California (all)	25	5	0

San Francisco Bay region employment loss reaches about 480,000 jobs in 2018 when building damage effects, transportation and commute flow effects, and the sector recovery time adjustments are combined; employment loss continues at a slower pace over the next four years of the scenario, and employment reaches a net gain of more than 4,600 jobs in 2022, five years after the earthquake. Ten years after the earthquake, the bay region still maintains a net gain of 6,000 jobs, but by 2040, the region is projected to have 1,300 fewer jobs than in the ABAG Plan Bay Area 2040 projection for the bay region, which is an insignificant difference from the projected 4.7 million jobs in 2040 (table 16).

Table 16. Total difference in employment numbers from revised output loss effects, relative to the Association of Bay Area Governments (ABAG) regional projection.

[Difference in employment numbers listed as negative where number of jobs are lost and positive where gained. Subregions are defined in table 3; Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	−220,659	−42,429	−25,153	−10,515	526	2,861	−637
North bay	−19,953	−4,818	−2,714	−1,217	−314	275	−121
West bay	−136,545	−14,379	−5,565	−715	1,474	1,239	−347
South bay	−103,048	−16,626	−2,560	1,558	2,956	1,707	−191
San Francisco Bay region	−480,204	−78,252	−35,992	−10,888	4,642	6,084	−1,295
Percent compared to ABAG projection							
	−9.4	−1.5	−0.7	−0.2	0.1	0.1	0.0

Population in the bay region does not recover as fast as employment. The region loses about 101,000 people in the first year related to reductions in employment. By 2022, the population remains about 63,000 below projections (although 300,000 above the population level in 2018). Ten years after the earthquake, the region still has a net deficit of 25,000 people compared to the ABAG Plan Bay Area 2040 projection. By 2040, the region's population would slightly surpass the ABAG Plan Bay Area 2040 projection for the year, by around 1,000 people—again an insignificant difference in the projection of 9.5 million people in 2040 (table 17).

Effects on Population Beyond Employment

Up to this point in the discussion, the model analysis of the earthquake effects on population levels has come entirely through the changes to output—economic activity changes. Yet, as described by Johnson and others (this volume), the size of the labor supply and the characteristics of the labor force (such as education level, labor participation rate, age, and gender) of a region are some factors that determine the vitality of its economy. Post-disaster population movements and compositional changes that lead to regional labor force shifts would affect the economy. There is a broad base of household and community-scale socioeconomic characteristics that affect population displacement risk more than just race, income, and age (Esnard and others, 2011; Johnson and others (this volume). After a disaster, businesses might relocate because of damages. They may choose more distant locations if the damage has left few available spaces. This can also disrupt their customer base, and population movement may even lead to the establishment of new economic centers outside the affected areas.

Johnson and others (this volume) have extensively discussed areas at risk of population displacement and long-term community recovery challenges, such as assembling the resources for recovery; repairing and replacing damaged housing; finding interim housing; overcoming other recovery dependencies, such as jobs and neighborhood-serving businesses, transportation and utilities, and schools and community services; and addressing areas that require substantial replanning and intervention in order to recover. They estimate that about 216,000 to 268,000 households (almost 800,000 people and perhaps more) might be displaced in the short term in the HayWired scenario. However, long-term population movement remains hard to estimate, partly because of a lack of data and the complexity of different communities. In New Orleans, Louisiana, it took ten years for the city to regain 95 percent of its pre-Hurricane Katrina population, whereas in Puerto Rico, still recovering from Hurricane Maria, almost 90 percent of a sample of 407,000 people who left had returned home as of February 2018 (Echenique and Melgar, 2018).

The degree to which population displacement goes beyond the region is also complex to estimate. The region's total housing stock is large relative to the damage—households displaced from heavily damaged areas may find temporary or long-term living situations in other parts of the region. On the other hand, were the earthquake to happen during a period of very tight housing markets and rapidly escalating prices (as in 2017 and 2018), the costs could drive households who were barely able to afford their living situation prior to the disaster out of the region.

We used two levers in the model to address population displacement—housing prices and senior migration, which is a noneconomic migration in terms of how the model is structured.

Table 17. Total difference in population from revised output loss effects of the HayWired scenario, relative to the Association of Bay Area Governments Plan Bay Area 2040 projection for the San Francisco Bay region, California.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	−53,310	−48,627	−46,644	−42,134	−36,447	−16,077	134
North bay	−6,799	−6,791	−6,554	−5,900	−5,076	−1,782	55
West bay	−22,963	−19,388	−17,275	−14,741	−12,326	−4,196	467
South bay	−17,731	−15,100	−12,836	−10,692	−8,786	−3,131	291
San Francisco Bay region	−100,802	−89,906	−83,309	−73,467	−62,635	−25,186	947
Percent compared to ABAG projection							
	−1.3	−1.1	−1.1	−0.9	−0.8	−0.3	0.0

Post-earthquake Housing Price Changes

After nearly 170,000 properties were damaged in the Christchurch earthquake in New Zealand, the subsequent shortage in housing has resulted in a sharp increase in housing and rental prices. According to the Reserve Bank of New Zealand, housing prices in Christchurch are more than 40 percent higher than their pre-earthquake levels, which is more than double the increase that has occurred in the rest of New Zealand (Wood and others, 2016). Rents had increased by almost 50 percent in Christchurch by the start of 2015 (about four years after the initial earthquake in September 2010), compared with a nationwide increase of about 15 percent during that time. The increase in rents has been concentrated in the relatively unaffected suburbs because people have moved away from harder hit areas. This pattern is consistent with what has been observed after the 2017 Northern California wildfires. Housing prices in Sonoma County have increased faster than the whole San Francisco Bay region (North Bay Business Journal, 2018). Rents are also rising in the county and neighboring areas outside the immediate affected areas, although to a much lesser degree in Marin County; an observation perhaps attributable to Marin County's already high housing and rental prices (Halstead, 2018).

In the REMI model, we therefore increased the housing and rental prices for the four REMI subregions by the percentages shown in table 18 for the 7 years following the earthquake. We assumed that the price increase would remain relatively small in the first year, peak the fifth year, and then drop off as more housing and rental properties become available. We used "imputed rental of owner-occupied nonfarm" in the REMI model as the equivalent of housing sales price, and "rental of tenant-occupied nonfarm housing" for rents.

Post-earthquake Senior Outmigration Assumption

The housing price variable in combination with the economic variables captures some of the earthquake induced outmigration. Experience with the effects of the 2017 Northern California wildfires suggests that senior households may be particularly vulnerable to displacement, because of the costs and time involved in rebuilding. In this analysis, we chose to focus on retired migrants. Specifically, we assumed that seniors 65 years old and above that live with only a spouse, live in nonfamily households, or in group quarters in areas with concentrated damage would leave the region and not return. In 2016, there were 97,800 (5-year, American Community Survey, 2016) seniors in those heavily affected areas, more than 50 percent (50,400) of them meet the criteria for our assumption in this analysis. As such, we increased the outflow of retired migrants by 25,200 people in 2018, and by another 25,200 people in 2019 in the model.

We added these population effects into the REMI model with the effects on population from output changes described earlier. Job loss attributed to output losses from building damage, commute flow interruption, housing cost increases, and senior population displacement is estimated at around 515,000 jobs in 2018, around 96,000 five years after, and by 2040, the region still has a net loss of 10,000 jobs (table 19). Additionally, population loss for the region as a whole from the same effects, relative to projected levels, is estimated at around 150,000 people in 2018, around 264,000 people five years after, and by 2040, there remains a net loss of 23,000 people (table 20).

Table 18. Post-earthquake housing and rental price increases by year after the event, in percent, for the HayWired scenario in the San Francisco Bay region, California.

[Subregions are defined in table 3]

Detail	Subregion	1st	2d	3d	4th	5th	6th	7th
Imputed rental of owner-occupied nonfarm housing	East bay	5	5	10	15	30	5	5
Imputed rental of owner-occupied nonfarm housing	North bay	5	10	15	20	30	5	10
Imputed rental of owner-occupied nonfarm housing	West bay	5	5	10	10	10	5	5
Imputed rental of owner-occupied nonfarm housing	South bay	5	10	15	20	30	5	10
Rental of tenant-occupied nonfarm housing	East bay	5	5	15	20	30	5	5
Rental of tenant-occupied nonfarm housing	North bay	10	10	15	20	30	10	10
Rental of tenant-occupied nonfarm housing	West bay	5	5	10	15	20	5	5
Rental of tenant-occupied nonfarm housing	South bay	10	10	15	20	30	10	10

Table 19. Total employment difference from all loss effects in the HayWired scenario, relative to the Association of Bay Area Governments Regional Controls Forecast for the San Francisco Bay region, California.

[Difference in employment numbers is listed as negative where jobs are lost and positive where gained. Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	−238,518	−74,107	−60,033	−49,803	−48,398	−736	−3,149
North bay	−22,844	−10,136	−10,194	−10,440	−12,164	−780	−1,224
West bay	−145,844	−25,566	−22,522	−21,334	−25,422	−1,058	−3,619
South bay	−107,998	−22,300	−10,550	−8,425	−9,622	1,635	−2,380
San Francisco Bay region[1]	−515,204	−132,108	−103,299	−90,002	−95,606	−940	−10,373
Percent compared to ABAG projection							
	−10.1	−2.6	−2.0	−1.8	−1.9	0.0	−0.2

[1]Because of rounding, sum totals may not be exact.

Table 20. Total population difference from all loss effects in the HayWired scenario, relative to the Association of Bay Area Governments Regional Controls Forecast for the San Francisco Bay region, California.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	−86,779	−114,681	−119,304	−124,574	−136,189	−77,351	−8,065
North bay	−9,555	−13,575	−18,353	−23,220	−29,483	−17,126	−2,743
West bay	−30,516	−32,132	−38,904	−46,389	−57,828	−30,583	−5,404
South bay	−23,114	−24,154	−27,760	−32,784	−40,533	−24,214	−66,56
San Francisco Bay region[1]	−149,965	−184,541	−204,321	−226,968	−264,033	−149,274	−22,867
Percent compared to ABAG projection							
	−1.9	−2.4	−2.6	−2.9	−3.3	−1.8	−0.2

[1]Because of rounding, sum totals may not be exact.

Assumptions and Simulated Effects within the REMI Model—Part 2: Rebuilding the Region

The elements described above consist of losses directly caused by building damage, transportation network interruption from the earthquake, and potential housing price increase, as well as senior outmigration, that reflect the displacement risks and recovery challenges in the region. In the following section we look at how Federal disaster relief funding and State and local government spending affects the level and pace of rebuilding.

Government Response and Recovery Investment

Following an earthquake of such scale (M_w 7.0), disaster declarations at the State and Federal level would be expected. For Federal fiscal years 2005 through 2014, FEMA obligated more than $104.5 billion from the Disaster Relief Fund for federally declared disasters across the country (U.S. Government Accountability Office, 2016), of which $25.4 billion was obligated for the Individual Assistance programs, $45.7 billion for Public Assistance programs, and $5.4 billion for the Hazard Mitigation Assistance program. The remaining $28 billion paid for FEMA administrative and mission assignment related costs. In addition to financial

assistance available from the Disaster Relief Fund, during the same 10-year period, at least $173.1 billion across 17 Federal departments and agencies was provided for Federal disaster-specific and disaster-applicable programs and activities (U.S. Government Accountability Office, 2016), such as the Small Business Administration (SBA), which provides federally subsidized loans to repair or replace homes, personal property, or businesses that sustained damages not covered by insurance following a disaster, the Department of Housing and Urban Development Community Development Block Grant Program, the U.S. Department of Transportation Federal-Aid Highway Emergency Relief Program, the U.S. Department of Agriculture and Rural Assistance, and the U.S. Army Corps of Engineers Emergency Assistance.

There are three principal forms of Federal financial assistance from FEMA:

Public Assistance Program (FEMA, 2010).—This program provides grants to tribal, State, and local governments, and certain private nonprofit organizations to conduct debris removal operations (category A); provides emergency protective services (category B); and repairs or replaces damaged public infrastructure (category C-G). Although certain nonprofit organizations may be eligible for these grants, for-profit businesses are not.

Individual Assistance Program.—This program provides direct aid to affected households, can take the form of housing assistance (temporary housing, lodging expenses reimbursement, repair, replacement, and permanent or semipermanent housing construction), other needs assistance (child care, medical and dental expenses, funeral expenses, household, personal and work items, fuel, and moving expenses), crisis counseling, case management services, legal services, and disaster unemployment assistance. Total assistance under this program is capped at $33,300 per household, though that amount is adjusted annually (see https://www.fema.gov/individual-disaster-assistance for details on the program).

Hazard Mitigation Assistance Program.—This program funds mitigation and resiliency projects and programs typically across the entire State. This form of assistance is also cost shared. Mitigation projects can include the construction of safe rooms, buy-outs of frequently flooded properties, and retrofitting of facilities.

For Hurricane Katrina, Federal spending covered 72 percent of its damages, or $115 billion for the loss of $160 billion, whereas 80 percent of Hurricane Sandy's damages were covered by Federal spending. On average, the Federal Government has contributed funds to cover 62 percent of estimated damages for hurricanes that happened between Hurricanes Katrina and Sandy (Struyk, 2017). After the 2014 South Napa earthquake, financial assistance from FEMA and the California Governor's Office of Emergency Services reached $40.5 million, including $10.4 million in approved Housing Assistance Grants, $1.0 million in approved Other Needs Assistance Grants, and $5.5 million obligated Public Assistance Grants in categories A–B and $22.5 million in categories C–G (U.S. Department of Homeland Security and Federal Emergency Management Agency, 2014a). An additional $30.7 million in home disaster loans was given to 971 applicants and $10.7 million of business disaster loans to 125 applicants who were approved by the SBA (Carol Chastang, Public Affairs Specialist, U.S. SBA, written commun., 2018). SBA loans were included in the background analysis because they are an essential part of the recovery process that would increase spending in the economy. However, the potential effect of loan repayments was not included as part of the analysis. For the October 2017 Northern California wildfires, $18.0 million was approved under the Individual Assistance Program, and $357.9 million was approved under the Public Assistance Program (U.S. Department of Homeland Security and Federal Emergency Management Agency, 2014b). The SBA provided $151 million total in home and business disaster loans (Carol Chastang, Public Affairs Specialist, U.S. SBA, written commun., 2018). These recent figures were used to estimate the distribution of Government financial assistance, as discussed below.

Financial assistance from the Federal and State Governments is vital for the recovery and rebuilding of the region in the HayWired scenario because only 10 percent of residential fire insurance policyholders have earthquake insurance, and assistance from nonprofit organizations and foundations will be limited. CoreLogic, a real estate data company, estimates that insurance will only be able to cover 17.6 percent of the estimated losses—Federal assistance is important to bridge the funding gaps for the region's recovery (CoreLogic, 2018). Our model uses the assumption that insurance will only cover 15 percent of the estimated losses. Taking into account the timeline for releasing and spending approved grants and the cost-share factor between Federal, State, and local governments regarding governments' response, we assumed:

- Insured loss is 15 percent of the total estimated building-damage-related loss of $85 billion (2016 value). This consists of building, content loss, inventory, relocation cost, income, rent, and wage losses only for the nine San Francisco Bay region counties as estimated by Seligson and others (2018);
- Government assistance from all levels covers two-thirds of the uninsured loss; one-third of the uninsured loss is not recovered;
- Two-thirds of government assistance is spent on rebuilding, the other one-third covers all administrative functions;

- State and local governments are responsible for one-fourth of all government assistance, the rest is exogenous Federal spending into the region;
- Spending would be used throughout a 9-year period distributed by 10, 10, 20, 20, 15, 10, 5, 5, and 5 percent from the first to the ninth year; and
- Distribution of grants by San Francisco Bay subregion is based on the distribution of building damage related losses by subregion.

At the same time, spending from government, businesses, and individuals with the money received as part of the recovery could be seen as reinvestment into the region's economy: rebuilding and restoration of housing units, commercial properties, and public facilities will create huge demand in the construction sector, consumer spending on apparel and household items, and educational and healthcare services will also spur the recovery and growth of the economy. During 2011, when three magnitude 6 aftershocks affected Christchurch, New Zealand in February, June, and December, employment in the region kept falling through mid-2012 and has since risen by about 16 percent as of early 2016. The ratio of construction employment in Canterbury, New Zealand, to nationwide construction jobs has doubled, whereas corresponding ratios in other industries have fallen or remained flat (Wood and others, 2016). Retail sales in Christchurch held up well relative to nationwide sales in the initial period after the earthquakes, but experienced a noticeable increase since 2012, which slowed down in mid-2015. At the same time, import volumes into Canterbury have increased by more than nationwide imports as rebuild-related materials and replacement goods have been brought in (Wood and others, 2016). Given the observed delay in construction starts and retail sales increases, in this analysis, we assume:

- Three-fourths of government nonadministrative spending would be spent in the construction sector, and the remaining quarter would be spent on 28 selected consumer commodities (appendix 6);
- Spending in construction would be spread across a 9-year period, as recommended by volume coauthor Laurie Johnson (Laurie Johnson Consulting, written commun., 2018), based on her experience with the pace of recovery in other U.S. natural disasters, distributed by 10, 10, 20, 20, 15, 10, 5, 5, and 5 percent from the first to ninth year;
- Spending in consumer products would be used throughout a 10-year period distributed by 2.5, 7.5, 10, 20, 20, 15, 10, 7.5, 5, and 2.5 percent from the first to tenth year;
- Distribution of grants by San Francisco Bay subregion is based on the distribution of building damage related losses (the sum of building, contents, and inventory repair and replacement costs, relocation costs, income losses, and output losses) by subregion.

Government spending and recovery have a stimulating effect on the economy that can counteract some of the job and population losses. To understand the effect of government spending alone on employment and population, we first increased government spending in the ABAG Regional Control Forecast without including the effects of output loss or population outmigration loss. When added to the ABAG Regional Control Forecast, government spending creates 19,000 jobs in 2018, which increases to more than 39,000 in 2020 as the speed of recovery picks up. The effects disappear after the grants are exhausted. Meanwhile, the economic activity stimulated from this spending brings an additional 5,000 people to the San Francisco Bay region in 2018, and as many as 27,000 by 2022. By 2040, and assuming no further damaging earthquakes, the cumulative effects of recovery spending are no longer apparent compared to expected levels from the ABAG Regional Control Forecast. However, recovery would have been delayed without the recovery spending (tables 21, 22).

Table 21. Total employment gain from recovery spending, relative to the Association of Bay Area Governments Plan Bay Area 2040 projection for the San Francisco Bay region, California.

[Subregions are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	10,857	12,183	22,142	24,313	19,582	−91	443
North bay	637	804	1,556	1,822	1,529	78	58
West bay	3,418	3,844	6,933	7,594	5,894	−308	114
South bay	4,177	4,539	8,305	8,743	6,650	−847	72
San Francisco Bay region[1]	19,089	21,370	38,936	42,472	33,654	−1,169	686

[1]Because of rounding, sum totals may not be exact.

Table 22. Total population gain from recovery spending in the HayWired scenario, relative to the Association of Bay Area Governments regional projection for the San Francisco Bay region, California.

[Subreginos are defined in table 3. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model; analysis of the HayWired scenario from 2018 (this study)]

Subregion	2018	2019	2020	2021	2022	2027	2040
East bay	3,190	5,931	11,275	16,099	18,838	14,645	1,484
North bay	239	481	948	1,410	1,693	1,314	86
West bay	520	969	1,794	2,522	2,848	1,710	31
South bay	651	1177	2,199	3,062	3,462	2,115	91
San Francisco Bay region[1]	4,600	8,558	16,216	23,093	26,841	19,784	1,691

[1]Because of rounding, sum totals may not be exact.

HayWired Scenario Combined Effects on Employment and Population

Running the REMI model with all of the assumptions included shows a regional economy that could experience a deep recession (or depression in the east bay subregion of the San Francisco Bay region). It would ultimately recover, but some parts of the region do not recover to pre-earthquake employment levels until about 2025 (fig. 5*A*). Compared to projected employment and population levels, the region returns to within about 1 percent of the projected employment track by 2025 (fig. 5*B*). The absolute population in the region recovers more quickly than the employment totals (fig. 6*A*), but compared to the regional projection without an earthquake, the population level is reduced for more than a decade, especially in the east and north bay subregions (fig. 6*B*).

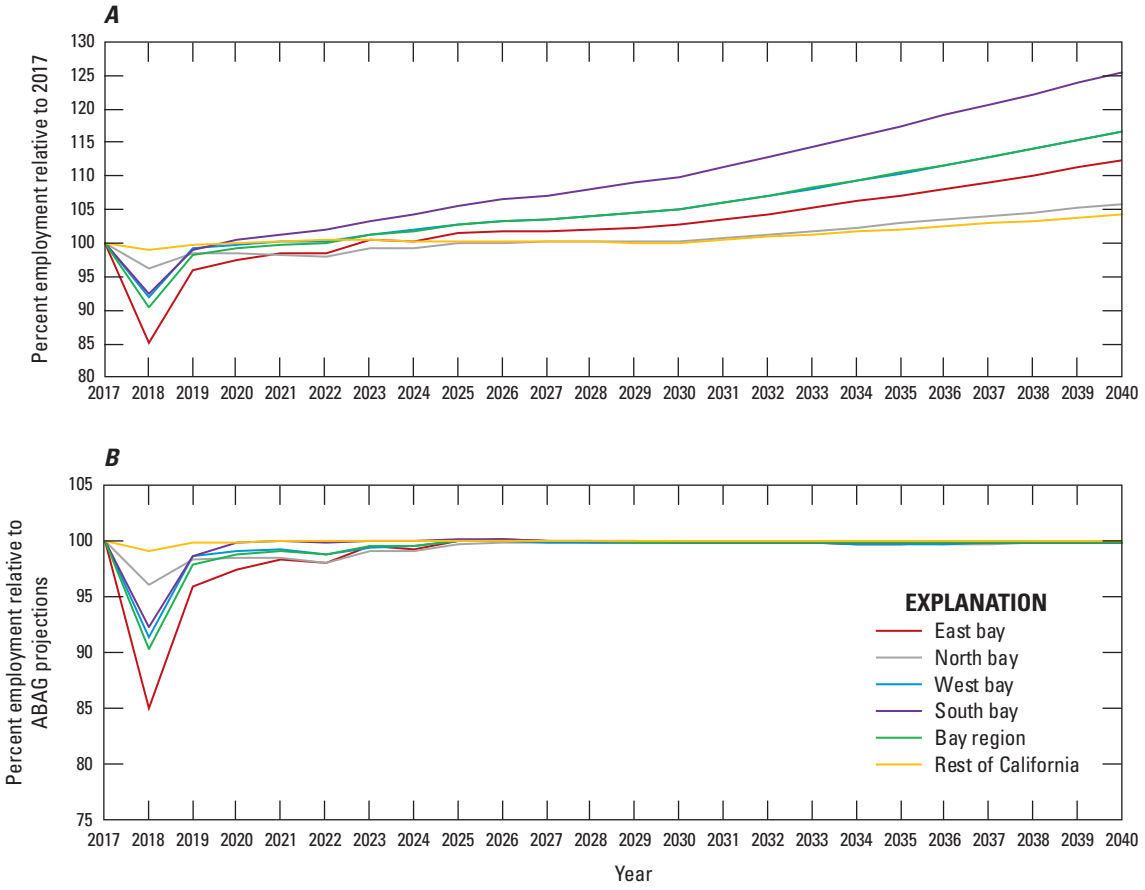


Figure 5. Graphs of employment curves in the HayWired scenario for the San Francisco Bay region, California, relative to 2017 levels (*A*) and the Association of Bay Area Governments (ABAG) Plan Bay Area 2040 projection (*B*). Data generated using the ABAG Planning and Research Department (2016) REMI model; analysis of the HayWired scenario from 2018 (this study). East, west, north, and south bay are defined in table 3. Bay region refers to the San Francisco Bay region. REMI refers to models produced by Regional Economic Models, Inc.

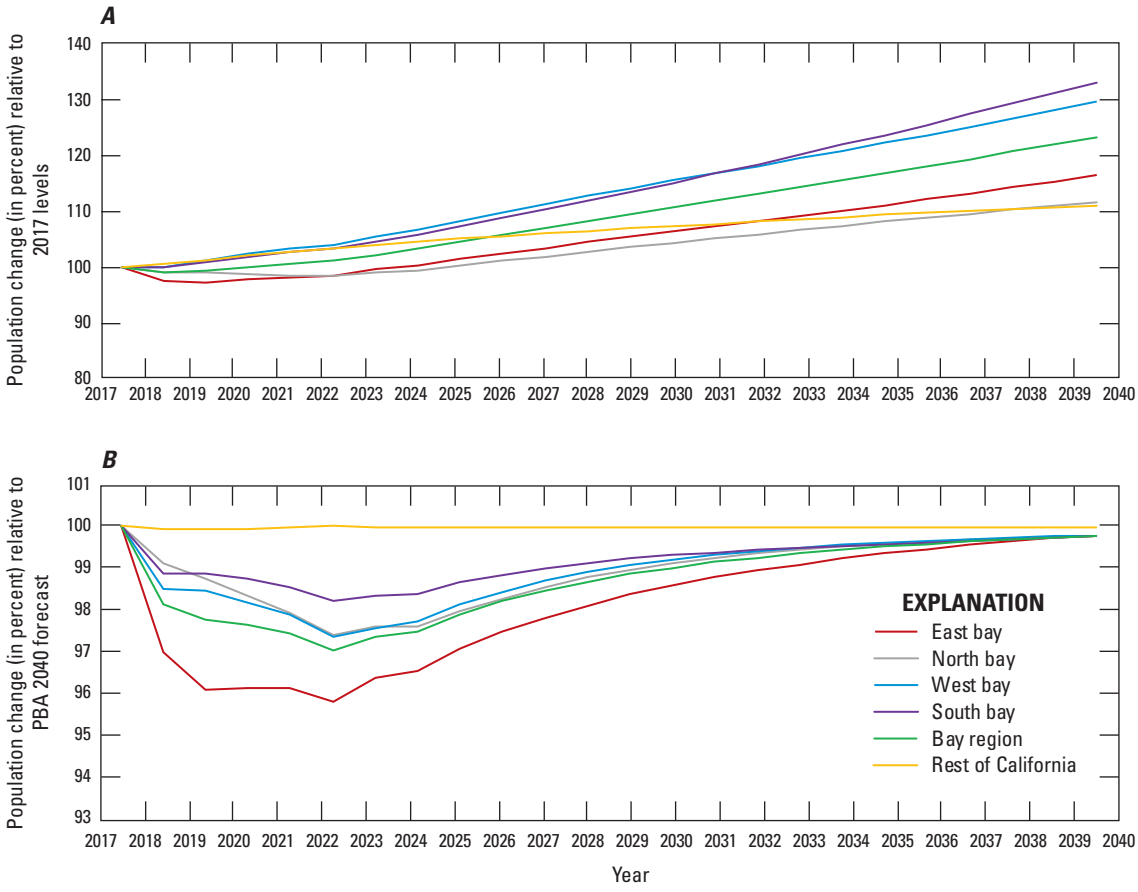


Figure 6. Graphs of population curves in the HayWired scenario for the San Francisco Bay region, California, relative to 2017 levels (*A*) and the Association of Bay Area Governments (ABAG) Plan Bay Area 2040 (PBA2040) projection (*B*). Data generated using the ABAG Planning and Research Department (2016) REMI model; analysis of the HayWired scenario from 2018 (this study). East, west, north, and south bay are defined in table 3. Bay region refers to the San Francisco Bay region. REMI refers to models produced by Regional Economic Models, Inc.

Employment Effects

All assumptions included, the region's net employment loss in the first year is more than 496,000 jobs, a 10 percent decrease compared to the regional control forecast (fig. 5*B*). All sectors experience job losses in the first few years after the earthquake. Food service and drinking places has the largest employment loss in 2018, almost 59,000 jobs (19 percent), followed by professional services (44,000 jobs or 7 percent), retail trade (43,000 jobs or 10 percent), and administrative services sector (32,000 jobs or 10 percent). By 2040, the region has a net job loss of 10,000, which can be attributed to losses in all sectors except petroleum manufacturing and apparel manufacturing (fig. 7). Appendix 5 shows detailed industry net employment change.

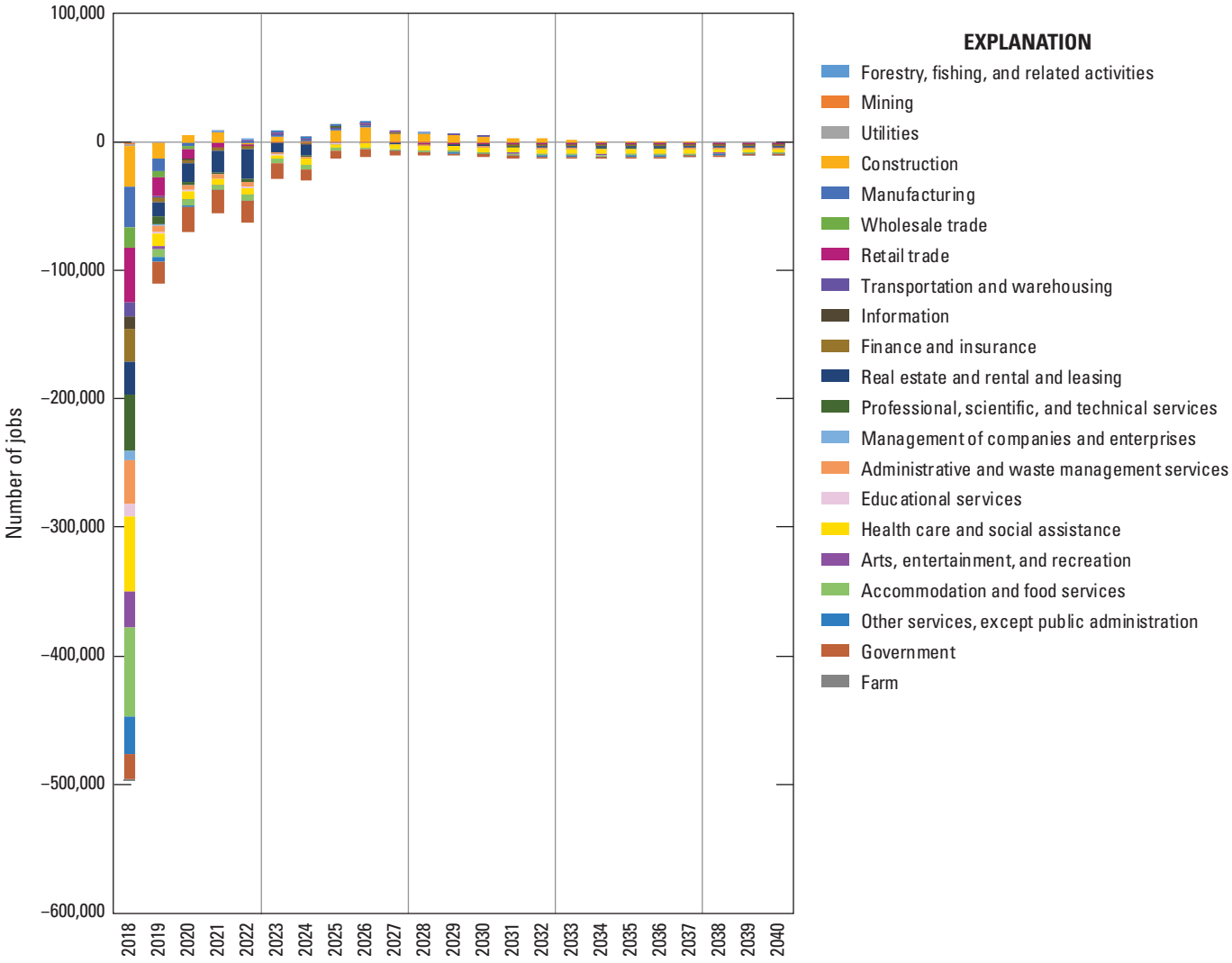


Figure 7. Collins diagram showing San Francisco Bay region, California, net employment change by sector in 2018–2040 for the HayWired scenario. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI model version 1.7.8, adjusted control NC3RC1. REMI refers to models produced by Regional Economic Models, Inc.

Population Effects

Combining the loss and stimulus effects, the San Francisco Bay region population decreases by about 145,000 in 2018, of which a decrease of 83,000 people occurs in the east bay subregion. Population net loss, especially from senior outmigration after the earthquake in the east bay subregion, continues to drive the earthquake's negative effects on the region's population until 2040. Housing price increases in other subregions also drive residents outside of the bay region. By 2040, the bay region population remains at a net loss of about 21,000 people compared to the ABAG Regional Control Forecast (fig. 8).

Gross Regional Production Effects

Overall, San Francisco Bay region GRP decreases by about $67 billion in 2018, almost 10 percent of GRP, of which a $26 billion loss occurs in the east bay subregion, $22 billion in the west bay subregion, and another $16 billion in the south bay subregion. The north bay subregion loss is the smallest, approximately $2 billion. Loss in GRP changes as recovery activities enter different stages. By 2040, the bay region GRP remains a net loss of about $1 billion relative to GRP projections from the Plan Bay Area 2040 regional projection, or less than one-tenth of one percent of the plan's projected GRP (fig. 9).

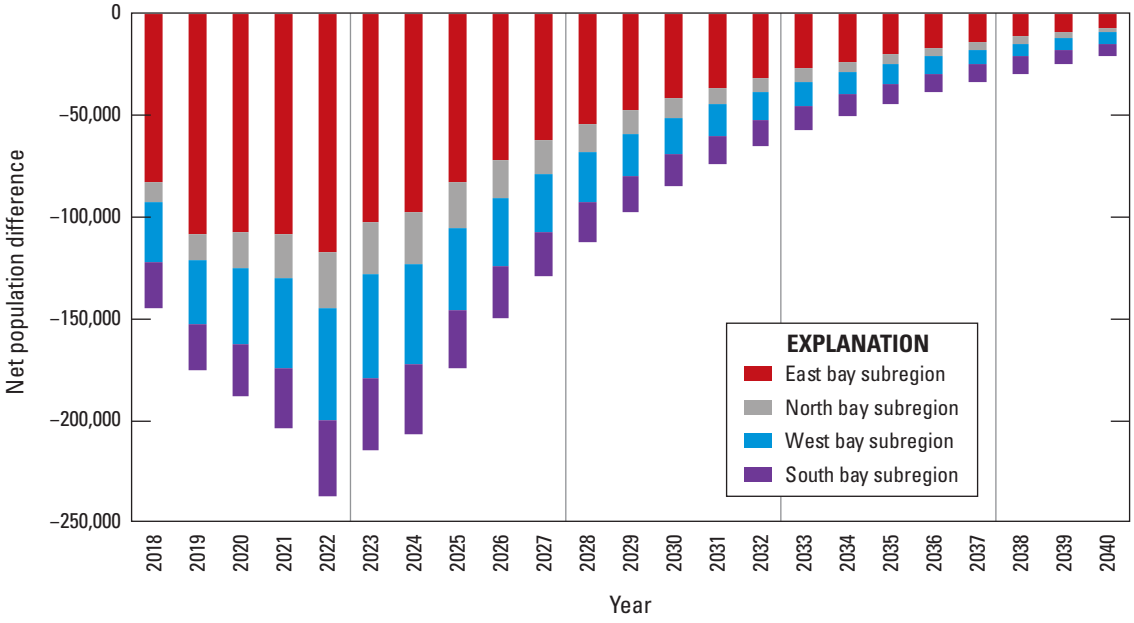


Figure 8. Collins diagram showing San Francisco Bay region, California, net population difference by subregion for the HayWired scenario compared to the Association of Bay Area Governments (ABAG) Regional Control Forecast. Data from ABAG Planning and Research Department (2016) REMI model version 1.7.8, adjusted control NC3RC1. Subregions are defined in table 3. REMI refers to models produced by Regional Economic Models, Inc.

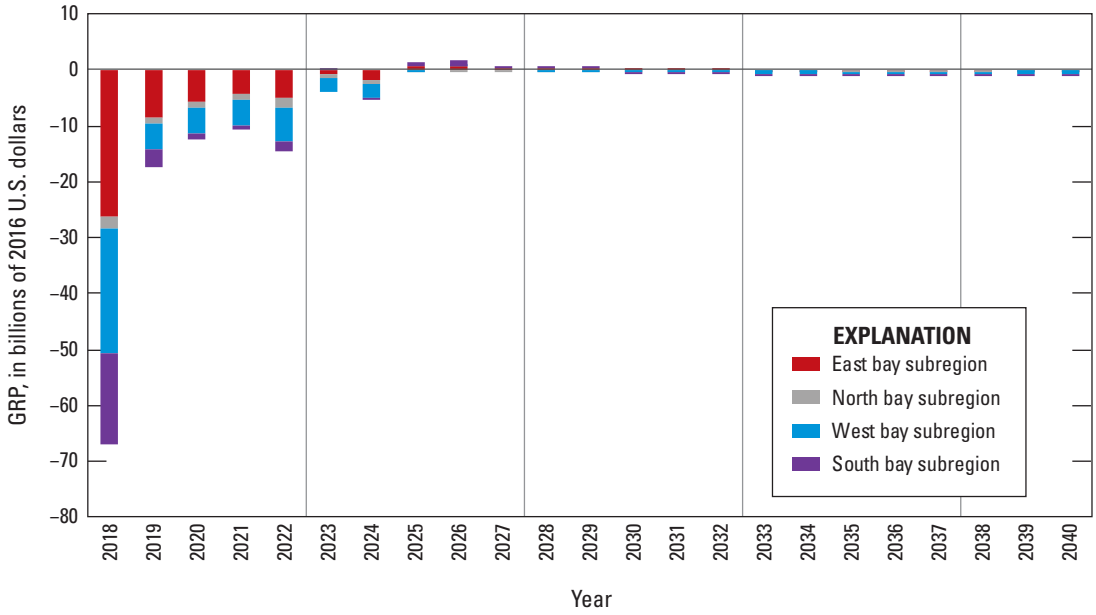


Figure 9. Collins diagram of San Francisco Bay region, California, net gross regional product (GRP) change by subregion for the HayWired scenario compared to the Association of Bay Area Governments (ABAG) Regional Control Forecast. Data from ABAG Planning and Research Department (2016) REMI model version 1.7.8, adjusted control NC3RC1. Subregions are defined in table 3. REMI refers to models produced by Regional Economic Models, Inc.

Summary of REMI Simulation of HayWired Scenario Effects

This analysis shows an economy that would experience substantial damages and losses in the short term from a magnitude 7.0 earthquake on the Hayward Fault. Much of the economy could recover within a few years, although a full return to the previous trajectory could take more than five years for the region and closer to a decade for the most severely affected counties. Recovery and rebuilding investments will be crucial to repairing the economic base of the region and returning to its projected growth trajectory.

The most severe economic losses are concentrated in the east bay subregion, where in 2018, there are reductions in GRP by 13 percent, employment by 15 percent, and population by 3 percent (table 23). Other parts of the region,

Table 23. Summary of year 1, year 5, year 10, and 2040 employment, population, and gross regional product (GRP) levels in the HayWired scenario relative to Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Subregions are defined in table 3. Negative percentage change in parentheses. GRP change is in billions of 2016 U.S. dollars. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model version 1.7.8, adjusted control NC3RC1]

Subregion	2018	2022	2027	2040
		Employment		
East bay	−227,564	−28,837	−915	−2,678
	(0.15)	(0.02)	(0.00)	(0.00)
North bay	−22,213	−10,661	−706	−1,164
	(0.04)	(0.02)	(0.00)	(0.00)
West bay	−142,438	−19,530	−1,389	−3,492
	(0.09)	(0.01)	(0.00)	(0.00)
South bay	−103,827	−2,959	772	−2,300
	(0.08)	(0.00)	0.00	(0.00)
San Francisco Bay region	−496,042	−61,987	−2,238	−9,634
	(0.10)	(0.01)	(0.00)	(0.00)
		Population		
East bay	−82,978	−117,468	−62,738	−6,738
	(0.03)	(0.04)	(0.02)	(0.00)
North bay	−9,313	−27,874	−15,846	−2,648
	(0.01)	(0.03)	(0.02)	(0.00)
West bay	−30,011	−55,005	−28,886	−5,349
	(0.02)	(0.03)	(0.01)	(0.00)
South bay	−22,408	−37,122	−22,120	−6,559
	(0.01)	(0.02)	(0.01)	(0.00)
San Francisco Bay regiona	−144,710	−237,469	−29,590	−21,294
	(0.02)	(0.03)	(0.02)	(0.00)
		GRP change		
East bay	−26.07	−5.15	0.40	−0.07
	(0.13)	(0.02)	0.00	(0.00)
North bay	−2.31	−1.44	−0.02	−0.11
	(0.03)	(0.02)	(0.00)	(0.00)
West bay	−22.29	−6.34	0.00	−0.42
	(0.08)	(0.02)	0.00	(0.00)
South bay	−16.21	−1.54	0.42	−0.26
	(0.06)	(0.01)	0.00	(0.00)
San Francisco Bay region	−66.88	−14.47	0.80	−0.86
	(0.08)	(0.02)	0.00	(0.00)

as well as neighboring counties, also experience losses and disruptions to work caused by building damage. These losses are exaggerated by disruptions to the transportation system. In 2018, the west bay subregion loses 8 percent in GRP, 9 percent in employment, and 2 percent in population; the south bay subregion loses 6 percent in GRP, 8 percent in employment, and 1 percent in population; and the north bay subregion loses 3 percent in GRP, 4 percent in employment, and 1 percent in population. The rest of California is estimated to lose more jobs than the west and south bay subregions (171,000 in places outside the bay region) and more people than the south bay subregion (23,000) in 2018. Although bay region employment, population, and GRP fall below the ABAG Regional Control Forecast for Plan Bay Area 2040, the negative effects are insignificant by 2040.

The HayWired analysis shows employment losses experienced in the east bay subregion will be much sharper and deeper than during recent recessions but will have a faster rate of recovery than from either the "dot-com" (2001–2004) or financial crisis (2008–2010) related recessions (fig. 10A). For the San Francisco Bay region as a whole (fig. 10B), employment losses are of a magnitude similar to that experienced in the "dot-com" bust, but it ultimately took the region much longer to recover the jobs lost then than the recovery illustrated here.

Achieving this pace of recovery happens naturally in the model but in actuality is not guaranteed, nor is it independent of policy actions taken before or after an earthquake. The following sections discuss limitations to the analysis, how different assumptions could affect the model results, and finally how policies before and after the earthquake may also determine the outcomes for individuals, communities, and the region as a whole.

Caveats and Limitations

In a number of ways, this economic analysis incorporates significant resilience features. The REMI model has built-in resilience, with a tendency to return to long-term trends over time. Our application of assumptions also includes some resilient features, with the expectation that transportation disruptions are moderated by worker behavior (finding alternative travel routes), employer adjustments (encouraging telecommuting), and a range of supports for housing workers close to jobs.

The assumptions provided by major transportation and utility providers also suggest expectations of a sequence of repairs that would allow the economy to return to normal within a year. Water, utilities, and communications are expected to be mostly restored within a few weeks to a couple of months. Where repairs are expected to take longer (for example, the BART line running south of Oakland to Fremont on fig. 2*B*), alternative transportation modes (buses, ferries, carpools, and individual drivers) can provide alternative travel options, once bridges are repaired. Some water repairs in limited parts of Alameda and Contra Costa Counties could take as long as six months, but this is incorporated in the population relocation and business dislocation assumptions.

If the restoration of services proceeds as assessed by the providers, then most of the negative effects occur in

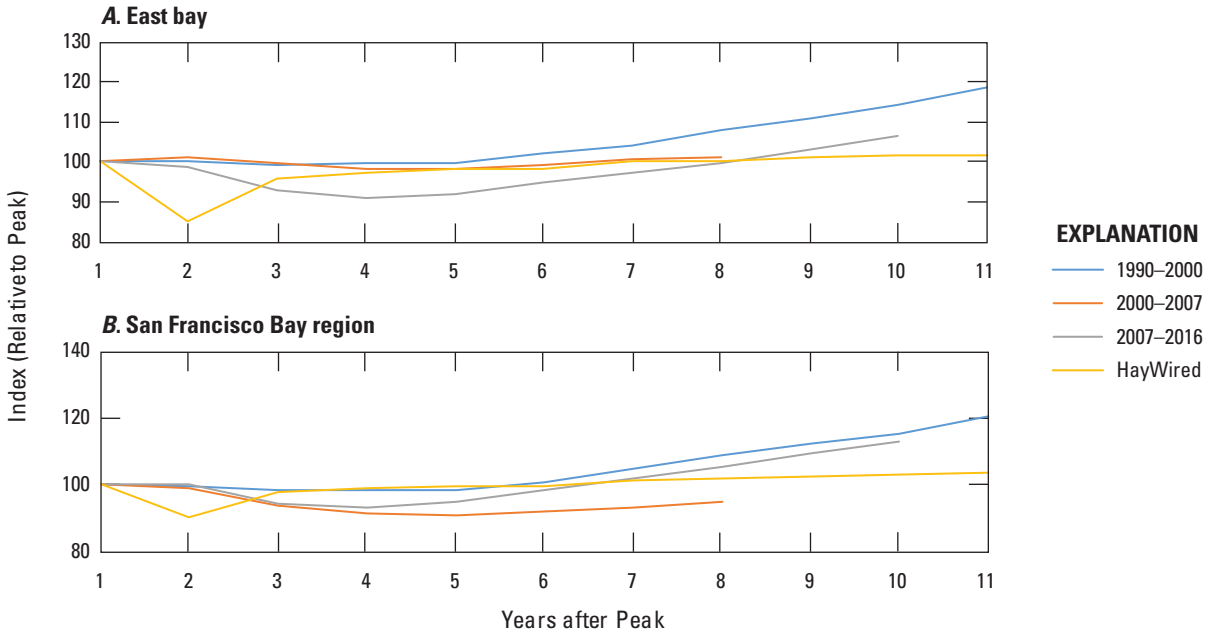


Figure 10. Graphs showing the recovery progression from prerecession peak to peak of recovery or next upturn for the east bay subregion (*A*) and San Francisco Bay region, California (*B*), compared to job projection in the HayWired scenario. Data from California Employment Development Department (2018) and Association of Bay Area Governments Planning and Research Department (2016) REMI model version 1.7.8, adjusted control NC3RC1. REMI refers to models produced by Regional Economic Models, Inc.

the first year. The job loss returns to below one percent of forecasted employment and population levels in the second year, assuming continued access to labor and goods from outside of the region and assuming substitution between labor and capital (that is, the built-in resilience of the economy in the model). Government recovery assistance is a key factor in this assessment, which significantly reduces the negative consequences of the earthquake through time and expedites the recovery process. In reality (as opposed to the model), the effectiveness of this recovery assistance will depend not only on the amount of dollars provided but on the capacity of State and local government to effectively allocate the resources and to efficiently manage the recovery efforts.

A number of factors and assumptions could change the outcome of this analysis. On the positive side, the Hazus-based estimate of building damage in 2018 could be high when applied as a percentage, especially for multifamily and office buildings. To the extent that the overall stock has a higher share of newly constructed buildings than the base used for the Hazus assessment, the share of buildings and square footage that experience extreme or complete damage may be lower than assumed for this analysis. Effective retrofit programs on residential units could reduce the number of displaced residents and decrease rebuilding costs after the event. These are not included in the model because of the timing of the event. Were this type of event to happen instead five years hence and were effective retrofits in place in a substantial number of buildings, the negative effects would be reduced.

Inclusion of insurance payments as a portion of rebuilding investment could reduce the amount of government spending cutbacks required, softening the adjustments made to the overall effects of government spending. We did not explicitly separate out insurance payments in the assessment because they would not be large relative to the damage. The built-in resilience in the model could be interpreted as including natural reinvestment that occurs in an area following a downturn, which could include the outside insurance payments. In contrast, government payments are an additional outside stimulus that would not be available to the region's economy without the earthquake and explicit recovery policy by Federal, State, and local agencies.

Our application of the REMI model does not model the unanticipated future evolution of industry in the San Francisco Bay region. For example, just as the "birth" of Silicon Valley provided a huge economic stimulus to the region, unforeseen new industries that could develop before 2040 would affect the amount of investment, the characteristics of industries, and, therefore, the speed of economic recovery, in the region. The model and analysis also do not explicitly include possible new industries that could emerge from the earthquake—for example, technology fixes to apply to seismically risky areas or industries that flourish as low-cost space emerges in heavily affected areas. The built-in resiliency feature of the model essentially relies on the ability of the region to respond in this way but, it does not assume the region recovers in a stronger growth path than would occur otherwise. Similarly, the model does not explicitly address changes in occupational training and labor productivity that would come from a significant structural change in the recovering economy. The San Francisco Bay region has a large enough economy that even with the devastating effects to the east bay subregion, the majority of the basic industries that are the major drivers of the economy would likely continue to operate, albeit at a reduced or adjusted level for location in the short run.

There are other factors that could lead to long-term changes in the outcome of the scenario. We have tried to account for a number of these effects with the model, but the levels of effect used could be too optimistic:

- Rising home prices and rents may move unevenly. Sales may be curtailed in the worst hit parts of the region, and land prices may drop, leading to foreclosures on loans, homelessness, or departure from the region for additional households.
- Higher wages paid to construction workers and worker shortages may delay rebuilding and repairs.
- Population displacement effects could persist for longer, especially in heavily affected parts of the east bay subregion. The slower repair of water systems in some of the heavily affected areas, not explicitly included, could increase the population displacement effects. The negative effect on population could be further exaggerated if inmigration is dampened for several years in the future, extending other effects as well for a longer period of time.
- We may have been too optimistic in our assessment of the ability of commuters to make flexible work arrangements or their willingness to adapt to alternate (and more time-consuming) routes.
- Branch operations may be closed down permanently as large employers reroute operations to other locations in the United States or globally.
- The need for planning for heavily affected areas may delay rebuilding even beyond the delays incorporated into the model.
- The earthquake could have a significant effect on local revenues and spending, beyond the shift in spending towards reconstruction activities. Places damaged by natural disasters are generally

reassessed, lowering the property tax revenues to local jurisdictions. This could cause sharp budgetary cuts, with consequent employment and income implications for some smaller east bay cities, where real-estate-related taxes and fees can account for close to half of all revenues, as estimated by the authors using California State Controller 2016 city budget data (California State Controller's Office, 2018). A back-of-the-envelope analysis shows that the share of lost revenues linked directly to building damage could be as high as 10 percent in smaller cities near the epicenter, and these shares could be substantially higher if inaccessible areas (owing to concentrated neighborhood damage and cordons) are considered.

Sensitivity Tests

Sensitivity tests were run on how changes in a few post-event factors could affect the results.

Construction Costs

If construction costs are increased for a 5-year period relative to their assumed levels in the model (by 20 percent in the first year, 40 percent in the second, 60 percent in the third and fourth years, and 40 percent in the fifth year) to reflect the unusually high demand for workers and construction materials, then the result is an additional 124,000 jobs lost in 2018, which expands to a loss of more than 401,000 more jobs in 2020 and 2021 when construction demand is particularly high because of recovery spending. By 2040, the San Francisco Bay region would lose an additional 22,000 jobs. The east bay and west bay subregions would lose an additional 174,000 and 129,000 jobs, respectively, in 2021. Bay region employment would not recover to the pre-earthquake level until after 2024. Population loss would increase by 47,000 people in 2018, and population levels would be lower by 348,000 in 2022. By 2040, the bay region population would be an additional 50,000 people fewer than in the primary HayWired scenario analysis described above. Table 24 shows the effects on the east bay subregion employment, population, and GRP; table 25 summarizes effects for the entire bay region.

Displaced Population

We tested the effects of a higher displacement rate. We assumed 25 percent of the displaced population (estimated to be 720,000 people displaced in addition to the senior population migration assumed in previous runs) leave the San Francisco Bay region in 2018. This is distributed according to each subregion's share of building and content loss (for example, 110,175 people from the east bay, 1,763 people from the north bay, 25,869 people from the west bay, and 42,193 people from the south bay). This displacement could lead to an additional 36,000 job loss, 191,000 population loss, and $4.5 billion in GRP loss in 2018. Because of higher outmigration compared to other subregions, total population in the east bay subregion would not recover to its pre-earthquake level until

Table 24. Employment, population, and gross regional product (GRP) effects with higher construction costs in the HayWired scenario relative to Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−274,559	−184,745	−14,652	−8,699
	(0.18)	(0.12)	(0.01)	(0.01)
Population	−104,263	−268,555	−165,078	−23,611
	(0.04)	(0.10)	(0.06)	(0.01)
GRP, in billions of 2016 U.S. dollars	−32.13	−27.37	−2.38	−1.19
	(0.16)	(0.13)	(0.01)	(0.01)

Table 25. Employment, population, and gross regional product (GRP) effects with higher construction costs in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parentheses. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−619,322	−474,817	−49,427	−31,567
	(0.12)	(0.09)	(0.01)	(0.01)
Population	−192,190	−587,373	−367,948	−70,814
	(0.03)	(0.07)	(0.04)	(0.01)
GRP, in billions of 2016 U.S. dollars	−85.68	−83.3	−13.09	−10.71
	(0.10)	(0.09)	(0.01)	(0.01)

Table 26. Employment, population, and gross regional product (GRP) effects with higher outmigration in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−253,103	−36,186	−5,793	−4,340
	(0.17)	(0.02)	(0.00)	(0.00)
Population	−203,217	−187,147	−99,364	−7,195
	(0.07)	(0.07)	(0.04)	(0.00)
GRP, in billions of 2016 U.S. dollars	−28.98	−5.84	0.02	−0.06
	(0.14)	(0.03)	0.00	(0.00)

Table 27. Employment, population, and gross regional product (GRP) effects with higher outmigration in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parenthesis. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−532,202	−73,353	−12,159	−13,665
	(0.11)	(0.01)	(0.00)	(0.00)
Population	−335,925	−344,202	−185,445	−24552
	(0.04)	(0.04)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−71.4	−15.708	−0.357	−1.071
	(0.09)	(0.02)	(0.00)	(0.00)

after 2025. By 2040, projected employment and population levels are also lower, with an additional 4,000 jobs lost, and 3,000 population loss; insignificant figures relative to the projections for 2040 (tables 26, 27).

Commuter Resilience

Commuting flexibilities help to mitigate business output losses entered into the final version of the scenario during the first year after the earthquake. Assuming more limited commuting flexibilities occur than previously considered—that is, two-thirds (rather than one-third) of output loss in goods producing, trade and transportation, and utilities industries, and one-half (rather than one-fourth) of output loss in services—total employment loss would increase to around 699,000 jobs and total population loss expand to 188,000 people in 2018, compared to 496,000 jobs lost and 145,000 population loss estimated with the original assumptions. Employment and population loss in the east bay subregion would still be the highest among the four subregions, but the west bay subregion

Table 28. Employment, population, and gross regional product (GRP) effects with worse commuting and telecommuting conditions in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−277,700	−28,558	−176	–2,933
	(0.18)	(0.02)	(0.00)	(0.00)
Population	−97,954	−126,498	−66,640	−6,954
	(0.04)	(0.05)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−32.13	−4.76	0.00	0.00
	(0.16)	(0.02)	0.00	0.00

would have more additional job and population loss than the rest of the region because of worse commuting conditions, reaching a total loss of 235,000 jobs (or 14 percent) and 46,000 people (2 percent). East bay and the total San Francisco Bay region employment would not recover to pre-earthquake levels until after 2022 (tables 28 and 29, respectively). In 2040, the bay region employment is 1,000 jobs below the primary HayWired scenario analysis, whereas the population is above by 200 people.

Table 29. Employment, population, and gross regional product (GRP) effects with worse commuting and telecommuting conditions in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parentheses. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−699,374	−59,495	159	−10,290
	(0.14)	(0.01)	0.00	(0.00)
Population	−188,491	−261,456	−138,941	−21,088
	(0.02)	(0.03)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−71.4	−97.58	−14.28	1.19
	(0.12)	(0.02)	0.00	(0.00)

Insurance

Rather than assuming insurance is one of the financing sources for the overall investment built into the model, we added insurance spending (15 percent of $85 billion, or $12.75 billion in 2016 U.S. dollars) into the economy separately over 5 years, distributed by 10, 20, 25, 25, and 20 percent from the first to fifth year, respectively. Again, we assumed the distribution is based on the share of building damage related losses (the sum of building, contents, and inventory repair and replacement costs, relocation costs, income losses, and output losses) by subregion, and three-quarters of the payment would be spent on construction, with one-quarter on the various aforementioned consumer commodities. Because of the stimulus effect from the extra spending, total employment loss would decrease by 13,000 to around 483,000 jobs (10 percent) and total population loss would be reduced to 141,000 people (2 percent) in 2018. Employment and population loss in the east bay subregion would decrease by 8,000 and 2,000, respectively, in 2018. Insurance spending would also help the region recover faster, San Francisco Bay region and east bay subregion employment would recover to pre-earthquake levels in 2021 (tables 30, 31).

Table 30. Employment, population, and gross regional product (GRP) effects with insurance spending in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−219,870	−13,835	−1,829	−2,465
	(0.15)	0.01)	0.00)	(0.00)
Population	−80,634	−103,476	−56,116	−6,403
	(0.03)	(0.04)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−24.99	−3.57	0.00	0.00
	(0.13)	(0.02)	0.00	0.00

Table 31. Employment, population, and gross regional product (GRP) effects with insurance spending in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parenthesis. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−482,910	−36,851	−4,169	−9,277
	(0.10)	(0.01)	(0.00)	(0.00)
Population	−141,348	−217,081	−120,764	−20,928
	(0.02)	(0.03)	(0.01)	(0.00)
GRP, in billions of 2016 U.S. dollars	−65.45	−11.9	0	−1.19
	(0.08)	(0.01)	0.00	(0.00)

Government Spending

Rather than assuming Federal, State, and local government spending would cover two-thirds of the uninsured loss, we assumed a worse situation where the Federal Government is not responsive, State and local governments are not able to gather enough resources for the recovery because of financial distress from the earthquake, and government spending in the region would be delayed until years later. Specifically, we made the following changes to the assumptions of the main analysis:

- Only one-third of the uninsured loss would be covered, and
- Government spending and spending in construction would be distributed by 10, 10, 10, 15, 15, 10, 10, 10, and 10 percent over a 9-year period.

As a result of lower level government spending, total employment loss and total population loss would increase by 9,000 to about 503,000 jobs (10 percent) and total 147,000 people (2 percent) in 2018, respectively. Employment and population loss in the east bay subregion would increase by 5,000 and 2,000, respectively, in 2018. Lower government spending would delay the recovery process in the bay region. Bay region and east bay subregion employment would not recover to pre-earthquake levels until after 2024 (tables 32, 33).

Table 32. Employment, population, and gross regional product (GRP) effects with lower government spending in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−232,259	−39,447	−848	−2,915
	(0.15)	(0.03)	(0.00)	(0.00)
Population	−84,666	−128,497	−69,561	−7,288
	(0.03)	(0.05)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−26.11	−5.94	0.00	0.00
	(0.13)	(0.03)	0.00	(0.00)

Table 33. Employment, population, and gross regional product (GRP) effects with lower government spending in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parentheses. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Affected categories	2018	2022	2027	2040
Employment	−503,920	−80,018	−1,664	−10,006
	(0.10)	(0.02)	(0.00)	(0.00)
Population	−146,947	−253,002	−138,565	−21,947
	(0.02)	(0.03)	(0.02)	(0.00)
GRP, in billions of 2016 U.S. dollars	−67.66	−16.62	1.19	−1.19
	(0.08)	(0.02)	0.00	(0.00)

Technology Sector Exodus

For this sensitivity test, we assumed that the San Francisco Bay region would lose half of the job gain permanently in the internet publishing and broadcasting; internet service providers, search portals, and data processing; and other information services sectors between 2011 and 2015. The Plan Bay Area 2040 REMI-model baseline estimates that these sectors saw an increase of 39,000 jobs in the four subregions (east bay, west bay, north bay, and south bay). We reduced the job increase to about 20,000 for the whole bay region for the rest of the forecasting years (2018–2040). In addition to the job loss assumption in the information subsector, we also reduced the number of jobs in the professional, scientific, and technical services sector proportionally. Based on Quarterly Census of Employment and Wages data from 2011 to 2016 (https://www.bls.gov/cew/#databases) this sector grew by 30 percent in the bay region, with technology-associated computer system design and related services accounting for 60 percent of the growth, whereas growth in other technology-driven professional, scientific, and technical services subsectors, including advertising, public relations, and related services; scientific research and development services; specialized design services; and other professional and technical services accounted for 21 percent of the total job growth in the five-year period. In this analysis, we reduced half of all job growth

in the computer system design and related services sector and 50 percent of the growth in other aforementioned professional, scientific, and technical services subsectors; that is, half of the 70 percent job gains in the professional, scientific, and technical services sector permanently, or 41,000 for the bay region using the Association of Bay Area Governments Plan Bay Area 2040 REMI-model baseline. In the Plan Bay Area 2040 REMI model, the north bay subregion experienced negative job change in the professional, scientific, and technical services sector between 2011 and 2015; we kept the north bay subregion unchanged.

The technology sector exodus would remove 229,000 additional jobs, for a total job loss of 725,000 (14 percent), and total population loss would be 201,000 people (3 percent) in 2018. The east bay subregion would lose an additional 39,000 jobs and 12,000 residents in 2018. A technology sector exodus would lead to ripple effects in the economy, decreasing overall recovery and expansion for the full forecast period. San Francisco Bay region and east bay subregion employment would not recover to pre-earthquake levels until after 2028 and would still lag behind the projected employment and population totals in 2040 (tables 34, 35).

Table 34. Employment, population, and gross regional product (GRP) effects with technology sector exodus in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the east bay subregion of the San Francisco Bay region, California.

[Negative percentage change in parentheses. East bay subregion refers to Alameda and Contra Costa Counties. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Categories affected	2018	2022	2027	2040
Employment	−266,809	−71,327	−38,839	−45,036
	(0.18)	(0.05)	(0.03)	(0.03)
Population	−95,389	−153,072	−111,624	−68,378
	(0.03)	(0.05)	(0.04)	(0.02)
GRP, in billions of 2016 U.S. dollars	−30.821	−10.591	−4.879	−6.902
	(0.15)	(0.05)	(0.02)	(0.02)

Table 35. Employment, population, and gross regional product (GRP) effects with technology sector exodus in the HayWired scenario relative to Association of Bay Area Governments Plan Bay Area 2040 projections for the San Francisco Bay region, California.

[Negative percentage change in parentheses. Data from the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model version 1.7.8, adjusted control NC3RC1]

Categories affected	2018	2022	2027	2040
Employment	−724,939	−300,263	−226,487	−266,531
	(0.14)	(0.06)	(0.04)	(0.05)
Population	−201,480	−413,822	−384,891	−356,294
	(0.03)	(0.05)	(0.05)	(0.04)
GRP, in billions of 2016 U.S. dollars	−108.171	−59.738	−46.886	−66.759
	(0.13)	(0.07)	(0.04)	(0.05)

Figures 11*A* and 11*B* compare the results of the sensitivity tests for the San Francisco Bay region as a whole. Most changes in post-event factors result in relatively small changes compared to the primary HayWired scenario results. This indicates that many of the effects are captured in the primary analysis. There are a few exceptions. Higher outmigration slightly lowers employment levels and has a somewhat larger effect on population levels for several years after the earthquake. Higher construction costs have a much larger and long-term slowing effect to the economy and population. Because construction costs filter throughout the economy, higher costs can slow down not only the rebuilding effort but also many types of employment growth and the pace of population recovery. A technology sector exodus also exacerbates the employment loss, leading to permanent employment and population net loss compared to the Plan Bay Area 2040 forecast.

The sensitivity tests show some of the uncertainty in assessing possible effects over time. Furthermore, the built-in resiliency of the model may be particularly problematic for understanding the implications for the east bay subregion. Although the whole San Francisco Bay region is strong, diverse, and has a large enough economy that a return close

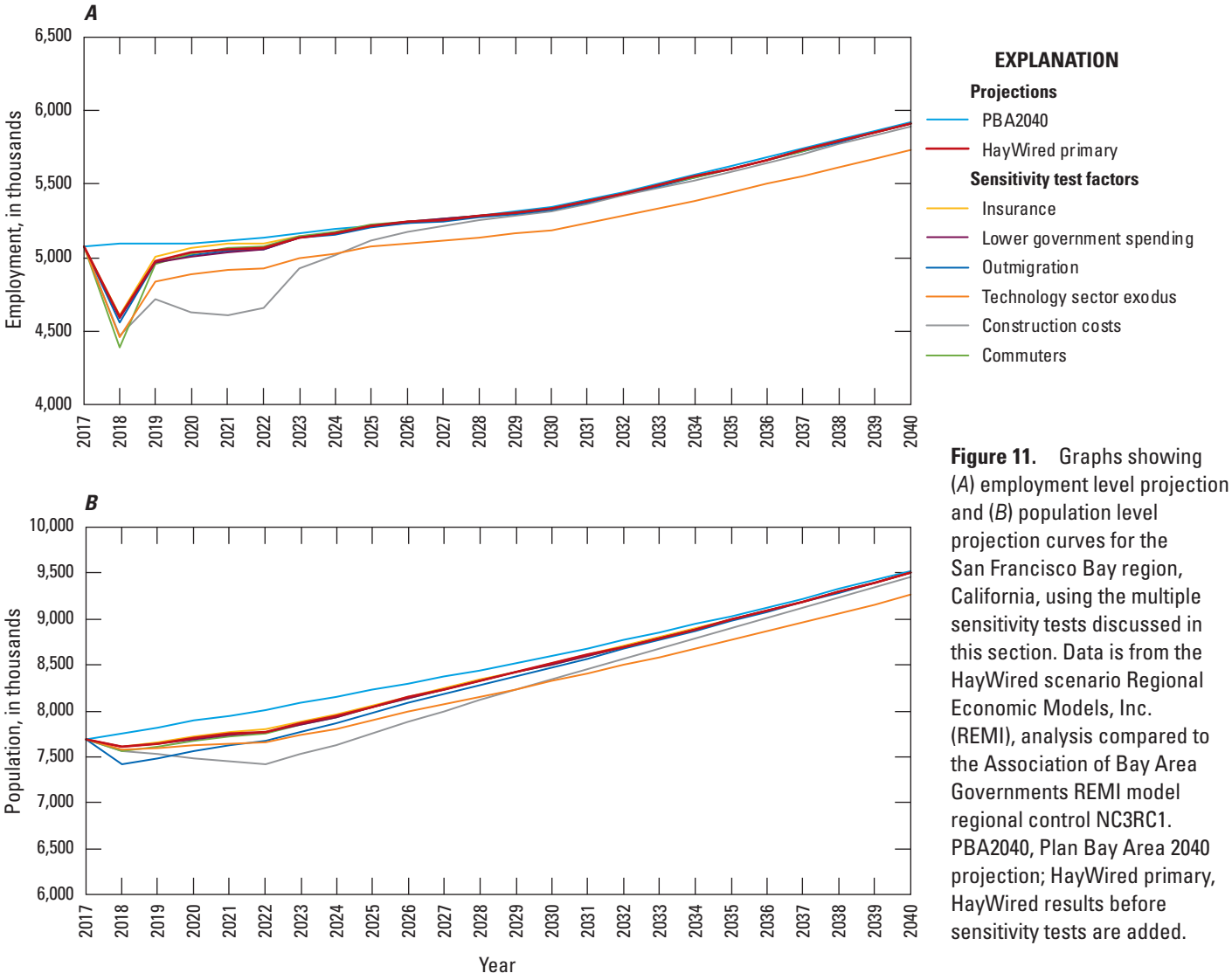


Figure 11. Graphs showing (*A*) employment level projection and (*B*) population level projection curves for the San Francisco Bay region, California, using the multiple sensitivity tests discussed in this section. Data is from the HayWired scenario Regional Economic Models, Inc. (REMI), analysis compared to the Association of Bay Area Governments REMI model regional control NC3RC1. PBA2040, Plan Bay Area 2040 projection; HayWired primary, HayWired results before sensitivity tests are added.

to the previous trend does not seem unreasonable, there could be local effects that are more permanent that are not captured by the model. If infrastructure repair is a lengthy process, the communities in the epicenter of the earthquake are likely to recover much more slowly than the model suggests, even as the region as a whole rebounds. The local- and regional-serving employment base in that area will find it particularly difficult to recover, and even companies with a larger customer base may become much less competitive and may either move or close down. As recovery proceeds, building brand new resources in these heavily damaged places could lead to a boom, but the analysis suggests nothing about the distributional effects of these changes. Without intervention by the public sector (or with the wrong type of intervention), small businesses and lower income and wealth-poor individuals are likely to suffer lifelong negative effects. The effects of displacement on vulnerable populations is addressed in depth by Johnson and others (this volume), whereas neighborhood economic effects are addressed by Wein, Belzer, and others (this volume).

Policy Implications

Public policy will be a critical aspect of addressing the economic effects of a HayWired scenario-like event. In light of the results of the HayWired REMI analysis, some public policies that focus on the following areas may reduce and (or) mitigate the effects of a major earthquake through investments or planning before it occurs and through post-event responses.

- Direct output loss from building damage may be reduced through building design and retrofits that reduce the amount of damage that occurs to both residential and nonresidential space.

- The duration and total effects of output loss from building damage and inventory loss can be reduced by cooperative responses among businesses and neighbors and even between heavily and less affected areas. Efforts to build networking ties before the event can make it easier to develop these cooperative responses in a crisis period.
- Output loss and associated effects caused by fire after the earthquake can be mitigated by making buildings and neighborhoods more fire resistant to any extent. This will reduce not only earthquake related hazards but those related to wild land and urban wildfires. The effects of fire can be further reduced if cities, counties, and the State have identified means for fighting fires in cases where water delivery has been interrupted.
- The vulnerability of local serving businesses like food services, retail, and health care can have long-term effects on neighborhood resilience. Planning for neighborhood response and business relocation in advance, as well as providing temporary facilities and support services for businesses after the event, can help mitigate the otherwise widespread losses expected in these sectors.
- The increased demand for construction workers coincides with direct effects to the sector. Also, there is currently an urgency for construction capability in the San Francisco Bay region to build more housing and for funded and approved transportation infrastructure projects. Loss of construction capacity or increases in construction costs will slow the ability to recover. Long-term planning for resilience in the construction industry, by major employers, trade organizations, educational institutions, and local, State and Federal government can improve the industry's ability to respond not only to catastrophic events but also to the wide swings experienced by the industry in business cycles.
- The role of major employers in all sectors is also of key importance in terms of their ability to provide support for their larger workforce and their role in the regional economy. Inclusion of major employers such as those in the technology sector at all stages—in advanced planning, initial responses, and recovery—can contribute to the success of recovery efforts by augmenting the resources available when most needed and also ensuring that employees, suppliers, and other linked sectors are informed about immediate conditions and resources as well as choices that may have long-term effects during an event.
- The quick recovery in overall employment depends heavily on investment for rebuilding homes, nonresidential buildings, and infrastructure. The public sector plays a critical role in this by not only providing a portion of the funding but by also providing the means for clearance of debris, safety checks, and issuance of new permits. Without the robust level of recovery spending assumed in this analysis, the east bay subregion would require at least 5 years to reach within 1 percent of the projected employment levels.
- Investment in recovery is not only the responsibility of the public sector. In the sensitivity analysis, private insurance payments have a relatively small effect on the outcome because these payments cover such a small share of the total damage. Were a larger share of homes and buildings covered by insurance, recovery would be better resourced, and displacement and outmigration could be less. Judging from past experience, close cooperation among assistance agencies, such as FEMA, and the California Governor's Office of Emergency Services and private insurers may be needed to ensure the timely consideration and payment of claims.
- Restoration of the telecommunications sector is also a major factor in allowing many economic sectors to fully restore their operations. As seen in the sensitivity tests, if networking through telecommunications cannot be achieved, then the commute effects could be much more severe.
- Temporary housing services will be crucial in maintaining the labor force needed to keep ongoing businesses in operation and provide the labor force needed for reconstruction. Identification of successful efforts in previous disasters may make it easier to respond effectively after an event.
- Expedited permitting will be needed to allow rebuilding to happen in the time period shown in the model, whereas advanced planning for future contingencies would better prepare jurisdictions to address rebuilding efforts from a comprehensive perspective and effective retrofit programs could reduce displacement in the first place.
- Advanced planning to better address the effects of a major seismic event should address the likely issues faced by vulnerable populations. Clearance of damaged neighborhoods can also lead to clearance of communities and lower income renter households. Advanced planning may make it more likely that assistance is available to displaced households and could also require that the displaced populations be given the opportunity to participate in planning for rebuilding. This will affect who stays and who leaves the region and the level of resilience of existing businesses. This type of planning can happen as a mitigating pre-event approach, rather than only relying on it as an approach to react to the event.

Future Research with REMI Modeling

Using the REMI model to examine the HayWired scenario made it possible to explore how a range of different negative effects or different recovery investments could affect the San Francisco Bay region economy. With a modeling approach like REMI, there is an unlimited number of tests that could be run and effects examined. Although the descriptions above may seem exhaustive, there are additional areas of research with the model that could be informative. We mention a few of these here.

First, the analysis relies on Hazus for output estimates because the model lacks a complete link between the loss of capital stock and economic and population effects. A closer link between capital losses and the economic and demographic impacts would improve the analysis. A few additional directions to explore include, for one, considering the unreconstructed capital stock lost as a factor to determine the residential and nonresidential investment totals. Second, population displacement from damaged buildings was entered in an artificial way in this analysis. Further experiments with levers in the model to reflect this effect could include the use of residential capital stock or investment, more extreme price changes, or additional ways to estimate the change in the amenity variable. Third, changes in public revenues could be explored further by inserting changes in Federal spending, incorporating shifts in local government revenues, and by including property and sales taxes in the model.

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Appendixes 1–6

Appendix 1

Table 1.1 shows the sector description for each Hazus occupancy class and North American Industry Classification System (NAICS) codes included in each Hazus sector. Using the corresponding relation between NAICS and Hazus occupancy class from this table, we can map Regional Economic Models, Inc., (REMI) sectors into each Hazus occupancy class, shown in table 1.2, which would then be used to summarize output loss by REMI sector using Hazus output.

Table 1.1. Industry sector with the corresponding Hazus occupancy class and North American Industry Classification System (NAICS) code.

Sector description	NAICS code	HAZUS occupancy class
Agriculture, forestry, fishing and hunting	11	AGR1
Retail trade	44–45	COM1
Wholesale trade, warehousing and storage	42	COM2
Truck transportation	484	COM2
Repair and maintenance	811	COM3
Personal services / private households	812, 814	COM3
Electric power generation, transmission, and distribution	2211	COM4
Natural gas distribution	2212	COM4
Water, sewage, and other systems	2213	COM4
Air transportation	481	COM4
Rail transportation	482	COM4
Water transportation	483	COM4
Transit and ground passengers	485	COM4
Pipeline transportation	486	COM4
Sightseeing transportation	487 and 488	COM4
Couriers and messengers	492	COM4
Internet publishing and broadcasting	51913	COM4
Data processing, hosting, and related services	518	COM4
Other information services	51911–2	COM4
Computer systems design and related services	5415	COM4
Professional scientific and technical services	54 except for 5415	COM4
Other business services	55, 56	COM4
Finance, insurance, real estate, and leasing	52, 53	COM4, COM5
Ambulatory health care and hospitals	621, 622	COM6, COM7
Telecommunications	517	COM8
Arts, entertainment, and recreation	711–713, 722	COM8
Educational services	6111, 6112–3, 6114–7	EDU1, EDU2
Government and nonNAICS	n.a.	GOV1, GOV2
Heavy industry	313, 321, 322, 327, 332,333, 336	IND1
Light industry	314, 315, 316, 323, 326,part of 334 (except for334111, 334112,334411, 334412,334413), 335, 337, 339,511, 516	IND2
Publishing, motion picture, and broadcasting	511, 512, 515	IND2, COM4
Petroleum refineries	32411	IND3
Food, drug, and chemicals	311, 312, 324 except for32411, 325	IND3
Oil and gas extraction	211	IND4
Coal mining	2121	IND4

Table 1.1. Tabulated description of each sector with the corresponding Hazards U.S. (HAZUS) occupancy class and North American Industry Classification System (NAICS) code—Continued.

Sector description	NAICS code	HAZUS occupancy class
Other mining	212–213 except for 2121	IND4
Primary metal manufacturing	331	IND4
Electronic computer manufacturing	334111	IND5
Computer storage device manufacturing	334112	IND5
Semiconductor and related device manufacturing	334413	IND5
Other high technology related manufacturing	334411, 334412	IND5
Construction		IND6
Religious, grantmaking, and similar organizations	813	REL1
Imputed rental value for owner-occupied dwellings	n.a.	RES1–RES3
Accommodations	721	RES4
Nursing home/social assistance	623, 624	RES6, COM3

Table 1.2. Tabulated description of Regional Economic Models, Inc. (REMI) 70 sectors and corresponding Hazus occupancy class and North American Industry Classification System (NAICS) code.

REMI sectors	NAICS code	HAZUS occupancy class
Forestry and logging; fishing, hunting, and trapping	113-114	AGR1
Agriculture and forestry support activities	115	AGR1
Oil and gas extraction	211	IND4
Mining (except oil and gas)	212	IND4
Support activities for mining	213	IND4
Utilities	22	COM4
Construction	23	IND6
Wood product manufacturing	321	IND1
Nonmetallic mineral product manufacturing	327	IND1
Primary metal manufacturing	331	IND4
Fabricated metal product manufacturing	332	IND1
Machinery manufacturing	333	IND1
Computer and electronic product manufacturing	334	IND2
Electrical equipment and appliance manufacturing	335	IND2
Motor vehicles, bodies and trailers, and parts manufacturing	3361-3363	IND1
Other transportation equipment manufacturing	3364-3369	IND1
Furniture and related product manufacturing	337	IND2
Miscellaneous manufacturing	339	IND2
Food manufacturing	311	IND3
Beverage and tobacco product manufacturing	312	IND3
Textile mills; textile product mills	313-314	IND1, IND2
Apparel, leather and allied product manufacturing	315-316	IND2
Paper manufacturing	322	IND1
Printing and related support activities	323	IND2
Petroleum and coal products manufacturing	324	IND3
Chemical manufacturing	325	IND3

Table 1.2. Tabulated description of Regional Economic Models, Inc. (REMI) 70 sectors and corresponding Hazus occupancy class and North American Industry Classification System (NAICS) code.—Continued

REMI sectors	NAICS code	HAZUS occupancy class
Plastics and rubber product manufacturing	326	IND2
Wholesale trade	42	COM2
Retail trade	44-45	COM1
Air transportation	481	COM4
Rail transportation	482	COM4
Water transportation	483	COM4
Truck transportation	484	COM2
Couriers and messengers	492	COM4
Transit and ground passenger transportation	485	COM4
Pipeline transportation	486	COM4
Scenic and sightseeing transportation and support activities for transportation	487-488	COM4
Warehousing and storage	493	COM3
Publishing industries, except internet	511	IND2
Motion picture and sound recording industries	512	IND2, COM4
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	518-519	COM4
Broadcasting, except internet	515	IND2, COM4
Telecommunications	517	COM8
Monetary authorities and other credit institutions	521,522,525	COM4, COM5
Securities, commodity contracts, investments	523	COM4, COM5
Insurance carriers and related activities	524	COM4, COM5
Real estate	531	COM4, COM5
Rental and leasing services; lessors of nonfinancial intangible assets	532,533	COM4, COM5
Professional, scientific, and technical services	54	COM4
Management of companies and enterprises	55	COM4
Administrative and support services	561	COM4
Waste management and remediation services	562	COM4
Educational services; private	61	EDU1, EDU2
Ambulatory health care services	621	COM6, COM7
Hospitals; private	622	COM6, COM7
Nursing and residential care facilities	623	RES6, COM3
Social assistance	624	RES6, COM3
Performing arts and spectator sports	711	COM8
Museums, historical sites, zoos, and parks	712	COM8
Amusement, gambling, and recreation	713	COM8
Accommodation	721	RES4
Food services and drinking places	722	COM8
Repair and maintenance	811	COM3
Personal and laundry services	812	COM3
Membership associations and organizations	813	REL1

Table 1.2. Tabulated description of Regional Economic Models, Inc. (REMI) 70 sectors and corresponding Hazus occupancy class and North American Industry Classification System (NAICS) code.—Continued

REMI sectors	NAICS code	HAZUS occupancy class
Private households	814	COM3
State and local government	NA	GOV1, GOV2
Federal civilian	NA	GOV1, GOV2
Federal military	NA	GOV1, GOV2
Farm	111-112	AGR1

For each subregion, we first calculated the share of output loss for each Hazus occupancy class in each year of the first three years where output loss is estimated. We then determined that the share of loss for each REMI sector was equal to the share of loss for the occupancy class the sector belongs to. For example, both telecommunication (NAICS 517) and performing arts and spectator sports (NAICS 711) are in Hazus occupancy class COM8. Therefore, shares of output loss in these two sectors are the same, even if the activities are significantly different. In the case where a sector is mapped to two Hazus occupancy classes, the share of output loss for this sector equals the combined share of loss as calculated for those occupancy classes. Next, we applied the share of loss calculated for each REMI sector in each year to REMI-projected 2018 output to determine the dollar loss which was then put in as changes in REMI output variables. Table 1.3 shows the results of translation.

Table 1.3. San Francisco Bay region, California, industry direct output loss by year in the HayWired scenario using Regional Economic Models, Inc., output baseline.

[Sectors are sorted by first year loss amount. Data from Association of Bay Area Governments calculated using Hazus loss by occupancy class results]

Sector	Value of output loss, in millions of 2016 U.S. dollars			Loss of 2018 industry output, in percent		
	1st year	2d year	3d year	1st year	2d year	3d year
Petroleum and coal products manufacturing	2016.0	2.1	0.0	4	0	0
Food services and drinking places	1900.5	77.3	0.0	9	0	0
Ambulatory health care services	1770.4	89.7	0.0	6	0	0
Machinery manufacturing	1594.2	4.1	0.0	12	0	0
Real estate	1277.6	34.1	0.0	1	0	0
Professional, scientific, and technical services	1237.0	49.6	0.0	1	0	0
Computer and electronic product manufacturing	1117.1	19.9	0.0	1	0	0
Hospitals; private	1073.7	72.2	0.0	6	0	0
Construction	848.9	5.1	0.0	2	0	0
Wholesale trade	795.0	17.3	0.0	2	0	0
Retail trade	736.8	12.6	0.0	2	0	0
Fabricated metal product manufacturing	710.5	1.7	0.0	11	0	0
Motor vehicles, bodies and trailers, and parts manufacturing	635.9	0.6	0.0	22	0	0
Performing arts and spectator sports	544.4	19.7	0.0	9	0	0
Other transportation equipment manufacturing	505.6	2.3	0.0	9	0	0
Accommodation	493.8	55.9	0.0	5	1	0

Table 1.3. San Francisco Bay region, California, industry direct output loss by year in the HayWired scenario using Regional Economic Models, Inc., output baseline.—Continued

Sector	Value of output loss, in millions of 2016 U.S. dollars			Loss of 2018 industry output, in percent		
	1st year	2d year	3d year	1st year	2d year	3d year
Chemical manufacturing	416.0	2.6	0.0	1	0	0
Monetary authorities and other credit institutions	385.9	10.5	0.0	1	0	0
Oil and gas extraction	365.1	0.3	0.0	8	0	0
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	358.7	50.6	0.0	0	0	0
Publishing industries, except internet	349.9	4.9	0.0	1	0	0
Amusement, gambling, and recreation	326.1	11.1	0.0	9	0	0
Management of companies and enterprises	316.1	4.5	0.0	1	0	0
Nonmetallic mineral product manufacturing	314.7	0.6	0.0	12	0	0
Food manufacturing	302.2	0.8	0.0	2	0	0
Administrative and support services	276.8	8.9	0.0	1	0	0
Paper manufacturing	222.6	0.4	0.0	16	0	0
Primary metal manufacturing	206.9	0.3	0.0	5	0	0
Social assistance	189.3	17.8	3.8	2	0	0
Beverage and tobacco product manufacturing	178.9	0.6	0.0	1	0	0
Insurance carriers and related activities	176.7	2.7	0.0	1	0	0
Miscellaneous manufacturing	176.3	0.8	0.0	2	0	0
Utilities	159.1	2.5	0.0	1	0	0
Nursing and residential care facilities	151.4	13.4	3.1	3	0	0
Repair and maintenance	143.7	7.2	0.0	2	0	0
Securities, commodity contracts, investments	138.3	5.2	0.0	0	0	0
Wood product manufacturing	134.1	0.3	0.0	11	0	0
Rental and leasing services; lessors of nonfinancial intangible assets	99.4	2.4	0.0	1	0	0
Personal and laundry services	95.0	4.7	0.0	2	0	0
Truck transportation	93.9	1.4	0.0	2	0	0
Museums, historical sites, zoos, and parks	62.5	2.4	0.0	6	0	0
Air transportation	59.6	0.8	0.0	1	0	0
Waste management and remediation services	59.1	0.9	0.0	1	0	0
Motion picture and sound recording industries	57.6	0.5	0.0	1	0	0
Electrical equipment and appliance manufacturing	54.4	0.4	0.0	2	0	0
Couriers and messengers	46.7	0.6	0.0	2	0	0
Printing and related support activities	41.0	0.2	0.0	2	0	0

Table 1.3. San Francisco Bay region, California, industry direct output loss by year in the HayWired scenario using Regional Economic Models, Inc., output baseline.—Continued

Sector	Value of output loss, in millions of 2016 U.S. dollars			Loss of 2018 industry output, in percent		
	1st year	2d year	3d year	1st year	2d year	3d year
Water transportation	40.0	0.1	0.0	2	0	0
Plastics and rubber product manufacturing	35.9	0.1	0.0	3	0	0
Warehousing and storage	33.8	0.6	0.0	4	0	0
Telecommunications	33.2	0.0	0.0	0	0	0
Educational services; private	31.3	3.9	0.0	0	0	0
Broadcasting, except Internet	30.2	0.5	0.0	1	0	0
Scenic and sightseeing transportation and support activities for transportation	30.1	0.4	0.0	1	0	0
Furniture and related product manufacturing	24.9	0.1	0.0	2	0	0
Membership associations and organizations	21.5	2.0	0.0	0	0	0
Private households	19.9	0.9	0.0	2	0	0
Textile mills; textile product mills	17.5	0.1	0.0	6	0	0
Mining (except oil and gas)	16.9	0.0	0.0	3	0	0
Rail transportation	12.8	0.2	0.0	2	0	0
Transit and ground passenger transportation	12.0	0.2	0.0	1	0	0
Pipeline transportation	11.9	0.1	0.0	2	0	0
Apparel, leather and allied product manufacturing	5.5	0.0	0.0	2	0	0
Support activities for mining	0.7	0.0	0.0	1	0	0
Agriculture and forestry support activities	0.1	0.0	0.0	0	0	0
Forestry and logging; fishing, hunting, and trapping	0.0	0.0	0.0	0	0	0

Appendix 2

Table 2.1. San Francisco Bay region, California, total output loss by private industry sector in 2018.

[These output losses include the direct output loss calculated in Hazus from building damage as well as additional output loss the model identifies in linked industries and because of the initial output-related population losses. Output losses and sorted by 1st year loss. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models Inc.) model analysis from 2018 (this study)]

Category	Output loss, in millions of 2016 U.S. dollars	Share of output loss, in percent
Real estate	4095.2	2.8
Professional, scientific, and technical services	3304.4	2.3
Construction	3053.1	7.4
Ambulatory health care services	2625.5	8.4
Petroleum and coal products manufacturing	2485.8	5.2
Food services and drinking places	2315.7	10.4
Retail trade	1958.7	4.0
Wholesale trade	1897.3	4.0
Machinery manufacturing	1830.1	13.9
Monetary authorities and other credit institutions	1694.1	3.8
Hospitals	1349.2	6.9
Computer and electronic product manufacturing	1308.4	1.0
Administrative and support services	1133.2	3.9
Management of companies and enterprises	969.1	4.1
Fabricated metal product manufacturing	951.2	15.4
Securities, commodity contracts, investments	893.9	2.9
Chemical manufacturing	841.8	1.9
Telecommunications	806.7	2.7
Motor vehicles, bodies and trailers, and parts manufacturing	771.2	26.3
Performing arts and spectator sports	770.4	13.3
Accommodation	700.8	6.8
Publishing industries, except internet	674.6	1.5
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	673.4	0.7
Insurance carriers and related activities	624.5	3.5
Food manufacturing	604.6	4.5
Oil and gas extraction	594.6	13.5
Utilities	562.0	4.2
Other transportation equipment manufacturing	558.9	9.7
Nonmetallic mineral product manufacturing	453.4	16.8
Primary metal manufacturing	445.4	11.7

Table 2.1. San Francisco Bay region, California, total output loss by private industry sector in 2018.—Continued

Category	Output loss, in millions of 2016 U.S. dollars	Share of output loss, in percent
Amusement, gambling, and recreation	410.2	11.0
Beverage and tobacco product manufacturing	376.0	1.3
Repair and maintenance	363.9	6.1
Rental and leasing services; lessors of nonfinancial intangible assets	358.3	3.1
Social assistance	342.5	4.4
Paper manufacturing	273.8	19.7
Miscellaneous manufacturing	271.0	3.0
Personal and laundry services	251.1	5.1
Nursing and residential care facilities	237.3	4.2
Truck transportation	233.0	5.0
Educational services	223.8	2.0
Membership associations and organizations	221.2	3.3
Wood product manufacturing	206.2	16.4
Waste management and remediation services	171.6	4.3
Air transportation	169.5	2.0
Broadcasting, except internet	120.9	4.3
Couriers and messengers	115.8	4.2
Electrical equipment and appliance manufacturing	100.3	3.0
Motion picture and sound recording industries	96.0	2.4
Printing and related support activities	94.7	4.3
Plastics and rubber product manufacturing	94.6	7.5
Scenic and sightseeing transportation; support activities for transportation	83.9	3.5
Museums, historical sites, zoos, and parks	80.6	7.3
Warehousing and storage	75.2	8.8
Furniture and related product manufacturing	63.8	5.3
Water transportation	63.2	3.8
Private households	47.6	5.1
Transit and ground passenger transportation	47.2	4.2
Mining (except oil and gas)	36.3	7.5
Pipeline transportation	33.2	4.8
Rail transportation	30.3	4.7
Textile mills; textile product mills	25.1	8.3
Apparel manufacturing; leather and allied product manufacturing	6.9	2.3
Support activities for mining	4.6	5.2
Forestry and logging; fishing, hunting, and trapping	4.2	4.1

Appendix 3

Table 3.1. Revised San Francisco Bay region, California, output loss from building damage and transportation network interruption in the HayWired scenario by year using Regional Economic Models, Inc., output baseline.

[Sectors are sorted by first year loss]

Sector	Value of output loss			Loss of 2018 industry output, in percent		
	1st year	2d year	3d year	1st year	2d year	3d year
Professional, scientific, and technical services	4416.3	49.6	0.0	3	0	0
Real estate	4250.9	34.1	0.0	3	0	0
Computer and electronic product manufacturing	3674.9	19.9	0.0	3	0	0
Food services and drinking places	3141.3	77.3	0.0	14	0	0
Ambulatory health care services	2696.0	89.7	0.0	9	0	0
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	2693.8	50.6	0.0	3	0	0
Machinery manufacturing	2490.4	4.1	0.0	19	0	0
Petroleum and coal products manufacturing	2386.6	2.1	0.0	5	0	0
Retail trade	2104.6	12.6	0.0	4	0	0
Wholesale trade	2060.3	17.3	0.0	4	0	0
Construction	1856.2	5.1	0.0	5	0	0
Hospitals; private	1673.1	72.2	0.0	9	0	0
Chemical manufacturing	1656.4	2.6	0.0	4	0	0
Publishing industries, except internet	1354.1	4.9	0.0	3	0	0
Monetary authorities and other credit institutions	1329.6	10.5	0.0	3	0	0
Fabricated metal product manufacturing	1094.9	1.7	0.0	18	0	0
Other transportation equipment manufacturing	1052.8	2.3	0.0	18	0	0
Accommodation	934.6	55.9	0.0	9	1	0
Securities, commodity contracts, investments	907.5	5.2	0.0	3	0	0
Administrative and support services	887.7	8.9	0.0	3	0	0
Performing arts and spectator sports	877.9	19.7	0.0	15	0	0
Management of companies and enterprises	817.0	4.5	0.0	3	0	0
Motor vehicles, bodies and trailers, and parts manufacturing	691.6	0.6	0.0	24	0	0
Insurance carriers and related activities	542.8	2.7	0.0	3	0	0
Amusement, gambling, and recreation	525.0	11.1	0.0	14	0	0
Food manufacturing	514.1	0.8	0.0	4	0	0
Telecommunications	485.4	0.0	0.0	2	0	0
Beverage and tobacco product manufacturing	467.3	0.6	0.0	2	0	0
Nonmetallic mineral product manufacturing	448.9	0.6	0.0	17	0	0
Utilities	430.6	2.5	0.0	3	0	0

Table 3.1. Revised San Francisco Bay region, California, output loss from building damage and transportation network interruption in the HayWired scenario by year using Regional Economic Models, Inc., output baseline.—Continued

Sector	Value of output loss			Loss of 2018 industry output, in percent		
	1st year	2d year	3d year	1st year	2d year	3d year
Oil and gas extraction	417.4	0.3	0.0	9	0	0
Social assistance	358.2	17.8	3.8	5	0	0
Rental and leasing services; lessors of nonfinancial intangible assets	340.4	2.4	0.0	3	0	0
Miscellaneous manufacturing	302.4	0.8	0.0	3	0	0
Paper manufacturing	290.0	0.4	0.0	21	0	0
Primary metal manufacturing	284.4	0.3	0.0	7	0	0
Air transportation	268.2	0.8	0.0	3	0	0
Nursing and residential care facilities	264.5	13.4	3.1	5	0	0
Repair and maintenance	263.8	7.2	0.0	4	0	0
Educational services; private	221.6	3.9	0.0	2	0	0
Personal and laundry services	208.9	4.7	0.0	4	0	0
Truck transportation	193.6	1.4	0.0	4	0	0
Wood product manufacturing	191.5	0.3	0.0	15	0	0
Motion picture and sound recording industries	143.2	0.5	0.0	4	0	0
Membership associations and organizations	132.8	2.0	0.0	2	0	0
Waste management and remediation services	132.8	0.9	0.0	3	0	0
Museums, historical sites, zoos, and parks	126.8	2.4	0.0	11	0	0
Electrical equipment and appliance manufacturing	110.6	0.4	0.0	3	0	0
Couriers and messengers	96.8	0.6	0.0	4	0	0
Broadcasting, except internet	89.1	0.5	0.0	3	0	0
Scenic and sightseeing transportation and support activities for transportation	80.3	0.4	0.0	3	0	0
Printing and related support activities	76.7	0.2	0.0	3	0	0
Water transportation	69.9	0.1	0.0	4	0	0
Plastics and rubber product manufacturing	47.3	0.1	0.0	4	0	0
Warehousing and storage	47.2	0.6	0.0	6	0	0
Furniture and related product manufacturing	41.0	0.1	0.0	3	0	0
Private households	40.8	0.9	0.0	4	0	0
Transit and ground passenger transportation	34.4	0.2	0.0	3	0	0
Textile mills; textile product mills	29.2	0.1	0.0	10	0	0
Pipeline transportation	26.1	0.1	0.0	4	0	0
Rail transportation	24.6	0.2	0.0	4	0	0
Mining (except oil and gas)	23.1	0.0	0.0	5	0	0
Apparel, leather and allied product manufacturing	10.5	0.0	0.0	3	0	0
Agriculture and forestry support activities	2.8	0.0	0.0	1	0	0
Support activities for mining	2.7	0.0	0.0	3	0	0
Forestry and logging; fishing, hunting, and trapping	1.9	0.0	0.0	2	0	0

Appendix 4

Table 4.1. San Francisco Bay region, California, total output loss from combined building and transportation effects in the HayWired scenario by private industry sector in 2018.

[Categories are sorted by 1st year loss. Data generated using the Association of Bay Area Governments Planning and Research Department (2016) REMI (Regional Economic Models, Inc.) model analysis from 2018 (this study)]

Category	Output loss, in millions of 2016 U.S dollars	Share of output loss, in percent
Real estate	10,934.9	7.6
Professional, scientific, and technical services	9,531.9	6.5
Construction	6,772.3	6.5
Retail trade	4,993.2	10.3
Monetary authorities and other credit institutions	4,652.9	10.4
Ambulatory health care services	4,623.2	14.9
Wholesale trade	4,517.2	9.4
Food services and drinking places	4,174.5	18.7
Computer and electronic product manufacturing	4,091.2	3.2
Petroleum and coal products manufacturing	3,562.9	7.4
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	3,502.2	3.4
Administrative and support services	2,998.8	10.2
Machinery manufacturing	2,954.8	22.4
Securities, commodity contracts, investments	2,853.6	9.2
Chemical manufacturing	2,716.8	6.3
Telecommunications	2,425.2	8.0
Hospitals	2,303.8	11.8
Management of companies and enterprises	2,245.5	9.5
Publishing industries, except Internet	2,192.0	4.9
Insurance carriers and related activities	1,644.6	9.2
Fabricated metal product manufacturing	1,562.5	25.2
Accommodation	1,469.7	14.2
Performing arts and spectator sports	1,389.9	24.0
Utilities	1,278.1	9.6
Other transportation equipment manufacturing	1,173.3	20.3
Food manufacturing	1,125.7	8.3
Rental and leasing services; lessors of nonfinancial intangible assets	959.1	8.4
Beverage and tobacco product manufacturing	903.2	3.1
Motor vehicles, bodies and trailers, and parts manufacturing	897.3	30.6
Oil and gas extraction	753.3	17.1
Repair and maintenance	737.8	12.4
Amusement, gambling, and recreation	731.9	19.6
Nonmetallic mineral product manufacturing	727.1	26.9

Table 4.1. San Francisco Bay region, California, total output loss from combined building and transportation effects in the HayWired scenario by private industry sector in 2018.—Continued

Category	Output loss, in millions of 2016 U.S dollars	Share of output loss, in percent
Social assistance	718.8	9.3
Educational services	687.8	6.1
Primary metal manufacturing	655.7	17.3
Membership associations and organizations	610.5	9.0
Personal and laundry services	574.8	11.6
Miscellaneous manufacturing	529.6	5.9
Air transportation	523.6	6.3
Truck transportation	474.8	10.2
Nursing and residential care facilities	457.0	8.2
Paper manufacturing	380.8	27.5
Waste management and remediation services	377.2	9.4
Wood product manufacturing	321.3	25.6
Broadcasting, except Internet	317.7	11.4
Couriers and messengers	260.6	9.5
Motion picture and sound recording industries	235.6	5.9
Scenic and sightseeing transportation; support activities for transportation	210.6	8.8
Electrical equipment and appliance manufacturing	208.3	6.3
Printing and related support activities	204.7	9.2
Museums, historical sites, zoos, and parks	166.6	15.1
Plastics and rubber product manufacturing	145.2	11.5
Water transportation	126.1	7.6
Furniture and related product manufacturing	122.6	10.3
Warehousing and storage	121.4	14.3
Transit and ground passenger transportation	117.8	10.3
Private households	105.9	11.3
Pipeline transportation	67.8	9.8
Rail transportation	57.1	8.9
Mining (except oil and gas)	55.9	11.5
Textile mills; textile product mills	45.2	14.8
Apparel manufacturing; leather and allied product manufacturing	14.3	4.7
Support activities for mining	13.1	4.5
Forestry and logging; fishing, hunting, and trapping	9.5	8.9

Appendix 5

Table 5.1. San Francisco Bay region, California, total employment net change.

[Year 1 of the scenario is 2018, year 5 is 2022, year 10 is 2027, and year 23 is 2040]

Category	2018	2022	2027	2040
Forestry and logging; Fishing, hunting, and trapping	−62	−1	2	−1
Agriculture and forestry support activities	−252	−7	−2	−5
Oil and gas extraction	−802	45	68	−5
Mining (except oil and gas)	−522	9	30	−7
Support activities for mining	−283	11	39	−6
Utilities	−1,354	−156	−43	−27
Construction	−31,641	−1,406	6,416	−294
Wood product manufacturing	−1,159	−86	42	−3
Nonmetallic mineral product manufacturing	−2,152	−28	71	−11
Primary metal manufacturing	−704	8	8	−2
Fabricated metal product manufacturing	−5,731	56	78	−18
Machinery manufacturing	−5,292	−14	16	−16
Computer and electronic product manufacturing	−3,084	821	269	−47
Electrical equipment and appliance manufacturing	−492	24	10	−4
Motor vehicles, bodies and trailers, and parts manufacturing	−1,056	−13	5	−5
Other transportation equipment manufacturing	−2,345	13	2	−6
Furniture and related product manufacturing	−613	−10	16	−6
Miscellaneous manufacturing	−1,324	68	25	−12
Food manufacturing	−2,486	−233	−102	−40
Beverage and tobacco product manufacturing	−750	−70	−32	−24
Textile mills; Textile product mills	−215	23	8	−1
Apparel manufacturing; Leather and allied product manufacturing	−165	242	79	3
Paper manufacturing	−724	−1	−1	−2
Printing and related support activities	−1,010	−25	0	−9
Petroleum and coal products manufacturing	−482	45	46	2
Chemical manufacturing	−1,305	29	11	−18
Plastics and rubber product manufacturing	−509	4	8	−3
Wholesale trade	−15,094	−131	−85	−221
Retail trade	−43,420	−750	−633	−1,018
Air transportation	−1,328	56	42	−22
Rail transportation	−119	3	4	−1
Water transportation	−194	5	5	−4
Truck transportation	−2,237	14	33	−26
Couriers and messengers	−1,761	36	24	−11

Table 5.1. San Francisco Bay region, California, total employment net change. —Continued

Category	2018	2022	2027	2040
Transit and ground passenger transportation	−1,958	211	65	−56
Pipeline transportation	−81	−7	0	−1
Scenic and sightseeing transportation; support activities for transportation	−1,762	133	88	−19
Warehousing and storage	−1,412	−24	14	−18
Publishing industries, except Internet	−1,744	26	15	−34
Motion picture and sound recording industries	−742	77	41	−5
Internet publishing and broadcasting; ISPs, search portals, and data processing; other information services	−3,064	0	−20	−53
Broadcasting, except Internet	−1,063	−37	−8	−21
Telecommunications	−2,525	−114	−28	−77
Monetary authorities and other credit institutions	−13,005	−2,355	90	−222
Securities, commodity contracts, investments	−6,516	−86	94	−72
Insurance carriers and related activities	−6,233	−817	−138	−199
Real estate	−24,108	−23,162	−796	−892
Rental and leasing services; lessors of nonfinancial intangible assets	−1,864	−2	35	−23
Professional, scientific, and technical services	−44,184	−2,479	−7	−806
Management of companies and enterprises	−7,016	44	68	−53
Administrative and support services	−32,247	−3,143	−71	−418
Waste management and remediation services	−1,578	−373	−23	−31
Educational services	−9,126	−769	−193	−352
Ambulatory health care services	−23,390	−713	−696	−972
Hospitals	−11,009	−1,170	−778	−451
Nursing and residential care facilities	−5,366	−765	−487	−272
Social assistance	−19,307	−2,273	−1,373	−780
Performing arts and spectator sports	−14,706	−52	58	−90
Museums, historical sites, zoos, and parks	−905	16	6	−9
Amusement, gambling, and recreation	−12,535	−117	0	−97
Accommodation	−10,226	−535	−207	−236
Food services and drinking places	−59,287	−3,994	−1,571	−437
Repair and maintenance	−6,893	96	125	−114
Personal and laundry services	−9,940	−59	9	−193
Membership associations and organizations	−6,272	−652	−121	−198
Private households	−5,613	−6	−26	−28
Government	−19,501	−17,469	−2,866	−534
Farm	−199	0	0	0

Appendix 6

Table 6.1. Consumer commodities and services that would account for one-quarter of spending and reinvestment into the San Francisco Bay region, California, economy in the HayWired scenario.

Commodities	
New motor vehicles	Furniture and furnishings
Net purchases of used motor vehicles	Household appliances
Motor vehicle parts and accessories	Household supplies
Motor vehicle fuels, lubricants, and fluids	Glassware, tableware, and household utensils
Motor vehicle maintenance and repair	Men's and boy's clothing
Other motor vehicle services	Women's and girl's clothing
Fuel oil and other fuels	Children's and infants' clothing
Ground transportation	Other clothing materials and footwear
Tools and equipment for house and garden	Personal care products
Musical instruments	Physician services
Books, educational and recreational	Dental services
Telephone and facsimile equipment	Paramedical services
Video, audio, photographic, and information processing equipment and media	Hospitals
Audio-video, photographic, and information processing equipment	Pharmaceutical and other medical products

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Chapter V4

Characteristics of Businesses Disrupted by Building Damages from the HayWired Scenario Mainshock

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Abstract

A review of business characteristics associated with business vulnerability after a disaster (for example, type of business, location, sector, size, age, and owner demographics) accompanies a spatial analysis of business characteristics exposed to disruptive building damages in the HayWired scenario, San Francisco Bay region, California. The National Establishment Time-Series Database contains business and owner characteristics. Extensive and complete building damages from the HayWired scenario mainshock earthquake and fire hazards are used to estimate the percentage (or risk) of disruptive building damage by occupancy in census tracts. The spatial analysis of businesses in nine counties within the San Francisco Bay region with regard to building occupancy damage estimations provides a more nuanced assessment of business establishment and employment vulnerability than can be gleaned from building occupancy damage results alone. The analysis and literature are used to inform policies, mitigation approaches, and programs and implementations that could be helpful in the San Francisco Bay region after a large earthquake.

We estimate a 7–8 percent risk of disruptive building damage to business establishments and employment in the San Francisco Bay region; at least 40,000 establishments and 240,000 employees could be affected by extensive or complete damage at their workplaces. The risks vary by sector and range from 5–6 percent (for businesses in utility, other, finance and insurance, and management of companies sectors) to 10–11 percent (for establishments in the construction, education, and warehouse and transportation sectors and employment in the manufacturing sector). Business location strongly differentiates disruptive building damage risk for all types of businesses. About 25 percent of Alameda County businesses and employees could be affected by limited or restricted use of their buildings, and the risk increases to 35 and 40 percent in central Alameda and western Contra Costa Counties, respectively, because of their close proximity to the HayWired scenario epicenter. In Alameda County, risk of disruptive building damage by sector range from 15–19 percent (agricultural and utility businesses) to about 33–35 percent (construction and education businesses) and in central Alameda County, sectoral risks can be as large as 57 percent for public administration employment and 50 percent for construction business establishments. All Alameda County establishment and employment risks exceed risks in other counties; disruptive building risk in Contra Costa County is 12–13 percent, followed by 3–4 percent in Santa Clara County. Overall, the shares of business characteristics in Alameda County largely drives the result for the region. For example, the slightly larger regional risk to minority-owned businesses and branch-type establishments reflect a larger representation of these business characteristics in Alameda County.

The disaster research literature identifies the prevalent and vulnerable business characteristics of small size (measured either by number of employees or revenue). Small businesses (less than 50 employees) represent 98 percent of establishments and 60 percent of employment in the San Francisco Bay region. About 33 percent of establishments and 10 percent of employment have annual business revenues under $100,000. Recent studies find that small businesses are underserved by disaster recovery resources and seek more innovative solutions. Larger businesses have more resources for disaster mitigation, preparedness, and recovery, and based on location in the HayWired scenario, they show slightly less disruption from building damage than medium- and small-sized businesses in the region, but not in each county. In Santa Clara County, large businesses face a greater risk of building damage, suggesting they are located in more hazardous places in the HayWired scenario or in more vulnerable buildings than small- and medium-sized businesses in the county.

Businesses in the retail sector have also been vulnerable after disasters, although retail sales may be maintained as customers switch to other retailers. Programs to ensure continued operations have assisted retail businesses impacted by disasters. Such programs will be important for the retail sector in the San Francisco Bay region, which has an above-average disruptive building damage risk and a larger composition of small businesses. Business establishments in the construction sector face larger disruptive building

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damage and are more likely to be small businesses—this may impede their ability to reap the benefits of reconstruction in the absence of programs ensuring their participation. Manufacturing businesses also face above-average disruptive building damage risk, and combined with the difficulty of relocating fixed assets, may result in changes to the business base in Alameda County, requiring coordinated economic development. Transportation and warehouse establishments are disproportionately located in Alameda County and, therefore, the sector is at greater risk of disruptive building damage, which could create a need for public and private coordination around emergency and production supply networks. The risk to education establishments and employees is potentially exacerbated by fire following the HayWired scenario mainshock and reinforces the importance of fire prevention and safety management in schools with laboratories. Slightly larger disruptive building damage risk for minority-owned businesses is a reminder to follow up on programs for minority business owners. Male-minority-owned businesses are exposed to more risk in the HayWired scenario and female-owned businesses have been found to be more vulnerable after previous disasters.

After the direct benefit of constructing stronger buildings to reduce disruptive building risk, opportunities to improve business preparedness and recovery reside in interorganizational arrangements and programs.

Introduction

Macroeconomic impacts, measured as national and regional Gross Domestic Product (GDP) losses, can mask business interruption at the microeconomic level (Dahlhamer and Tierney, 1998; duPont and Noy, 2015). Individual businesses may experience impacts of disasters in widely varying ways (Dahlhamer and Tierney, 1998). A disaster may interrupt businesses directly through

- Damages to buildings, contents, and inventory (Marquis and others, 2015), and
- Transportation and utility (electricity, water, gas, voice and data) service outages (for example, Webb and others, 2002; Scarinci, 2016),

and indirectly through

- Disruptions to downstream businesses in supply chains (Altnay and Ramirez, 2010),
- Damages to neighborhoods and safety perceptions that deter customers (Dahlhamer and Tierney, 1998; Chang and Falit-Baiamonte, 2002; [New Zealand] Department of Labour, 2011),
- Socioeconomic status of customers (Lam and others, 2012), and
- Staff issues[4] (Corey and Deitch, 2011; Seville and others, 2014).

If a business is closed for any reason, it is vulnerable to losing market share (Alesch and others, 2001).

In this study of businesses in the San Francisco Bay region, we focus on building damages as the source of business disruption from the HayWired scenario earthquake. Of the businesses that reported physical damage after the 1989 Loma Prieta earthquake, 55 percent of them described it as disruptive or very disruptive (Wasileski and others, 2011). Building damage and relocation was a top issue for the Christchurch, New Zealand, business community for at least eight months after the magnitude (*M*) 6.3 Christchurch earthquake (Recover Canterbury, n.d.). The effects of other sources of business disruption for the HayWired scenario are examined in other chapters of this volume: neighborhood impacts by Wein, Belzer, and others (this volume); supply chain ripple effects by Sue Wing and others (this volume); and labor and transportation effects by Kroll and others (this volume).

Researchers have sought to identify pre-existing business and owner characteristics that make businesses vulnerable to failure or slow to recover after a disaster (for example, Webb and others, 2002; Marshall and others, 2015). The goals of such research are to inform policies and programs to increase the resilience of businesses before, during, and after disasters (for example, Alesch and others, 2001; Zhang and others, 2009; Hatton and others, 2012; Marshall and others, 2015). In this chapter, we draw upon this body of research and a detailed inventory of businesses to shed light on potential business vulnerability to building damages in the San Francisco Bay region after a hypothetical large earthquake on the Hayward Fault.

In the HayWired scenario, the Federal Emergency Management Agency's Hazus model is used to estimate building damages for building occupancy classes, which broadly defines the industrial sector and their building types (Seligson and others, 2018). Fire following earthquake damages (Scawthorn, 2018) are integrated as additional complete building damages (Johnson and others, this volume). We assume extensive and complete building damage states are particularly disruptive because they approximate conditions of building use (that is, restricted use of yellow-tagged buildings and prohibited use of red-tagged buildings, respectively). We define the risk of disruptive building damage for businesses as the percentage of building square footage that is extensively or completely damaged in their occupancy class in their census tract. Using the National Establishment Time-Series (NETS) Database, a more detailed accounting of the businesses and owner characteristics with respect to building damage states in census tracts allows application of findings from earlier disasters to discuss business vulnerability factors for the HayWired scenario.

Therefore, this report combines a review of past disaster research on business vulnerability factors with a spatial analysis of San Francisco Bay region businesses to provide a more nuanced

[4]Staff issues include (1) difficulties finding qualified or suitable staff; (2) the additional burden of managing and supporting staff; and (3) reduced productivity caused by staff being stressed, emotionally drained, and burned out (Seville and others, 2014).

assessment of business vulnerability than is conveyed in Hazus occupancy class building damage results. The literature review summarizes business and owner characteristics in relation to business outcomes (for example, temporary or permanent closure or partial recovery) after a natural disaster. The method section describes the approach to perform a spatial analysis, combining disruptive building damage (derived from Hazus results) with the detailed business establishment data available from NETS—that is, disruptive building damage risk for businesses and employees within a specific sector, geographical area, business size, business age, establishment type, and owner demographic. The results section tallies business characteristics regionally and identifies those at high risk of disruptive building damage from HayWired mainshock earthquake hazards with and without fire following the earthquake.[5] We relate these results to findings from the business demise and recovery literature to illuminate potential business vulnerability in the region after such an event. In the concluding sections, we acknowledge the gaps in the data and limitations of our method and refer to policy insights from prior studies to discuss opportunities to increase business resilience to an earthquake in the San Francisco Bay region.

Literature on Business and Owner Characteristics

Drawing upon theoretical frameworks of business resilience, studies have considered the influences of business owner demographics (for example, Alesch and others, 2001; Marshall and others, 2015), business characteristics (for example, Zhang and others, 2009), and organizational attributes (for example, Lengnick-Hall and others, 2011; Doerfel and others, 2013). "Owner characteristics" include the education and business experience, gender, minority/majority designation, age, household resources, personal resilience, and industry and disaster experience of the business owner. "Business characteristics" include the business location, sector to which it belongs, establishment type, operation in an owned or leased building, size, market reach, labor source, business condition and growth, prior business experience in the industry, prior business experience with disasters, prior short-term disaster business closure, and prior cash flow issues. "Organizational resilience" is defined by Lengnick-Hall and others (2011) in terms of cognitive, behavioral, and contextual attributes of organizations and framed as the corporate cultural dimension of resilience by Sheffi (2005). Doerfel and others (2013) find resilience in interorganizational relations that (pre-disaster) form communities of practice and involve multiple ties with each type of supporting organization. Our literature review focuses on business and owner characteristics because only these types of data are tracked in the NETS data.

The literature spans different approaches and contexts that complicate conclusions about the characteristics influencing business demise or recovery after a disaster. These study differences include:

- Different definitions and measurements of business impacts—for example, the condition and experience of businesses (Wasileski and others, 2011), business demise (Marshall and others, 2015), or recovery relative to impact (Brown and others, 2014). See Stevenson and others (2018) for a discussion of a business recovery framework.
- Different time periods of measuring business status—for example, 8 months (Webb and others, 2002; [New Zealand] Department of Labour, 2011) or 8 years (Marshall and others, 2015) after an event, such that businesses are subjected to different influences on reopening within different time periods (Lam and others, 2012).
- Extent to which business closure is differentiated from temporary arrangements (for example, owner/employees working for another business), consolidation of the business at another location, or reopening under a different name (Hatton, 2015).
- Different geographical settings, such as rural versus urban (for example, Stevenson and others, 2011).
- Different types and sizes of disasters—earthquakes, floods, and cyclones (for example, Webb and others, 2002; Wasileski and others, 2011; Hsiang and Jina, 2014).
- Different ways of identifying survey participants, including random sampling (for example, Marshall and others, 2015) and drawing from recipients of disaster loans (for example, Scarinci, 2016) or members of a business alliance organization (for example, Recover Canterbury, n.d.).
- Treatment of background noise of business failure or other market trends in the absence of a disaster.
- Recognition of pre-existing economic conditions including regional economic structure, commercial and residential space vacancy rates, and insurance penetration.
- Documentation of support programs provided to businesses after each disaster. Examples include a temporary space to congregate businesses (Kroll and others, 1990), a subsidy to pay employees (Brown and others, 2014) versus a loan (Alesch and others, 2001; Webb and others, 2002), and other programs in response to monitored business issues (Recover Canterbury, n.d).

Business Owner Characteristics

Marshall and others (2015) provide a state-of-the-art literature review of small business owner demographics and their cognitive attributes. Based on research and intuition, they make a case to investigate a slate of owner characteristics: education and disaster experience, gender, race/ethnicity, veteran status,

[5]This analysis addresses only building damages, rather than the impacts of roadway or utility damages on business activity. These additional impacts are discussed in more detail in other chapters of the HayWired scenario analysis, including by Kroll and others (this volume) and Johnson and others (this volume).

household size and disaster experience, and personal resilience with respect to business states (reopened, closed and reopened, and closed) eight years after Hurricane Katrina. They found the likelihood of business closure (with and without reopening) increased for female owners. They note consistency with Fothergill (1996) and Council of Economic Advisers (2015), who explain that women, in general, have a greater exposure to risk because of their social roles as caregivers, lack of mobility, and access to capital (for example, aid, savings, insurance, and wages) compared to their male counterparts.

The experience of prior damage to business owners' homes did not appear to predispose their business for recovery; rather, prior home damage was associated with an increased likelihood of immediate or eventual business closure (Marshall and others, 2015). Recovering from damage to a home may limit household resources for business recovery investments.

Marshall and others (2015) found the likelihood of business closure (without reopening) was increased for minority or veteran owners. They point out that whereas the effects of ethnicity and race on business survival and preparedness are inconclusive, African-American owned businesses (in the retail and service sectors, in particular) have been found to fail more often in general, a trend that could be exacerbated in a disaster. Compared to non-veteran owners, veteran owners had lower perceived business success (which was associated with increased likelihood of closure) and owned fewer businesses in the service sector (that had a lower likelihood of demise).

The business owner's personal resilience is thought to be an important factor in the owner's ability to cope with stress resulting from a natural disaster (Marshall and others, 2015). Marshall and others (2015) found that owner resilience was associated with increased likelihood of reopening then closing. This corresponds to Alesch and others' (2001) observations of extraordinary psycho-social resiliency that commonly gave in to post-disaster stress and pressures, eventually resulting in business failure.

Marshall and others (2015) surmise that the business owner's household may be both a source of resources that the business can draw upon or a source of competition for those resources. They found opposing relationships between business status and the owner's household size. Owners with larger households were more likely to close and remain closed (suggesting resource competition between a larger household and business) and less likely to reopen and close (suggesting that resources from the larger household were available for the business).

Furthermore, Marshall and others (2015) found that businesses with partnerships were less likely to close. However, if businesses with partnerships closed for a time and then reopened, they were more likely to close again (perhaps caused by a perception of having more resources initially in the partnership).

Business Characteristics

Numerous business characteristics have been examined by researchers after a disaster. The vulnerabilities summarized here pertain to business location; sector; establishment type; size; premise type (either owned or leased and [or] home based); age; experience with disruption; and pre-existing business conditions.

Business Location

Business location differentiates impacts from hazard exposure, property and neighbor damages, and utility disruptions to businesses (Kroll and others, 1991; Tierney and Nigg, 1995; Tierney, 1997; Webb and others, 2002; Wasileski and others, 2011; Brown and others, 2014; Marshall and others, 2015). Location is also relevant where businesses are dependent on local customers ([New Zealand] Department of Labour, 2011; Whitman and others, 2013). In contrast, businesses with international markets have recovered more quickly (Webb and others, 2000), although there is evidence that Christchurch businesses needed to assure national and international customers that they were reliable sources despite the ongoing earthquakes (observed by A.M. Wein during a 2011 visit to Christchurch; Resilient Organizations, 2018).

Business Sector

Business sector has been related to business demise and recovery status after a disaster. Businesses in the retail and wholesale sectors have fairly consistently been found to be more vulnerable to disaster damages and disruption, including that from earthquakes: Kroll and others (1990) and Wasileski and others (2011) discuss the 1989 Loma Prieta earthquake,[6] Webb and others (2002) discuss the 1997 Northridge earthquake, and Chang and Falit-Baiamonte (2002) discuss the 2001 Nisqually earthquake. The [New Zealand] Department of Labour (2011) and Statistics New Zealand (2012) showed employment declines in the wholesale and combined retail and accommodation/food sectors in the Canterbury region for more than a year after the most damaging 2011 *M*6.3 aftershock in Christchurch, New Zealand. Retail and wholesale sectors were not highlighted in Canterbury earthquake surveys of business impact and recovery (Brown and others, 2014), but the surveyed businesses in these sectors did not appear among the most impacted. The vulnerability of retail and wholesale has been explained by the competitive nature of the business and tendency for small retail businesses to depend on local customers and to occupy older buildings (Alesch and others, 2001; Chang and Falit-Baiamonte, 2002).

After Hurricane Katrina, Marshall and others (2015) found service businesses survived more often than goods-producing businesses that rely more on fixed assets. Similarly, Zhang and others (2009) classify professional, scientific, and technical services as low-vulnerability businesses and manufacturing and construction as moderate-vulnerability businesses. Businesses in manufacturing and construction sectors were noted to recover better than expected after the 1989 Loma Prieta earthquake

[6]However, business assistance muted the effect for retail.

(Wasileski and others, 2011). The construction sector has shown initial decline that can be followed by a building boom (Kroll and others, 1990; Statistics New Zealand, 2012) to place it among the most recovered sectors (Brown and others, 2015).[7] Reconstruction brings in construction workers that are new customers for food and accommodation sectors that suffer from decreases in tourism after a disaster (Brown and others, 2015). The number of tourists declined in Christchurch when hotel capacity was impacted and tourists were encouraged to visit other parts of New Zealand because of ongoing aftershocks (Orchiston and others, 2013). In central Italy, there was a drop in tourism that lasted nine months after the 1997 earthquake (Mazzocchi and Montini, 2001). After the 2014 South Napa earthquake, visitors to restaurants declined in the City of Napa for as long as six months (observed by A.M. Wein in 2016). Amongst business sectors that typically benefit from an influx of potential customers, only the arts, entertainment, and recreation sector did not gain from new construction worker customers in Christchurch—these businesses were the most impacted and the least recovered relative to impact (Brown and others, 2015).

Zhang and others (2009) classify finance, insurance, and real estate businesses as moderately vulnerable. These businesses were considered to be better prepared, but not immune to earthquake impacts, surrounding damage, and transportation disruption after the Loma Prieta earthquake (Kroll and others, 1990). Brown and others (2014) rank finance and insurance businesses among the most recovered businesses relative to operations preceding the earthquakes and rank rental, hiring, and real estate businesses among the most recovered relative to impact (taking into account the level of impact as well as strength of business operations in the recovery period).

Business-oriented studies have had less to say about public and educational entities. The public administration sector was ranked among the least recovered entities in Christchurch, but one of the most recovered relative to size of impact (Brown and others, 2015). In Christchurch, the closure of hundreds of public schools affected 70,000 students and reopening of schools was delayed by water and wastewater services. Most schools reopened a month after the 2011 earthquake and school sites were shared to accommodate students from schools that remained closed (Earthquake Engineering Research Institute, 2011).

Continued operation of universities has depended on the restoration of other support services, including public schools. Tulane University was closed for a semester after Hurricane Katrina and reopening the university depended on the university's role in rebuilding support services, such as public schools, health services, and arranging for housing, as well as on the physical repairs (Cowen, 2007). During the hiatus, Tulane University helped students find education alternatives. In Christchurch, the University of Canterbury progressively reopened after 3–4 weeks using temporary (tent) structures onsite, off-site facilities, and online instruction. The university suffered from loss of fee-paying international students. In the San Francisco Bay region, Comerio (2006) reports that the University of California, Berkeley, plans for a maximum closure of one month and Stanford University plans to reopen within one week after an earthquake.

Business Establishment Type

Establishment type, as in headquarters, branch/affiliates, or stand-alone operations, indicate the range of resources and informed support and advice that may be available for managing business interruption. Headquarters typically have resources for emergency planning. Larger companies that have multiple sites in the region and nationally are able to shift operations (Comerio, 2006). The value of external advice from affiliates and headquarters was evident in Bowden's (2011) survey of four national companies when managers with "quake brain" had to make relocation decisions. In contrast, stand-alone businesses lack the benefit of preparedness guidance from headquarters, alternative sites, and (or) advice from others that are familiar with their business.

Business Premises

Researchers have fairly consistently found that businesses that own their buildings fared better than renters (for example, Dahlhamer and Tierney, 1998; Chang and Falit-Baiamonte, 2002; Wasileski and others, 2011). Building ownership is an indicator of wealth for the business (Wasileski and others, 2011), whereas, as Comerio (2006) points out, resolving rental lease agreements can be a lengthy process. In contrast, Brown and others (2014) found that, in the Canterbury earthquakes, businesses that owned buildings fared worse than those that rented. Marquis and others (2015) shed light on the potential disadvantage of building ownership in Christchurch in the aftermath of the earthquake sequence, revealing unique issues and complexities for commercial building owners in relation to unexpected technical, legal, and financial challenges when making decisions about the future of their buildings and a paradoxical effect of insurance[8] on the recovery of Christchurch. In Brown and others' (2014) study on the Christchurch earthquakes, businesses that both owned and rented buildings recovered better, suggesting an advantage of having more options and more flexibility with multiple locations (Tierney, 1997).

Marshall and others (2015) found that home-based businesses had an advantage, perhaps because of better preparedness (for dual purposes) and because homes are built to higher codes than commercial spaces. Home-based businesses may be less likely to be located in built-up areas that are subject to concentrated neighborhood damage (see Wein, Belzer, and others, this volume). It is noteworthy that the number of people

[7]Brown and others (2015) distinguish between recovery relative to operations preceding the earthquake and recovery relative to the size of impact. A sector that has not fully recovered to previous levels may still have recovered strongly relative to the level of impact experienced.

[8]The paradoxical effect refers to the expectation that insurance aids during recovery from a disaster, yet various insurance issues and challenges in Christchurch caused delays in repairs and rebuilding.

working from home is increasing but is more prevalent in some sectors than others. Working from home has been most prevalent in management, business, and financial occupations and has been increasing most rapidly for computer, engineering, and science occupations (Mateyka and others, 2012). In 2015, the U.S. Bureau of Labor Statistics (2016) measured 24 percent of workers are working from home in some capacity, including 30–40 percent of the management, business, and financial and professional service occupations, but fewer than 10 percent of production and transportation workers work from home.

Business Size

Business size, measured by number of employees, wages, or revenues, is consistently found to be a factor in business recovery—small businesses are identified as more vulnerable to disasters than larger businesses (Dahlhamer and Tierney, 1998; Chang and Falit-Baiamonte, 2002). For example, small businesses had a lower probability of reopening in New Orleans after Hurricane Katrina (Lam and others, 2012). Small business size corresponds to less resources to prepare, fewer cash reserves, lower uptake of insurance, and a lack of access to government programs for recovery (Kroll and others, 1990; Webb and others, 2000; Alesch and others, 2001; Dunaway and Shaw, 2010; Collier and others, 2016). Wasileski and others (2011) caution that small business use of external aid may exacerbate the problem of debt.

Brown and others (2014) did not detect a small business size effect on business recovery, but small businesses were underrepresented in their sample. Although the five businesses in their survey that ceased operation had less than 50 employees (Brown and others, 2014), four of these businesses reopened under a new name (Tracy Hatton, Resilient Organizations, written communication, 2018). Also, the government earthquake support subsidy to compensate employees in Canterbury after the Christchurch earthquake was reportedly very helpful for keeping businesses going ([New Zealand] Department of Labour, 2011) and was taken up by relatively more small- and medium-sized businesses (Brown and others, 2015).

Business Age

Some studies find evidence of the vulnerability of young business age caused by limited resources (including insurance), less experience, and smaller size (Dahlhamer and Tierney, 1998; Webb and others, 2002; Collier and others, 2016). However, results vary. No age effect was detected with respect to business recovery in Christchurch, but older businesses prevailed (Brown and others, 2014). Conversely, old businesses struggled more in Miami-Dade County, Florida, in the aftermath of Hurricane Andrew (Webb and others, 2002) and Scarinci (2016) gathered evidence that some smaller and newer businesses could relocate more easily than larger and more established businesses. Business age might align with experience, but younger businesses could benefit from having an experienced owner, whereas older businesses headed by older proprietors may be less likely to survive (Brüderl and Ziegler, 1992). This could especially be the case where the level of damage requires extensive rebuilding and investment on the part of the owner, who may prefer to retire.

Business Experience with Disruption

Marshall and others (2015) found positive effects from industry experience and business experience with disruption (including cash flow issues) on reopening, although, industry experience did not necessarily keep businesses from eventually closing. Scarinci's (2016) post-disaster preparedness investigation reinforced that small businesses can be inhibited by a lack of reflection caused by intense focus on recovery and even "amnesia" to wipe the horrible experience from business owners' minds.

Pre-existing Business Conditions

Past studies have shown that disasters tend to intensify pre-existing business conditions (Marshall and others, 2015). Pre-disaster growth and financial condition have been identified as indicators of business survival and recovery (Dahlhamer and Tierney, 1998; Alesch and others, 2001; Webb and others, 2002). Positive owner perceptions of business success prior to Hurricane Katrina were associated with lower likelihood of demise (Marshall and others, 2015). Financial condition was the second strongest predictor of long-term recovery in Santa Cruz, Calif., after the Loma Prieta earthquake, but counterintuitively was found to have a negative effect (Webb and others, 2002).

Methods

Past research, then, shows that a broad range of long-term effects are possible after a disaster relative to the severity of the event, and vary with the types of physical damage, particular circumstances of the economy, assistance provided, industry sector and mix, business size and age, establishment type, and other characteristics of business ownership. In the description of business characteristics in the San Francisco Bay region that follows this section, we highlight a few key factors that may contribute to business vulnerability, including location with respect to disruptive building damage, industry sector, business size, age, establishment type, and ethnic and gender characteristics of the business owner. None of these factors in themselves is a predictor of business outcomes, and indeed two different factors may interact to mitigate the effect a single characteristic might have (for example, a large retail business would have greater survival chances than a smaller one, but if heavily damaged relative to the smaller one, the survival likelihood of each could be reversed). Additionally, businesses facing compounding challenges are less likely to recover (Dahlhamer and Tierney, 1998). We analyze business characteristics for disruptive building risk in the HayWired scenario to investigate whether an analysis of business and

owner characteristics may illuminate the types of policies, mitigation approaches, or responses that could be helpful in the San Francisco Bay region. Next, we describe our methods for relating business characteristics to building damage estimates for the HayWired mainshock hazards of shaking, liquefaction, landslides, and fire.

Data Sources

The NETS database is an annual collection of data pertaining to all of the business establishments in the United States between 1989 and 2013 sourced from Dunn and Bradstreet (Walls and Associates, 2011; Feldman, 2018). "Business" is broadly defined to include private for-profit and nonprofit organizations as well as government agencies (Barnatchez and others, 2017). In NETS, an establishment is a specific line of business at a specific location, and employment includes all workers at an establishment, potentially including proprietors, independent contractors, and temporary workers supplied by outside organizations (Barnatchez and others, 2017).[9]

Barnatchez and others (2017) review studies of comparable business datasets and conduct their own comparison of NETS data with that from more robust official data collection activities of U.S. statistical agencies. Using National NETS data for 1992–2014, they find that the correlation of NETS employment counts and U.S. Census Bureau County Business Patterns employment counts across U.S. counties can exceed 0.99; correlations across state-industry-size class cells are above 0.9 on restricted samples; and that zip-code-level correlations are also remarkably high. On the other hand, they find that NETS overrepresents establishments that have fewer than 10 employees, especially business sizes of 1.[10] A smaller, but significant, discrepancy is found for the largest establishments, but explained by large, public educational establishments that are difficult to identify as government owned, as well as establishments that mistakenly report firm employment numbers in NETS. Also relevant is the finding that post-2000 developments in U.S. mining, construction, and manufacturing employment do not appear to be well captured in NETS, possibly caused in part by industry labeling differences. When Barnatchez and others (2017) omit very small establishments (especially businesses of size 1), NETS agrees reasonably well with official datasets. The advantage of using NETS is that it does not require extensive proposal and security clearance processes and can be used outside of secure government facilities (Barnatchez and others, 2017).

The data used for this analysis come from the 2014 version of the NETS dataset, and includes all of the business establishments in operation in the San Francisco Bay region as of January 2013. The San Francisco Bay region is defined as the following counties: Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco.

Business characteristic data in NETS used in this analysis include:

- Location,
- Size (number of employees, revenues),[11]
- Age,
- Establishment type, and
- Owner characteristics pertaining to gender and minority[12]/ majority demographics.

Based on the discrepancies between datasets on business size, we also examined the distribution of businesses of size 1 (which may have 0 employees) across characteristics. Some additional characteristics were excluded because of many missing data entries. Even so, some location data had to be recalibrated, and some establishments were dropped from the dataset because location reporting concerns could not be resolved.[13] In all, the starting total of 627,856 establishments in the database was reduced to 570,659 when those with missing or unresolvable data were excluded.

The building damage data were sourced from the Seligson and others (2018) estimate of earthquake hazards and the Scawthorn (2018) estimate of fire hazards. The Hazus building damage states in a census tract are separated into: none, slight, moderate, extensive, and complete damage states. This analysis uses the percentage of building square footage that suffers the disruptive (extensive or complete) damage in each census tract for each occupancy class. Building damages are reported in Hazus by occupancy classes, which in turn are tied through a crosswalk to North American Industry Classification System (NAICS) codes, as shown in appendix 1. Fire damages were classified as complete damage, distributed to occupancy

[9]We do not know the extent to which the shadow economy (including nannies, gardeners, house cleaners, or day labor) is represented, but a Red Cross network of voluntary organizations estimated that about 450 nonprofit agencies provided some type of disaster service to 160,000 victims seeking help outside the regular channels compared to 130,000 families that received temporary housing assistance after the 1997 Northridge earthquake (Comerio [1998]).

[10]NETS imputes values for two-thirds of businesses that have less than 5 employees.

[11]Four establishments were dropped because they contained implausible data on either employment or revenues, most likely because they are headquarters with data that reflects activities at various establishments in other locations. The owner of the dataset did not respond to inquiries about these establishments. A much larger number of establishments were excluded because of missing records for revenue (mostly government offices) and age.

[12]Proprietor of non-European ancestry.

[13]The NETS data provided detailed geographic information on each establishment, including latitude and longitude, address, and level code. A level code indicates how the establishment was located by street, block, census tract, or zip code. Some establishments were not located in the level code indicated. Where possible, the establishment location was corrected and latitude and longitude were recalculated. For example, if an establishment was verified at the zip code level, but was not actually found to be located in the zip code indicated, the location for that establishment was moved to the indicated zip code centroid. 732 establishments with locations outside of the study area were relocated in the process of using zip code level codes. Relocating the remaining 35 establishments with insufficient data on their location was not attempted because it is a time-consuming manual process.

classes, and integrated with the Hazus earthquake damages (appendix in Johnson and others, this volume). The combination of earthquake hazard damages (Hazus) and fire following earthquake damages is referred to as "all hazards."

Algorithm

For counties in the San Francisco Bay region, we used an algorithm that counts business characteristics in each census tract by establishment and by numbers of employees. The counts are summed using the weight of the percentage of extensive and complete damage in the establishment's census tract for the establishment's occupancy class to calculate disruptive building damage risk to establishments and employees. Essentially, the risk is the percentage of establishments or employees that are in buildings that are extensively or completely damaged.

The steps are as follows:

1. Correct establishment location data in the 2013 NETS database for the San Francisco Bay region and assign it to a census tract using a geographical information system. Each business record contains the census tract, sector (6-digit NAICS code), employment, 2013 revenues, ownership (gender/race), and establishment type (headquarters/branch/stand alone).
2. Add further sector classifications to the business records. In this case, the 6-digit NAICS code is aligned with the Hazus occupancy classes and collapsed to the NAICS 2-digit industry code. Note that where there is no industry in the NAICS data field, the industry is classified as "other" and is subject to the average risk for all occupancies in the census tract.
3. Assign the sector risk measure to each record according to census tracts for both cases of earthquake hazards and all hazards to each establishment.
4. Use establishment-level risks assigned by census tract and occupancy class to aggregate into a measure of overall risk for each business characteristic.
    A. The risk aggregation for business characteristics is performed for each sector (2-digit NAICS code) and all establishments (total) and aggregations are made across establishments using a weighted average of risk.
        I. Weights for aggregating risk across characteristics are:
            a. One for the risk aggregation by establishment.
            b. Establishment employment for risk aggregated by employment.
    B. The referenced business characteristics are the following:
        I. County (or subarea) in which the business is located,
        II. Number of employees in the establishment (various size categories),
        III. Age of the establishment in years (various age categories),
        IV. Overall revenues of the establishment (various revenue categories),
        V. Type of establishment (stand-alone, headquarters, or branch), and
        VI. Gender (male, female) and race/ethnicity (non-minority, minority) characteristics of the owner.

Results

First, we summarize characteristics of San Francisco Bay region businesses and owners. We follow with the disruptive building risk results for businesses with these characteristics. Detailed results are presented in a set of tables in the appendixes, each set showing disruptive building damage risk results for each characteristic as equally weighted by establishment and weighted by number of employees in each establishment for the two cases of earthquake hazards only and all hazards (including fire following the earthquake).

Business Characteristics in the San Francisco Bay Region

As of January 2013, the NETS data is summarized as follows:

1. *Establishments and employees.*—There are approximately 3,200,000 employees working in approximately 600,000 establishments in the dataset. Santa Clara County hosts the most businesses (24 percent of establishments; 28 percent of employment) followed by Alameda County (18 percent of establishments; 19 percent of employment).
2. *Distribution of employees by size of establishment.*—Within the region, 15 percent of employees are in businesses that have more than 500 employees (representing 0.1 percent of establishments); more than 60 percent of employees are in businesses that have less than 50 employees (representing 98 percent of establishments). Almost half of small business employees (almost 30 percent of all employees) work in businesses that have less than 5 employees (in 82 percent of establishments) and businesses of size 1 are 25 percent of establishments in the region. The remaining 25 percent of employees are in mid-sized business establishments that have 50–500 employees (representing 1 percent of establishments).

3. *Business sizes and sectors.*—Large establishments (>500 employees) are primarily in the public administration, utility, manufacturing, or information sectors. Sectors with the fewest employees in large establishments (>500 employees) include accommodation/food, retail, and construction. Sectors that have the largest share of employees in small businesses are administrative support and waste management; real estate, rental, and leasing; and management of companies. Businesses of size 1 are most prevalent in professional, scientific, and technical services (the share of businesses of size 1 in this sector is 163 percent of the regional share of establishments in this sector), followed by arts, entertainment, and recreation (144 percent of the regional share) and construction (133 percent of the regional share).

4. *Establishment revenues.*—One-third of businesses make less than $100,000 (containing 10 percent of employees), and a total of 77 percent of establishments make less than $250,000 (containing 28 percent of employees). Ninety-two percent of businesses of size 1 report revenues less than $100,000. The establishments in the largest revenue category ($2.5 million and above) contain 42 percent of all employees.

5. *Ages of business establishments.*—Most employees work for young or old companies: 25 percent of employees are in business establishments younger than 6 years (45 percent of establishments), and 34 percent of employees are in business establishments older than 26 years (13 percent of establishments).

6. *Establishment type.*—Most employees (77 percent) are in stand-alone companies (97.5 percent of establishments), followed by 20 percent of employees in headquarters (2 percent of establishments), and the remainder in branches (3 percent of employees; 0.5 percent of establishments).

7. *Owner characteristics.*—Most employees (90 percent) are in businesses that do not qualify as minority- or female-owned businesses (91 percent of establishments), 5 percent of employees work for establishments that are non-minority female-owned businesses (6 percent of establishments), and another 5 percent of employees work for minority male- or female-owned businesses (3 percent of establishments). Businesses of size 1 are disproportionately non-minority female owned and to a lesser degree, minority female owned.

Distribution of Employment at Risk across Counties

Because the building risks are shaped by the geography of the region and the earthquake event, we begin with a summary of the geographic characteristic. The results described below reflect the geographic concentration of the shaking and fire damage of the HayWired scenario near the cities of Hayward and San Leandro in Alameda County. As illustrated in figure 1, Alameda County has 19 percent of the region's employment (as measured in the NETS dataset), but 62 percent of the employment that is at risk of disruptive building damage from the HayWired mainshock scenario. Contra Costa County has 10 percent of the region's jobs, but 16 percent of employment that is at risk of disruptive building damage. Santa Clara County, with the largest concentration of the region's employment (28 percent) has 13 percent of the region's employment that is at risk of disruptive building damage, whereas San Francisco and San Mateo Counties, with 17 and 11 percent of the region's employment, have 3 and 4 percent that are at risk of disruptive building damage, respectively.

The characteristics of business establishments at risk in each county differ by the sectoral mix of their businesses and the types of buildings that they occupy, as well as any other business characteristics that distinguish the mix of business establishments in each county. Note that, as shown in other economic analyses in this volume, business impacts increase and shift in their distributions when additional sources of disruption from the transportation, communication, water, and power systems, neighborhoods, and supply and customer chains (not covered in this chapter) are added to the analysis. This assessment differs from Hazus building losses and business output losses used in the macroeconomic computable general equilibrium and Regional Economic Models, Inc., analyses (Kroll and others, this volume; Sue Wing and others, this volume), but the overall results are consistent across analyses.

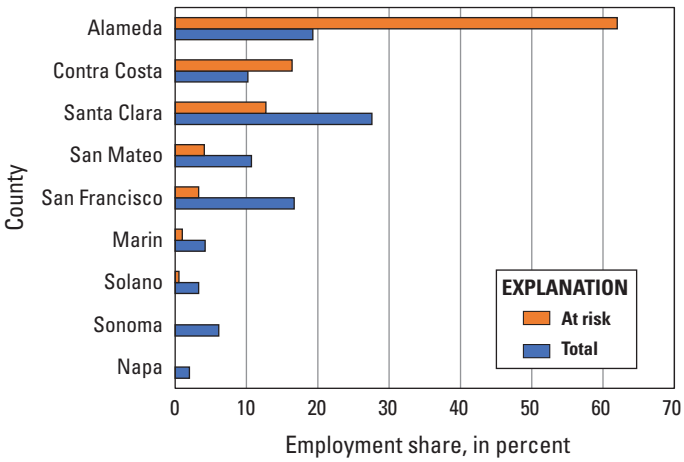


Figure 1. Plot of the total and at-risk employment shares by county for the HayWired scenario mainshock earthquake in the San Francisco Bay region, California. Risk pertains to disruptive building damage from earthquake hazards and fire but does not include utility and transportation system impacts.

Disruptive Building Damage Risk by Business Characteristics

Both business establishment and employment at risk portray the following results for business characteristics affected by disruptive building damage from all hazards.

1. The risk of disruptive building damage from earthquake hazards could be greatest for businesses in the construction and manufacturing sectors. When fire hazards are included, mining and education could slightly surpass these sectors for the greatest risk of disruptive building damage (fig. 2). Businesses belonging to the agriculture/forestry/fishing/hunting and utility sectors show the lowest risk of disruptive building damage (relative to the number and size of establishments in those sectors) because of their more distant locations from the epicenter of the earthquake (for example, almost half of utility sector employees are employed in San Francisco County). However, when separated out by county, even these relatively low-risk sectors in Alameda County are at substantially greater risk of disruptive building damages than even the largest risk sectors for the San Francisco Bay region as a whole. The risk is accentuated further in subareas (appendix 4); as much as 57 percent of employment (in public administration) and 50 percent of establishments (in construction) could be at risk of disruptive building damage in central Alameda County.

2. For the most part, businesses in different size categories have similar risks of disruptive building damage. However, the largest businesses (500 or more employees) show a slightly lower level of risk, as shown in figure 3, because San Francisco and Santa Clara Counties have larger shares of large businesses and lower building damage risk. Overall, this means that smaller sized businesses may not be disproportionately damaged but are susceptible to the vulnerability of their size, as seen after prior disasters.

3. The disruptive building damage risk is distributed fairly evenly by establishment age (fig. 4) and the results reflect the greater risks in Alameda County, However, this does not suggest that risks and problems are evenly spread among firms of all ages. Firms may experience differential responses to disaster, as found by previous researchers (see discussion above).

4. The lowest revenue businesses (less than $100,000) are slightly more likely to be at risk of disruptive building damage, relative to all other revenue categories, but the differences are quite small (see fig. 5). This implies that riskier buildings may house a disproportionate share of businesses that have a lower revenue base overall to cope with the disruptive event. Contrary to the regional result, the percentage of employment shares of high-revenue businesses affected by disruptive building damage is larger in Santa Clara County when compared to other counties in the region. This is because Santa Clara County hosts more businesses in the largest revenue category compared to the other counties.

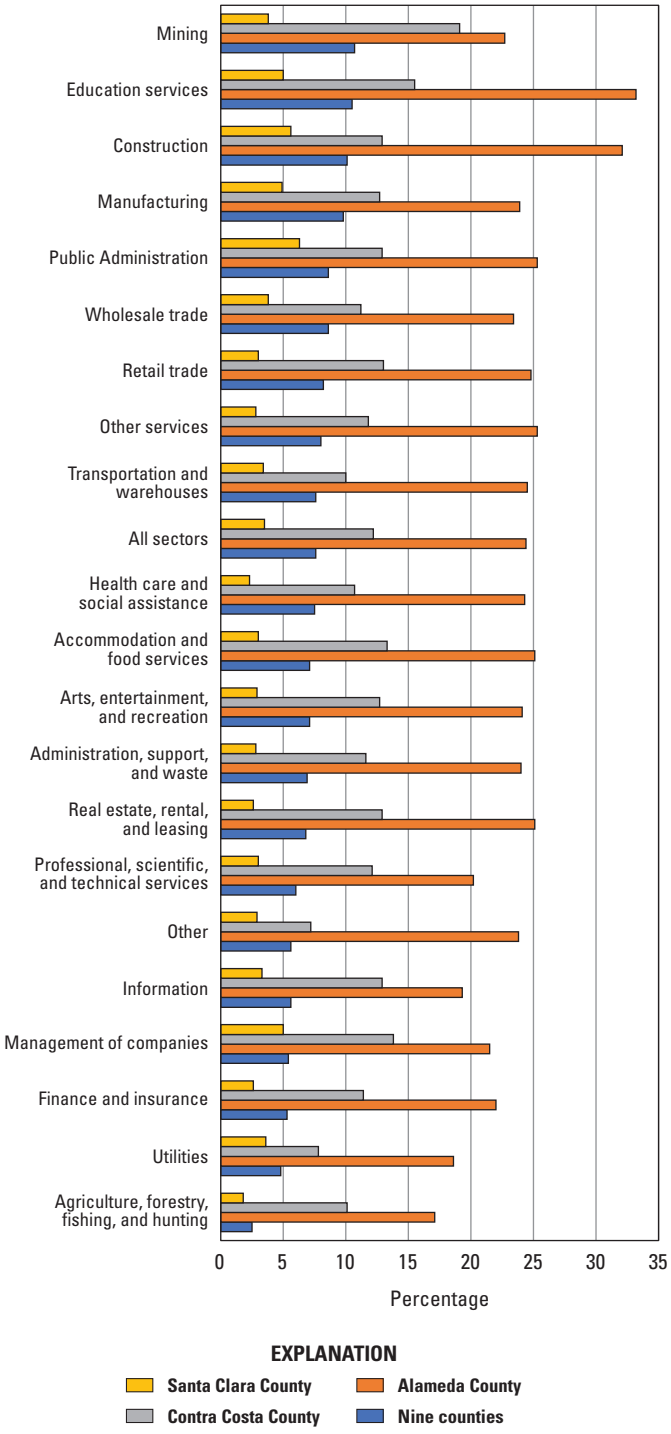


Figure 2. Plot of at-risk employment share by industry sector for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for the three riskiest counties (Santa Clara, Contra Costa, and Alameda Counties) and the total sector employment in the nine-county region. Data are ordered by decreasing risk to all counties (from top to bottom). The impacts of fire in the HayWired scenario are included, but utility and transportation system impacts are not.

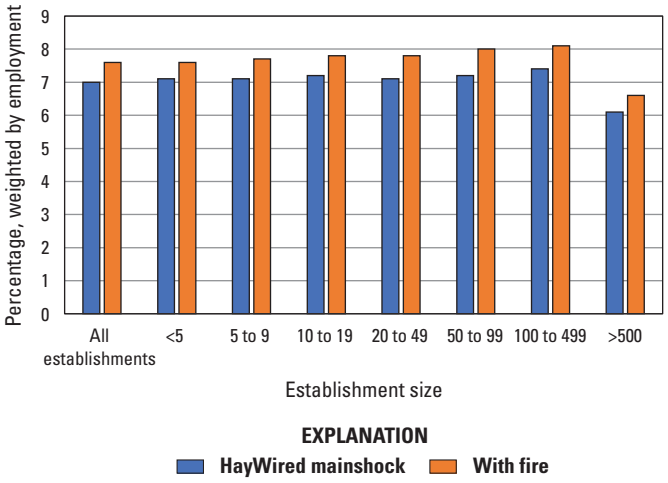


Figure 3. Plot of at-risk employment share by establishment size (number of employees) for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for scenarios with and without fire following the earthquake. The analysis is relative to the total for the nine-county region, excluding damage beyond the bay region. Utility and transportation system impacts are not included.

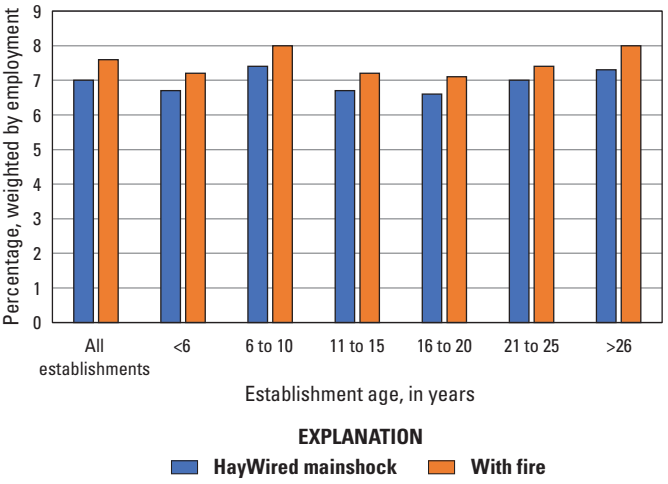


Figure 4. Plot of at-risk employment share by establishment age for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for scenarios with and without fire following the earthquake. The analysis is relative to the total for the nine-county region, excluding damage beyond the bay region. Utility and transportation system impacts are not included.

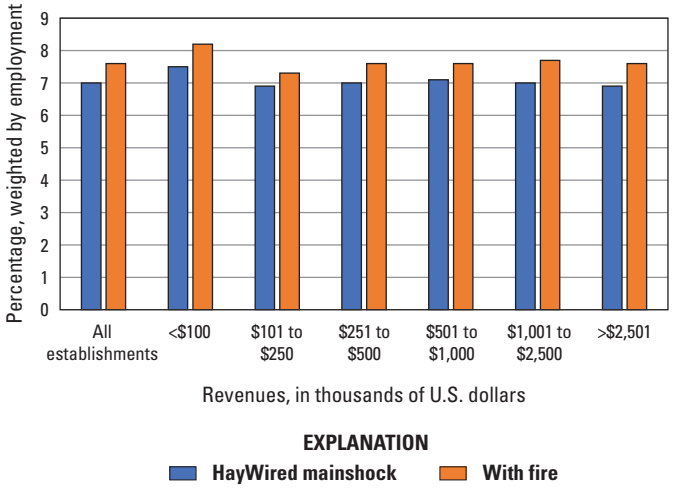


Figure 5. Plot of at-risk employment share by establishment revenue for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for scenarios with and without fire following the earthquake. The analysis is relative to the total for the nine-county region, excluding damage beyond the bay region. Utility and transportation systems impacts are not included.

5. Disruptive building damage risk by business ownership characteristics differ marginally from the overall ownership profile of establishments in the region. Minority-owned businesses are at a slightly greater risk of disruptive building damage—over 9 percent, compared to 6 to 8 percent of all establishments and non-minority-owned establishments (fig. 6). This is because relatively more minority-owned establishments are located in the most heavily impacted county, Alameda County (4.6 percent of establishments and 7 percent of employment), and the sectors to which these businesses belong experience larger risk of disruptive building damage. We see relatively more minority-owned businesses in the manufacturing, wholesale trade, and transportation and warehouse sectors, which sustain more disruptive building damage risk. Whereas some research has shown minority-owned establishments to be more vulnerable than other businesses, we should not assume this is necessarily the case in the San Francisco Bay region, as many successful start-ups in the region are minority owned.

6. There are relatively more employees in branches in Alameda and Contra Costa Counties and branch businesses in the region are at a slightly greater risk of disruptive building damage based on their location and building type (fig. 7). These businesses may be resilient in the short term as relates to company survival because they may have other options for production outside of the area or be able to reestablish supply networks more quickly. Contrary to regional results, Santa Clara County has a larger share of headquarters that have a slightly greater risk among all establishment types.

The regional average disruptive building damage risk for all business and owner characteristic categories that have above-average risk is shown in figure 8. Note that the risks for earthquake hazards and all hazards are averaged in two ways: the average across business establishments and a weighted (by employment) average of business establishments. Overwhelmingly, the risk of disruptive building damage from HayWired earthquake hazards and fire befalls at least 25 percent of the business establishments in Alameda County and 12 percent of establishments in Contra Costa County. Within subareas, the average building risk rises to about 40 and 35 percent in central Alameda County and western Contra Costa County, respectively (appendix 4). For Alameda and Contra Costa Counties and most of the other characteristics in figure 8, the risk is larger for establishments than employment—meaning that relatively fewer employees are in the riskier buildings in this earthquake scenario. An exception is in the mining sector (albeit represents a very small share, 0.08 percent, of the region's employment), where employment-related risk (about 10 percent) is noticeably larger than establishment risk (about 7.5 percent).

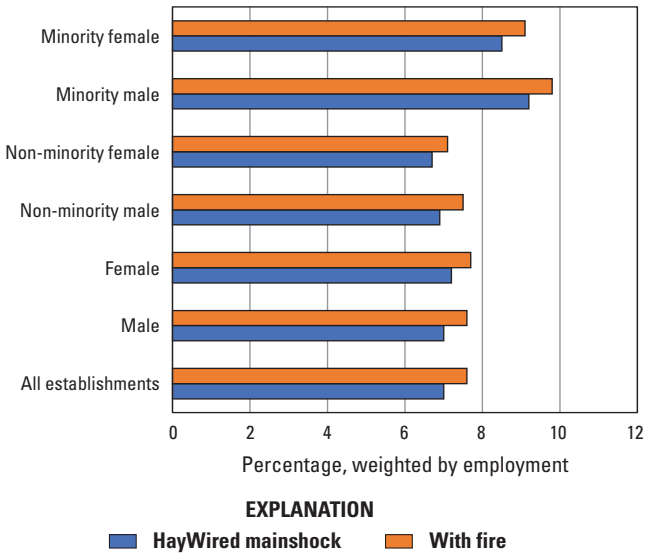


Figure 6. Plot of at-risk employment share by business-owner demographics for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for scenarios with and without fire following the earthquake. The analysis is relative to the total for the nine-county region, excluding damage beyond the bay region. Utility and transportation system impacts are not included.

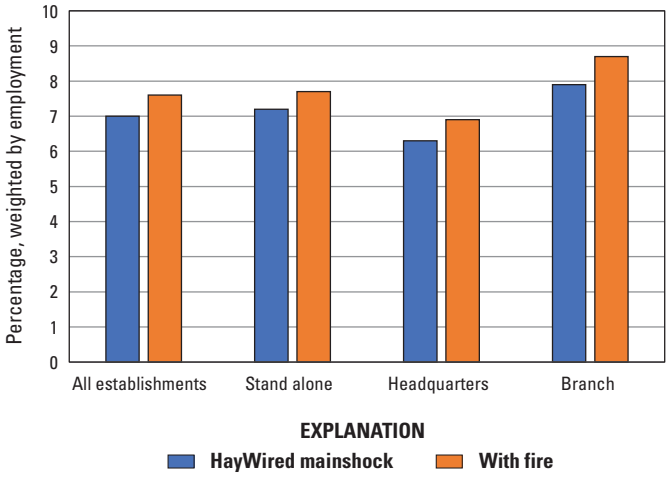


Figure 7. Plot of at-risk employment share by establishment type for the HayWired mainshock earthquake scenario in the San Francisco Bay region, California. Data are shown for scenarios with and without fire following the earthquake. The analysis is relative to the total for the nine-county region, excluding damage beyond the bay region. Utility and transportation system impacts are not included.

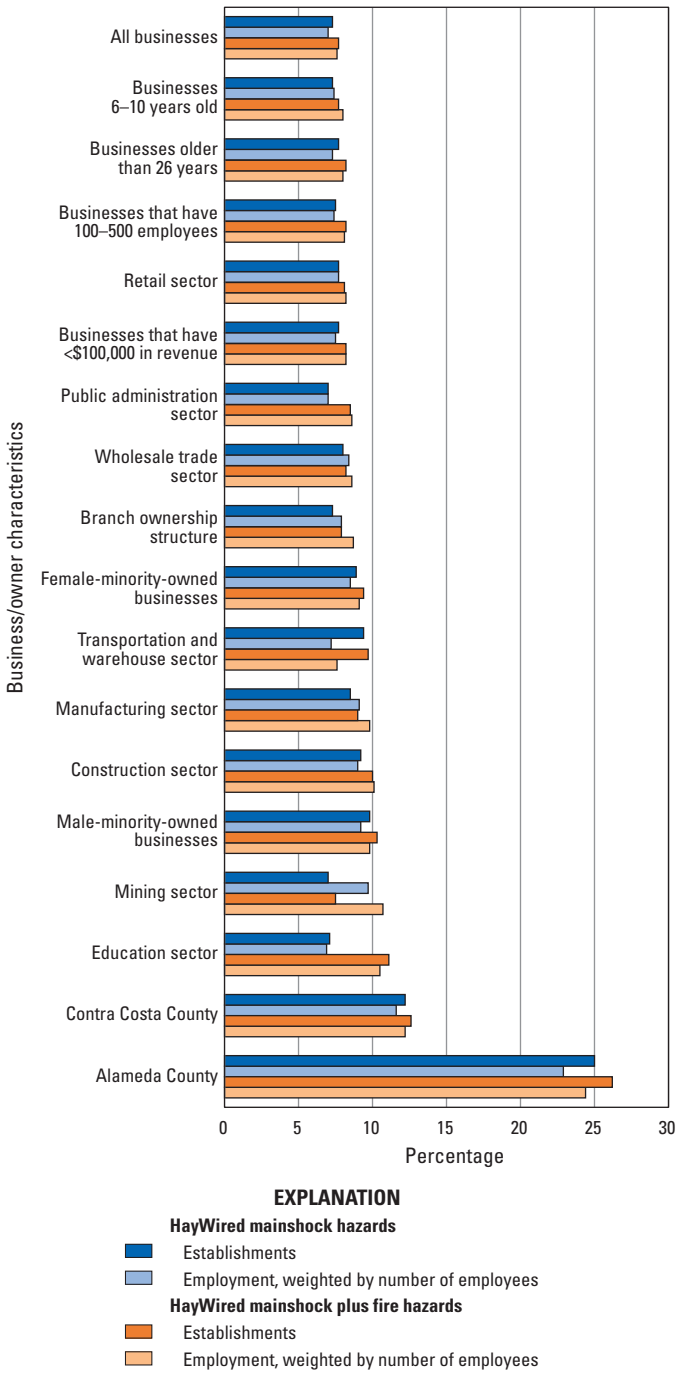


Figure 8. Plot of the business characteristics with the largest disruptive building damage risk in the HayWired scenario in the San Francisco Bay region, California. Risk is calculated both as percentage of establishments and percentage of employment with disruptive building damage. Data are shown for hazard scenarios with and without fire following the earthquake. Utility and transportation system impacts are not included.

After location, most of the business characteristic categories that have larger disruptive building damage risk in the region are sectors reflecting the performance of the building types they occupy and the geographical distribution of employment in those sectors. Integrating location and sector, the largest disruptive building damage risk for the HayWired mainshock earthquake all-hazard case are for establishments and employees working in construction in Alameda County (affecting about 32 percent of those employees and 35 percent of those establishments from earthquake hazards alone) (tables 2.25 and 2.31 of appendix 2). Mining is the industry at most risk of disruptive building damage in Contra Costa County, showing 16–19 percent risk to mining establishments and employment (fig. 2), although this industry is very small in the bay region. The disproportionate effect of fire damage in Alameda and Contra Costa Counties on the education sector is evident in the increased establishment risk from 7 to over 10 percent.

Minority-owned businesses, particularly male-minority-owned businesses, have larger disruptive building damage risk compared to businesses with different owner demographics. Other business characteristics featured in figure 8 pertain to size (smallest revenue or mid-sized businesses) and age (businesses 6–10 years old), but the differences in these average characteristic risks in the region are negligible.

Study Limitations

Our analysis is limited to data tracked by NETS and to building damages as the only source of disruption. Some discrepancies in the NETS database were identified in the method section. The NETS data do not measure some characteristics that have been found to differentiate business vulnerability, such as owner experience in the industry, business experience with disruption and disasters, owned versus leased premises, market reach, or home-based businesses. The data in NETS on establishment pre-disaster performance were also not adequate for this analysis.[14] Age of business, which is analyzed in the data, may act as a partial proxy for some of these or related characteristics (such as experience in the industry and long-term performance).

The resolution of Hazus building data at the census-tract scale does not match the available business data by establishment. Future work could more tightly associate building damages to business establishment data and results could be sensitive to increasing the resolution of the damage estimation. Building data is captured by UrbanSim (http://www.urbansim.com), but crosswalks between Hazus damage estimation to the buildings

[14]We considered two other variables in the NETS data that we thought might indicate the condition of the business prior to disaster. We found the establishment-based payment performance (PayDex)—how quickly bills are paid—to be a useful statistic. The SalesGrowthPeer data could have been useful, but are considered unreliable. In both cases, there were too many missing entries in the database.

would be needed. Current efforts to develop tools that increase the resolution of damage estimates to buildings within census tracts (for example, those by SimCenter, available at https://simcenter.designsafe-ci.org/research-tools/pbe-application) would avoid introducing errors from the crosswalks.

The building damage state results are estimated using Hazus (Seligson and others, 2018) and a distribution of burned building square footage (Scawthorn, 2018) to occupancy classes using 1994 Northridge earthquake fire data (see appendix of Johnson and others, this volume). Hazus representation of construction offices as manufactured buildings and fires in school laboratories after the Northridge earthquake are influencing the results for the HayWired scenario.

By only considering disruptive building damage, we underestimate the risk of business disruption from concentrations of damage in neighborhoods. Neighborhood damage and home-to-workplace relation effects are examined by Wein, Belzer, and others (this volume). Their study uses subareas, defined by contiguous city boundaries, containing census tracts with concentrated building damages. We also calculate disruptive building damage risk for subareas using the Hazus building damage and NETS data; results are available in appendix 4.

Utility outage geographies are not analyzed here. Dahlhamer and Tierney (1998) called attention to effects of utility disruptions and Kachali and others (2015) also identified them as a significant factor impacting organizations in Canterbury, New Zealand, after the 2011 earthquakes. Across utilities and transportation, the duration of electric power outages has been found to most adversely affect business productivity (Tierney and Nigg, 1995; Wasileski and others, 2011), and for manufacturing businesses in particular (Kajitani and Tatano, 2009). Brown and others (2014) noted that 30 percent of businesses were able to operate without power, water, and (or) wastewater services at their site for short durations or by relocation, such that businesses tended to underestimate their ability to operate without these services. Various utility restoration curves are available by county for the HayWired scenario (see Jones and others, this volume). Utility and transportation disruptions include initial widespread electrical power outages, days to weeks of disrupted voice and data services, months of water supply outages in Alameda, Contra Costa, and San Mateo Counties, months of highway bridge repairs, and years of rapid transit service disruptions along the east bay corridor.

Policy Discussion and Conclusion

In conclusion, we consider the implications of our results in conjunction with what is known about business vulnerability after a disaster, as well as policy and program ideas and implementations that can influence business outcomes. Here, we consider findings for business location and various sectors that show the largest disruptive building damage risks. We also discuss characteristics that were found to be associated with vulnerable establishments in previous disasters, such as small businesses and various business-owner characteristics.

Risk from Business Location

First and foremost, location (primarily Alameda County and secondarily Contra Costa County) most strongly differentiates disruptive building damage risk for all types of businesses. Many of the programs and resources developed to address post-event impacts of the earthquake and related issues in the San Francisco Bay region would need to be centered in the areas of greatest impact, but also cannot disregard the range of impacts to and needs of businesses outside the high-damage zones. Preparatory actions, however, should be widespread, because the HayWired scenario is only one of many possible earthquakes that could affect the bay region.

Sector Risk and Vulnerability

Large disruptive building damage risk reflects low-performing building types that certain industries tend to occupy and the concentration of certain industries in heavily impacted areas. In the HayWired scenario, these industries are manufacturing, transportation and warehousing, wholesale and retail, construction, and education (caused by fire only). Although employment-weighted risk in the mining sector is relatively large, we do not draw any conclusions for this small sector of a few thousand employees.

Marshall and others (2015) propose targeting businesses in the goods sectors (that have fixed assets, such as equipment and inventory) with pre-disaster assistance. Post-disaster, manufacturing businesses with disruptive building damage may be more difficult to relocate in the region. There could be larger risk of long-term displacement from property owners that choose to rebuild to a higher value use (see Wein, Belzer, and others, this volume). Although manufacturing has tended to recover in the wake of reconstruction, establishments may not remain in devastated areas. The region's proposed Priority Production Area program (see Kroll and Jaramillo, 2017) could include pre-disaster planning for preserving space for critical industries. Coordinated economic development in the most heavily impacted areas also may be needed to provide a viable business base after the event.

The large presence of the transportation and warehouse sector in Alameda County leads to a larger risk of disruptive building damage for the sector in the region, particularly for establishments (as opposed to where the employees work). The establishments are important to supply networks. The public sector will need to work cooperatively with private logistics firms to ensure the delivery of necessary emergency supplies at the outset, to ease supply bottlenecks for local producers during recovery, and to maintain pathways for distributing final products. Growing automation in the sector and the use of drones and autonomous delivery equipment (for example, electric carts) may provide an opportunity for supporting supply networks to residents and businesses in the region. Advanced planning would be needed to ensure this type of equipment is licensed to operate in a post-earthquake setting and to establish enough redundancy in logistics operations to adapt to areas with downtime. However, even if this approach addresses the

delivery problem around damaged roadways, stored goods will be lost on damaged sites and logistics functions may be disrupted or require relocation.

Wholesale and retail businesses fairly consistently show vulnerability after disasters. In the HayWired scenario, retail has both larger disruptive building damage risk and a contingent of small businesses (see below). Retail businesses have not emerged as vulnerable when there has been local government intervention, for example, to provide a space for businesses to congregate near their customers (for example, Kroll and others, 1990) or (government-funded) employee subsidies after the 2011 Christchurch earthquake. Assistance of this type may be particularly critical where damage is extensive and widespread.

The presence of small businesses in the construction sector (33 percent of the construction sector's employees are in businesses that have less than 5 employees) potentially compounds the vulnerability of these types of businesses with disruptive building damage. Although, construction businesses could benefit from rebuilding, Zhang and others (2009) caution that many of the smaller, local contractors miss out on reconstruction when they are still recovering themselves, are unable to take on large jobs, or both. Pre-registration of construction firms and coordination of programs to help in business recovery and to encourage the use of local firms in reconstruction could help local construction firms survive the challenges posed by the damage.

Fire increases the risk for all sectors, but disproportionately affects education. The effect on the education sector is an artifact of the 1994 Northridge fire-following-earthquake data that was used to distribute burned buildings for the HayWired scenario. Reportedly, school laboratories were the source of fires in schools. Safety management of hazardous materials can address how materials are stored and how to best separate materials to prevent potentially volatile mixtures in earthquake-prone areas.

Small Business Vulnerability

Small businesses are a significant source of local employment and add to the economic vitality of a community (Zhang and others, 2009). Our business type analysis showed that the largest businesses (500 or more employees) are somewhat less likely than businesses with 500 or fewer employees to be located in the riskiest locations or building types in the HayWired scenario. The literature (summarized in the "Literature on Business and Owner Characteristics" section) suggests that among businesses where damage occurs, those with less than 50 employees are more likely to close, perhaps because they are less diversified in locations and lack assets and financial cushions to allow for recovery. However, small businesses also may be more flexible in terms of response alternatives, providing opportunities to maintain or grow the business after a disaster.

In the NETS database, businesses that have fewer than 50 employees make up 98 percent of establishments and have 60 percent of the employees in the San Francisco Bay region; half of those employees work in establishments that have less than 5 employees. Another measure of business size is revenue: 33 percent of establishments and 10 percent of employment are in the lowest revenue category (<$100,000).

In the bay region, small businesses account for a large share of administration, support and waste, and other services sectors (99.6 percent of sector establishments have less than 50 employees). The largest numbers of small businesses in the bay region are in these two sectors plus the professional, technical, and scientific services sector. The businesses in professional, technical, and scientific services show a slight advantage of lower disruptive building damage risk from the HayWired scenario because the industry is more concentrated in office buildings on the San Francisco Peninsula (as opposed to the east bay, which is closer to the Hayward Fault). They could benefit from increased demand for engineering, accounting, and legal services (for example, Recover Canterbury, n.d.), and they could have more mobility and flexibility for working from home. Lister (2017) reports that the professional, scientific, and technical service sector has the largest percentage of telecommuters, corroborating the mobility of the assets in this service sector.

Small business revenue vulnerability would be compounded by disruptive building damage in Alameda and Contra Costa Counties. For the region, businesses in the lowest revenue category are among those with slightly larger disruptive building damage risk. Small Business Administration loans that increase debt are not likely to be attractive or obtainable (because of restrictive criteria) by low-revenue businesses (Collier and others, 2016). Lam and others (2012) conclude that small businesses need assistance within 6–9 months of disruption. Business recovery funding gaps (for small and young businesses, in particular) require small, rapidly deployed loans and grants to provide a bridge for small businesses between the time when a disaster strikes and when State and Federal funds first become available, as well as after they are no longer available (Collier and others, 2016; Federal Reserve Banks, 2017).

Research has found that small business owners may not know what can be done to prepare for earthquakes. Alesch and others (2001) identify business management practices to reduce business exposure and vulnerability to disaster. These include diversifying the organization's customer base, diversifying the location of the organization's inventory, protecting organizational electronic and hard-copy data, and having multiple business outlets (for example, multiple locations and [or] e-commerce). More recently, the effects of Hurricane Sandy underscored that computer system and document/file recovery were most costly and time consuming for small businesses (Scarinci, 2016). Regarding building and content risk, insurance helps to protect equity and lease arrangements can be checked for repair responsibility and timing. Other considerations include coping with psychological stress, entrepreneurial skill to adapt to changes in the business environment, and support from family, friends, and employees.

Preparedness planning and testing is seen to decrease with business size (Scarinci, 2016). Small business preparedness actions tend to be limited to safety (for example, acquiring first aid kits) and fall short for business continuity (for example, relocation plans, generators for emergency power, training and drills, and structural assessment) (Webb and others, 2000). The actions that small businesses take are less complicated, less expensive, and protect against a range of emergencies rather than actions that are technically difficult, more expensive, and time consuming (Webb and others, 2000). Lindell and others (2006) promote the need for policies, such as incentives, that encourage small businesses to engage in emergency planning. Marshall and others (2015) add that policies intended to reduce small business demise should concurrently consider the interrelatedness of family needs, demands, and resources with those of the affected business. Overall, Marshall and others (2015) propose that small business vulnerability be mitigated with policies that target the characteristics of small businesses that make them vulnerable.

Business Owner Vulnerability

Minority-owned businesses are associated with slightly larger disruptive building damage risk in the HayWired scenario. The risk for minority-owned businesses is a reflection of the concentration of minority-owned businesses in Alameda County relative to the rest of the bay region and relatively larger representation in manufacturing and wholesale trade sectors. This illuminates the proposal of Marshall and others (2015) for policy support and educational assistance for disaster preparedness that targets minority-, female-, and veteran-owned business. They note that, even though the Small Business Administration has targeted disaster programs for these groups, more awareness and education may be necessary. Given limited resources, one approach may be to intensify outreach to small businesses in sectors with greater building occupancy type vulnerabilities.

Other Vulnerable Business Characteristics

The risk of disruptive building damage is strongly differentiated by location relative to the earthquake, and secondarily by sector according to building performance. We found slight differences in the risk for other business characteristics, but the vulnerability still remains for those businesses located in riskiest locations and building types. Just because our methodolgy could not support analyses of other potentially vulnerable business characteristics does not mean they are unimportant. Other considerations from the literature pertaining to disruptive building damages include:

- Leased business spaces. The business owner is subjected to the building owner's decisions about rebuilding, affecting business relocation planning, especially for single-location businesses. Education of commercial building owners on the likely needs and possible services to offer tenants after an event could reduce tenants' vulnerability.
- Owner resilience and prior disaster experience. Businesses whose owners lack this kind of experience may be more vulnerable. Targeted education and shared experiences from those with prior disaster experience could assist inexperienced business owners to become more informed and better prepared.
- Businesses in decline can have that trend exacerbated by a disaster and may need additional business and financial planning assistance to make decisions about whether to continue the business after the event.
- Business culture may affect business vulnerability—this topic has not been explored in this chapter.

Finally, recall that direct building damage is only one source of business disruption. Vulnerable business characteristics are relevant to other sources of disruption, such as utility outages. Wein, Belzer, and others (this volume) consider how businesses are impacted by damages in their neighborhoods. Business establishments without strong support systems (for example, sole proprietorships and [or] dependence on a displaced customer base) will be particularly vulnerable regardless of the sector, business age, business size, or business-owner characteristics. Policy development can consider how to coordinate programs to address geographical, sectoral, and other vulnerable characteristics of establishments and firms.

Turning Risk into Opportunity

Stronger buildings and codes directly reduce disruptive building risk. Interorganizational arrangements and programs present opportunities to improve business preparedness and recovery. With the widespread distribution of risk across firms of small, medium, and large sizes, preparedness and resources will vary in the region. Programs like the California State-led Outsmart Disaster Business Resilience Challenge (visit https://outsmartdisaster.com/be-resilient/at-work/resilient-business-challenge for more information), which grew out of the HayWired scenario, encourages businesses to take the next challenge to "outsmart disaster"—whether it be at a business level, collaboration with their community, or demonstration of innovative practices for businesses in the State. Outsmart Disaster encourages larger businesses to look beyond themselves and provide preparedness assistance to the smaller neighborhood businesses on which they depend. In support of this incentive, Dunaway and Shaw (2010) found that participation in a collaborative partnership was correlated with motivation to prepare. Post-disaster, Aldrich (2012) makes the case for the role of social capital. After the 2014 South Napa earthquake, the tight-knit small business community in the City of Napa lent support to each other, and the community as a whole rallied to provide financial support to businesses in need (Almufti and others, 2016). Stevenson and others (2014) document how organizations managed and utilized networks to reduce the impacts of the Canterbury earthquake

sequence (2010–14) and to adapt to altered post-earthquake environments. For example, similar and competitive businesses assisted each other by sharing functional space.

Zhang and others (2009) promote coordination between business and local government regarding exchanges of information about hazards, business buildings and structures, employees, business linkages, and response and recovery needs. For example, the 2018 California Assembly Bill AB–2681 sought to require local communities to inventory potentially vulnerable buildings. Although the bill was vetoed by the governor, some cities in the bay region are already creating such inventories. For those communities that have inventoried vulnerable buildings, it might help to also inventory the uses of those buildings (for example, commercial versus residential) and to understand if specific business types or sectors are concentrated in vulnerable buildings and to plan for potentially disruptive building risk. Local government can plan for temporary business locations, restoring transportation and utility systems, expediting building inspection and permitting, and other support for local businesses facing external competition (Zhang and others, 2009).

Recovery funding for small businesses is an innovation opportunity in community development (Collier and others, 2016; Federal Reserve Banks, 2017). Beyond suggestions to make changes to the Small Business Administration loan policy (Collier and others, 2016), cross-sector and cross-agency collaboration can support and guide small businesses by providing individualized small business risk assessments and a small grant to help implement recommendations (for example, adequate insurance coverage, digitizing records, or adding a generator) (Federal Reserve Banks, 2017). Small businesses could be incentivized to become eligible for post-disaster funding that fits their needs during the critical time periods by implementing preparedness actions (Collier and others, 2016).

Doerfel and others (2013) find, more generally, that resource-vulnerable businesses exhibit diverse interorganizational relations that are associated with low resilience after a disaster because the relations lack redundancy. Post-disaster, Doerfel and others (2013) suggest that businesses can increase resilience (access to resources and information) by building pre-disaster interorganizational relations. Examples include building communities of practice (for example, professional associations, similar types of business functions), establishing relations with cross-community entities (that is, suppliers, clients, different types of businesses, banks, endowment or funding sources, nonprofits, and city government), and having multiple ties with each type of these supporting organizations. Scarinci (2016) reports that new small business alliances developed after Hurricane Sandy helped businesses by facilitating the sharing of information and resources and assisting with loan applications. Based on the finding of inhibited learning after a disaster, implementing programs for small business preparedness with recovery resources and assistance could improve business resilience from its pre-disaster state.

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Appendixes 1–4

Appendix 1. Crosswalk between Hazus Occupancy Classes and NAICS Categories

In order to evaluate risk to San Francisco Bay region businesses, we needed to first convert results for Hazus occupancy classes to results for North American Industry Classification System (NAICS) codes. Risk values have been estimated using Hazus for occupancy classes. The following table provides a mapping to translate those risks to NAICS codes. The table lists the NAICS code and the equivalent Hazus occupancy class (Federal Emergency Management Agency, 2002).

A single NAICS code may map to several Hazus occupancy classes. In this case, a new Hazus occupancy class is created that combines the several classes in the mapping. The new combined occupancy class is created simply by adding together the total and extensive and complete damaged square footage in each class for the geographic unit. The sum of the extensive complete damage square footage is then divided by the sum of the total square footage.

Table 1.1. Mapping of NAICS codes to Hazus occupancy classes.

[Table derived from Sue Wing and others (this volume). NAICS, North American Industry Classification System]

Sector description	NAICS code[1]	Hazus occupancy class
Agriculture, forestry, fishing and hunting	11	AGR1
Oil and gas extraction	211	IND4
Coal mining	2121	IND4
Other mining	212–213 except for 2121	IND4
Electric power generation, transmission, and distribution	2211	COM4
Natural gas distribution	2212	COM4
Water, sewage, and other systems	2213	COM4
Construction		IND6
Heavy industry	313, 321, 322, 327, 332, 333, 336	IND1
Light industry	314, 315, 316, 323, 326, part of 334 (except for 334111, 334112, 334411, 334412, 334413), 335, 337, 339, 511, 516	IND2
Petroleum refineries	32411	IND3
Food, drug, and chemicals	311, 312, 324 except for 32411, 325	IND3
Primary metal manufacturing	331	IND4
Electronic computer manufacturing	334111	IND5
Computer storage device manufacturing	334112	IND5
Semiconductor and related device manufacturing	334413	IND5
Other high-technology-related manufacturing	334411, 334412	IND5
Wholesale trade, warehousing, and storage	42	COM2
Retail trade	44–45	COM1
Air transportation	481	COM4
Rail transportation	482	COM4
Water transportation	483	COM4
Truck transportation	484	COM2
Transit and ground passengers	485	COM4
Pipeline transportation	486	COM4
Sightseeing transportation	487 and 488	COM4
Couriers and messengers	492	COM4
Publishing, motion picture, and broadcasting	511, 512, 515	IND2, COM4
Internet publishing and broadcasting	51913	COM4
Telecommunications	517	COM8
Data processing, hosting, and related services	518	COM4
Other information services	51911–2	COM4
Finance, insurance, real estate, and leasing	52, 53	COM4, COM5
Computer systems design and related services	5415	COM4
Other professional scientific and technical services	54 except for 5415	COM4
Other business services	55, 56	COM4
Educational services	6111, 6112–3, 6114–7	EDU1, EDU2
Ambulatory health care and hospitals	621, 622	COM6, COM7
Nursing home/social assistance	623, 624	RES6, COM3
Arts, entertainment, and recreation	711–713, 722	COM8
Accommodations	721	RES4
Repair and maintenance	811	COM3
Personal services/private households	812, 814	COM3
Religious, grantmaking, and similar organizations	813	REL1
Government and non-NAICS	92	GOV1, GOV2

[1]See the NAICS website (available at https://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2017) for examples of establishments in the various NAICS sectors.

Appendix 2. Building Damage Risk Results for the HayWired Scenario, San Francisco Bay Region

This appendix contains four sets of tables of HayWired building damage risk for business characteristics in the San Francisco Bay region with respect to the sector to which the businesses belong. The four sets pertain to two different ways of calculating the risk: (1) average across establishments and (2) employment weighted average; risk is also calculated for two different sets of extensive and complete (disruptive) building damages: (1) from earthquake hazards only (no fire) and (2) from earthquake plus fire hazards. Within each set, business characteristics are summarized by county, business size, revenue, ownership structure, and owner demographics. There are two tables for each characteristic; the first table presents risk calculations and the second table shows the distribution of establishments or employees in the categories of interest. The business distribution table is not repeated for fire hazard risk (third and fourth sets) because the distribution of business characteristics stays the same.

Disruptive Building Damage Risk from Earthquake Hazards for Establishments in the HayWired Scenario

Table 2.1. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by county and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments in 9 counties	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	3.2	17.8	9.8	0.7	0.0	1.5	1.4	2.1	0.0	0.0
Mining	7.0	27.7	16.3	1.0	0.1	1.3	4.5	3.0	0.2	0.0
Utilities	4.5	19.1	10.0	0.9	0.0	1.6	1.8	2.7	0.1	0.0
Construction	9.2	33.3	14.2	1.0	0.0	1.3	2.2	3.8	0.2	0.0
Manufacturing	8.5	27.1	13.3	1.1	0.0	1.9	2.9	3.8	0.3	0.0
Wholesale trade	8.0	25.5	11.4	1.0	0.0	1.8	2.5	3.0	0.2	0.0
Retail trade	7.7	25.2	12.7	0.9	0.0	1.4	2.2	2.7	0.3	0.0
Transportation and warehouses	9.4	25.8	11.9	1.1	0.0	1.6	2.2	3.0	0.2	0.0
Information	6.7	23.9	13.8	0.9	0.0	1.5	2.4	2.4	0.2	0.0
Finance and insurance	6.2	24.0	11.1	0.9	0.0	1.3	2.3	2.2	0.2	0.0
Real estate, rental, leasing	7.2	25.2	11.5	1.0	0.0	1.3	2.2	2.3	0.2	0.0
Professional, scientific, and technical services	6.7	23.0	12.1	0.9	0.0	1.4	2.2	2.4	0.2	0.0
Management of companies	6.1	21.8	12.7	0.9	0.0	1.3	2.1	2.2	0.3	0.0
Administration, support, and waste	6.6	24.2	11.7	0.8	0.0	1.1	1.9	2.2	0.1	0.0
Education services	7.1	22.2	11.5	0.9	0.0	1.2	2.2	2.1	0.4	0.0
Health care and social assistance	7.1	23.8	11.8	0.9	0.0	1.0	1.8	2.1	0.3	0.0
Arts, entertainment, and recreation	7.5	25.3	13.1	0.9	0.0	1.3	2.1	2.3	0.2	0.0
Accommodation and food services	7.3	24.8	13.0	0.8	0.0	1.3	1.9	2.7	0.4	0.0
Other services	7.6	24.8	11.5	1.0	0.0	1.3	2.2	2.3	0.4	0.0
Public administration	7.0	20.7	12.7	0.7	0.0	1.7	2.1	3.8	0.5	0.0
Other	5.6	21.0	7.9	0.7	0.0	1.3	1.8	2.3	0.0	0.0
Total	7.3	25.0	12.2	0.9	0.0	1.3	2.1	2.5	0.2	0.0

Table 2.2. Distribution of establishments (in percent) in the San Francisco Bay region, California, by county and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	5,002	9.7	10.2	5.2	13.8	5.2	7.1	14.1	7.7	27.1
Mining	240	12.1	14.2	7.9	0.8	13.8	11.7	21.3	7.5	10.8
Utilities	596	11.6	11.2	6.4	2.0	18.8	13.4	22.5	2.9	11.2
Construction	45,328	17.1	15.6	5.8	2.5	9.9	11.5	22.0	5.1	10.4
Manufacturing	20,899	20.9	9.0	4.3	3.7	10.6	10.1	29.7	3.1	8.7
Wholesale trade	23,316	21.4	11.4	4.8	3.7	13.1	10.5	23.0	3.7	8.3
Retail trade	43,904	20.1	12.3	5.1	2.5	15.0	9.7	22.1	5.0	8.2
Transportation and warehouses	9,938	25.7	13.6	3.4	2.1	9.8	14.6	18.8	5.8	6.1
Information	15,155	17.5	9.4	7.1	1.2	20.0	10.5	26.2	2.7	5.4
Finance and insurance	25,675	14.8	13.8	6.4	1.4	16.9	12.3	26.0	3.0	5.4
Real estate, rental, leasing	25,765	17.9	14.1	5.7	1.8	14.2	11.1	24.1	4.4	6.7
Professional, scientific, and technical services	92,391	17.7	12.6	6.7	1.6	16.9	10.2	25.0	3.0	6.1
Management of companies	1,701	15.3	12.7	5.4	1.2	22.9	12.6	22.6	2.9	4.3
Administration, support, and waste	113,786	16.6	13.1	5.8	1.8	12.5	10.9	27.8	4.5	6.8
Education services	9,802	21.4	12.0	6.1	1.8	13.8	9.7	24.8	3.7	6.8
Health care and social assistance	47,398	19.9	12.9	5.9	1.8	15.2	9.8	23.7	4.0	6.9
Arts, entertainment, and recreation	11,472	19.4	12.3	7.1	2.3	17.5	8.9	20.0	4.5	7.8
Accommodation and food services	21,452	19.3	10.8	4.3	2.3	21.5	10.1	20.8	4.0	6.8
Other services	55,809	20.5	13.7	4.7	1.9	14.1	10.2	22.8	5.1	7.2
Public administration	587	19.4	13.6	6.1	2.4	15.7	12.1	14.7	6.5	9.5
Other	443	16.3	14.4	4.7	1.6	18.7	9.3	26.0	3.6	5.4
Total	570,659	18.4	12.8	5.7	2.2	14.4	10.5	24.4	4.2	7.4

Table 2.3. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by number of employees and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	3.2	3.4	2.6	1.8	3.1	0.9	1.0	
Mining	7.0	7.1	8.1	4.8	4.0	5.2	13.0	
Utilities	4.5	4.1	3.4	6.0	7.1	8.6	5.5	6.3
Construction	9.2	9.2	9.0	9.0	9.4	9.8	9.8	3.6
Manufacturing	8.5	8.4	8.5	8.2	8.7	9.4	10.1	7.3
Wholesale trade	8.0	7.9	8.3	8.5	8.4	9.4	10.2	5.4
Retail trade	7.7	7.8	7.2	7.2	6.9	7.7	8.1	8.5
Transportation and warehouses	9.4	9.6	8.7	7.9	7.6	6.8	8.1	1.6
Information	6.7	7.0	5.5	6.8	5.1	4.6	6.1	4.7
Finance and insurance	6.2	6.3	5.8	5.5	5.2	5.0	5.2	3.5
Real estate, rental, leasing	7.2	7.2	7.1	7.1	6.8	7.8	5.5	2.4
Professional, scientific, and technical services	6.7	6.8	6.2	6.3	5.6	5.4	4.7	4.1
Management of companies	6.1	6.1	5.6	6.9	4.3	4.8	1.2	4.2
Administration, support, and waste	6.6	6.6	5.6	6.9	7.3	7.1	8.1	6.4
Education services	7.1	7.0	7.3	7.4	7.5	6.3	8.6	5.7
Health care and social assistance	7.1	7.1	6.9	7.5	7.9	8.3	7.2	6.9
Arts, entertainment, and recreation	7.5	7.6	6.9	7.4	5.8	6.5	6.8	6.8
Accommodation and food services	7.3	7.5	7.3	7.2	6.6	6.0	4.2	6.0
Other services	7.6	7.7	7.3	7.3	7.0	5.3	4.5	9.7
Public administration	7.0	6.9	10.4	2.8	4.3	10.7	8.6	4.4
Other	5.6	5.7	5.1	3.3	7.5	1.5		
Total	7.3	7.3	7.1	7.3	7.1	7.2	7.5	5.9

Table 2.4. Distribution of establishments (in percent) in the San Francisco Bay region, California, by number of employees and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	5,002	84.8	8.0	3.9	2.3	0.7	0.4	
Mining	240	68.3	17.1	5.8	5.4	1.7	1.7	
Utilities	596	64.8	13.4	10.7	5.9	2.5	2.2	0.5
Construction	45,328	84.4	7.8	3.9	2.7	0.7	0.4	0.0
Manufacturing	20,899	63.0	15.3	8.9	7.2	2.8	2.4	0.4
Wholesale trade	23,316	76.5	12.2	6.1	3.5	1.1	0.6	0.0
Retail trade	43,904	83.0	10.1	3.9	1.9	0.7	0.3	0.0
Transportation and warehouses	9,938	83.1	8.2	4.2	3.1	0.8	0.5	0.0
Information	15,155	79.7	9.3	4.7	3.4	1.5	1.2	0.2
Finance and insurance	25,675	87.5	6.7	2.9	1.9	0.6	0.4	0.1
Real estate, rental, leasing	25,765	86.9	7.4	3.0	1.8	0.7	0.2	0.0
Professional, scientific, and technical services	92,391	85.4	7.4	3.7	2.3	0.8	0.4	0.0
Management of companies	1,701	94.1	2.9	1.1	1.1	0.4	0.2	0.1
Administration, support, and waste	113,786	95.1	2.8	1.0	0.7	0.3	0.1	0.0
Education services	9,802	57.3	24.0	8.3	6.4	2.7	1.1	0.2
Health care and social assistance	47,398	71.5	20.3	4.6	2.3	0.8	0.4	0.1
Arts, entertainment, and recreation	11,472	79.2	11.8	4.3	2.8	1.4	0.5	0.1
Accommodation and food services	21,452	33.7	37.0	18.5	8.3	1.8	0.7	0.0
Other services	55,809	86.8	8.4	2.9	1.5	0.3	0.1	0.0
Public administration	587	39.0	11.6	9.0	14.8	11.8	11.1	2.7
Other	443	84.2	7.7	4.7	2.7	0.7		
Total	570,659	82.2	9.9	4.1	2.4	0.8	0.4	0.1

Table 2.5. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by establishment age (in years) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across all establishments	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	3.2	4.0	3.6	3.0	2.4	2.2	1.9
Mining	7.0	9.7	5.7	5.1	5.2	7.5	6.6
Utilities	4.5	4.5	5.8	2.4	3.5	3.5	5.9
Construction	9.2	9.5	9.2	9.1	8.4	8.6	8.9
Manufacturing	8.5	8.2	8.3	7.8	8.1	7.9	9.7
Wholesale trade	8.0	7.8	8.1	8.1	8.4	8.0	8.3
Retail trade	7.7	7.7	7.7	7.8	7.1	7.4	8.0
Transportation and warehouses	9.4	10.2	9.5	8.6	7.4	7.1	7.9
Information	6.7	6.7	6.9	6.4	6.9	6.7	7.2
Finance and insurance	6.2	6.1	6.6	6.1	5.9	5.9	6.7
Real estate, rental, leasing	7.2	6.8	7.7	7.5	7.4	7.6	7.0
Professional, scientific, and technical services	6.7	6.7	6.8	6.6	6.7	6.8	6.9
Management of companies	6.1	6.1	6.4	4.6	7.0	7.1	5.7
Administration, support, and waste	6.6	6.6	6.7	6.1	6.5	6.9	7.1
Education services	7.1	7.1	7.2	7.3	7.2	6.7	7.2
Health care and social assistance	7.1	6.9	7.3	7.2	6.9	7.1	7.5
Arts, entertainment, and recreation	7.5	7.7	7.6	6.8	6.8	7.6	7.3
Accommodation and food services	7.3	7.2	7.6	7.3	7.1	6.9	7.2
Other services	7.6	7.3	7.5	7.9	8.1	8.0	8.0
Public administration	7.0	8.1	3.6	8.6	3.7	12.0	6.1
Other	5.6	5.2	4.1	6.6	6.8	7.3	5.7
Total	7.3	7.2	7.3	7.2	7.2	7.3	7.7

Table 2.6. Distribution of establishments (in percent) in the San Francisco Bay region, California, by establishment age (in years) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	5,002	35.8	20.4	13.7	6.7	2.4	21.0
Mining	240	30.8	22.5	13.8	8.8	2.5	21.7
Utilities	596	45.6	17.1	16.1	3.5	1.3	16.3
Construction	45,328	45.3	19.4	9.7	5.4	4.0	16.2
Manufacturing	20,899	28.7	19.8	11.7	9.1	5.3	25.3
Wholesale trade	23,316	41.4	19.2	9.9	7.0	4.6	17.9
Retail trade	43,904	37.1	19.9	11.7	8.3	4.3	18.7
Transportation and warehouses	9,938	47.4	21.2	10.7	5.5	3.2	12.0
Information	15,155	48.6	20.8	13.1	6.9	2.8	7.8
Finance and insurance	25,675	48.8	21.1	12.2	4.8	2.9	10.2
Real estate, rental, leasing	25,765	41.8	19.9	11.5	5.8	3.9	17.2
Professional, scientific, and technical services	92,391	44.8	19.9	11.5	7.5	4.3	11.9
Management of companies	1,701	65.1	23.5	6.4	1.7	0.9	2.4
Administration, support, and waste	113,786	59.2	26.6	8.4	1.9	1.0	2.9
Education services	9,802	45.2	18.9	11.4	6.5	3.5	14.5
Health care and social assistance	47,398	39.3	19.3	11.7	7.6	5.3	16.7
Arts, entertainment, and recreation	11,472	44.5	20.2	12.1	6.8	3.4	13.1
Accommodation and food services	21,452	35.6	20.5	11.4	8.9	5.0	18.5
Other services	55,809	40.4	18.1	12.0	7.1	4.2	18.2
Public administration	587	43.8	6.6	6.8	3.7	2.2	36.8
Other	443	43.8	14.9	36.8	2.3	1.1	1.1
Total	570,659	45.3	21.1	10.9	6.0	3.6	13.2

Table 2.7. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	3.2	4.0	2.3	2.1	2.2	2.5	1.4
Mining	7.0	6.5	6.8	9.4	7.0	4.9	5.9
Utilities	4.5	4.2	3.8	2.6	4.4	7.1	6.6
Construction	9.2	9.6	9.0	8.9	9.0	9.0	9.3
Manufacturing	8.5	8.7	8.5	7.9	8.3	8.7	8.9
Wholesale trade	8.0	8.4	8.0	7.4	8.2	8.4	9.1
Retail trade	7.7	7.7	7.9	7.5	7.6	7.5	7.5
Transportation and warehouses	9.4	9.7	9.6	7.9	8.9	8.3	8.7
Information	6.7	7.6	6.5	6.0	5.6	5.7	5.0
Finance and insurance	6.2	6.8	6.3	5.9	6.4	5.1	5.7
Real estate, rental, leasing	7.2	7.3	7.1	7.3	7.5	6.9	6.6
Professional, scientific, and technical services	6.7	7.3	6.4	6.3	5.9	6.0	5.3
Management of companies	6.1	4.5	6.2	5.6	6.1	7.3	3.0
Administration, support, and waste	6.6	7.7	6.0	6.2	6.6	7.3	6.7
Education services	7.1	7.0	7.2	7.1	7.7	6.8	7.1
Health care and social assistance	7.1	8.0	6.8	6.8	6.8	7.7	7.9
Arts, entertainment, and recreation	7.5	7.9	7.1	6.4	7.0	5.4	6.5
Accommodation and food services	7.3	7.8	7.4	7.3	6.7	5.6	5.4
Other services	7.6	7.7	7.5	7.6	8.0	7.1	6.1
Public administration	7.0	7.1	4.7				
Other	5.6	5.7	3.4	1.1	1.4	3.3	0.7
Total	7.3	7.7	6.9	7.1	7.3	7.2	7.4

Table 2.8. Distribution of establishments (in percent) in the San Francisco Bay region, California, by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	5,002	56.5	28.3	6.9	4.5	2.3	1.5
Mining	240	14.6	30.4	20.0	16.3	10.0	8.8
Utilities	596	30.2	24.3	10.1	12.6	4.4	18.5
Construction	45,328	30.3	43.7	11.8	6.7	4.1	3.4
Manufacturing	20,899	23.6	30.0	14.4	11.7	8.6	11.8
Wholesale trade	23,316	10.9	32.3	26.9	13.1	8.4	8.3
Retail trade	43,904	30.9	38.5	14.5	8.5	4.5	3.2
Transportation and warehouses	9,938	31.6	46.1	10.3	5.2	3.8	2.9
Information	15,155	41.4	35.8	8.2	5.2	4.3	5.0
Finance and insurance	25,675	7.4	64.6	16.5	5.0	3.5	3.0
Real estate, rental, leasing	25,765	12.9	66.7	11.7	4.8	2.3	1.5
Professional, scientific, and technical services	92,391	43.1	36.9	9.0	5.0	3.4	2.6
Management of companies	1,701	3.4	87.2	4.1	1.8	1.6	1.9
Administration, support, and waste	113,786	31.8	61.7	3.2	2.0	0.8	0.6
Education services	9,802	44.6	18.6	17.2	7.9	5.8	5.8
Health care and social assistance	47,398	23.3	43.4	23.4	5.5	2.7	1.7
Arts, entertainment, and recreation	11,472	55.8	30.5	6.1	3.4	2.1	2.0
Accommodation and food services	21,452	15.3	31.4	38.5	9.2	4.3	1.4
Other services	55,809	63.5	23.3	6.8	3.3	1.9	1.0
Public administration	587	99.1	0.3		0.2	0.3	
Other	443	96.8	1.1	0.5	0.9	0.2	0.5
Total	570,659	33.3	43.4	12.0	5.4	3.2	2.7

Table 2.9. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by type of establishment and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	3.2	3.2	4.6	3.6
Mining	7.0	7.0	7.9	0.4
Utilities	4.5	4.3	8.5	5.2
Construction	9.2	9.2	11.4	13.2
Manufacturing	8.5	8.5	8.5	8.9
Wholesale trade	8.0	8.0	9.4	8.0
Retail trade	7.7	7.7	7.0	7.7
Transportation and warehouses	9.4	9.4	9.2	9.3
Information	6.7	6.8	5.3	5.1
Finance and insurance	6.2	6.3	4.8	5.1
Real estate, rental, leasing	7.2	7.2	6.2	7.5
Professional, scientific, and technical services	6.7	6.7	5.8	6.5
Management of companies	6.1	6.1	4.3	12.1
Administration, support, and waste	6.6	6.6	7.0	8.5
Education services	7.1	7.1	6.9	7.1
Health care and social assistance	7.1	7.1	7.7	6.7
Arts, entertainment, and recreation	7.5	7.5	5.3	5.9
Accommodation and food services	7.3	7.3	7.5	7.4
Other services	7.6	7.6	7.5	5.7
Public administration	7.0	6.9	6.8	8.3
Other	5.6	5.6	4.6	
Total	7.3	7.3	7.3	7.3

Table 2.10. Distribution of establishments (in percent) in the San Francisco Bay region, California, by type of establishment and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	5,002	98.7	1.2	0.2
Mining	240	89.2	9.6	1.3
Utilities	596	91.9	6.4	1.7
Construction	45,328	98.8	1.1	0.2
Manufacturing	20,899	93.1	6.2	0.6
Wholesale trade	23,316	94.8	4.4	0.8
Retail trade	43,904	96.1	2.6	1.3
Transportation and warehouses	9,938	96.9	2.4	0.7
Information	15,155	96.2	3.3	0.5
Finance and insurance	25,675	96.6	2.6	0.8
Real estate, rental, leasing	25,765	97.1	2.2	0.7
Professional, scientific, and technical services	92,391	97.6	2.0	0.4
Management of companies	1,701	96.1	3.6	0.2
Administration, support, and waste	113,786	99.4	0.4	0.1
Education services	9,802	94.8	3.6	1.5
Health care and social assistance	47,398	97.6	1.8	0.6
Arts, entertainment, and recreation	11,472	98.2	1.2	0.6
Accommodation and food services	21,452	97.0	2.7	0.3
Other services	55,809	98.6	1.1	0.4
Public administration	587	59.8	24.7	15.5
Other	443	99.1	0.9	
Total	570,659	97.6	1.9	0.5

Table 2.11. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by business owner demographics and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	3.2	3.2	3.9	3.2	3.9	3.6	3.9
Mining	7.0	7.0	7.0	7.0	6.4	7.1	7.5
Utilities	4.5	4.4	9.3	4.1	5.4	18.4	23.0
Construction	9.2	9.2	10.1	9.1	9.5	12.5	11.3
Manufacturing	8.5	8.4	9.4	8.3	9.1	10.7	10.3
Wholesale trade	8.0	8.0	8.4	7.9	7.9	10.9	9.7
Retail trade	7.7	7.8	7.4	7.7	7.1	9.3	8.9
Transportation and warehouses	9.4	9.3	10.0	9.3	9.9	10.6	10.1
Information	6.7	6.7	7.7	6.6	7.5	8.4	8.5
Finance and insurance	6.2	6.2	7.4	6.2	7.1	9.3	8.3
Real estate, rental, leasing	7.2	7.2	7.3	7.2	6.6	8.8	10.3
Professional, scientific, and technical services	6.7	6.7	7.0	6.6	6.7	8.6	8.0
Management of companies	6.1	6.1	4.4	6.1	5.0	6.1	2.4
Administration, support, and waste	6.6	6.5	7.9	6.5	7.5	9.6	8.9
Education services	7.1	7.1	7.2	7.1	7.0	9.1	8.4
Health care and social assistance	7.1	7.1	7.7	7.1	7.6	8.6	8.2
Arts, entertainment, and recreation	7.5	7.6	6.3	7.6	6.1	9.4	7.9
Accommodation and food services	7.3	7.2	7.6	7.2	7.3	9.3	8.4
Other services	7.6	7.6	8.0	7.6	7.8	10.1	8.8
Public administration	7.0	7.1	0.0	7.1	0.0		
Other	5.6	5.5	6.3	5.5	7.0	4.8	4.1
Total	7.3	7.2	7.7	7.2	7.3	9.8	8.9

Table 2.12. Distribution of establishments (in percent) in the San Francisco Bay region, California, by business owner demographics and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	5,002	93.0	7.0	92.2	6.4	0.8	0.6
Mining	240	95.8	4.2	94.2	2.1	1.7	2.1
Utilities	596	97.0	3.0	95.0	2.3	2.0	0.7
Construction	45,328	97.0	3.0	94.6	2.1	2.4	0.9
Manufacturing	20,899	89.0	11.0	84.9	7.9	4.1	3.1
Wholesale trade	23,316	90.8	9.2	87.8	6.7	3.0	2.5
Retail trade	43,904	88.4	11.6	86.2	9.2	2.2	2.4
Transportation and warehouses	9,938	94.8	5.2	91.7	3.6	3.1	1.6
Information	15,155	93.8	6.2	92.1	4.9	1.7	1.3
Finance and insurance	25,675	95.8	4.2	94.8	3.3	1.0	0.9
Real estate, rental, leasing	25,765	94.0	6.0	93.0	4.9	1.1	1.1
Professional, scientific, and technical services	92,391	89.3	10.7	86.9	8.5	2.4	2.2
Management of companies	1,701	99.2	0.8	98.8	0.6	0.4	0.2
Administration, support, and waste	113,786	97.3	2.7	96.6	2.0	0.7	0.7
Education services	9,802	90.3	9.7	89.4	8.3	0.9	1.4
Health care and social assistance	47,398	91.5	8.5	90.5	7.0	1.0	1.6
Arts, entertainment, and recreation	11,472	91.2	8.8	90.3	7.8	0.9	1.0
Accommodation and food services	21,452	91.9	8.1	88.6	5.7	3.3	2.4
Other services	55,809	91.0	9.0	89.4	7.0	1.6	2.0
Public administration	587	99.8	0.2	99.8	0.2		
Other	443	91.9	8.1	88.3	6.3	3.6	1.8
Total	570,659	92.8	7.2	91.0	5.6	1.7	1.6

Disruptive Building Damage Risk from Earthquake Hazards for Employment

Table 2.13. Employment risk (in percent) from earthquake hazards in the HayWired scenario by county and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees in 9 counties	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	2.4	16.0	10.1	0.6	0.0	1.5	1.8	1.8	0.0	0.0
Mining	9.7	21.7	17.4	1.8	0.1	1.8	4.1	3.3	0.1	0.0
Utilities	4.6	18.0	7.5	0.9	0.0	0.7	3.5	3.4	0.0	0.0
Construction	9.0	29.7	12.2	1.4	0.1	2.0	3.2	4.5	0.3	0.0
Manufacturing	9.1	22.5	12.2	1.4	0.0	2.6	3.4	4.5	0.2	0.0
Wholesale trade	8.4	22.9	10.9	1.2	0.1	2.3	3.2	3.6	0.2	0.0
Retail trade	7.7	23.8	12.4	1.0	0.0	1.5	2.3	2.7	0.4	0.0
Transportation and warehouses	7.2	23.7	9.6	1.5	0.1	2.4	1.8	3.1	0.3	0.0
Information	5.2	18.4	12.5	1.1	0.1	1.8	3.3	3.0	0.1	0.0
Finance and insurance	5.1	21.2	11.0	1.1	0.1	1.2	3.6	2.3	0.2	0.0
Real estate, rental, leasing	6.6	24.4	12.5	1.0	0.0	1.3	2.6	2.4	0.2	0.0
Professional, scientific, and technical services	5.6	19.4	11.7	0.9	0.0	1.5	3.0	2.7	0.2	0.0
Management of companies	5.2	20.8	13.4	0.8	0.0	1.1	2.7	4.8	0.3	0.0
Administration, support, and waste	6.6	23.2	11.3	0.9	0.0	1.2	2.1	2.5	0.1	0.0
Education services	6.9	23.9	11.2	0.9	0.0	1.0	2.1	2.2	0.3	0.0
Health care and social assistance	7.1	23.1	10.2	1.0	0.0	1.2	1.7	2.0	0.3	0.0
Arts, entertainment, and recreation	6.7	23.1	12.2	1.2	0.0	1.5	2.0	2.6	0.2	0.0
Accommodation and food services	6.7	23.8	12.8	0.9	0.0	1.4	2.0	2.5	0.3	0.0
Other services	7.3	23.7	11.1	1.1	0.0	1.3	2.4	2.3	0.3	0.0
Public administration	7.0	21.4	11.7	0.5	0.1	1.2	1.6	4.8	0.2	0.0
Other	4.9	21.5	6.7	0.5	0.0	1.1	1.6	2.4	0.0	0.0
Total	7.0	22.9	11.6	1.0	0.0	1.5	2.6	3.1	0.2	0.0

Table 2.14. Distribution of employment (in percent) in the San Francisco Bay region, California, by county and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	20,740	7.4	7.5	3.3	19.6	4.1	6.2	15.4	9.3	27.2
Mining	2,451	7.8	41.5	5.9	0.2	7.0	5.2	11.9	12.9	7.6
Utilities	11,069	16.4	8.8	5.0	0.9	45.8	5.0	12.7	1.5	4.0
Construction	207,224	18.8	13.7	4.7	2.5	9.9	11.8	24.2	5.9	8.5
Manufacturing	370,952	27.1	5.4	1.3	2.2	5.0	7.9	43.8	1.7	5.4
Wholesale trade	146,761	25.6	8.0	3.1	3.0	11.1	10.9	28.0	3.2	7.0
Retail trade	201,716	21.9	11.6	4.4	2.2	15.8	10.3	21.3	4.4	8.1
Transportation and warehouses	60,505	21.2	9.3	2.9	2.2	9.7	30.1	15.4	4.4	4.9
Information	153,971	14.5	4.2	3.7	0.6	19.8	15.9	37.2	0.9	3.2
Finance and insurance	145,999	11.2	12.3	6.8	1.2	31.2	15.4	16.1	2.3	3.5
Real estate, rental, leasing	113,725	15.9	12.3	4.8	1.7	24.4	9.8	22.3	3.3	5.6
Professional, scientific, and technical services	446,889	15.8	8.7	4.1	1.0	21.0	9.7	34.3	1.6	3.8
Management of companies	7,595	8.6	7.2	3.6	0.7	24.3	9.3	39.0	4.7	2.7
Administration, support, and waste	341,069	17.7	11.8	4.6	1.4	17.6	10.2	26.7	3.8	6.2
Education services	112,573	20.0	9.7	4.8	2.0	19.1	8.3	22.9	3.8	9.4
Health care and social assistance	311,315	21.1	12.9	5.1	2.0	14.7	10.7	22.9	3.7	6.8
Arts, entertainment, and recreation	68,028	17.4	12.7	6.0	3.2	16.7	9.3	23.6	3.2	7.8
Accommodation and food services	235,814	17.5	11.1	4.4	3.1	23.7	9.5	20.3	3.8	6.5
Other services	195,238	20.8	12.3	4.3	1.8	16.7	10.1	22.5	4.8	6.7
Public administration	37,625	19.6	9.5	7.1	1.3	16.4	11.2	25.2	6.3	3.4
Other	1,644	15.0	9.3	4.7	0.6	23.1	11.9	26.6	3.2	5.5
Total	3,192,903	19.3	10.2	4.2	2.0	16.7	10.7	27.6	3.3	6.1

Table 2.15. Employment risk (in percent) from earthquake hazards in the HayWired scenario by establishment size (number of employees) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	2.4	3.2	2.5	1.7	3.2	0.9	1.1	
Mining	9.7	7.1	8.6	3.9	3.6	5.2	14.7	
Utilities	4.6	3.8	3.2	6.2	6.8	9.9	4.3	2.9
Construction	9.0	9.1	9.0	9.0	9.5	9.9	9.0	4.7
Manufacturing	9.1	8.3	8.5	8.2	8.8	9.4	10.1	8.9
Wholesale trade	8.4	7.8	8.5	8.6	8.5	9.5	9.6	4.9
Retail trade	7.7	7.8	7.2	7.1	6.9	7.9	8.2	10.5
Transportation and warehouses	7.2	9.4	8.8	7.8	7.8	6.9	8.1	1.3
Information	5.2	6.9	5.6	6.7	5.0	4.5	6.1	4.0
Finance and insurance	5.1	6.3	5.8	5.3	5.1	4.9	5.5	3.2
Real estate, rental, leasing	6.6	7.1	7.1	7.1	7.0	8.2	5.6	1.3
Professional, scientific, and technical services	5.6	6.7	6.1	6.2	5.5	5.4	4.4	4.1
Management of companies	5.2	6.1	5.6	6.6	3.5	4.6	1.4	5.6
Administration, support, and waste	6.6	6.3	5.7	6.9	7.0	6.9	8.1	7.0
Education services	6.9	7.0	7.3	7.4	7.3	6.4	8.1	5.2
Health care and social assistance	7.1	7.0	6.9	7.5	8.0	8.6	7.2	5.9
Arts, entertainment, and recreation	6.7	7.4	6.9	7.4	5.7	6.8	6.0	6.5
Accommodation and food services	6.7	7.5	7.3	7.2	6.6	5.9	3.9	9.0
Other services	7.3	7.6	7.3	7.3	6.8	5.3	4.1	12.7
Public administration	7.0	7.0	9.7	2.8	4.4	9.7	9.2	5.3
Other	4.9	5.7	6.2	3.0	6.6	1.5		
Total	7.0	7.1	7.1	7.2	7.1	7.2	7.4	6.1

Table 2.16. Distribution of employment (in percent) in the San Francisco Bay region, California, by establishment size (number of employees) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	20,740	36.6	11.7	11.6	15.4	11.5	13.3	
Mining	2,451	14.5	11.0	8.0	14.3	9.5	42.7	
Utilities	11,069	7.1	4.5	7.3	9.2	9.9	19.9	42.1
Construction	207,224	32.6	10.7	10.8	16.6	9.8	14.5	5.0
Manufacturing	370,952	7.7	5.5	6.4	11.9	10.6	25.5	32.4
Wholesale trade	146,761	25.5	11.9	12.3	16.1	11.4	16.5	6.4
Retail trade	201,716	36.4	13.5	10.7	11.9	10.3	11.5	5.7
Transportation and warehouses	60,505	28.0	8.6	8.6	14.3	8.9	14.5	17.1
Information	153,971	14.8	5.6	5.8	9.7	10.0	21.1	32.9
Finance and insurance	145,999	32.5	7.2	6.3	9.2	7.1	11.9	25.7
Real estate, rental, leasing	113,725	43.1	9.9	8.6	11.5	10.5	7.3	9.1
Professional, scientific, and technical services	446,889	30.5	9.5	9.7	13.3	10.3	13.6	13.1
Management of companies	7,595	43.8	3.7	2.9	7.4	5.8	10.5	25.9
Administration, support, and waste	341,069	59.3	5.3	4.2	6.3	5.4	7.1	12.4
Education services	112,573	8.9	13.4	9.1	16.9	15.6	16.9	19.2
Health care and social assistance	311,315	27.2	18.1	8.7	9.9	8.3	10.6	17.3
Arts, entertainment, and recreation	68,028	24.4	12.3	9.3	13.4	15.2	15.8	9.5
Accommodation and food services	235,814	7.6	24.6	21.2	21.5	10.6	10.6	3.8
Other services	195,238	49.5	14.7	10.5	11.7	5.7	4.7	3.2
Public administration	37,625	1.7	1.0	1.9	7.2	13.1	32.1	42.9
Other	1,644	40.5	13.0	15.6	17.8	13.1		
Total	3,192,903	28.8	11.1	9.2	12.5	9.5	13.8	15.1

Table 2.17. Employment risk (in percent) from earthquake hazards in the HayWired scenario by establishment age (in years) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	2.4	4.0	3.7	2.8	1.2	1.7	1.5
Mining	9.7	10.4	6.0	5.1	2.9	5.4	11.7
Utilities	4.6	5.0	7.4	3.0	5.5	2.7	4.3
Construction	9.0	9.4	8.8	9.3	6.8	9.6	9.1
Manufacturing	9.1	8.2	13.9	6.1	7.5	7.9	9.3
Wholesale trade	8.4	7.5	7.3	8.6	9.7	7.8	8.9
Retail trade	7.7	8.1	8.7	7.9	6.8	7.8	7.3
Transportation and warehouses	7.2	9.5	8.1	7.4	7.3	6.6	5.8
Information	5.2	5.4	4.9	5.4	4.0	5.5	6.4
Finance and insurance	5.1	5.7	5.7	5.9	5.2	5.8	4.3
Real estate, rental, leasing	6.6	6.5	5.4	8.1	7.6	6.3	6.9
Professional, scientific, and technical services	5.6	5.1	5.9	6.1	6.4	5.6	5.5
Management of companies	5.2	5.4	5.0	3.4	5.8	7.4	2.8
Administration, support, and waste	6.6	6.4	6.1	5.5	6.4	7.2	7.9
Education services	6.9	7.0	7.8	7.9	6.4	6.4	6.6
Health care and social assistance	7.1	6.8	7.4	7.6	7.4	6.1	7.0
Arts, entertainment, and recreation	6.7	7.3	5.9	5.3	6.9	5.5	7.2
Accommodation and food services	6.7	6.9	7.4	6.3	6.8	6.6	6.1
Other services	7.3	6.7	7.1	7.4	7.0	7.9	7.8
Public administration	7.0	8.8	2.6	10.2	7.0	6.1	6.9
Other	4.9	5.4	3.0	5.3	6.8	9.0	5.2
Total	7.0	6.7	7.4	6.7	6.6	7.0	7.3

Table 2.18. Distribution of employment (in percent) in the San Francisco Bay region, California, by establishment age (in years) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	20,740	18.9	13.3	10.1	8.4	3.3	46.0
Mining	2,451	10.4	9.5	5.5	8.2	5.1	61.2
Utilities	11,069	16.1	6.5	5.1	2.7	0.7	69.0
Construction	207,224	22.5	13.5	8.9	7.8	6.2	41.0
Manufacturing	370,952	8.5	12.3	11.4	10.8	6.9	50.1
Wholesale trade	146,761	18.3	14.4	10.9	9.1	7.2	40.1
Retail trade	201,716	23.6	16.6	10.6	9.2	4.7	35.4
Transportation and warehouses	60,505	20.4	15.7	8.6	5.9	4.5	44.8
Information	153,971	22.2	13.4	14.8	22.9	3.3	23.4
Finance and insurance	145,999	23.6	14.3	8.4	8.8	6.0	38.9
Real estate, rental, leasing	113,725	27.2	22.5	10.5	6.1	6.1	27.6
Professional, scientific, and technical services	446,889	30.9	16.2	14.7	11.1	6.3	20.8
Management of companies	7,595	39.9	16.8	10.1	1.6	19.1	12.5
Administration, support, and waste	341,069	40.5	21.9	8.8	5.4	2.5	20.7
Education services	112,573	24.2	10.2	6.5	4.5	2.5	52.1
Health care and social assistance	311,315	24.6	13.8	9.4	7.8	4.6	39.7
Arts, entertainment, and recreation	68,028	23.5	15.0	11.7	9.6	4.8	35.3
Accommodation and food services	235,814	29.3	19.2	11.9	11.2	5.0	23.4
Other services	195,238	28.7	14.0	10.9	7.9	4.4	34.0
Public administration	37,625	9.7	3.5	3.2	8.4	2.3	72.9
Other	1,644	51.4	19.9	25.5	0.6	0.5	2.1
Total	3,192,903	25.0	15.5	10.8	9.3	5.1	34.2

Table 2.19. Employment risk (in percent) from earthquake hazards in the HayWired scenario by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	2.4	4.1	2.3	2.1	2.2	2.5	1.1
Mining	9.7	10.0	6.4	10.4	6.4	4.3	11.5
Utilities	4.6	4.0	3.1	2.5	3.6	10.5	4.5
Construction	9.0	9.6	9.0	8.8	9.2	9.0	8.9
Manufacturing	9.1	8.4	8.7	8.2	8.0	8.7	9.4
Wholesale trade	8.4	8.3	8.1	7.3	8.3	8.1	8.7
Retail trade	7.7	7.7	7.8	7.2	7.4	7.3	8.1
Transportation and warehouses	7.2	9.4	9.3	7.4	8.1	7.8	5.6
Information	5.2	7.5	6.6	6.5	5.7	6.1	4.7
Finance and insurance	5.1	6.9	6.3	5.9	6.1	4.9	4.3
Real estate, rental, leasing	6.6	7.1	7.0	7.2	5.6	7.4	5.8
Professional, scientific, and technical services	5.6	7.3	6.5	6.4	5.8	6.0	4.7
Management of companies	5.2	4.6	6.1	5.4	5.2	6.5	4.2
Administration, support, and waste	6.6	7.5	5.9	5.9	6.8	7.5	7.1
Education services	6.9	7.0	7.4	7.2	7.5	7.0	6.6
Health care and social assistance	7.1	7.9	6.9	6.9	7.1	7.6	7.0
Arts, entertainment, and recreation	6.7	7.9	7.3	5.9	7.1	5.2	6.5
Accommodation and food services	6.7	7.6	7.4	7.4	6.8	5.7	5.5
Other services	7.3	7.6	7.2	7.3	7.9	6.8	6.9
Public administration	7.0	7.0	4.1				
Other	4.9	5.2	3.3	0.8	1.3	3.3	0.7
Total	7.0	7.5	6.9	7.0	7.1	7.0	6.9

Table 2.20. Distribution of employment (in percent) in the San Francisco Bay region, California, by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	20,740	21.2	17.3	10.3	12.3	13.9	25.1
Mining	2,451	2.4	6.5	5.8	9.5	12.3	63.5
Utilities	11,069	2.1	3.6	2.0	4.2	3.2	84.9
Construction	207,224	7.2	20.0	8.6	10.0	12.1	42.2
Manufacturing	370,952	2.0	4.2	3.6	5.0	7.1	78.0
Wholesale trade	146,761	2.1	9.6	11.3	10.5	12.1	54.4
Retail trade	201,716	8.9	18.7	11.6	11.1	11.7	38.0
Transportation and warehouses	60,505	8.0	18.1	8.4	8.3	11.2	46.0
Information	153,971	6.2	8.5	4.2	4.6	7.1	69.4
Finance and insurance	145,999	1.6	23.0	10.0	5.8	7.5	52.0
Real estate, rental, leasing	113,725	3.8	34.8	12.3	13.7	11.4	24.0
Professional, scientific, and technical services	446,889	10.3	17.1	8.2	8.4	11.1	44.9
Management of companies	7,595	1.0	40.7	3.5	2.3	5.6	46.8
Administration, support, and waste	341,069	13.9	44.8	5.2	5.5	5.7	25.0
Education services	112,573	6.3	6.8	10.4	8.8	12.4	55.3
Health care and social assistance	311,315	5.9	20.9	18.3	9.2	9.5	36.3
Arts, entertainment, and recreation	68,028	15.7	18.9	8.6	8.9	11.1	36.7
Accommodation and food services	235,814	2.3	13.0	32.9	17.1	16.1	18.5
Other services	195,238	32.9	21.4	11.5	9.8	10.0	14.3
Public administration	37,625	99.8	0.0		0.0	0.1	
Other	1,644	92.4	0.9	0.5	0.9	1.5	3.8
Total	3,192,903	9.6	18.8	10.7	8.7	9.9	42.2

Table 2.21. Employment risk (in percent) from earthquake hazards in the HayWired scenario by type of establishment and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	2.4	2.4	2.8	10.1
Mining	9.7	8.1	12.3	0.3
Utilities	4.6	4.1	4.7	9.2
Construction	9.0	9.0	8.7	12.2
Manufacturing	9.1	10.5	7.3	10.7
Wholesale trade	8.4	8.0	9.4	10.4
Retail trade	7.7	7.8	6.9	9.2
Transportation and warehouses	7.2	7.0	7.9	8.6
Information	5.2	6.1	4.1	5.0
Finance and insurance	5.1	5.5	4.1	5.4
Real estate, rental, leasing	6.6	6.7	6.0	6.1
Professional, scientific, and technical services	5.6	5.8	4.6	9.4
Management of companies	5.2	5.0	5.5	9.9
Administration, support, and waste	6.6	6.5	6.6	11.7
Education services	6.9	6.9	6.6	7.8
Health care and social assistance	7.1	7.6	5.4	4.9
Arts, entertainment, and recreation	6.7	7.0	4.4	4.1
Accommodation and food services	6.7	6.6	8.1	6.2
Other services	7.3	7.4	6.3	6.4
Public administration	7.0	7.3	7.1	6.6
Other	4.9	4.9	4.0	
Total	7.0	7.2	6.3	7.9

Table 2.22. Distribution of employment (in percent) in the San Francisco Bay region, California, by type of establishment and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	20,740	92.3	7.5	0.2
Mining	2,451	60.7	38.1	1.3
Utilities	11,069	43.2	53.2	3.6
Construction	207,224	87.6	11.5	0.9
Manufacturing	370,952	54.6	43.2	2.2
Wholesale trade	146,761	75.5	22.9	1.6
Retail trade	201,716	80.6	14.0	5.4
Transportation and warehouses	60,505	83.2	15.3	1.5
Information	153,971	58.0	41.0	1.0
Finance and insurance	145,999	67.9	29.7	2.4
Real estate, rental, leasing	113,725	85.6	11.5	2.8
Professional, scientific, and technical services	446,889	80.2	17.5	2.3
Management of companies	7,595	68.5	30.9	0.6
Administration, support, and waste	341,069	92.0	7.3	0.7
Education services	112,573	61.4	33.4	5.2
Health care and social assistance	311,315	78.2	18.4	3.4
Arts, entertainment, and recreation	68,028	88.5	8.0	3.5
Accommodation and food services	235,814	91.9	7.3	0.8
Other services	195,238	92.9	6.0	1.1
Public administration	37,625	15.7	60.3	24.1
Other	1,644	99.6	0.4	
Total	3,192,903	77.5	20.0	2.4

Table 2.23. Employment risk (in percent) from earthquake hazards in the HayWired scenario by business owner demographics and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	2.4	2.3	4.0	2.3	3.5	1.1	5.9
Mining	9.7	10.6	0.8	10.6	0.2	10.1	3.0
Utilities	4.6	4.6	3.0	4.5	2.2	26.5	6.7
Construction	9.0	8.9	11.4	8.8	10.7	9.7	12.7
Manufacturing	9.1	9.1	10.0	9.0	9.9	11.3	10.3
Wholesale trade	8.4	8.3	9.2	8.1	9.3	12.9	8.8
Retail trade	7.7	7.7	7.9	7.7	7.1	8.8	10.9
Transportation and warehouses	7.2	7.2	7.7	7.0	7.5	12.0	8.0
Information	5.2	5.2	6.3	5.2	5.8	6.8	8.0
Finance and insurance	5.1	5.1	7.1	5.0	7.0	9.4	7.3
Real estate, rental, leasing	6.6	6.6	6.7	6.6	6.0	6.4	9.4
Professional, scientific, and technical services	5.6	5.7	5.3	5.6	4.6	7.5	7.2
Management of companies	5.2	5.2	4.4	5.2	4.9	4.6	2.4
Administration, support, and waste	6.6	6.5	7.1	6.5	6.9	8.7	7.4
Education services	6.9	6.9	6.2	6.9	6.3	8.5	5.9
Health care and social assistance	7.1	7.0	7.4	7.0	7.3	11.1	8.0
Arts, entertainment, and recreation	6.7	6.7	7.6	6.7	7.9	6.7	5.8
Accommodation and food services	6.7	6.7	6.9	6.7	6.1	7.1	8.5
Other services	7.3	7.3	7.6	7.2	7.3	9.1	8.5
Public administration	7.0	7.0	0.0	7.0	0.0		
Other	4.9	4.8	7.5	4.9	9.1	2.5	4.6
Total	7.0	7.0	7.2	6.9	6.7	9.2	8.5

Table 2.24. Distribution of employment (in percent) in the San Francisco Bay region, California, by business owner demographics and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	Male	Female	Minority		Non-minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	20,740	93.3	6.7	91.6	5.2	1.7	1.5
Mining	2,451	91.1	8.9	90.6	7.1	0.4	1.8
Utilities	11,069	97.0	3.0	96.4	2.5	0.6	0.5
Construction	207,224	94.6	5.4	90.4	3.6	4.2	1.8
Manufacturing	370,952	94.2	5.8	90.6	3.8	3.6	2.0
Wholesale trade	146,761	91.0	9.0	86.3	5.7	4.7	3.3
Retail trade	201,716	91.0	9.0	88.3	7.0	2.7	2.0
Transportation and warehouses	60,505	93.9	6.1	90.2	3.8	3.7	2.3
Information	153,971	96.4	3.6	94.5	2.7	2.0	0.9
Finance and insurance	145,999	97.1	2.9	96.2	2.2	0.9	0.7
Real estate, rental, leasing	113,725	94.3	5.7	93.0	4.5	1.3	1.1
Professional, scientific, and technical services	446,889	85.2	14.8	80.8	10.9	4.4	3.9
Management of companies	7,595	99.6	0.4	98.9	0.3	0.8	0.1
Administration, support, and waste	341,069	92.3	7.7	89.4	4.7	2.9	3.0
Education services	112,573	96.8	3.2	96.4	2.7	0.4	0.5
Health care and social assistance	311,315	94.0	6.0	93.3	4.9	0.8	1.1
Arts, entertainment, and recreation	68,028	95.2	4.8	94.3	4.2	0.8	0.6
Accommodation and food services	235,814	94.1	5.9	91.0	4.0	3.1	1.9
Other services	195,238	92.6	7.4	90.7	5.4	1.9	2.0
Public administration	37,625	100.0	0.0	100.0	0.0		
Other	1,644	95.0	5.0	92.8	3.3	2.3	1.7
Total	3,192,903	92.7	7.3	90.0	5.2	2.7	2.0

Disruptive Building Damage Risk from Earthquake and Fire Hazards for Establishments

See section on "Disruptive Building Damage Risk from Earthquake Hazards for Establishments" for distribution tables.

Table 2.25. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by county and NAICS 2-digit sector.

[See table 2.2 for the distribution of establishments by county. NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments in 9 counties	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	3.3	18.6	9.8	0.7	0.0	1.5	1.5	2.1	0.3	0.0
Mining	7.5	28.8	17.1	2.0	0.1	1.3	4.7	3.3	0.6	0.0
Utilities	4.7	19.9	10.3	1.0	0.0	1.7	1.8	2.9	0.2	0.0
Construction	10.0	35.5	14.8	2.3	0.1	1.5	2.6	4.5	1.3	0.0
Manufacturing	9.0	28.3	13.7	2.0	0.0	2.0	3.2	4.2	1.2	0.0
Wholesale trade	8.2	25.9	11.6	1.3	0.0	1.9	2.6	3.1	0.4	0.0
Retail trade	8.1	26.3	13.1	1.4	0.0	1.4	2.4	3.0	1.0	0.0
Transportation and warehouses	9.7	26.7	12.2	1.4	0.1	1.7	2.4	3.3	0.6	0.0
Information	7.1	24.8	14.2	1.3	0.0	1.5	2.6	2.7	0.7	0.0
Finance and insurance	6.5	24.8	11.5	1.3	0.0	1.3	2.5	2.4	0.7	0.0
Real estate, rental, leasing	7.5	25.9	11.8	1.3	0.0	1.3	2.3	2.5	0.6	0.0
Professional, scientific, and technical services	7.0	23.7	12.4	1.2	0.0	1.4	2.4	2.6	0.6	0.0
Management of companies	6.3	22.5	13.1	1.0	0.0	1.3	2.2	2.4	0.5	0.0
Administration, support, and waste	6.8	25.0	11.9	1.1	0.0	1.2	2.0	2.4	0.4	0.0
Education services	11.1	32.4	15.3	5.2	0.1	1.5	4.0	4.8	3.6	0.1
Health care and social assistance	7.6	25.0	12.3	1.3	0.0	1.1	2.0	2.4	0.8	0.0
Arts, entertainment, and recreation	7.8	26.2	13.5	1.3	0.0	1.3	2.2	2.6	0.8	0.0
Accommodation and food services	7.7	26.0	13.5	1.4	0.0	1.3	2.2	3.0	1.0	0.0
Other services	8.3	26.3	12.2	1.7	0.0	1.3	2.5	2.8	1.6	0.0
Public administration	8.5	23.4	14.4	1.1	0.1	1.7	2.7	5.0	7.1	0.0
Other	6.4	23.9	8.5	2.1	0.0	1.4	2.2	2.9	0.8	0.0
Total	7.7	26.2	12.6	1.5	0.0	1.4	2.4	2.9	0.9	0.0

Table 2.26. Establishment risk (in percent) from earthquakes and fire in the HayWired scenario by number of employees and NAICS 2-digit sector.

[See table 2.4 for the distribution of establishments by number of employees. NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	3.3	3.5	2.7	1.8	3.3	1.0	1.2	
Mining	7.5	7.4	8.7	6.2	4.2	5.9	14.4	
Utilities	4.7	4.3	3.6	6.3	7.4	8.9	5.9	6.4
Construction	10.0	10.0	9.8	10.1	10.8	11.2	11.3	5.5
Manufacturing	9.0	8.9	9.1	8.8	9.3	10.1	10.7	7.9
Wholesale trade	8.2	8.0	8.5	8.7	8.6	9.6	10.5	5.5
Retail trade	8.1	8.2	7.7	7.6	7.3	8.1	8.6	9.1
Transportation and warehouses	9.7	10.0	9.2	8.2	7.9	7.3	8.6	1.9
Information	7.1	7.3	5.8	7.2	5.5	5.0	6.4	5.1
Finance and insurance	6.5	6.6	6.1	5.7	5.5	5.3	5.5	3.6
Real estate, rental, leasing	7.5	7.5	7.4	7.4	7.1	8.0	5.9	2.5
Professional, scientific, and technical services	7.0	7.1	6.5	6.6	6.0	5.8	5.0	4.4
Management of companies	6.3	6.3	5.9	7.2	4.5	4.9	1.3	4.3
Administration, support, and waste	6.8	6.8	5.8	7.2	7.7	7.5	8.5	6.8
Education services	11.1	10.8	11.3	11.6	11.6	11.0	12.1	7.7
Health care and social assistance	7.6	7.6	7.3	7.9	8.4	8.7	7.5	7.4
Arts, entertainment, and recreation	7.8	8.0	7.2	7.8	6.2	6.9	7.2	7.3
Accommodation and food services	7.7	8.0	7.7	7.6	7.0	6.5	4.7	7.2
Other services	8.3	8.3	7.9	8.0	7.7	6.1	5.1	10.2
Public administration	8.5	8.6	12.0	4.4	4.8	12.0	10.3	5.8
Other	6.4	6.6	5.9	3.9	7.9	1.9		
Total	7.7	7.7	7.7	7.9	7.8	8.0	8.2	6.4

Table 2.27. Establishment risk (in percent) from earthquakes and fire hazards in the HayWired scenario by establishment age (in years) and NAICS 2-digit sector.

[See table 2.6 for the distribution of establishments by establishment age. NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	3.3	4.2	3.7	3.1	2.5	2.3	2.0
Mining	7.5	10.1	6.1	5.3	6.1	7.9	7.1
Utilities	4.7	4.7	6.1	2.5	3.8	3.7	6.1
Construction	10.0	10.3	10.0	10.0	9.2	9.4	9.7
Manufacturing	9.0	8.7	8.9	8.2	8.6	8.4	10.2
Wholesale trade	8.2	8.0	8.2	8.3	8.6	8.2	8.5
Retail trade	8.1	8.2	8.2	8.2	7.5	7.8	8.4
Transportation and warehouses	9.7	10.6	9.9	9.0	7.7	7.4	8.2
Information	7.1	7.0	7.2	6.7	7.2	7.1	7.6
Finance and insurance	6.5	6.4	6.9	6.3	6.1	6.1	7.0
Real estate, rental, leasing	7.5	7.1	8.0	7.8	7.7	7.8	7.2
Professional, scientific, and technical services	7.0	7.0	7.1	6.9	6.9	7.1	7.1
Management of companies	6.3	6.3	6.6	4.8	7.2	7.5	5.9
Administration, support, and waste	6.8	6.8	6.9	6.4	6.8	7.2	7.4
Education services	11.1	11.0	11.5	11.3	11.1	10.4	10.6
Health care and social assistance	7.6	7.4	7.7	7.6	7.3	7.6	7.9
Arts, entertainment, and recreation	7.8	8.1	8.0	7.2	7.1	7.9	7.6
Accommodation and food services	7.7	7.6	8.0	7.8	7.5	7.4	7.6
Other services	8.3	8.0	8.1	8.5	8.6	8.4	8.6
Public administration	8.5	10.1	4.8	9.4	4.6	15.4	6.9
Other	6.4	6.0	4.8	7.5	7.6	8.1	6.1
Total	7.7	7.6	7.7	7.6	7.6	7.8	8.2

Table 2.28. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[See table 2.8 for the distribution of establishments by revenue. NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	3.3	4.2	2.3	2.1	2.2	2.6	1.4
Mining	7.5	6.8	7.1	9.9	7.3	5.4	7.2
Utilities	4.7	4.4	4.0	2.7	4.5	7.3	6.9
Construction	10.0	10.4	9.8	9.7	9.9	10.1	10.6
Manufacturing	9.0	9.2	9.0	8.4	8.9	9.2	9.6
Wholesale trade	8.2	8.6	8.1	7.6	8.3	8.6	9.4
Retail trade	8.1	8.1	8.3	7.9	8.1	7.9	8.0
Transportation and warehouses	9.7	10.0	10.0	8.3	9.3	8.7	9.1
Information	7.1	7.9	6.8	6.3	6.0	6.1	5.3
Finance and insurance	6.5	7.1	6.6	6.2	6.6	5.4	6.0
Real estate, rental, leasing	7.5	7.5	7.4	7.6	7.8	7.2	6.9
Professional, scientific, and technical services	7.0	7.6	6.7	6.6	6.2	6.3	5.6
Management of companies	6.3	4.7	6.4	5.8	6.4	7.7	3.1
Administration, support, and waste	6.8	8.0	6.3	6.5	6.8	7.6	7.1
Education services	11.1	10.9	11.2	11.0	11.4	11.4	11.0
Health care and social assistance	7.6	8.4	7.3	7.3	7.2	8.1	8.3
Arts, entertainment, and recreation	7.8	8.3	7.4	6.7	7.4	5.8	6.9
Accommodation and food services	7.7	8.3	7.9	7.7	7.2	6.1	6.0
Other services	8.3	8.3	8.2	8.3	8.6	7.8	6.8
Public administration	8.5	8.5	5.7				
Other	6.4	6.6	3.9	1.3	1.4	3.3	1.1
Total	7.7	8.2	7.3	7.6	7.8	7.8	8.0

Table 2.29. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by type of establishment and NAICS 2-digit sector.

[See table 2.10 for the distribution of establishments by type. NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	3.3	3.3	4.6	3.6
Mining	7.5	7.5	8.5	0.4
Utilities	4.7	4.4	8.8	5.6
Construction	10.0	10.0	13.0	14.2
Manufacturing	9.0	9.0	9.1	9.4
Wholesale trade	8.2	8.1	9.6	8.2
Retail trade	8.1	8.2	7.4	8.2
Transportation and warehouses	9.7	9.7	9.6	9.7
Information	7.1	7.1	5.6	5.3
Finance and insurance	6.5	6.6	5.1	5.4
Real estate, rental, leasing	7.5	7.5	6.5	7.9
Professional, scientific, and technical services	7.0	7.0	6.2	6.9
Management of companies	6.3	6.4	4.4	13.2
Administration, support, and waste	6.8	6.8	7.3	8.9
Education services	11.1	11.1	10.8	10.7
Health care and social assistance	7.6	7.6	8.1	7.3
Arts, entertainment, and recreation	7.8	7.9	5.7	6.3
Accommodation and food services	7.7	7.7	7.9	8.0
Other services	8.3	8.3	8.1	6.2
Public administration	8.5	8.5	7.9	9.8
Other	6.4	6.5	5.4	
Total	7.7	7.7	7.8	7.9

Table 2.30. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by business owner demographics and NAICS 2-digit sector.

[See table 2.12 for the distribution of establishments by business owner demographics. NAICS, North American Industry Classification System]

NAICS sector	Average risk across all establishments	Male	Female	Non-Minority		Minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	3.3	3.3	4.1	3.3	4.1	3.6	4.2
Mining	7.5	7.5	7.2	7.5	6.6	7.3	7.8
Utilities	4.7	4.6	9.5	4.3	5.5	18.8	23.3
Construction	10.0	10.0	11.1	9.9	10.4	13.6	12.7
Manufacturing	9.0	8.9	9.9	8.8	9.6	11.3	10.9
Wholesale trade	8.2	8.2	8.6	8.1	8.1	11.2	10.0
Retail trade	8.1	8.2	7.8	8.1	7.4	9.8	9.4
Transportation and warehouses	9.7	9.7	10.3	9.7	10.2	11.1	10.5
Information	7.1	7.0	8.0	7.0	7.8	8.9	8.9
Finance and insurance	6.5	6.5	7.7	6.4	7.4	9.6	8.8
Real estate, rental, leasing	7.5	7.5	7.6	7.4	6.9	9.3	10.6
Professional, scientific, and technical services	7.0	7.0	7.3	6.9	7.0	9.0	8.4
Management of companies	6.3	6.3	4.6	6.3	5.2	6.3	2.7
Administration, support, and waste	6.8	6.8	8.2	6.8	7.8	9.9	9.3
Education services	11.1	11.0	11.2	11.0	10.9	13.1	12.9
Health care and social assistance	7.6	7.5	8.1	7.5	8.0	9.2	8.7
Arts, entertainment, and recreation	7.8	7.9	6.6	7.9	6.4	9.9	8.2
Accommodation and food services	7.7	7.7	8.0	7.6	7.7	9.8	8.9
Other services	8.3	8.3	8.3	8.2	8.1	10.5	9.2
Public administration	8.5	8.5	0.0	8.5	0.0		
Other	6.4	6.4	7.4	6.4	8.2	5.8	4.6
Total	7.7	7.7	8.1	7.6	7.8	10.3	9.4

Disruptive Building Damage Risk from Earthquake and Fire Hazards for Employment

See section on “Disruptive Building Damage Risk from Earthquakes for Establishments” for distribution tables.

Table 2.31. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by county and NAICS 2-digit sector.

[See table 2.14 for the distribution of employment by county. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees in 9 counties	County								
		Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Agriculture, forestry, fishing, and hunting	2.5	17.1	10.1	0.6	0.0	1.5	1.9	1.8	0.1	0.0
Mining	10.7	22.7	19.1	3.8	0.1	1.8	4.3	3.8	0.2	0.0
Utilities	4.8	18.6	7.8	1.0	0.0	0.7	3.7	3.6	0.0	0.0
Construction	10.1	32.1	12.9	4.0	0.1	2.2	3.7	5.6	2.6	0.0
Manufacturing	9.8	23.9	12.7	2.9	0.0	2.6	3.8	4.9	0.7	0.0
Wholesale trade	8.6	23.4	11.2	1.5	0.1	2.3	3.3	3.8	0.3	0.0
Retail trade	8.2	24.8	13.0	1.4	0.0	1.5	2.5	3.0	0.8	0.0
Transportation and warehouses	7.6	24.5	10.0	2.2	0.1	2.4	2.0	3.4	0.6	0.0
Information	5.6	19.3	12.9	1.9	0.1	1.8	3.5	3.3	0.7	0.0
Finance and insurance	5.3	22.0	11.4	1.4	0.1	1.2	3.7	2.6	0.5	0.0
Real estate, rental, leasing	6.8	25.1	12.9	1.3	0.0	1.4	2.8	2.6	0.5	0.0
Professional, scientific, and technical services	6.0	20.2	12.1	1.5	0.0	1.5	3.2	3.0	0.7	0.0
Management of companies	5.4	21.5	13.8	1.0	0.0	1.2	2.8	5.0	0.3	0.0
Administration, support, and waste	6.9	24.0	11.6	1.3	0.0	1.3	2.3	2.8	0.5	0.0
Education services	10.5	33.2	15.5	4.9	0.1	1.9	3.8	5.0	4.9	0.1
Health care and social assistance	7.5	24.3	10.7	1.4	0.0	1.2	1.9	2.3	0.8	0.0
Arts, entertainment, and recreation	7.1	24.1	12.7	1.8	0.1	1.5	2.2	2.9	1.3	0.0
Accommodation and food services	7.1	25.1	13.3	1.3	0.0	1.5	2.3	3.0	0.7	0.0
Other services	8.0	25.3	11.8	2.0	0.0	1.3	2.7	2.8	1.7	0.0
Public administration	8.6	25.3	12.9	0.6	0.1	1.2	2.1	6.3	5.0	0.0
Other	5.6	23.8	7.2	1.0	0.0	1.1	2.2	2.9	0.5	0.0
Total	7.6	24.4	12.2	1.8	0.0	1.5	2.9	3.5	1.2	0.0

Table 2.32. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by number of employees and NAICS 2-digit sector.

[See table 2.16 for the distribution of employment by number of employees. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<5	5–9	10–19	20–49	50–99	100–499	>500
Agriculture, forestry, fishing, and hunting	2.5	3.3	2.7	1.8	3.3	1.0	1.3	
Mining	10.7	7.4	9.2	5.5	3.8	5.8	16.2	
Utilities	4.8	4.0	3.4	6.4	7.0	10.2	4.7	3.0
Construction	10.1	9.9	9.8	10.1	10.8	11.2	10.5	6.7
Manufacturing	9.8	8.8	9.1	8.8	9.4	10.1	10.8	9.6
Wholesale trade	8.6	8.0	8.7	8.8	8.7	9.7	9.9	5.1
Retail trade	8.2	8.2	7.6	7.6	7.4	8.3	8.7	10.9
Transportation and warehouses	7.6	9.7	9.2	8.2	8.1	7.4	8.6	1.6
Information	5.6	7.2	5.9	7.1	5.4	4.8	6.4	4.3
Finance and insurance	5.3	6.6	6.1	5.6	5.3	5.1	5.8	3.3
Real estate, rental, leasing	6.8	7.4	7.5	7.4	7.3	8.4	5.8	1.4
Professional, scientific, and technical services	6.0	6.9	6.4	6.5	5.9	5.8	4.8	4.3
Management of companies	5.4	6.3	5.8	6.9	3.7	4.8	1.7	5.7
Administration, support, and waste	6.9	6.6	5.9	7.3	7.4	7.3	8.5	7.3
Education services	10.5	10.8	11.2	11.6	11.4	11.2	11.3	7.3
Health care and social assistance	7.5	7.4	7.3	7.9	8.4	9.0	7.6	6.4
Arts, entertainment, and recreation	7.1	7.7	7.2	7.7	6.1	7.2	6.5	7.1
Accommodation and food services	7.1	8.0	7.7	7.5	7.0	6.4	4.3	10.0
Other services	8.0	8.3	7.9	8.1	7.5	6.2	4.7	13.2
Public administration	8.6	8.7	11.1	4.6	4.9	11.1	10.8	7.1
Other	5.6	6.5	7.1	3.5	7.0	1.8		
Total	7.6	7.6	7.7	7.8	7.8	8.0	8.1	6.6

Table 2.33. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by establishment age (in years) and NAICS 2-digit sector.

[See table 2.18 for the distribution of employment by establishment age. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<6	6–10	11–15	16–20	21–25	>26
Agriculture, forestry, fishing, and hunting	2.5	4.1	3.9	3.1	1.3	1.7	1.6
Mining	10.7	10.8	6.4	5.3	4.3	6.0	12.9
Utilities	4.8	5.1	7.7	3.3	6.0	2.9	4.5
Construction	10.1	10.2	10.0	10.4	8.0	10.6	10.4
Manufacturing	9.8	8.8	14.7	6.7	8.2	8.5	10.0
Wholesale trade	8.6	7.7	7.4	8.8	9.9	8.0	9.2
Retail trade	8.2	8.5	9.1	8.3	7.3	8.2	7.7
Transportation and warehouses	7.6	9.9	8.5	7.8	7.6	6.9	6.2
Information	5.6	5.8	5.2	5.8	4.2	5.8	6.8
Finance and insurance	5.3	5.9	6.0	6.1	5.3	6.2	4.5
Real estate, rental, leasing	6.8	6.8	5.6	8.4	7.9	6.5	7.1
Professional, scientific, and technical services	6.0	5.4	6.2	6.5	6.7	5.9	5.8
Management of companies	5.4	5.7	5.1	3.5	6.0	7.6	2.9
Administration, support, and waste	6.9	6.6	6.4	5.7	6.8	7.6	8.3
Education services	10.5	10.9	13.4	11.4	10.0	10.1	9.7
Health care and social assistance	7.5	7.3	7.8	8.0	7.9	6.5	7.5
Arts, entertainment, and recreation	7.1	7.6	6.2	5.7	7.2	5.8	7.7
Accommodation and food services	7.1	7.2	7.9	6.7	7.2	7.0	6.5
Other services	8.0	7.5	7.7	8.0	7.5	8.4	8.5
Public administration	8.6	11.2	3.5	11.3	11.5	8.4	8.1
Other	5.6	6.1	3.5	6.0	7.6	10.1	5.4
Total	7.6	7.2	8.0	7.2	7.1	7.4	8.0

Table 2.34. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by establishment revenue (in thousands of U.S. dollars) and NAICS 2-digit sector.

[See table 2.20 for the distribution of employment by establishment revenue. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	<$100	$101–250	$251–500	$501–1,000	$1,001–2,500	>$2,501
Agriculture, forestry, fishing, and hunting	2.5	4.3	2.4	2.2	2.3	2.6	1.2
Mining	10.7	10.4	6.8	11.0	6.7	4.6	12.8
Utilities	4.8	4.1	3.3	2.6	3.7	10.7	4.7
Construction	10.1	10.4	9.8	9.5	10.1	10.2	10.3
Manufacturing	9.8	8.9	9.2	8.7	8.5	9.2	10.0
Wholesale trade	8.6	8.4	8.2	7.4	8.5	8.3	9.0
Retail trade	8.2	8.1	8.3	7.6	7.9	7.8	8.5
Transportation and warehouses	7.6	9.8	9.7	7.7	8.5	8.1	6.0
Information	5.6	7.8	7.0	6.8	6.0	6.5	5.0
Finance and insurance	5.3	7.1	6.6	6.2	6.4	5.1	4.5
Real estate, rental, leasing	6.8	7.4	7.2	7.5	5.9	7.6	6.0
Professional, scientific, and technical services	6.0	7.6	6.7	6.7	6.1	6.4	5.0
Management of companies	5.4	4.8	6.4	5.6	5.4	6.8	4.3
Administration, support, and waste	6.9	7.8	6.2	6.2	7.1	7.8	7.5
Education services	10.5	10.8	11.5	11.2	11.0	12.0	9.8
Health care and social assistance	7.5	8.3	7.3	7.4	7.5	8.1	7.4
Arts, entertainment, and recreation	7.1	8.2	7.6	6.2	7.5	5.5	6.9
Accommodation and food services	7.1	8.1	7.9	7.8	7.2	6.1	6.1
Other services	8.0	8.2	7.9	7.9	8.6	7.5	7.6
Public administration	8.6	8.6	5.1				
Other	5.6	5.9	3.8	0.9	1.4	3.3	1.1
Total	7.6	8.2	7.3	7.6	7.6	7.7	7.6

Table 2.35. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by type of establishment and NAICS 2-digit sector.

[See table 2.22 for the distribution of employment by establishment type. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Stand alone	Headquarters	Branch
Agriculture, forestry, fishing, and hunting	2.5	2.5	2.8	10.1
Mining	10.7	8.8	13.6	0.3
Utilities	4.8	4.2	4.9	9.4
Construction	10.1	10.0	10.7	13.6
Manufacturing	9.8	11.2	7.9	11.2
Wholesale trade	8.6	8.2	9.6	10.7
Retail trade	8.2	8.2	7.2	9.7
Transportation and warehouses	7.6	7.4	8.3	9.0
Information	5.6	6.4	4.3	5.2
Finance and insurance	5.3	5.8	4.3	5.6
Real estate, rental, leasing	6.8	6.9	6.2	6.3
Professional, scientific, and technical services	6.0	6.1	4.9	9.8
Management of companies	5.4	5.2	5.7	11.0
Administration, support, and waste	6.9	6.8	7.0	12.1
Education services	10.5	10.8	9.7	12.2
Health care and social assistance	7.5	8.0	5.8	5.2
Arts, entertainment, and recreation	7.1	7.4	4.8	4.4
Accommodation and food services	7.1	7.0	8.6	7.1
Other services	8.0	8.0	7.0	7.1
Public administration	8.6	10.7	8.5	7.6
Other	5.6	5.6	5.2	
Total	7.6	7.7	6.9	8.7

Table 2.36. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by business owner demographics and NAICS 2-digit sector.

[See table 2.24 for the distribution of employment by business owner demographics. NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Agriculture, forestry, fishing, and hunting	2.5	2.4	4.4	2.4	3.6	1.2	6.8
Mining	10.7	11.6	0.8	11.7	0.2	10.4	3.2
Utilities	4.8	4.8	3.1	4.7	2.3	26.8	6.8
Construction	10.1	10.0	12.6	9.9	11.6	10.8	14.7
Manufacturing	9.8	9.7	10.6	9.6	10.4	12.2	10.9
Wholesale trade	8.6	8.5	9.4	8.3	9.5	13.3	9.1
Retail trade	8.2	8.2	8.3	8.1	7.4	9.3	11.5
Transportation and warehouses	7.6	7.5	8.1	7.3	7.9	12.5	8.4
Information	5.6	5.5	6.8	5.5	6.3	7.4	8.4
Finance and insurance	5.3	5.3	7.3	5.2	7.2	9.7	7.6
Real estate, rental, leasing	6.8	6.8	6.9	6.8	6.3	6.8	9.7
Professional, scientific, and technical services	6.0	6.0	5.5	5.9	4.8	8.1	7.6
Management of companies	5.4	5.4	4.6	5.4	5.1	4.7	2.7
Administration, support, and waste	6.9	6.8	7.4	6.8	7.2	9.1	7.7
Education services	10.5	10.5	10.5	10.5	10.2	13.5	12.6
Health care and social assistance	7.5	7.5	7.8	7.4	7.7	11.5	8.5
Arts, entertainment, and recreation	7.1	7.1	8.0	7.1	8.3	7.2	6.2
Accommodation and food services	7.1	7.1	7.3	7.1	6.5	7.5	9.1
Other services	8.0	8.0	8.0	7.9	7.6	9.5	8.9
Public administration	8.6	8.6	0.0	8.6	0.0		
Other	5.6	5.4	8.6	5.5	10.6	3.2	4.9
Total	7.6	7.6	7.7	7.5	7.1	9.8	9.1

Appendix 3. Building Damage Risk Results for the HayWired Scenario by Business Owner Demographics and San Francisco Bay County

These tables explain the large disruptive building damage risk for minority business owners found in this study that is caused by larger concentrations of minority business owners in Alameda County—the most heavily impacted county in the region.

Table 3.1. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by business owner demographics and county.

County	Average risk across employees	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	25.0	24.9	25.7	24.9	25.9	26.1	25.0
Contra Costa	12.2	12.1	12.9	12.1	12.8	14.7	13.2
Marin	0.9	0.9	0.8	0.9	0.8	1.0	1.0
Napa	0.0	0.0	0.0	0.0	0.0	0.0	0.0
San Francisco	1.3	1.3	1.3	1.3	1.3	1.4	1.4
San Mateo	2.1	2.1	2.1	2.1	2.0	2.5	2.5
Santa Clara	2.5	2.5	2.6	2.5	2.4	3.3	3.0
Solano	0.2	0.2	0.3	0.2	0.2	0.4	0.3
Sonoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	7.3	7.2	7.7	7.2	7.3	9.8	8.9

Table 3.2. Employment risk (in percent) from earthquake hazards in the HayWired scenario by business owner demographics and county.

County	Average risk across establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	24.4	24.3	25.3	24.4	26.2	22.1	23.8
Contra Costa	12.2	12.2	12.4	12.1	12.6	13.4	11.7
Marin	1.8	1.9	1.6	1.9	1.4	2.4	2.9
Napa	0.0	0.0	0.0	0.0	0.0	0.0	0.1
San Francisco	1.5	1.5	1.8	1.5	1.7	1.9	1.9
San Mateo	2.9	2.9	3.4	2.8	2.5	3.4	4.8
Santa Clara	3.5	3.6	3.2	3.5	2.9	4.0	3.9
Solano	1.2	1.3	0.7	1.3	0.6	0.9	0.9
Sonoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	7.6	7.6	7.7	7.5	7.1	9.8	9.1

Table 3.3. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by business owner demographics and county.

County	Average risk across establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	26.2	26.2	26.9	26.1	27.1	27.2	26.2
Contra Costa	12.6	12.6	13.3	12.5	13.2	15.1	13.6
Marin	1.5	1.5	1.3	1.5	1.3	1.8	1.7
Napa	0.0	0.0	0.0	0.0	0.0	0.1	0.1
San Francisco	1.4	1.4	1.3	1.3	1.3	1.5	1.4
San Mateo	2.4	2.4	2.3	2.3	2.2	2.7	2.7
Santa Clara	2.9	2.9	2.9	2.8	2.7	3.7	3.4
Solano	0.9	0.9	0.8	0.9	0.8	1.1	0.9
Sonoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	7.7	7.7	8.1	7.6	7.8	10.3	9.4

Table 3.4. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by business owner demographics and county.

County	Average risk across establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	24.4	24.3	25.3	24.4	26.2	22.1	23.8
Contra Costa	12.2	12.2	12.4	12.1	12.6	13.4	11.7
Marin	1.8	1.9	1.6	1.9	1.4	2.4	2.9
Napa	0.0	0.0	0.0	0.0	0.0	0.0	0.1
San Francisco	1.5	1.5	1.8	1.5	1.7	1.9	1.9
San Mateo	2.9	2.9	3.4	2.8	2.5	3.4	4.8
Santa Clara	3.5	3.6	3.2	3.5	2.9	4.0	3.9
Solano	1.2	1.3	0.7	1.3	0.6	0.9	0.9
Sonoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	7.6	7.6	7.7	7.5	7.1	9.8	9.1

Table 3.5. Distribution of establishments (in percent) in the San Francisco Bay region, California, by business owner demographics and county.

County	Number of establishments	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	105,186	92.3	7.7	89.8	5.6	2.5	2.1
Contra Costa	73,127	93.1	6.9	91.7	5.5	1.4	1.4
Marin	32,458	91.7	8.3	91.0	7.5	0.7	0.8
Napa	12,334	92.5	7.5	91.8	6.8	0.6	0.8
San Francisco	82,230	92.6	7.4	90.3	5.6	2.2	1.8
San Mateo	60,163	92.9	7.1	91.2	5.6	1.7	1.5
Santa Clara	139,293	93.4	6.6	91.6	4.8	1.8	1.7
Solano	23,870	92.1	7.9	90.7	6.2	1.4	1.7
Sonoma	41,998	92.9	7.1	92.2	6.6	0.6	0.6
Total	570,659	92.8	7.2	91.0	5.6	1.7	1.6

Table 3.6. Distribution of employment (in percent) in the San Francisco Bay region, California, by business owner demographics and county.

County	Number of employees	Male	Female	Non-minority		Minority	
				Male	Female	Male	Female
Alameda	615,336	92.9	7.1	88.5	4.5	4.4	2.6
Contra Costa	324,598	93.2	6.8	90.9	5.0	2.3	1.8
Marin	133,599	92.5	7.5	91.8	6.5	0.7	0.9
Napa	63,453	94.3	5.7	93.2	4.9	1.1	0.8
San Francisco	532,713	94.4	5.6	92.1	4.0	2.4	1.6
San Mateo	343,010	93.0	7.0	90.7	4.4	2.4	2.6
Santa Clara	879,667	91.3	8.7	88.4	6.3	2.9	2.4
Solano	104,978	92.8	7.2	90.6	5.2	2.1	2.0
Sonoma	195,549	92.5	7.5	91.3	6.8	1.2	0.7
Total	3,192,903	92.7	7.3	90.0	5.2	2.7	2.0

Appendix 4. Building Damage Risk Results for the HayWired Scenario by San Francisco Bay Subarea

This appendix contains four tables of building damage risk to businesses separated by subarea (seven San Francisco Bay region subareas that contain concentrations of extensive and complete damages in the HayWired scenario) with respect to the industry sector to which the businesses belong. The four tables pertain to two different ways of calculating risk: (1) average across establishments and (2) employment-weighted average; risk is also calculated for two different sets of extensive and completed (disruptive) building damages: (1) from earthquake hazards only (no fire) and (2) from earthquake plus fire hazards. Also included in this appendix are two tables showing the distribution of establishments and employment in each subarea.

Table 4.1. Establishment risk (in percent) from earthquake hazards in the HayWired scenario by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments in 9 counties	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	21.1	32.4	19.4	22.4	0.6	11.2	0.5	35.8
Mining	26.6	45.6	27.3	28.0	1.2	15.4	1.1	52.3
Utilities	20.5	36.2	22.6	22.8	0.7	6.7	0.2	36.7
Construction	32.5	47.7	31.2	28.6	0.7	18.0	0.7	47.8
Manufacturing	27.3	41.4	26.4	26.0	1.2	11.4	1.0	36.8
Wholesale trade	25.6	38.8	22.7	23.3	1.0	10.7	0.8	33.0
Retail trade	24.9	39.3	22.9	19.8	0.7	12.8	1.1	36.1
Transportation and warehouses	26.0	34.9	21.0	21.1	0.8	12.5	0.6	37.9
Information	23.9	39.9	21.4	21.8	0.9	11.5	0.4	42.5
Finance and insurance	23.2	40.2	19.5	22.6	0.8	11.0	0.7	34.9
Real estate, rental, leasing	24.5	38.9	20.3	21.9	0.7	11.9	0.7	36.4
Professional, scientific, and technical services	22.9	38.3	19.9	22.0	0.8	10.9	0.6	38.2
Management of companies	22.4	37.0	18.3	23.2	0.4	9.4	1.1	33.9
Administration, support, and waste	23.7	38.3	19.4	23.2	0.5	12.0	0.4	39.2
Education services	22.7	37.3	21.0	20.3	0.7	11.0	2.0	32.9
Health care and social assistance	23.3	41.4	20.4	19.5	0.7	10.7	0.9	36.3
Arts, entertainment, and recreation	25.2	42.6	24.4	21.3	0.8	11.7	0.6	39.0
Accommodation and food services	24.9	42.7	23.2	18.2	0.7	12.6	1.2	38.4
Other services	24.1	38.6	21.5	18.5	0.7	11.9	1.1	34.2
Public administration	21.9	37.9	20.3	20.0	0.3	10.3	1.4	33.9
Other	19.5	31.5	13.0	18.5	1.1	8.4	0.2	18.6
Total	24.7	39.9	21.6	21.6	0.7	12.0	0.8	37.9

Table 4.2. Employment-weighted risk (in percent) from earthquake hazards in the HayWired scenario by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	19.9	28.5	19.0	17.2	0.5	11.2	0.5	33.7
Mining	25.1	37.3	27.4	28.2	3.0	16.1	1.2	48.3
Utilities	19.3	22.2	26.6	21.3	0.6	5.7	0.1	52.7
Construction	29.2	44.8	31.8	27.0	1.1	14.8	0.8	38.4
Manufacturing	23.5	37.5	25.0	22.0	1.7	8.6	1.1	26.5
Wholesale trade	23.4	36.2	21.7	23.5	1.2	8.5	1.0	27.0
Retail trade	24.2	39.2	21.7	19.0	0.7	11.5	1.4	36.0
Transportation and warehouses	23.8	32.6	23.0	20.6	1.3	10.0	1.4	30.0
Information	18.2	44.9	21.8	19.1	0.9	6.6	0.3	44.2
Finance and insurance	18.1	39.7	18.2	20.2	0.5	10.3	0.6	32.9
Real estate, rental, leasing	24.5	40.4	20.5	21.0	0.6	11.1	0.7	37.0
Professional, scientific, and technical services	19.4	35.9	19.1	21.1	1.1	8.4	0.7	34.7
Management of companies	21.9	37.5	19.4	23.6	0.4	9.8	1.5	31.6
Administration, support, and waste	23.3	37.2	18.2	23.3	0.7	10.7	0.4	36.7
Education services	24.8	40.1	22.5	20.7	0.9	9.0	1.9	33.5
Health care and social assistance	22.7	40.4	21.2	17.6	0.7	9.8	1.0	33.6
Arts, entertainment, and recreation	23.7	42.5	22.5	21.2	0.9	11.3	0.5	36.0
Accommodation and food services	23.8	43.1	21.8	17.7	0.7	11.8	0.8	38.7
Other services	23.2	38.2	25.7	17.5	0.9	11.0	1.0	33.7
Public administration	20.8	52.8	24.2	18.8	0.4	9.6	0.7	37.0
Other	19.5	32.7	13.2	18.8	0.3	8.5	0.2	18.5
Total	23.0	39.1	22.2	20.4	0.8	9.6	0.9	34.5

Table 4.3. Establishment risk (in percent) from earthquake and fire hazards in the HayWired scenario by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across establishments	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	22.1	33.3	20.2	23.8	0.6	11.6	5.0	35.9
Mining	28.5	47.6	29.0	28.6	6.1	16.6	4.6	55.1
Utilities	21.2	37.1	23.7	23.3	0.7	7.8	0.8	37.2
Construction	35.0	50.2	34.1	30.4	4.3	21.1	5.9	48.9
Manufacturing	28.7	43.0	27.5	26.9	4.1	12.7	5.3	37.8
Wholesale trade	26.1	39.4	23.1	23.6	2.0	11.2	1.9	33.4
Retail trade	26.2	40.7	24.1	20.6	2.3	14.2	3.5	37.0
Transportation and warehouses	27.0	36.0	22.0	21.5	1.8	13.5	2.1	38.7
Information	24.9	40.9	22.2	22.6	2.9	12.8	2.5	43.1
Finance and insurance	24.1	41.1	20.4	23.2	2.1	12.1	2.5	35.6
Real estate, rental, leasing	25.3	39.8	21.1	22.5	1.7	12.9	2.3	37.3
Professional, scientific, and technical services	23.7	39.2	20.7	22.6	2.2	11.9	2.3	38.8
Management of companies	23.2	37.9	19.1	23.8	0.7	10.3	1.9	34.6
Administration, support, and waste	24.5	39.2	20.2	23.9	1.2	12.9	1.7	39.7
Education services	33.5	48.6	34.6	29.5	16.5	23.1	18.2	39.9
Health care and social assistance	24.5	42.5	21.6	20.6	1.9	12.6	2.7	37.3
Arts, entertainment, and recreation	26.3	43.6	25.4	22.1	2.8	13.0	3.3	39.7
Accommodation and food services	26.2	44.1	24.4	19.2	2.6	14.1	3.7	39.3
Other services	25.9	40.3	23.3	19.9	3.0	13.8	5.1	35.8
Public administration	26.3	41.6	23.1	22.3	0.3	16.5	26.3	36.3
Other	22.4	35.3	15.6	21.1	6.2	11.0	4.2	19.2
Total	26.1	41.4	23.0	22.7	2.5	13.5	3.5	38.9

Table 4.4. Employment risk (in percent) from earthquake and fire hazards in the HayWired scenario by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Average risk across employees	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	21.2	30.1	21.5	18.7	0.5	11.6	3.5	33.8
Mining	28.2	38.7	29.2	28.7	16.0	17.2	5.0	52.5
Utilities	19.9	23.0	28.3	21.7	0.6	6.9	0.5	53.6
Construction	32.5	47.9	35.0	28.7	8.2	17.9	9.8	39.7
Manufacturing	24.9	39.3	25.9	23.1	6.9	9.8	5.7	27.3
Wholesale trade	24.0	36.9	22.1	23.8	2.4	9.0	2.1	27.6
Retail trade	25.3	40.4	22.5	19.9	2.2	12.9	3.3	37.5
Transportation and warehouses	24.7	33.6	24.2	21.1	3.7	11.0	2.7	31.0
Information	19.2	46.0	22.4	19.8	3.5	7.8	3.2	44.8
Finance and insurance	18.9	40.7	19.1	20.8	0.9	11.5	2.6	33.7
Real estate, rental, leasing	25.4	41.3	21.3	21.6	1.6	12.1	2.3	38.3
Professional, scientific, and technical services	20.4	36.8	19.9	21.7	3.3	9.6	2.9	35.7
Management of companies	22.8	38.4	20.1	24.3	0.7	10.8	2.0	32.9
Administration, support, and waste	24.2	38.2	19.0	24.1	1.8	11.7	1.9	37.5
Education services	35.4	50.7	36.9	29.5	22.9	18.2	30.2	45.5
Health care and social assistance	23.9	41.6	22.4	18.7	1.6	12.1	2.7	34.5
Arts, entertainment, and recreation	25.0	43.5	23.3	22.3	3.4	12.7	4.3	36.9
Accommodation and food services	25.1	44.4	23.4	19.0	2.1	13.4	2.6	39.6
Other services	25.1	39.9	27.4	19.0	4.7	13.0	5.7	35.4
Public administration	25.8	57.3	25.9	21.1	0.4	16.3	24.7	38.0
Other	21.6	35.2	15.9	21.0	0.9	10.7	5.9	19.1
Total	24.7	40.9	23.5	21.8	3.4	11.2	5.5	36.0

Table 4.5. Distribution of establishments (in percent) in the San Francisco Bay region, California, by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of establishments in 9 counties	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	412	20.9	12.9	30.1	8.0	12.6	5.3	10.2
Mining	34	17.6	11.8	26.5	8.8	20.6	5.9	8.8
Utilities	73	17.8	9.6	32.9	8.2	19.2	4.1	8.2
Construction	8,917	35.1	7.6	21.3	7.9	12.0	5.5	10.5
Manufacturing	4,640	34.3	6.8	25.0	4.5	19.6	3.0	6.9
Wholesale trade	5,352	35.9	7.2	23.5	4.8	17.9	3.0	7.7
Retail trade	10,168	30.9	6.8	28.5	4.0	13.8	5.7	10.3
Transportation and warehouses	2,891	43.9	5.4	19.7	2.6	13.5	5.3	9.7
Information	3,013	21.4	7.4	40.8	6.3	13.1	3.3	7.7
Finance and insurance	4,242	25.2	12.1	28.6	6.6	15.7	4.7	7.1
Real estate, rental, leasing	5,219	30.4	8.4	29.0	6.0	12.9	5.2	8.2
Professional, scientific, and technical services	18,242	20.8	9.7	38.7	5.8	14.0	3.5	7.5
Management of companies	266	23.7	14.3	31.2	4.1	15.4	4.5	6.8
Administration, support, and waste	22,043	26.5	8.4	26.8	7.1	16.2	5.5	9.4
Education services	2,395	23.0	8.0	38.5	4.5	12.9	3.7	9.3
Health care and social assistance	10,782	23.4	8.1	38.3	4.0	12.8	5.1	8.2
Arts, entertainment, and recreation	2,498	24.1	6.4	39.5	4.6	11.4	4.9	9.1
Accommodation and food services	4,712	26.9	7.2	36.1	3.6	12.1	4.7	9.3
Other services	13,395	31.7	7.2	28.3	3.9	12.3	6.5	10.1
Public administration	127	18.9	7.1	48.0	3.1	5.5	6.3	11.0
Other	83	28.9	8.4	37.3	4.8	8.4	3.6	8.4
Total	119,504	27.9	8.1	30.6	5.4	14.1	4.9	8.9

Table 4.6. Distribution of employment (in percent) in the San Francisco Bay region, California, by subarea and NAICS 2-digit sector.

[NAICS, North American Industry Classification System]

NAICS sector	Number of employees	Central Alameda County	Dublin-Pleasanton	North Alameda County	Novato	South Alameda County	Vallejo	West Contra Costa County
Agriculture, forestry, fishing, and hunting	1,426	19.0	9.4	37.3	4.8	11.6	3.1	14.8
Mining	144	20.1	19.4	18.1	12.5	14.6	6.2	9.0
Utilities	1,823	12.5	8.6	56.1	5.3	14.5	0.4	2.7
Construction	42,059	33.5	10.5	20.2	6.4	13.6	7.4	8.4
Manufacturing	99,457	36.1	8.3	19.4	1.2	30.7	0.8	3.5
Wholesale trade	39,038	34.2	10.1	21.1	2.9	24.3	1.0	6.4
Retail trade	48,312	27.3	18.5	25.6	3.1	12.7	4.3	8.5
Transportation and warehouses	13,834	40.9	5.2	27.7	1.9	13.1	4.1	7.1
Information	24,039	11.7	15.2	32.5	5.8	30.5	1.2	3.1
Finance and insurance	21,133	15.6	18.1	25.9	19.6	11.5	3.0	6.3
Real estate, rental, leasing	20,124	28.2	8.5	29.7	5.2	15.6	3.8	9.1
Professional, scientific, and technical services	75,728	14.0	12.8	39.4	5.1	21.6	2.0	5.0
Management of companies	631	21.1	15.1	27.7	4.0	19.8	4.3	8.1
Administration, support, and waste	66,000	25.4	9.4	31.8	6.1	14.3	4.4	8.5
Education services	24,650	28.7	5.3	41.4	2.4	11.9	3.6	6.8
Health care and social assistance	72,692	26.5	5.6	40.9	3.9	11.4	4.6	7.1
Arts, entertainment, and recreation	12,861	19.1	9.8	39.8	5.5	10.6	4.9	10.2
Accommodation and food services	46,070	24.4	9.8	38.3	3.7	11.0	5.1	7.7
Other services	46,061	27.5	11.3	31.8	3.1	11.8	6.2	8.3
Public administration	8,492	15.2	0.9	42.7	3.3	25.3	5.4	7.3
Other	278	32.7	11.5	30.6	10.8	9.4	1.4	3.6
Total	664,852	26.5	10.3	30.9	4.4	17.8	3.5	6.7

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Chapter V5

Spatial Analysis of Industries, Employment, and Commute Flows in Areas of Concentrated Damage from the HayWired Earthquake Scenario

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Abstract

After a large earthquake, heavily damaged areas face challenging recoveries and businesses and employees can be more impacted by their work and home surroundings than direct damages to the buildings they occupy. This spatial analysis explores how California's San Francisco Bay region industries, jobs, and residence-workplace relations could be disrupted by concentrations of damages to homes and business establishments in census tracts (as a representation of neighborhoods). In the HayWired earthquake scenario mainshock, building damages are caused by shaking, liquefaction, landslides, and fire following earthquake. These estimated building damages are used to define areas of concentrated damage where 20 percent or more of building square footage in census tracts would be extensively or completely damaged. Analyses show: (1) building occupancy square footage contained in areas of concentrated damage; (2) industry employment in areas of concentrated damage; and (3) relations between employees' homes and (or) workplaces in areas of concentrated damage.

Results vary across geographical subareas and industry sectors. Areas of concentrated damage are largely determined by presence and vulnerability of industrial/warehouse, retail/commercial, and multifamily or group-living buildings. The central Alameda County subarea is a focal point for concentrated damage that contains a large share of the region's industrial/warehouse employment and residents working in these jobs. The concentration of vulnerable buildings could engender neighborhood effects that spread disruption to buildings that are otherwise still usable. For example, population displacement from usable single-family/duplex buildings could be caused by neighborhood disruption of household services (such as schools). Neighborhood effects may be further spread through commute patterns if employees' performance is adversely affected by the physical and psychological toll of living in concentrated-damage areas. Some of these employees would work in less-impacted areas of Alameda and Contra Costa Counties, in San Francisco office jobs, and in Santa Clara County goods-producing jobs. On the other hand, employees with jobs in concentrated-damage areas could lose jobs and income, further affecting the communities where they live throughout the San Francisco Bay region. Overall, around 442,000 employees live and (or) work in areas of concentrated damage from earthquake hazards, which is about 10 percent of the nine-county San Francisco Bay region employment. These numbers increase to 595,000 employees and 14 percent of employment if damages from fire following earthquake hazards are included. Some of these employees would lose income for various periods of time, lose jobs, change workplaces, and (or) be displaced from their residences.[6]

Leveraging recent disaster literature and regional studies, analyses of concentrated-damage areas and the home-workplace relation raises a number of considerations for emergency managers, businesses, communities, cities, and regional entities to mitigate, prepare, respond, and recover from a large earthquake in the San Francisco Bay region. The spatial perspective of building damages reinforces the merits of systematic building retrofits to protect a neighborhood and planning for a quick recovery that is consistent with its community characteristics and its balance of residential and business functions. Potential cordons around heavily concentrated damage incites preparations for cordon implementation and the management of tensions between public safety and business resumption, and location or redundancy of critical assets outside potential cordons. The home-workplace

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[6]Broad consequences of employment losses are addressed in the HayWired macroeconomic chapters by Kroll and others (this volume) and Sue Wing and others (this volume).

relation prompts businesses to plan for stranded employees after a large earthquake; for incapacitated, less productive, or displaced employees during response and recovery; for transportation and communication barriers between the workplaces and homes; and for relocation of business premises. Across sectors, effects of concentrated building damage and home-workplace relations prompts consideration of organizational adaptation and where support and resources may need to be focused. For example, construction and goods-movement industries, an important source for middle income jobs, are disproportionately impacted, yet instrumental for recovery. Job and commute disruptions from a large earthquake on the Hayward Fault could affect the current industrial land uses by accelerating the exit of declining manufacturing and construction industries (in Alameda and Contra Costa Counties, respectively). This could exacerbate the already precarious position of specialized industrial clusters in older manufacturing districts, especially in the central Alameda County subarea, and move manufacturing to more affordable places, which would create ripple effects to suppliers, customers, research and development, and headquarter operations. Accelerating the gradual conversion of industrial to higher uses of mixed land uses and priority development areas (PDAs), would additionally dislocate jobs. After a large earthquake, spatial economic demand shifts of businesses and residences may boost and stress less-damaged areas while recovery lags in the concentrated-damage areas and resource allocations would be a regional issue for the San Francisco Bay region and beyond. The findings also have broad implications for economic development policy in the region, suggesting value in focusing forward-looking resilience policies on geographies where key middle-wage industrial activities are concentrated in the region, so that they have more capacity to plan for and recover from a large earthquake.

Introduction

The HayWired scenario examines a hypothetical earthquake (mainshock) with a moment magnitude (M_w) of 7.0 occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region (Detweiler and Wein, 2017). An estimate of building damages and costs caused by mainshock shaking, liquefaction, landslides, and fire are documented in Seligson and others (2018) and Scawthorn (2018). However, the specific geography of the damage to the region's places of work and its residential communities, as well as the relation between them, will affect the function of the region's economy following the mainshock. This chapter provides a spatial analysis of how the San Francisco Bay region's industries, jobs, and employee residences could be disrupted by concentrations of building damages (defined as more than 20 percent extensive and complete damage to building square footage in a census tract). Using relations between homes and workplaces, the analysis shows how damaged neighborhood effects could spread through job/income losses and (or) difficult living conditions. The analysis uses the same maps of concentrated damages developed by Johnson and others (this volume) to complement a focus on potential residential population displacement with a perspective on potential disruption to industry sectors and jobs and also to connect the two analyses through the relation between employee workplaces and (or) their homes in heavily damaged neighborhoods in the San Francisco Bay region.

This spatial analysis is informed by the disaster literature (summarized in the next section) in the following ways:

- macroeconomic analyses can hide uneven microeconomic-level or business impacts;
- neighborhood effects of concentrated damage can have larger impacts on businesses than direct damages alone;
- spatial economic demand shifts occur in response to concentrated damages, which may have broad implications for long-term survival of an industry where it is concentrated in a damaged area; and
- businesses can be affected by employee productivity losses and population displacement caused by concentrated damage in their residential neighborhoods such that business and residential recoveries are intertwined.

Our first analytical step is to define concentrated building damage that likely impacts its surrounding residential neighborhood or business districts. We use the same definition justified by Johnson and others (this volume), that is, 20 percent of the building square footage in a census tract is extensively or completely damaged as categorized by the Federal Emergency Management Agency's (FEMA) Hazus-MH 2.1 loss-estimation software (hereafter referred to as Hazus) in Federal Emergency Management Agency (2012). The 20-percent damage concentration threshold is not ironclad, but follows from observations of how much damage an area (beyond individual buildings) can sustain and still function and readily recover, with the implication that beyond this threshold, which functions as a tipping point of sorts, recovery challenges become increasingly greater (Johnson and others, this volume). Two cases of building-damage concentrations are considered: (1) damage from only ground shaking, liquefaction, and landslide hazards (estimated by Seligson and others, 2018; hereafter referred to as "earthquake hazards") and (2) damage from fire following earthquake in addition to the three earthquake hazards (from Johnson and others, this volume; hereafter referred to as "all hazards"). The examination of the earthquake hazards and all hazards cases illustrates the different distribution of impacts that fire could add in this spatial analysis, separates out the larger uncertainty of the fire analysis, and aligns with the other analyses in this volume that examine both cases (Johnson and others, this volume; Wein, Haveman, and others, this volume; Sue Wing and others, this volume).

We group concentrated-damage areas within seven geographic subareas (of census tracts and [or] cities) to capture the general spatial distribution of the HayWired mainshock

damages and develop broad insights about business vulnerability and recovery needs based on lessons from prior studies and experience. We present spatial analyses of the two hazard cases and subareas from three perspectives:

1. Building occupancy damage inside and outside of concentrated-damage areas to illustrate potential neighborhood disruption to otherwise usable buildings;
2. Employment by industry groups in areas of concentrated building damage to estimate the number of jobs that are potentially affected; and
3. Relations between employees' homes and (or) their workplaces in concentrated-damage areas to illustrate potential employed resident issues (for example, displacement or difficult living situation) and (or) employee issues (for example, job relocation or loss).

In conclusion, we incorporate insights from the disaster literature and regional studies to discuss mitigating, preparing for, responding to, and recovering damaged neighborhoods and implications for businesses, emergency managers, communities, governments, and their corresponding policies and programs.

Disaster Literature on Spatial Aspects

Macroeconomic analyses are included in this volume, but they may obscure localized economic impacts (Dahlhamer and Tierney, 1998). One example of this is the 2010–present Canterbury earthquake sequence in New Zealand—the regional economy remained strong and was reasonably resilient (Parker and Steenkamp, 2012) despite damages that were 20 percent of the country's total Gross Domestic Product and despite the loss of the use of workplaces for 50,000 employees and hundreds of residences in the City of Christchurch's central business district (CBD).

Not all buildings in the Christchurch CBD were unsafe for occupancy, but 110 city blocks were initially cordoned in response to aftershock risks from damaged and weakened buildings (Kim and others, 2017). Most businesses were able to relocate, but the accommodation and hospitality sector was one of the hardest hit because two-thirds of the hotels were concentrated in the CBD; the retail sector was also impacted, but not the manufacturing sector that was located outside of the worst hit area (Parker and Steenkamp, 2012). However, after the 1995 Kobe, Japan, earthquake that more directly and disproportionately impacted productive industries and the port (Horwich, 2000), employment in manufacturing shifted to (lower paying) service jobs faster than the rates of de-industrialization (duPont and others, 2015).

Neighborhood effects have been documented before in the San Francisco Bay region, starting with the 1989 Loma Prieta earthquake. Kroll and others (1990) reported that single-location retail and some finance, insurance, real estate, and service businesses were not only affected by direct damages, but also surrounding damage. After the more recent 2014 South Napa earthquake, a single-location retail business was ordered to evacuate away from an unsafe adjacent building and was closed for more than a year before it could re-establish in an affordable space (observed by A. Wein during an Earthquake Engineering Research Institute [EERI] reconnaissance trip in 2016).

Neighborhood effects on businesses were first substantiated by Dahlhamer and Tierney (1998) when they found that shaking intensity was a stronger explanatory variable than direct physical damage for a business being worse off 18 months after the 1995 Northridge earthquake. Similarly, Chang and Falit-Baiamonte (2002) found that physical damage was a weak predictor of business loss and business recovery was determined by conditions and perceptions of the neighborhood, including street closures, lost parking spaces, and media portrayals that deterred foot traffic. Brick-and-mortar retail and commerce, and city/local government services, have been vulnerable to losing the local customer base, in particular (Brown and others, 2015; Chang and Falit-Baiamonte, 2002; Whitman and others, 2014).

Christchurch CBD businesses adapted to the cordon by relocating with similar businesses and sharing work spaces, in other business locations, in homes by teleworking, by using cafes outside of the cordoned area for meetings, and in vacant rental space (observed by A. Wein during an EERI reconnaissance trip in 2011; Bowden, 2011; Donnelly and Proctor-Thomson, 2013). Businesses were reluctant to move because of financial, social, and market costs, but feasible relocations occurred in waves that increased in distance from their original location over time (Brown and others, 2015). The spatial shifts of businesses pushed out of the Christchurch CBD cordon appeared as hotspots of business activity change in the suburbs (Brown and others, 2015). The eventual demolition of 70 percent of the buildings in the Christchurch CBD (Kim and others, 2017) left a hole in the middle of the city. As the CBD was rebuilt, business activity trickled back, but the redevelopment of the CBD has been patchy for a number of years (for example, Anderson, 2014).

Similarly, one year after Hurricane Katrina (which adversely affected several states in the southern United States in 2005), Xiao and Nilawar (2013) describe the core disaster area as a doughnut hole of low income and employment growth surrounded by an edge of high growth counties and parishes within 60 miles. Although growth picked up in the core disaster area in subsequent years, employment and income still lagged behind four years later. The competitive advantages of the high-growth edge were lower transportation time and costs for customers. Xiao and Nilawar (2013) recognize that the edge sustained high growth from higher levels of educated labor, resident income, and growth prior to Hurricane Katrina. In both the Christchurch earthquake and Hurricane Katrina examples, recovery of business and residential neighborhoods with concentrated damage lagged behind less-impacted areas and spatial shifts in business activity were mapped from holes in the cities to the suburbs

and the edges, respectively. Similarly, duPont and others (2015) detect long-term shifts in population, income, and employment away from the core disaster area of the 1995 Kobe earthquake.

Damages to employee homes and neighborhoods have contributed to declines in business productivity when distracted employees check on their families and homes immediately after an earthquake (Chang and others, 2014). After the 2011 Christchurch earthquake, some employees (including executives) departed to keep their children in school and some workplaces provided for basic needs of employees (for example, shower and laundry facilities) (Malinen and others, 2018; observed by A. Wein during an EERI reconnaissance trip in 2011). Employee well-being impacts persisted during the Canterbury earthquake sequence because of stresses of aftershocks and resolving homeowner insurance (Neilsen, 2018) and was a top issue for businesses (Brown and others, 2015).

Xiao and Van Zandt (2011) were the first to quantify a relation between business and residential recovery; the return of households and businesses were mutually dependent across space in Galveston, Texas, after Hurricane Ike in 2008. They found that the re-opening of businesses influenced nearby (within 2.42 kilometers [km]) households' decisions to return to their homes and the return of households in the market area (within 3.22 km) increased the chances of those businesses returning. How to manage this interdependence was a question asked by city council members of visiting social scientists during a reconnaissance of the 2011 Christchurch earthquake (observed by A. Wein during an EERI reconnaissance trip in 2011).

Xiao and Van Zandt (2011) did not differentiate among business sectors, but the interdependence of residents and retail businesses (Chang and Falit-Baiamonte, 2002) has been noted—retail businesses are more likely to fail if residents leave a neighborhood, whereas closure of neighborhood retail businesses can reduce the ability of residents to stay in an impacted area. The vulnerability of impacted retail businesses was seen after the 1989 Loma Prieta earthquake, where retail business losses in damaged areas were picked up as gains elsewhere in the region (Brady and Perkins, 1991).

Analytical Framework

The analytical framework combines information from building damage analyses of HayWired scenario earthquake hazards (Seligson and others, 2018) and fire following earthquake (Scawthorn, 2018) with data available through the U.S. Census Bureau. We describe the analytical steps and terms used to identify areas with concentrated damages and summarize the building damage, employment levels, and workplace-home relation by geography in these areas. We conclude this section by recognizing the limitations of our approach and its scope.

The Spatial Building Blocks in Hazus: Census Tracts

The HayWired scenario mainshock building-damage assessment for earthquake hazards produces results down to the census-tract level using tract boundaries from the 2000 census (Seligson and others, 2018). Fire-following-earthquake building damages (Scawthorn, 2018) were allocated to the 2000 census tracts and integrated with the earthquake hazard damages (Johnson and others, this volume). For this analysis, the results for the 2000 tract boundaries were redistributed into 2010 tract geographies to allow for comparisons to more recent employment data available through the U.S. Census Longitudinal Employer-Household Dynamics (LEHD) Program and LEHD Origin-Destination Employment Statistics (LODES) datasets (U.S. Census Bureau, 2017). To redistribute building damages from 2000 census tracts to 2010 census tracts, housing units in 2010 tracts were used to weight the distribution of losses. For example, a 2000 census tract split into two tracts in 2010 uses the relative share of housing units in each tract to break up the losses for the original tract. This method is more accurate for housing (residential) distribution but may be less representative for commercial distributions where there is less housing in those areas (Johnson and others, this volume). In all, there are 2,386 census tracts (of the 2010 vintage) analyzed in the HayWired scenario building-damage assessment, of which 1,588 are in the nine-county San Francisco Bay region, with the remainder located in adjacent counties to more fully account for commute flows beyond the region.

Building Damage States

Seligson and others (2018) use Hazus to estimate building losses from HayWired scenario mainshock shaking, liquefaction, and landslides. An intermediate step in this calculation was the estimation of building damage states. Building square footage was tallied for five damage states: none, slight, moderate, extensive, and complete. The additional square footage of buildings burned by fire following earthquake damage is classified as complete damage (Johnson and others, this volume). Recall that the four mainshock hazards plus fire hazards are referred to as all hazards and earthquake hazards refers to only the mainshock hazards without fire. Building square footage in each damage state can be converted to building counts in each damage state using the Hazus correspondence table in appendix 1.

Extensive building damage state repairs may take weeks to months. The complete building damage state repairs or replacements may take months to years. This analysis focuses only on concentrations of extensively or completely damaged building square footage for defining the areas of concentrated damage, consistent with HayWired community-at-risk analyses that focus on residential population displacement and consequences for housing recovery (Johnson and others, this volume). A map showing

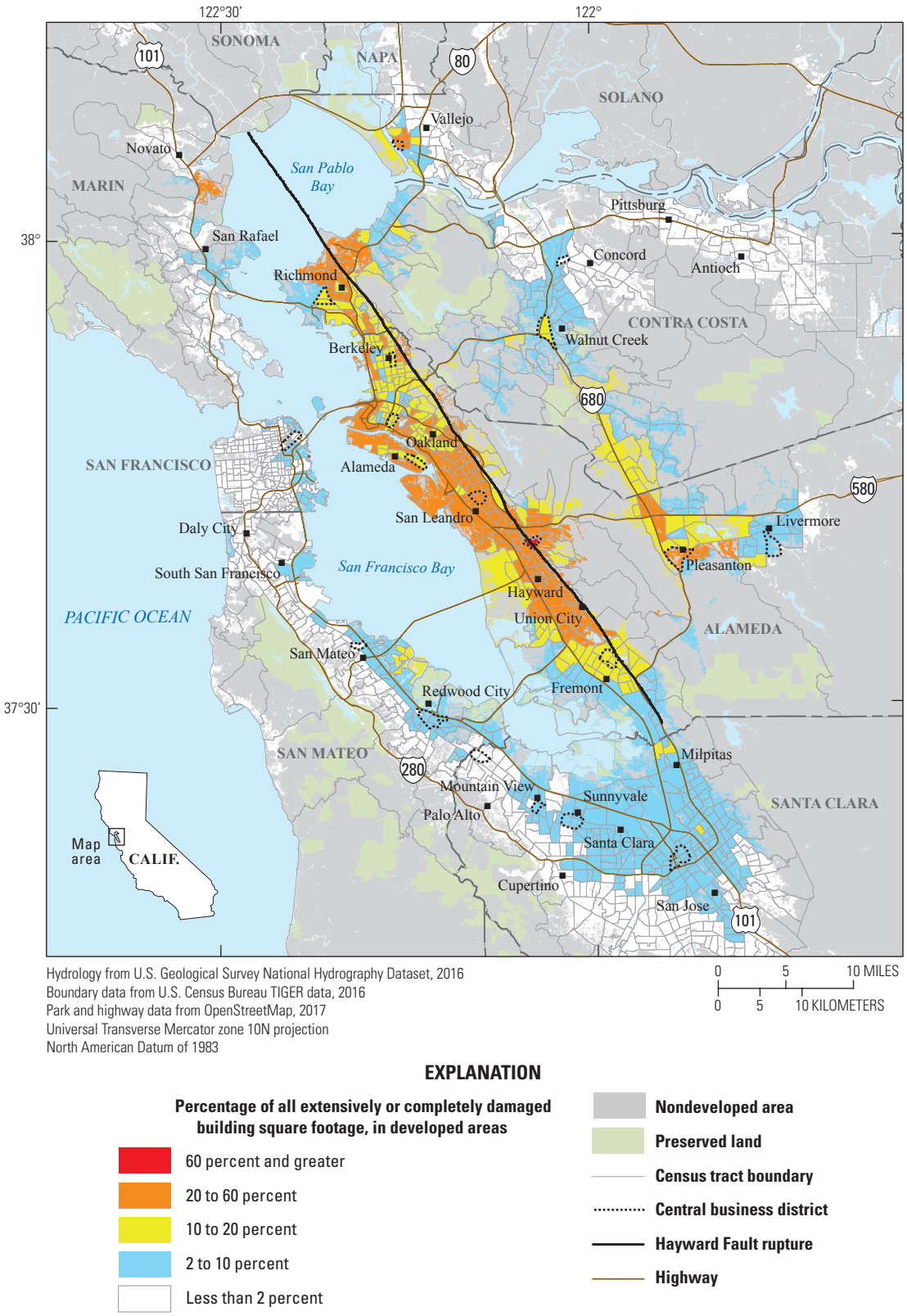


Figure 1. Map of the San Francisco Bay region, California, showing the percentage of building square footage that is extensively or completely damaged across all occupancy groups as a result of all HayWired earthquake scenario mainshock hazards (ground shaking, landslide, liquefaction, and fire following earthquake). Modified from Johnson and others (this volume).

the percentage of all building occupancy square footage that has extensive or complete damage caused by all hazards in each census tract is shown in figure 1. Maps of damage concentration for each building occupancy group are presented by Johnson and others (this volume).

Areas of Concentrated Damage

Based on literature reviews and other information sources, Johnson and others (this volume) determined that a threshold for causing significant displacement of businesses and households following a major disaster was 20 percent or more of extensive or complete damage to total building square footage in an area. If the threshold is applied to census tracts in the San Francisco Bay region, 11 percent (173 tracts) of the total meets this concentrated damage threshold for all hazards damages. Of these, 115 tracts qualify as concentrated-damage areas from earthquake hazard damages (7 percent of the tracts in the area). These tracts are predominantly in Alameda County with the remainder in Contra Costa County; the addition of fire following earthquake damage is responsible for concentrated-damage areas in the cities of Novato and Vallejo, as shown in figure 2. Santa Clara County is broadly impacted but contains no tracts where concentrations of damage exceed the 20 percent extensive or complete building damage threshold. Significant damage in most of the areas in Santa Clara County is within the range of 2 to 10 percent of all buildings. For additional information about concentrated-damage areas for the HayWired earthquake scenario, please refer to Johnson and others (this volume) (for methods) and Jones, Johnson, and others (2020) (for data).

Subareas

Concentrated-damage areas were aggregated into county subareas: northern Alameda County, central Alameda County, southern Alameda County, Dublin-Pleasanton, western Contra Costa County, Novato, and Vallejo (fig. 2). We defined these subareas to provide a general geographic context for the most significant concentrations of damage from the HayWired scenario mainshock. Although the subareas were defined using census tract boundaries, the cities with concentrated-damage areas included in each subarea are listed below; all census tracts within the subareas are defined in the accompanying data release for this chapter (Jones, Au, and Olsen, 2020).[7]

- Northern Alameda County: Berkeley, Emeryville, north Oakland, West Oakland, downtown Oakland, Albany, and Alameda
- Central Alameda County: east Oakland, San Leandro, Castro Valley, San Lorenzo, Hayward, and Union City
- Southern Alameda County: Fremont and Newark
- Dublin-Pleasanton: Dublin and Pleasanton
- Western Contra Costa County: El Cerrito, Richmond, San Pablo, and Pinole
- Novato: Novato
- Vallejo: Vallejo

Figure 3 shows the distribution of tracts with concentrated damage from all hazards and earthquake hazards by subarea. The tracts shown in dark orange in this figure are additional tracts added to the concentrated-damage footprint if fire is incorporated into the HayWired scenario damages; the sum of dark orange and light orange represents the all hazards footprint (fig. 3). In general, subareas are referred to by name, and unless otherwise noted, the references to subarea impacts only consider tracts with concentrated damage within each subarea, not every tract in the subarea. The tracts in subareas with less-concentrated damage are accounted for as, for example, "Alameda County remainder."

Building Occupancy Groups

The building damage results are broken out into 33 detailed building occupancy classes (defined by Hazus), which represent uses of the buildings. For the purposes of this analysis, the building occupancies are collapsed into five nonresidential occupancy groups: industrial/warehouse; offices; retail/commercial; household serving; and agricultural uses. Residential classes are aggregated into three occupancy groups: single family/duplex; multifamily; and group living. A correspondence between Hazus building occupancies to occupancy groups is shown in table 1.

Industry Employment Groups

The 2015 LEHD dataset from the U.S. Census Bureau provides information on employment by industry (U.S. Census Bureau, 2017). LEHD's employment data are reported for 20 industry sectors. As for the occupancy groups, we collapsed the more detailed sector data from LEHD into five broad industry groups that correspond to the occupancy groups: industrial/warehouse; offices; retail/commercial; household serving; and agricultural uses. A correspondence between LEHD industry sectors to industry groups is shown in table 2. Please note that although the names of nonresidential occupancy groups and industry groups are the same, these terms are not used interchangeably. Occupancy groups relate to the Hazus building inventory data, whereas industry groups describe employment data. The data subset used for this analysis is provided by Jones, Au, and Olsen (2020).

[7]Multicity subareas avoided the problem of census tract boundaries crossing city lines; a single tract can straddle two cities.

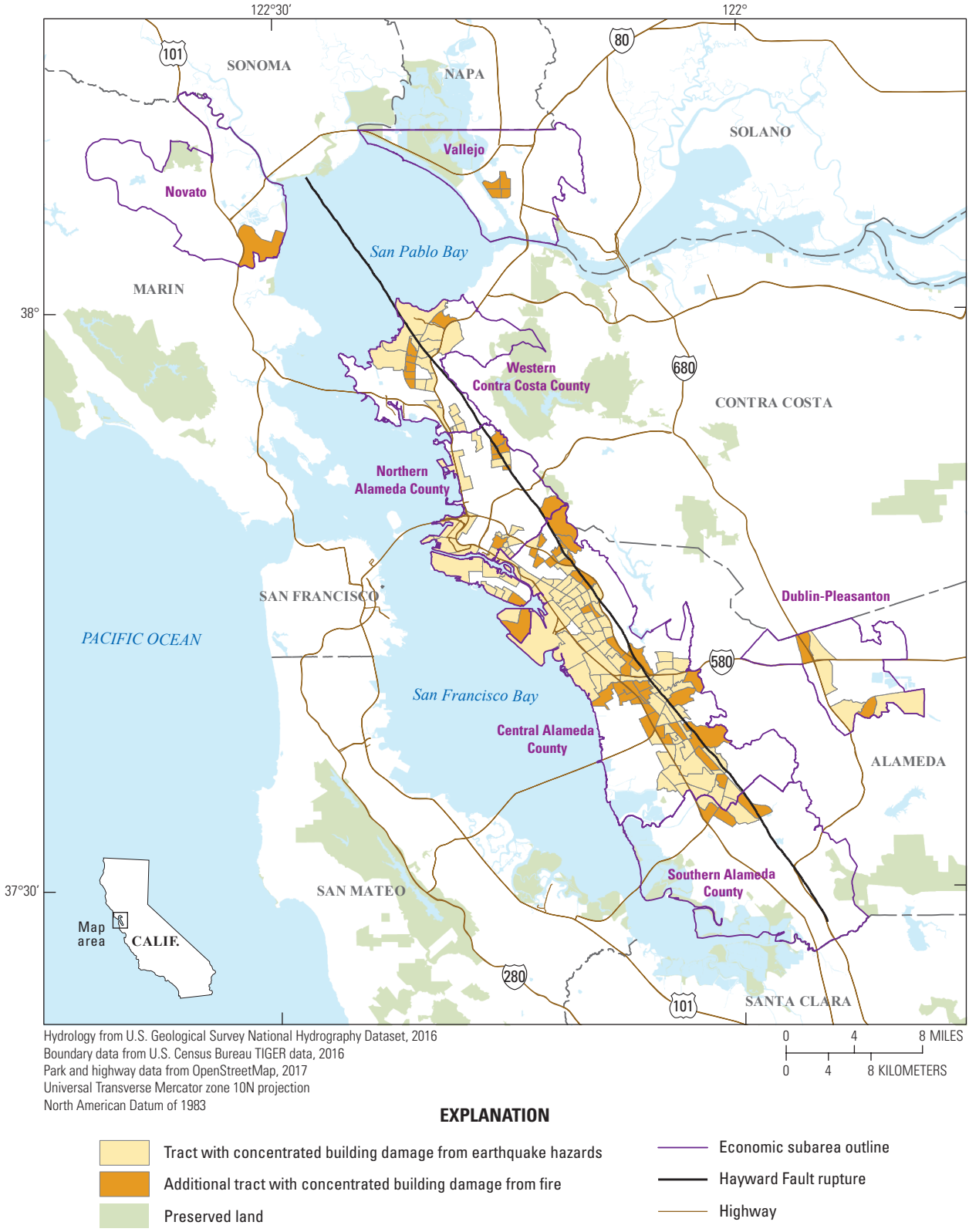


Figure 2. Map of the San Francisco Bay region, California, showing concentrated-damage areas and subareas as a result of hazards caused by the HayWired earthquake scenario mainshock on the Hayward Fault. Concentrated-damage areas are defined as census tracts with 20 percent or more of their total building square footage in extensive or complete damage according to the Hazus analysis (Seligson and others, 2018). Light orange areas are those affected only by earthquake hazards (ground shaking, liquefaction, and landslide) and dark orange areas are added if fire following earthquake damages are included.

Table 1. Hazus occupancy classification to occupancy group correspondence.

Occupancy group	Hazus classification	Hazus occupancy description
Nonresidential		
Industrial/warehouse	COM2	Warehouse
	IND1	Industrial-Heavy
	IND2	Industrial-Light
	IND3	Industrial-Food/drugs/chemicals
	IND4	Industrial-Metals/minerals processing
	IND5	Industrial-High tech
	IND6	Industrial-Construction
Offices	COM4	Professional/technical services
Retail/commercial	COM1	Retail trade
	COM10	Parking
	COM3	Personal and repair services
	COM5	Banks
	COM8	Entertainment and recreation
	COM9	Theaters
	RES4	Hotel/motel
Household serving	COM6	Hospital
	COM7	Medical office/clinic
	EDU1	Grade schools
	EDU2	Colleges/universities
	GOV1	Government-General services
	GOV2	Government-Emergency response
	REL1	Church/non-profit
Agricultural uses	AGR1	Agriculture
Residential		
Single family/duplex	RES1	Single family
	RES3A	Duplex
	RES2	Mobile home
Multifamily	RES3B	Multifamily (3–4 units)
	RES3C	Multifamily (5–9 units)
	RES3D	Multifamily (10–19 units)
	RES3E	Multifamily (20–49 units)
	RES3F	Multifamily (50+ units)
Group living	RES5	Dormitories
	RES6	Nursing home

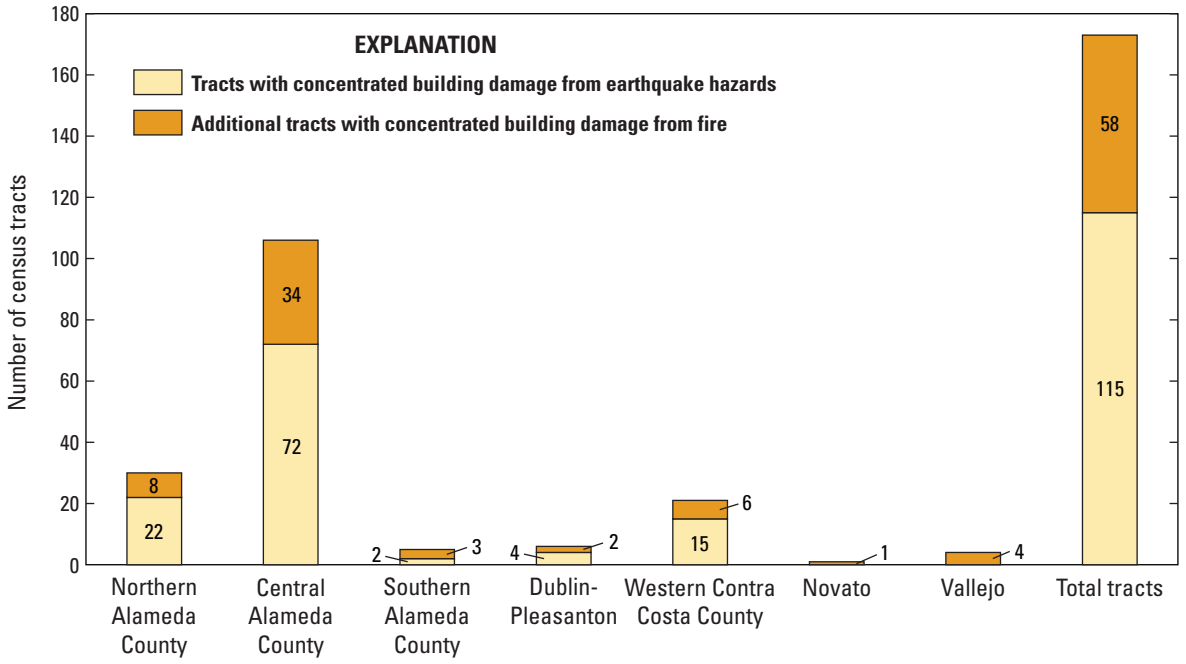


Figure 3. Bar chart showing census tracts with concentrated damage by subarea, identified by damages from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. Consistent with the map in figure 2, light orange represents tracts with concentrated damage from earthquake hazards (ground shaking, liquefaction, and landslide) and dark orange represents additional tracts when fire following earthquake damages are included.

Table 2. U.S. Census Bureau industry classification to industry group correspondence.

[NAICS, North American Industry Classification System]

Industry group	NAICS sector	NAICS industry description
Industrial/warehouse	21	Mining, quarrying, and oil and gas extraction
	22	Utilities
	23	Construction
	31–33	Manufacturing
	42	Wholesale trade
	48–49	Transportation and warehousing
Offices	51	Information
	52	Finance and insurance
	53	Real estate and rental and leasing
	54	Professional, scientific, and technical services
	55	Management of companies and enterprises
Retail/commercial	44–45	Retail trade
	71	Arts, entertainment, recreation
	72	Accommodation and food
	81	Other services
Household serving	56	Administration, support and waste management, and remediation
	61	Education
	62	Health and social services
	92	Public administration
Agricultural uses	11	Agriculture, forestry, fishing, and hunting

Household and Workplace Relation

The LODES dataset provides detailed spatial distributions of workers' employment and residential locations (U.S. Census Bureau, 2017). Our analysis tallies workers and employed residents working and (or) living in concentrated-damage areas according to where they live and work in subareas and beyond. However, since the San Francisco Bay region workforce extends beyond the nine counties bordering San Francisco Bay, this analysis includes employees that commute from the San Joaquin Valley region (Merced, San Joaquin, and Stanislaus Counties), the Sacramento Valley region (Sacramento and Yolo Counties), the central coast region (Monterey, San Benito, and Santa Cruz Counties), and other areas within California to work in concentrated-damage areas. Please note that LODES aggregates the origin-destination industry sector data into three segments: goods producing; trade, transportation, and utilities; and all other services. These data cannot be broken out into the individual industry groups listed in table 2. A correspondence between LEHD industry sectors to LODES industry segments is provided in appendix 1. In addition, LODES data used in this analysis are focused on within-state workers. Because of this, the worker totals will vary slightly compared to the LEHD employment totals, which look at workers in the region regardless of where they reside. The data subset used for this analysis is provided by Jones, Au, and Olsen (2020).

Limitations and Knowledge Gaps of the Analytical Framework

We define concentrated-damage areas as tracts with at least 20 percent of the building square footage in an extensive or complete damage state. This threshold for defining concentrated damage is based on available data and expert opinion (Johnson and others, this volume). The definition has not considered whether the 20 percent threshold for neighborhood effects could vary by building height (commonly found in dense downtown areas) or the mix of building uses (for example, primarily single family/duplex versus industrial/warehouse or retail/commercial).

Census tracts could be impacted by other disruptive forces, including utility and transportation damages (such as Tierney, 1997) or toxic plumes. For example, in Johnson and others (this volume), areas with utility and transportation issues were illustrated by coarsely identifying areas where at least two services could potentially be disrupted for more than a month. We find that most (141 of the 173) tracts with concentrated damage from all hazards are contained or overlapping with these areas and another 107 tracts with less-concentrated damage are contained in or overlap with these areas. The average concentration of extensive and complete damage in these less-concentrated-damage tracts is 14 percent. Among the 17 tracts with less-concentrated damage that are completely contained within the long-term utility/transportation restoration areas, the average extensive and complete building damage is 16 percent. This suggests that tracts classified here with less-concentrated damage could potentially become areas with significant displacement of businesses and households because of long restoration times of multiple utility and transportation services. We find these borderline tracts in areas with high probability of ground failure and along the Hayward Fault and they may include areas with strong shaking and better performing buildings (for example, single family homes or offices).

For each step, it is necessary to use crosswalks between sector data in the form of 33 Hazus building occupancies, 20 LEHD employment sectors, and 3 LODES employment segments. Nonetheless, the sector results are in reasonable agreement, except for the household-serving group, where the Hazus square footage for education and government occupancies is less than the LEHD employment data suggests (which becomes evident in a comparison of results). Hazus building inventory data has been found to underestimate square footage of educational building occupancy (H. Seligson, Seligson Consulting, written commun., 2017).

Subareas are defined to reduce the detail of summarizing data and relations between census tracts and to capture spatial variations within the broader county geographies, since the tract boundaries do not necessarily correspond to city boundaries. The central Alameda County subarea is the largest area and defines the core of the disaster area. The subareas group tracts with concentrated damage within counties rather than transportation zones, meaning that the results are less specific about additional commute disruption between the homes and workplaces.

Building Occupancy Damages

In this section, we show how extensive and complete building damage is distributed between concentrated and less-concentrated-damage areas in the region. The spillover effect in the concentrated-damage areas means that otherwise usable buildings could suffer from neighborhood effects. Results, shown in figures and tables, vary by building occupancy class and subarea; more detailed tables of results are provided in appendix 2.

Regional

Figures 4 and 5 show the amount and percentage of building occupancy square footage in the nine-county San Francisco Bay region, divided into four categories based on two categories of building damage states (disruptive building damage, defined as extensive or complete damage to building square footage, or less-disruptive building damage, defined as none, slight, or moderate damage to building square footage) and two types of location (in concentrated-damage areas or less-concentrated-damage areas). The distinction here is that 20 percent or more disruptive building damage defines concentrated damage, indicating a spatially impaired neighborhood, whereas disruptive building damage in less-concentrated-damage areas is assumed to be contained to the building, not impairing the neighborhood.

We see that most building square footage is in residential classes, particularly single-family/duplex occupancy, and residential classes compose the largest amount of disruptive building damage (light and dark reds, fig. 4). A smaller percentage of single-family/duplex housing types incur disruptive building damage because they out-perform industrial and commercial building types (light and dark reds, fig. 5), making them a small contributor to concentrations of damage. Consequently, for earthquake hazards, disruptive building damage for single-family/duplex housing is largely in tracts with less-concentrated damage (light red). However, conflagrations concentrate residential damages such that disruptive damage is only slightly more present in less-concentrated-damage areas for all hazards than earthquake hazards (light red bars in fig. 5).

The multifamily and group living housing, industrial/warehouse, and retail/commercial occupancies have a larger share of their building square footage in concentrated-damage areas (compared to single-family/duplex residences and offices) (dark colors, fig. 5), which corresponds to these building occupancy types being more vulnerable to the effects of the mainshock hazards (light and dark reds, fig. 5) and fire (in the case of multifamily and group living occupancies) (all hazards versus earthquake hazards, fig. 5). The household-serving industry group is also disproportionately affected by fire based on the distribution of burned square footage relative to schools, applying 1995 Northridge earthquake burn data (where fires were initiated in school laboratories) to an underestimation of square footage in the occupancy class.

Neighborhood disruption from concentrated damage to otherwise usable buildings is larger than the square footage that is directly impacted in those tracts (shown in dark blue). This is an artifact of using the 20 percent disruptive building damage threshold for defining concentrated-damage areas. Most notably, less-disruptive single-family/duplex building damage in concentrated-damage areas (dark blue) is more than the total disruptive single-family/duplex building damage in the entire nine-county region (light and dark red combined) and usable homes are potentially more exposed to neighborhood disruptions than other usable building occupancies.

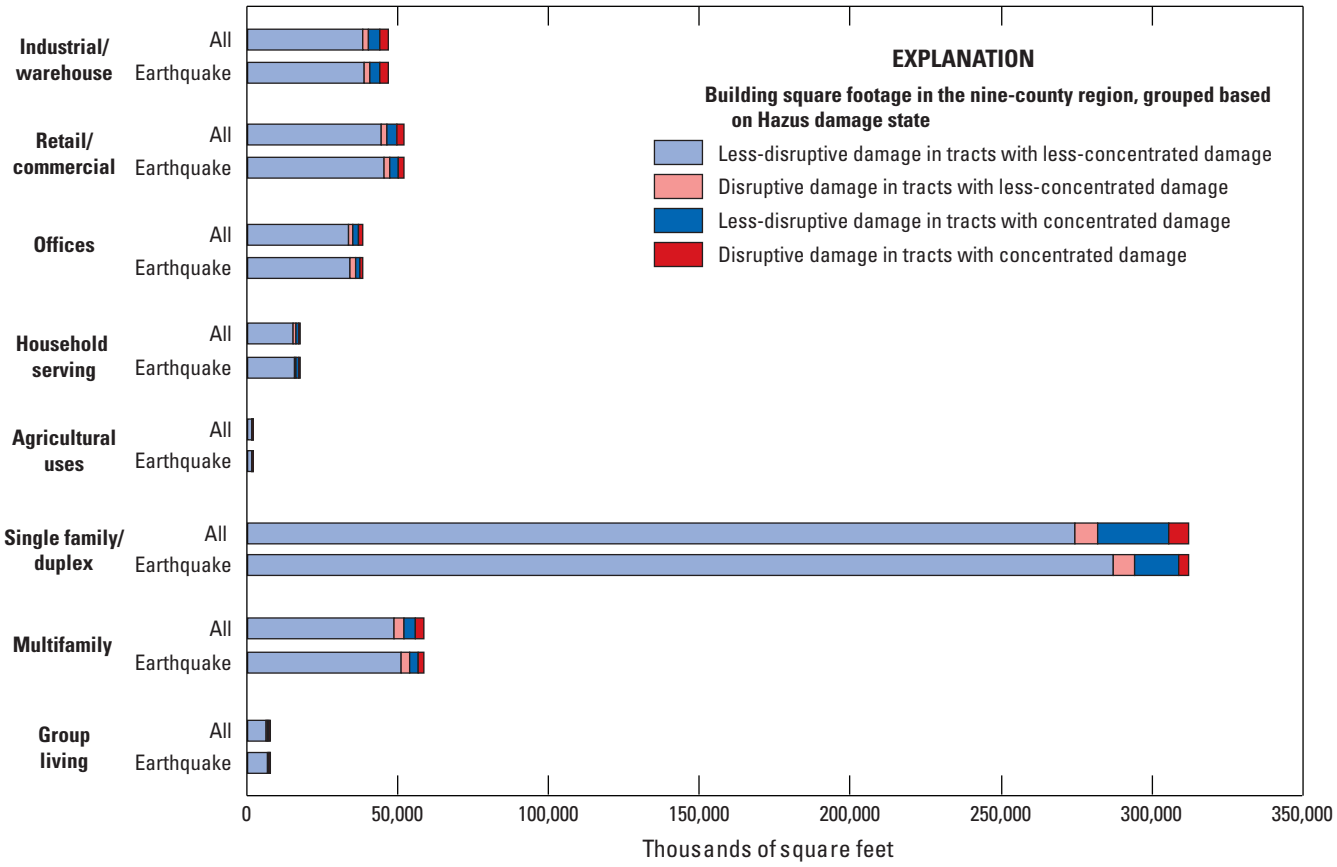


Figure 4. Bar chart showing building occupancy square footage damage for the HayWired earthquake scenario mainshock in the nine-county San Francisco Bay region, California. Results are separated into less-disruptive damage (none, slight, and moderate damage; blue colors) and disruptive damage (extensive and complete damage; red colors) according to the Hazus analysis and also separated based on location within less-concentrated-damage areas (<20 percent of building square footage is disruptively damaged; light colors) and concentrated-damage areas (≥20 percent of building square footage is disruptively damaged; dark colors). "All" refers to damage from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damage from earthquake hazards only: ground shaking, landslide, and liquefaction.

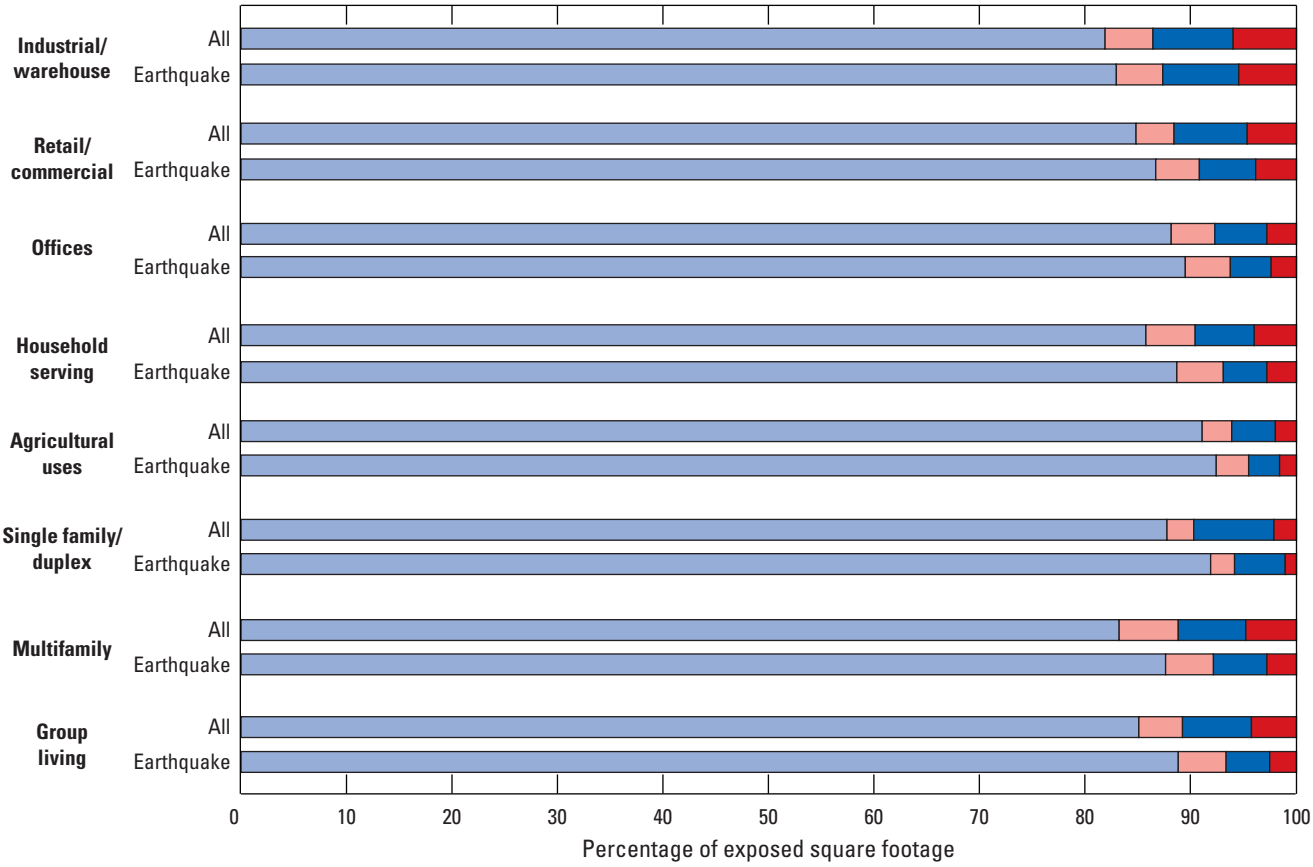


Figure 5. Bar chart showing the percentage of building occupancy square footage damage for the HayWired earthquake scenario mainshock in the nine-county San Francisco Bay region, California. Results are separated into less-disruptive damage (none, slight, and moderate damage; blue colors) and disruptive damage (extensive and complete damage; red colors) according to the Hazus analysis and also separated based on location within less-concentrated-damage areas (<20 percent of building square footage is disruptively damaged; light colors) and concentrated-damage areas (≥20 percent of building square footage is disruptively damaged; dark colors). "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards only: ground shaking, landslide, and liquefaction.

Concentrated-Damage Areas

Considering only concentrated-damage areas, 30 percent of building square footage from all hazards is disruptive (extensive and complete) building damage; 26 percent of residential square footage and 41 percent of nonresidential square footage is disruptive building damage (table 3 and dark colors compared to light colors in fig. 6). The single-family/duplex occupancy group has the most disruptive building damage square footage in concentrated-damage areas (dark purple color in fig. 6),[8] however, disruptive damage to multifamily and industrial/warehouse buildings is more common in concentrated-damage areas, followed by retail/commercial (dark colors compared with light colors in fig. 6 and lower percentages in table 3). The percentages of disruptive building damage in concentrated-damage areas range from 19 percent (single family/duplex, earthquake hazards) to 44 percent (industrial/warehouse, all hazards). The disruptive building damage percentage for an occupancy group can be less than the concentrated-damage threshold of 20 percent depending on the mix of occupancy groups in census tracts.

Subareas

Concentrated building occupancy damage results vary across subareas (that contain the concentrated-damage areas). The central Alameda County subarea covers the largest area, has the largest building square footage in concentrated-damage areas (light and dark bars in fig. 7*A*, *B*), and the largest share of disruptive (extensive and complete) building damage by square footage (dark bars in fig. 7*A*, *B*). The central Alameda County subarea contains 60 percent of the total square footage in

[8]In terms of buildings, 59 percent of square footage in concentrated-damage areas (for all hazards) is in residential use but represents 94 percent of the buildings in the same extent because, on average, nonresidential buildings tend to be bigger than residential buildings. For example, a single warehouse building could have approximately the same square footage as four single-family homes.

Table 3. Disruptive building damage in concentrated-damage areas by occupancy group for the HayWired scenario in the San Francisco Bay region, California.

[Disruptive building damage is defined as extensive or complete damage according to Hazus. Concentrated-damage areas are defined for both all hazards and earthquake hazards. All hazards are defined by damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards are defined by damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Occupancy group	Earthquake hazards		All hazards	
	Disruptive building damage, in ft^2	Disruptive building damage, in percent	Disruptive building damage, in ft^2	Disruptive building damage, in percent
Nonresidential				
Industrial/warehouse	25,492,796	44	27,599,713	44
Retail/commercial	19,636,682	41	24,030,474	40
Offices	8,744,959	37	10,479,760	36
Household serving	4,734,527	39	7,000,208	42
Agricultural uses	247,644	35	313,649	33
All nonresidential	**58,856,608**	**41**	**69,423,804**	**41**
Residential				
Single family/duplex	33,582,773	19	65,198,410	22
Multifamily	16,331,727	36	28,022,305	43
Group living	1,841,762	37	3,121,621	39
All residential	**51,756,262**	**22**	**96,342,336**	**26**
Total	**110,612,870**	**29**	**165,766,140**	**30**

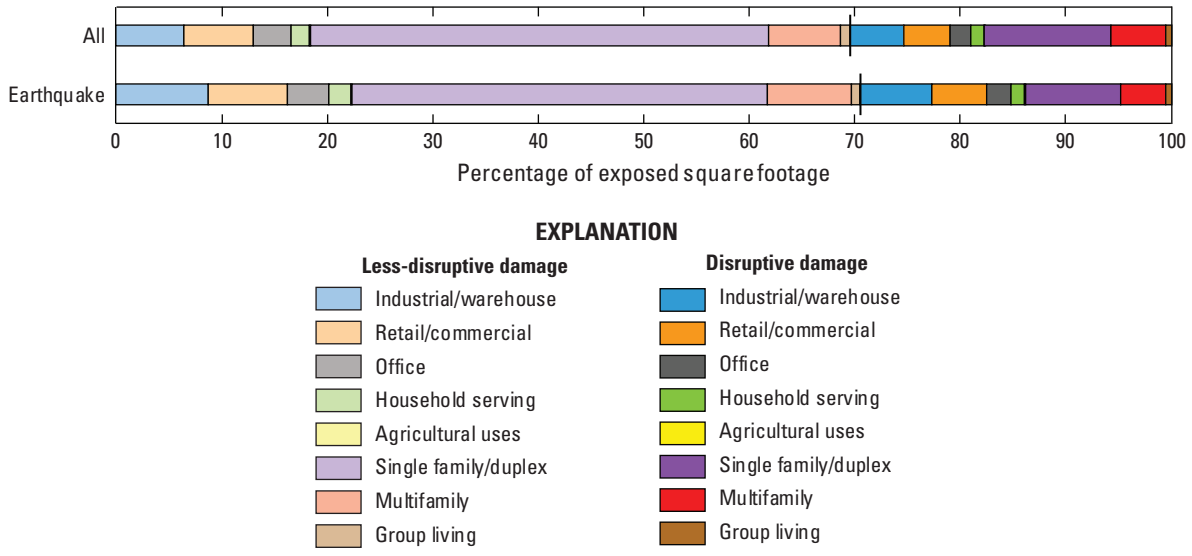


Figure 6. Bar chart showing the percentage of building occupancy square footage in concentrated-damage areas that is disruptive (extensive or complete damage according to Hazus) and less disruptive (none, slight, or moderate damage according to Hazus) for the HayWired earthquake scenario mainshock in the nine-county San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards only: ground shaking, landslide, and liquefaction. The black vertical line on each row of stacked bars represents the break point between disruptive and less-disruptive building damage.

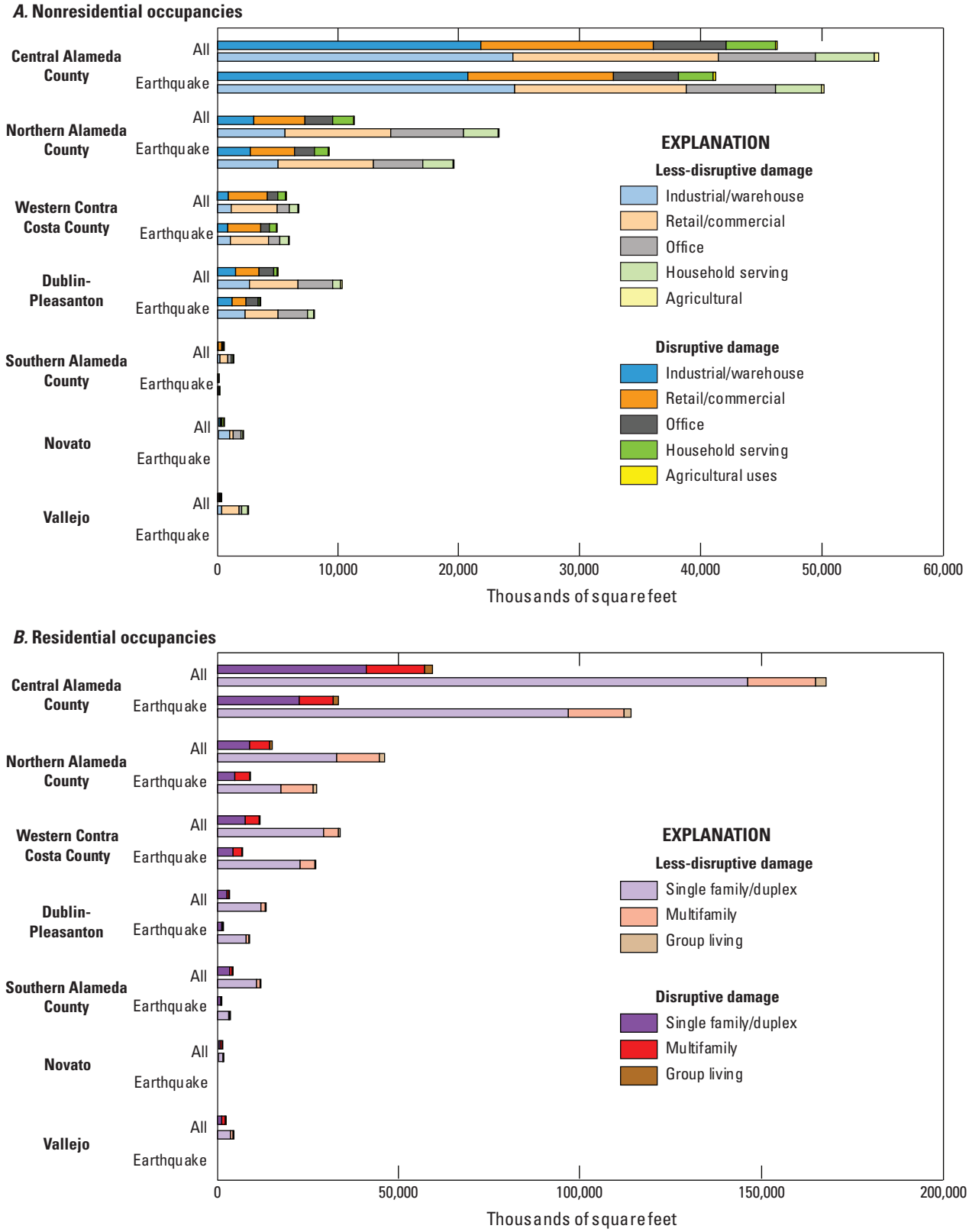


Figure 7. Bar charts showing building occupancy square footage in concentrated-damage areas by subarea for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards only: ground shaking, landslide, and liquefaction. Dark colors represent disruptive (extensive or complete damage according to Hazus) building damage; light colors represent less-disruptive (none, slight, or moderate damage according to Hazus) building damage.

concentrated-damage areas for all hazards and accounts for 67 percent of the total disruptive building damage in the all hazard concentrated-damage areas. As such, damages in the central Alameda County subarea are largely driving the results for the San Francisco Bay region.

There are some notable building occupancy differences across the subareas:

- Central Alameda County subarea hosts most (about 74–77 percent) of the industrial/warehouse building square footage in concentrated-damage areas (blue colors) and most of the disruptive damage to these buildings occurs in this subarea (fig. 7*A*).
- Western Contra Costa County subarea hosts relatively more retail/commercial square footage in concentrated-damage areas than other subareas (orange in fig. 8*A*) and most of the disruptive damage in this subarea is to buildings in these occupancies group (dark orange in fig. 8A).
- Dublin-Pleasanton subarea hosts relatively more office buildings in concentrated-damage areas except for Novato (gray in fig. 8*A*), which shows the largest proportion of disruptive damage to these building occupancies (dark purple in fig. 8*A*) compared to other subareas.
- Northern Alameda County subarea shows relatively more multifamily and group living housing in its residential square footage than other subareas (likely related to student housing) and the largest percentage of multifamily and group living residential building square footage with disruptive damage (light and dark red) as compared to other subareas (fig. 8*B*).
- Southern Alameda County subarea's concentrated-damage areas predominantly host residential buildings (fig. 7*A*, *B*).
- Fires in the Novato subarea result in the largest percentages of residential building square footage with disruptive building damage in concentrated-damage areas relative to other subareas—that is, 34 percent of single-family/duplex and 93 percent of multifamily building square footage (fig. 8*B*).

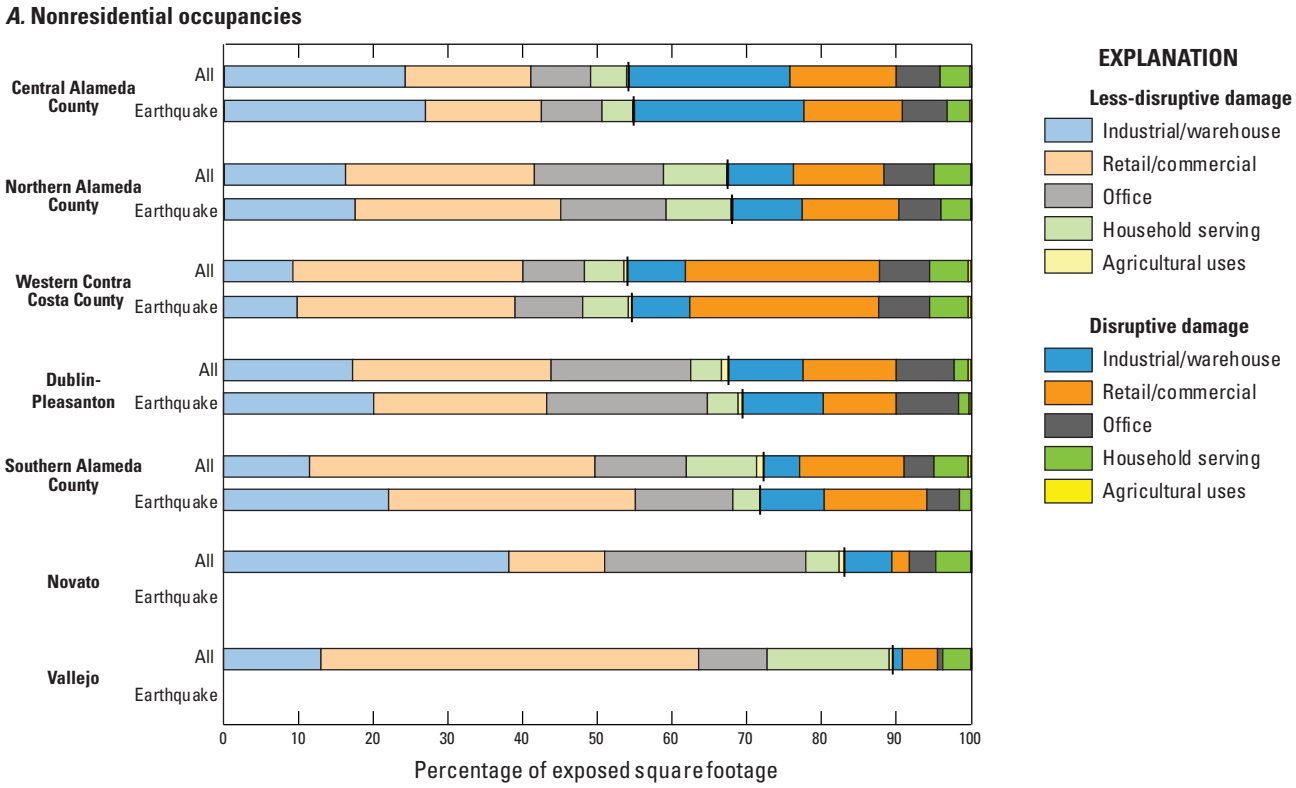


Figure 8. Bar charts showing the percentage of building occupancy square footage in concentrated-damage areas of subareas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards only: ground shaking, landslide, and liquefaction. Dark colors represent disruptive (extensive or complete damage according to Hazus) building damage; light colors represent less-disruptive (none, slight, or moderate damage according to Hazus) building damage. The black vertical line on each row of stacked bars represents the break point between disruptive and less-disruptive building damage. Figure continues on page 604.

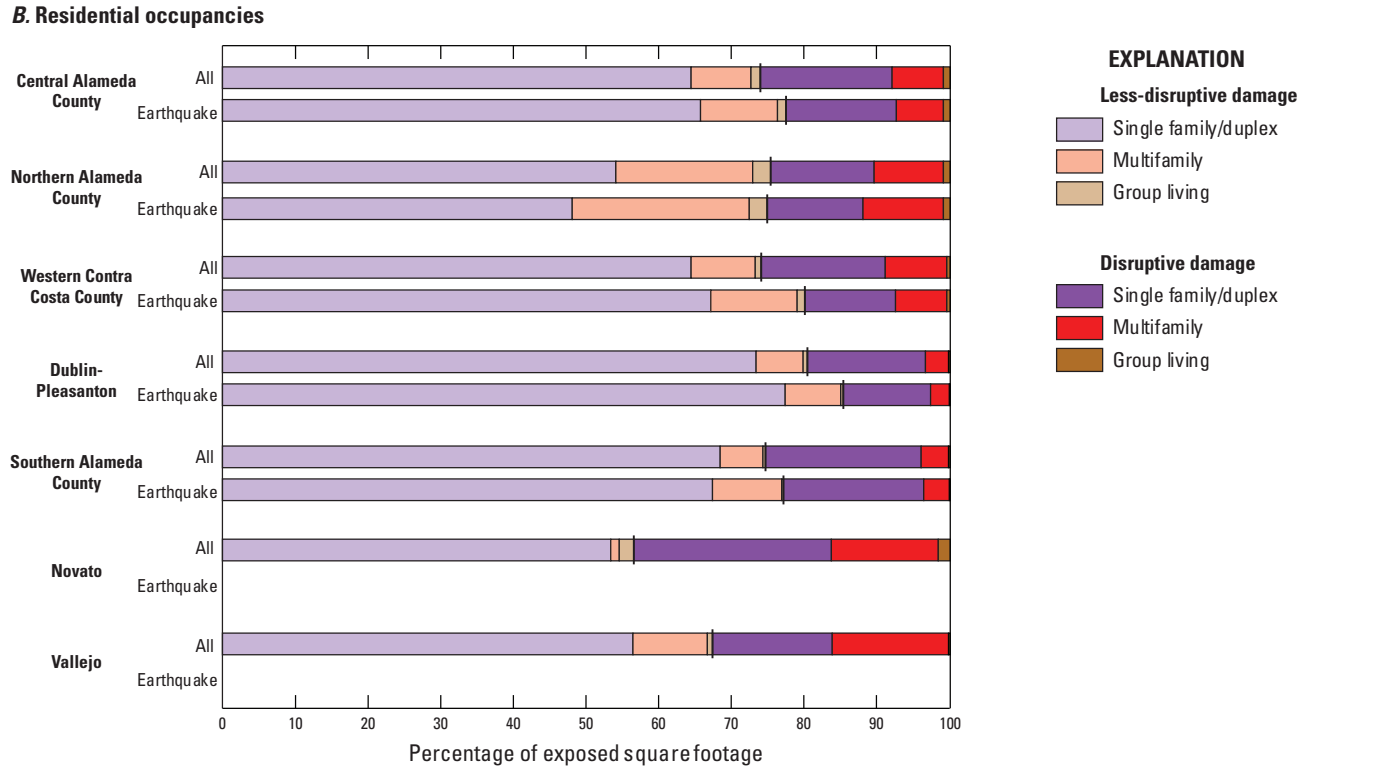


Figure 8. Bar charts showing the percentage of building occupancy square footage in concentrated-damage areas of subareas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards only: ground shaking, landslide, and liquefaction. Dark colors represent disruptive (extensive or complete damage according to Hazus) building damage; light colors represent less-disruptive (none, slight, or moderate damage according to Hazus) building damage. The black vertical line on each row of stacked bars represents the break point between disruptive and less-disruptive building damage.—Continued

Employment by Industry Group

The U.S. Census Bureau's LEHD 2015 dataset (U.S. Census Bureau, 2017) includes information on employment by 20 industry sectors. As with the nonresidential occupancy groups in the previous section, the data are collapsed into five industry groups: industrial/warehouse; retail/commercial; offices; household serving;[9] and agricultural uses. A correspondence between LEHD industry sectors to industry groups are shown in table 2.

Regional Employment

In 2015, there were approximately 330,000 jobs distributed across concentrated-damage areas from all hazards (10 percent of San Francisco Bay region jobs). The employment mix in these concentrated-damage areas is diverse: 39 percent were in the household-serving industry group (approximately 127,000), followed by 27 percent in industrial/warehouse (approximately 88,000), 24 percent in retail/commercial (approximately 80,000), and 11 percent in office jobs (approximately 35,000) (fig. 9*A*). In comparison to figure 9*B*, figure 9*A* shows the disproportionate effect of fire on household-serving employment (because the model applies the 1995 Northridge earthquake fire data). The percentage of employment in agricultural uses is less than one percent in concentrated-damage areas (all hazards and earthquake hazards), which is not surprising, because agriculture is generally found in rural areas outside the concentrated damage in urbanized areas. However, more recently, the cannabis industry has been expanding into large warehouses in the San Francisco Bay region (Roach and Chapple, 2018).

The industry employment mixes in areas of concentrated damage from all hazards differ somewhat from the industry mixes for the four counties that contain concentrated-damage areas and for the region (fig. 9). The concentrated-damage areas have a markedly higher proportion of industrial/warehouse jobs, and a much lower percentage of office jobs, which is consistent with the building occupancy damage results discussed above. The overall larger share of household-serving jobs is

[9]The household-serving occupancy group includes government, education, healthcare, and religious building occupancies.

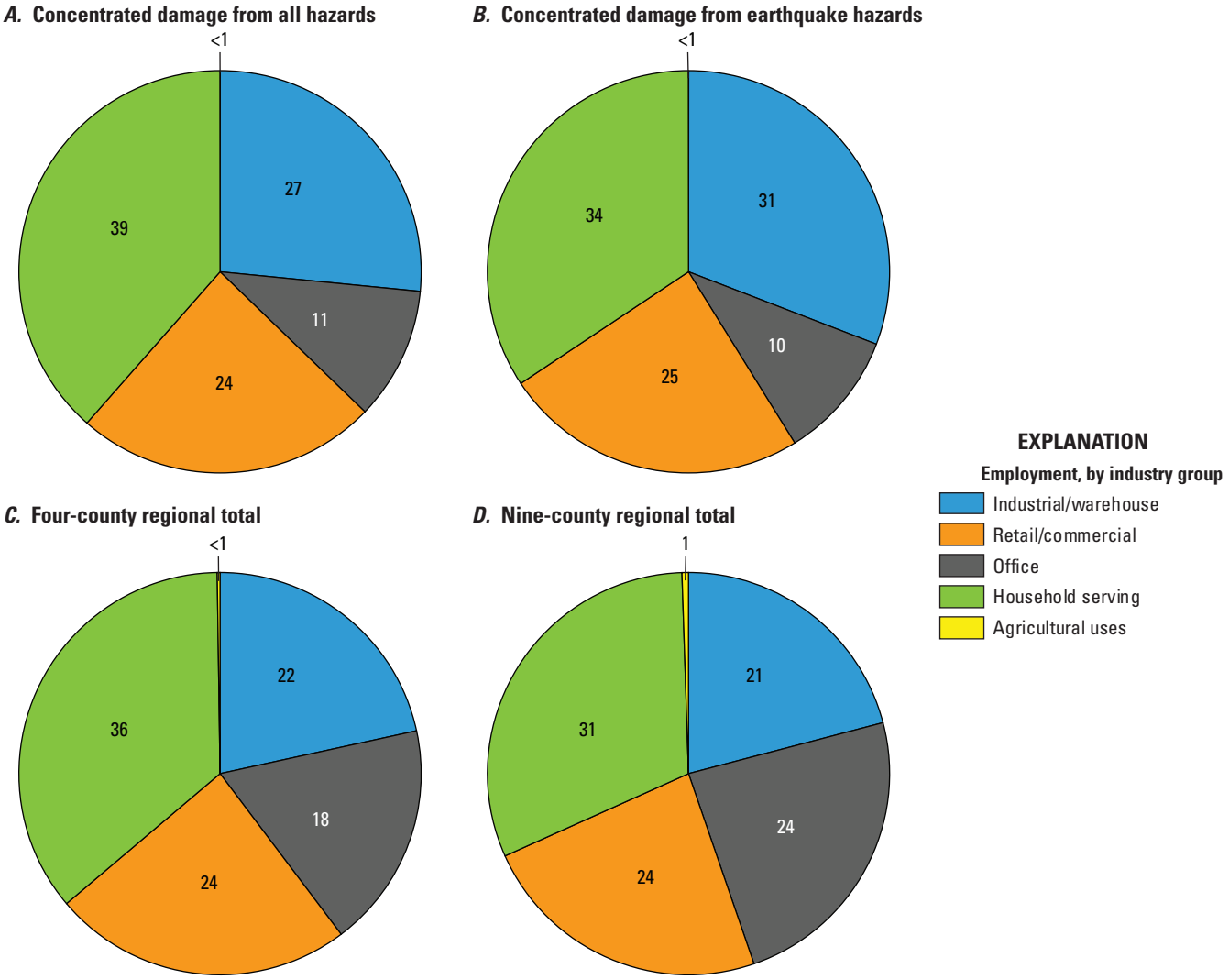


Figure 9. Pie diagrams showing employment by industry group for concentrated-damage areas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. Number indicates percentage of total employment in concentrated-damage areas for an individual industry group. *A*, Employees affected by concentrated-damage areas from all hazards (ground shaking, landslide, liquefaction, and fire following earthquake); total number of employees is 330,159. *B*, Employees affected by concentrated-damage areas from earthquake hazards (ground shaking, landslide, and liquefaction); total number of employees is 259,095. *C*, Total employment by industry group for the four counties that encompass all of the concentrated-damage areas (Alameda, Contra Costa, Solano, and Marin Counties); total number of employees is 1,367,946. *D*, Total employment by industry group for the nine counties bordering San Francisco Bay; total number of employees is 3,730,011.

not commensurate with the square footage results discussed above and likely reflects a known underestimation of education occupancy square footage, and perhaps other government occupancies as well, in the Hazus inventory (H. Seligson, Seligson Consulting, written commun., 2017).

Subarea Employment

Fifty-seven percent of the 330,159 jobs in concentrated-damage areas from all hazards are located in the central Alameda County subarea (fig. 10), commensurate with the percentage of nonresidential square footage in the subarea. To put this number in further context, the jobs in the central Alameda County subarea's concentrated-damage areas represented one-quarter of all jobs in Alameda County. The subarea has a larger share of industrial/warehouse jobs and smaller share of office jobs (fig. 11) than other counties in the region. Jobs in the northern Alameda County subarea's concentrated-damage areas account for nearly one-quarter of all jobs in concentrated-damage areas (78,514 jobs), and account for 10 percent of Alameda County jobs overall. In contrast to central Alameda County, northern Alameda County has larger shares of office and household-serving jobs than industrial/

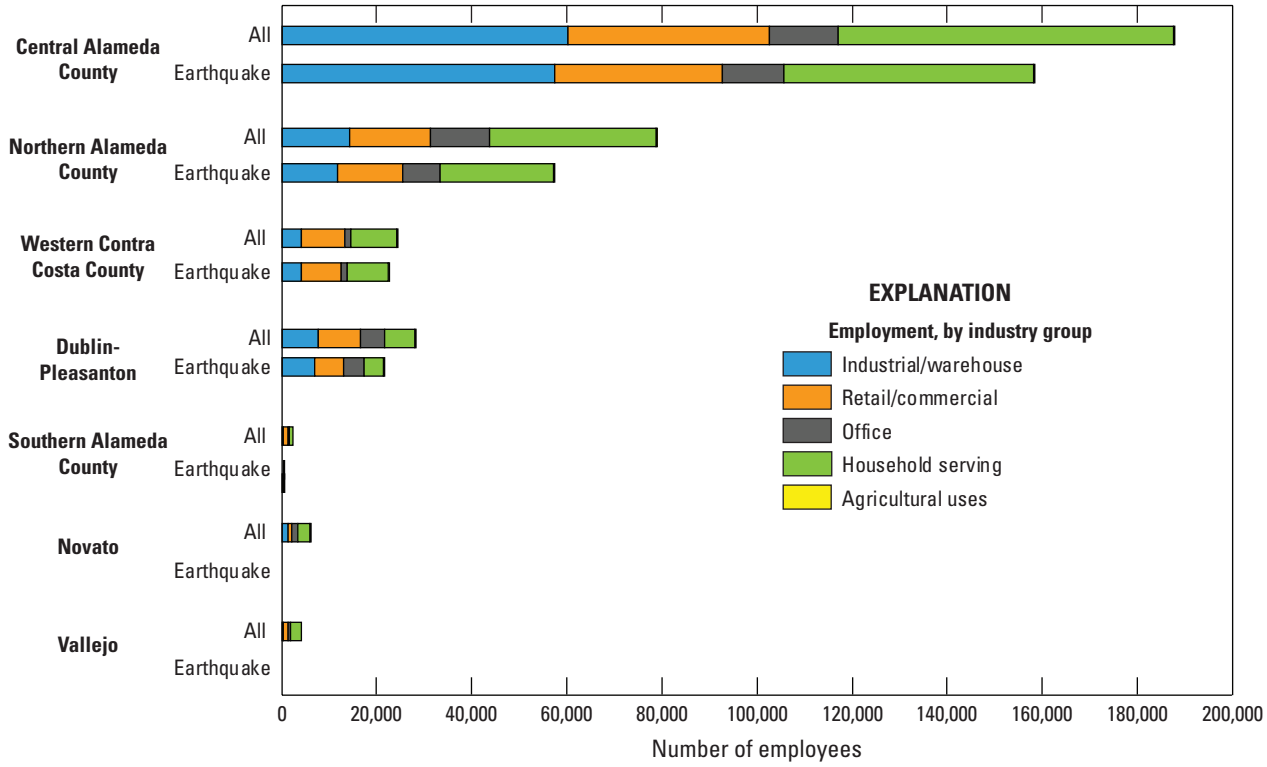


Figure 10. Bar chart showing employment in concentrated-damage areas by industry group in subareas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards: ground shaking, landslide, and liquefaction.

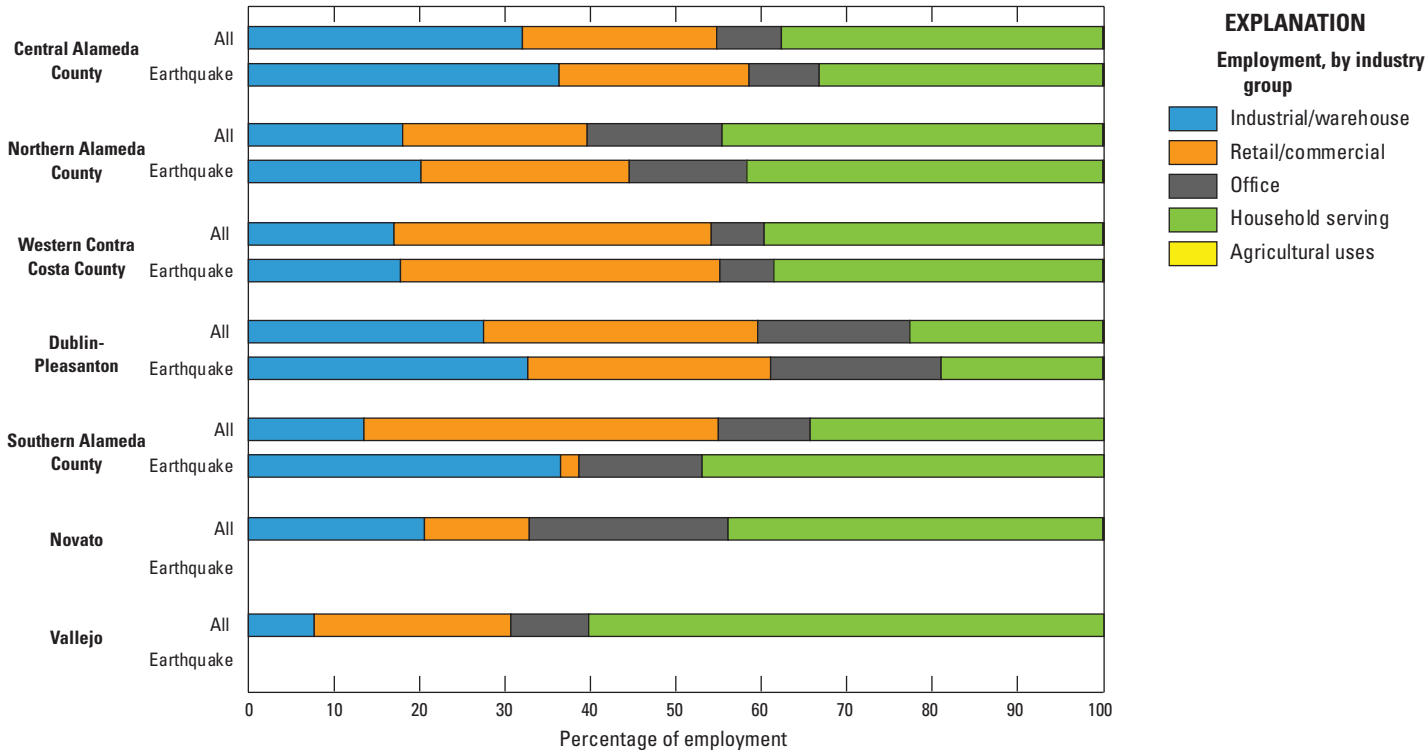


Figure 11. Bar chart showing the percentage of employment by industry group in concentrated-damage areas by subareas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. "All" refers to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. "Earthquake" refers to damages from earthquake hazards: ground shaking, landslide, and liquefaction.

warehouse jobs. Very little employment is in concentrated-damage areas in the southern Alameda County subarea, which agrees with the predominance of residential buildings in the concentrated-damage areas in this subarea.

The area of concentrated damage from all hazards in the Dublin-Pleasanton subarea contain 8 percent of total jobs in concentrated-damage areas (27,843 jobs). However, these tracts accounted for 23 percent of all jobs in the Tri-Valley area (defined as the cities of Dublin, Pleasanton, and Livermore).

The areas of concentrated damage from all hazards in the western Contra Costa County subarea contained about 24,000 jobs, composing 7 percent of all jobs in concentrated-damage areas, and 7 percent of Contra Costa County employment. However, these areas accounted for half of all jobs in the cities of El Cerrito, Richmond, San Pablo, Pinole, and Hercules. Areas of concentrated damage in western Contra Costa contain less employment in offices and more in retail/commercial.

Concentrated-damage areas from the fire hazard in Novato and Vallejo expose office and household-serving jobs, in particular, respectively (fig. 11).

Employee Residence and Workplace Relation

A major earthquake event on the Hayward Fault would impact businesses beyond the concentrated-damage areas through the geographic relations of residences and workplaces. For example, people who work in concentrated-damage areas but live in communities with less-concentrated damage could lose their jobs or be out of work for an extended period without a paycheck, spreading impacts to areas less affected by physical damage. People who live in concentrated-damage areas may be displaced or burdened in a way that interferes with their productivity, even if their job is in a less-concentrated-damage area.

We broadly calculate how many workers live and (or) work in concentrated-damage areas in the region and subareas. More detailed analysis by industry group follows, but is limited, because, though the LEHD employment data allow for establishing industry groups that could be easily organized to match occupancy groups, the LODES data are reported for only three aggregated industry segments: goods producing; trade, transportation, and utilities; and all other services. (A correspondence between LEHD industry sectors to LODES industry segments is provided in appendix 1.)

Regional

Home and workplace relations are defined as one of the following: employees (1) live and work in areas with concentrated damage, (2) live in areas with concentrated damage but work in areas with less-concentrated damage, (3) work in areas with concentrated damage but live in areas with less-concentrated damage, or (4) live and work in areas with less-concentrated damage (fig. 12).

Table 4 presents numbers of employees that live in concentrated-damage areas (employed residents) and (or) work in

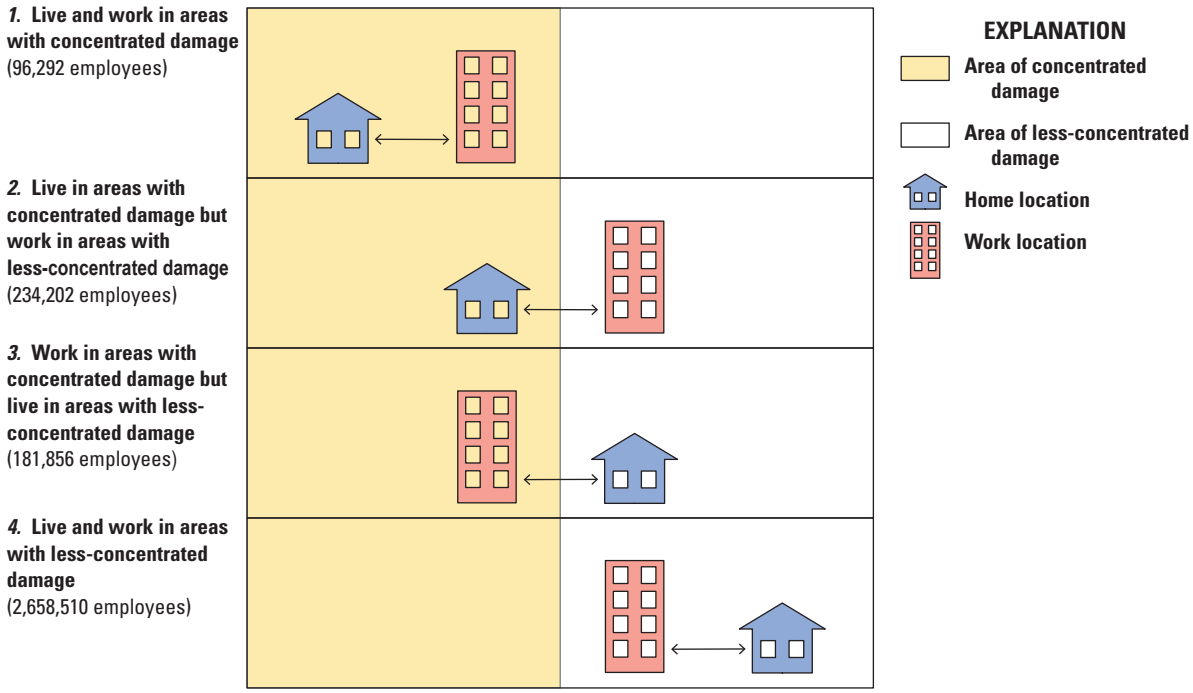


Figure 12. Cartoon showing possible home-workplace relations associated with areas of concentrated and less-concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. Employee numbers are calculated for the nine counties for all hazards (ground shaking, landslide, liquefaction, and fire following earthquake).

concentrated-damage areas (workers) in 2015. Note that the region of study expands to a larger 17-county region to capture workers living beyond the nine counties that border San Francisco Bay. In total, almost 600,000 employees work and (or) live in areas of concentrated damage from all hazards (and 25 percent fewer employees if only earthquake hazards are considered).

In the nine-county region, 96,292 employees both live and work in areas of concentrated damage from all hazards—that is, 3 percent of the nine-county region's employment. This is almost double the number of employees working and living in areas of concentrated damage from earthquake hazards. Another 5 percent of employees work in concentrated-damage areas and another 6 percent of employees live in concentrated-damage areas, which have the potential to greatly widen impacts. In the four counties that contain concentrated-damage areas (Alameda, Contra Costa, Marin, and Solano Counties), 26 percent of the employees work and (or) live in areas of concentrated damage from all hazards, accounting for 6 percent of the 17-county region's employment. Analogous numbers for earthquake hazards are given in table 4; notably, 19 percent of employees in the two counties that contain concentrated-damage areas (Alameda and Contra Costa Counties) work and (or) live in concentrated-damage areas, accounting for 5 percent of the nine-county region's employment.

In 2015, there were more employed residents (about 364,000) than workers (about 328,000) in areas of concentrated damage from all hazards, indicating that these tracts are an overall net exporter of workers (although not for all subareas). For the earthquake hazards case, concentrated-damage areas are a net importer of workers from other locations (about 258,000 workers compared to about 236,000 employed residents). This switch is a result of the disproportionate effect of conflagrations on residences in the HayWired scenario, which increases the number of affected residents more than affected workers. Furthermore, of the approximately 96,000 employees that both work and live in areas of concentrated damage from all hazards, about 70 percent work and live in the same subarea (blue in fig. 13), most commonly in central Alameda County, and the rest live and work in concentrated-damage areas across other subareas (orange in fig. 13).

Industry Segment

For context, employment in the LODES data in the San Francisco Bay region is composed of 15 percent goods-producing jobs, 17 percent trade, transportation, and utilities jobs, and 68 percent all other services jobs. Using the LODES data to track employee residences and workplaces by industry segments, we find that only the industry distribution of workers in concentrated-damage areas (for all hazards) diverges from the region's job composition—10 percent more in trade, transportation, and utilities, and 11 percent less in other services (fig. 14), relating to the lower seismic performance, larger exposure to fire, and more impacted location of industrial/warehouse buildings that strongly determine the designation of concentrated-damage areas compared to other occupancies. The relatively larger percentage of trade, transportation, and utilities industry workers employed in concentrated-damage areas highlights another path by which impacts may spread: if goods shipment to local producers is slowed by damage in the east bay.

Table 4. Employees (in thousands) living and (or) working in concentrated-damage areas for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. Values in thousands of people. Percentages may not sum exactly because of rounding. Numbers for employed residents and workers change with area because some people work or live (respectively) outside of the region. %, percent]

	All hazards			Earthquake hazards		
	Four-county region	Nine-county region	Total region	Four-county region	Nine-county region	Total region
Total employment	1,361	3,708	5,511	1,361	3,708	5,511
People living and working in concentrated-damage areas	96 (7%)	96 (3%)	96 (2%)	51 (4%)	51 (1%)	51 (1%)
Employed residents living in concentrated-damage areas only	121 (9%)	234 (6%)	267 (5%)	91 (7%)	163 (4%)	184 (3%)
Workers working in concentrated-damage areas only	130 (10%)	182 (5%)	232 (4%)	122 (9%)	164 (4%)	206 (4%)
Total employees living and (or) working in concentrated-damage areas	348 (26%)	512 (14%)	595 (11%)	264 (19%)	379 (10%)	442 (8%)

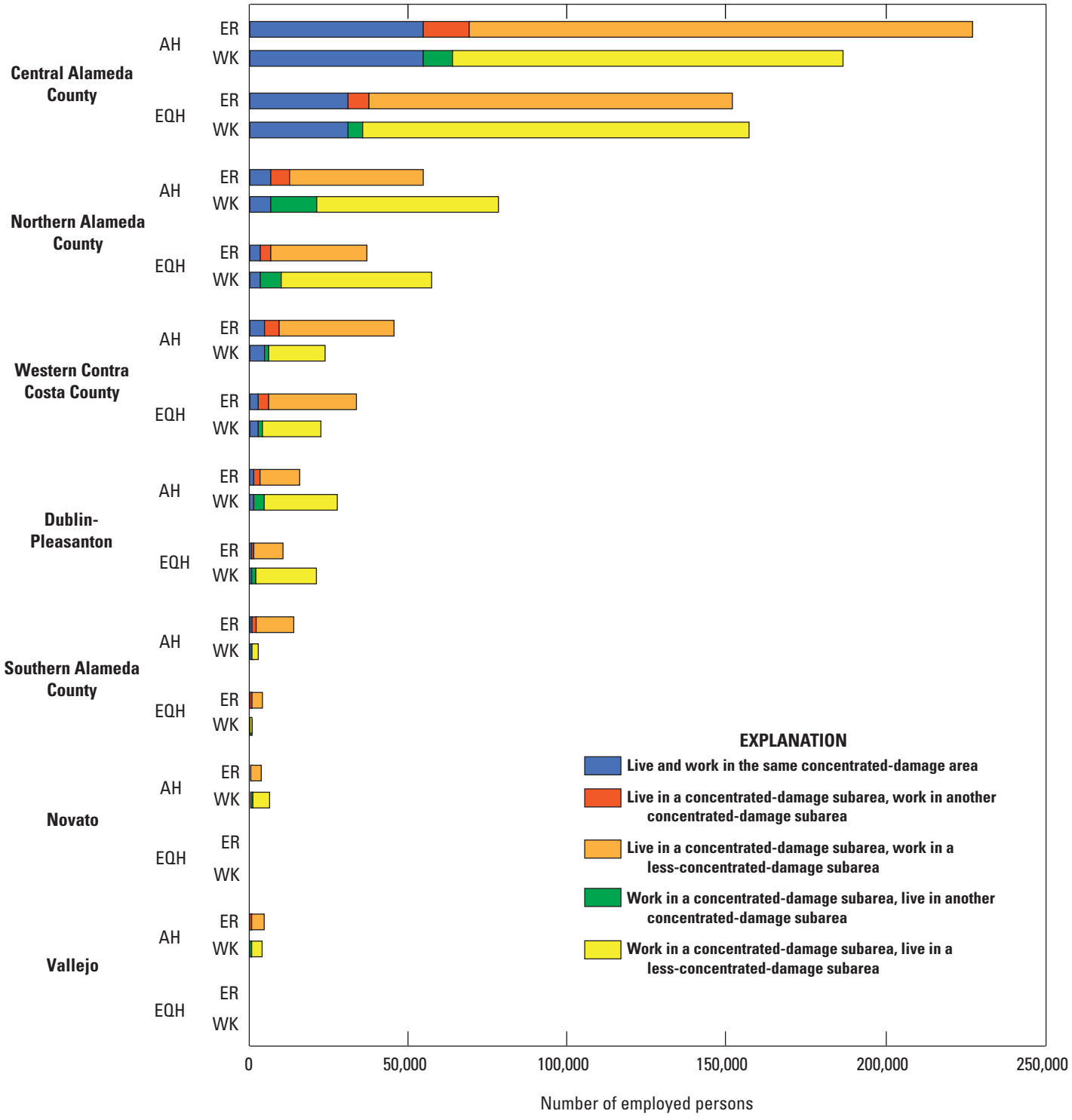


Figure 13. Bar chart showing employed residents and workers in concentrated-damage areas by subarea for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. EQH, earthquake hazards (ground shaking, landslide, liquefaction); AH, all hazards (earthquake hazards plus fire); WK, workers; ER; employed residents.

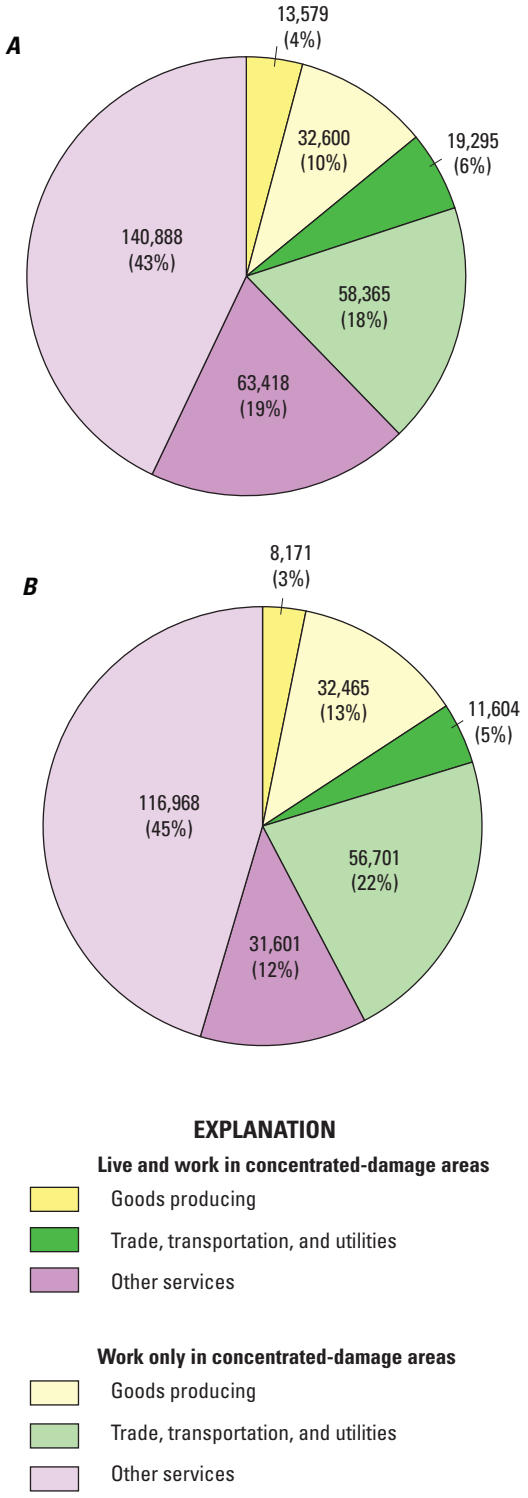


Figure 14. Pie diagrams showing percentages of workers by industry segment in concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California. *A*, All hazards (ground shaking, landslide, liquefaction, and fire following earthquake). *B*, Earthquake hazards (ground shaking, landslide, and liquefaction).

Subarea and Industry Segment

Employed Residents

Figure 15 shows work locations of employed residents living in areas of concentrated damage from all hazards to show the spread of impacts to jobs from employees living in concentrated-damage areas. More than half of these residents have jobs in less-concentrated-damage areas: 81,000 (22 percent) commute to jobs in the remainder of Alameda County (outside of the northern, central, and southern Alameda County subareas), about 51,000 (14 percent) commute to San Francisco, 32,000 commute to Santa Clara County, 25,000 commute to San Mateo County, and 28,000 work in the remainder of Contra Costa County (outside of the western Contra Costa County subarea). Employment districts with less concentrated damage, such as downtown San Francisco, could be adversely affected if many of the people who work in that district have lost their homes, are dealing with repairs, and (or) can no longer get to work because of transportation and (or) relocation challenges (Kroll and others, this volume, explore the economic impacts of commute disruptions). Extensive workforce disruption could occur for about 267,000 employees who live in concentrated-damage areas and work in less-concentrated-damage areas; the degree and duration of impact will depend on the types of plans businesses, responding agencies, and organizations have for employees displaced from their homes or living under difficult conditions.

Breaking out the jobs of employed residents who live in areas of concentrated damage (from all hazards) by industry segment, figure 16 shows that the majority of the goods-producing jobs are in concentrated-damage areas or the less-concentrated-damage areas in the remainder of Alameda County. Santa Clara County is also a significant goods-producing job destination for 13 percent of employed residents in the segment. Trade, transportation, and utilities and other services jobs of resident employees were more distributed across the region. San Francisco is a significant destination for both of these types of jobs and hosts 11 percent of trade, transportation, and utilities jobs and 16 percent of other services jobs held by employed residents living in concentrated-damage areas.

Workers

Figure 17 shows home locations of workers who work in areas of concentrated damage from all hazards to show the spread of impacts to residential neighborhoods and communities. Figures 13, 17, and 18 show that, of the approximately 328,000 workers employed in areas of concentrated damage from all hazards, most would be commuting primarily from three main residential locations: nearly 72,000 (22 percent) from Alameda County remainder, 69,000 (21 percent) from concentrated-damage areas in the central Alameda County subarea, and more than 42,000 (14 percent) from Contra Costa County remainder.

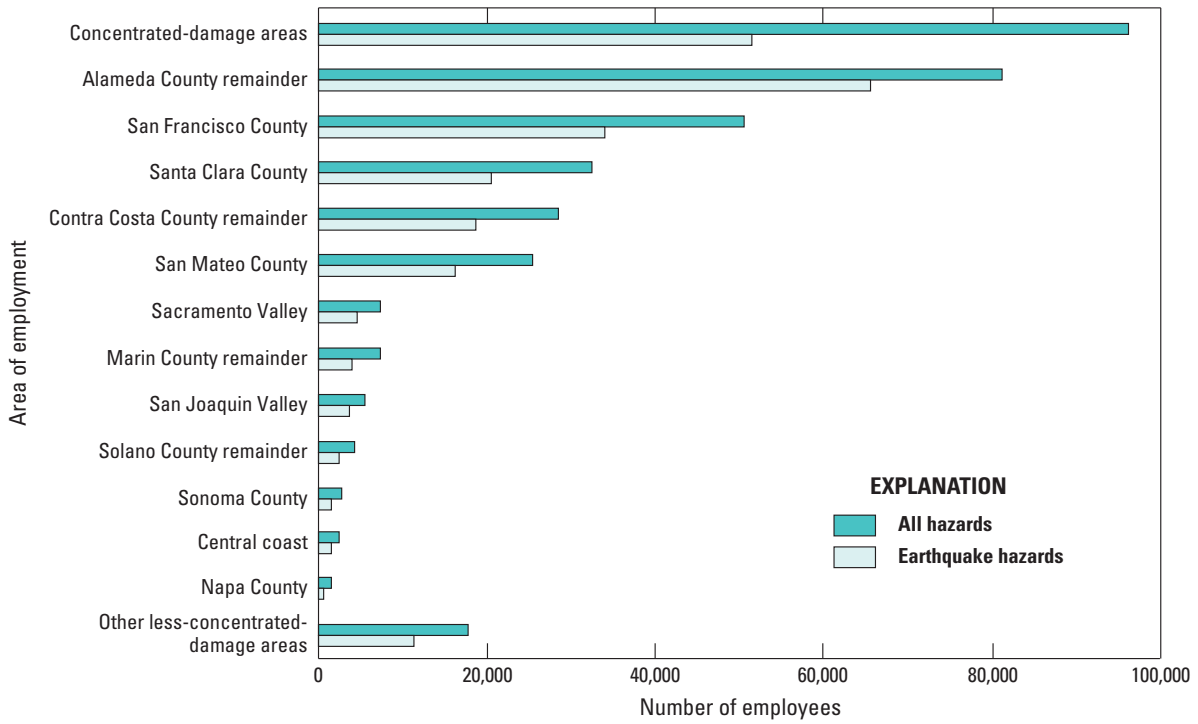


Figure 15. Bar chart showing job locations of employed residents who live in concentrated-damage areas resulting from the HayWired earthquake scenario in the San Francisco Bay region, California. Results are shown for areas of concentrated damage from all hazards (ground shaking, landslide, liquefaction, and fire following earthquake) and earthquake hazards (ground shaking, landslide, and liquefaction). This figure shows the spread of impacts to jobs from workers living in concentrated-damage areas.

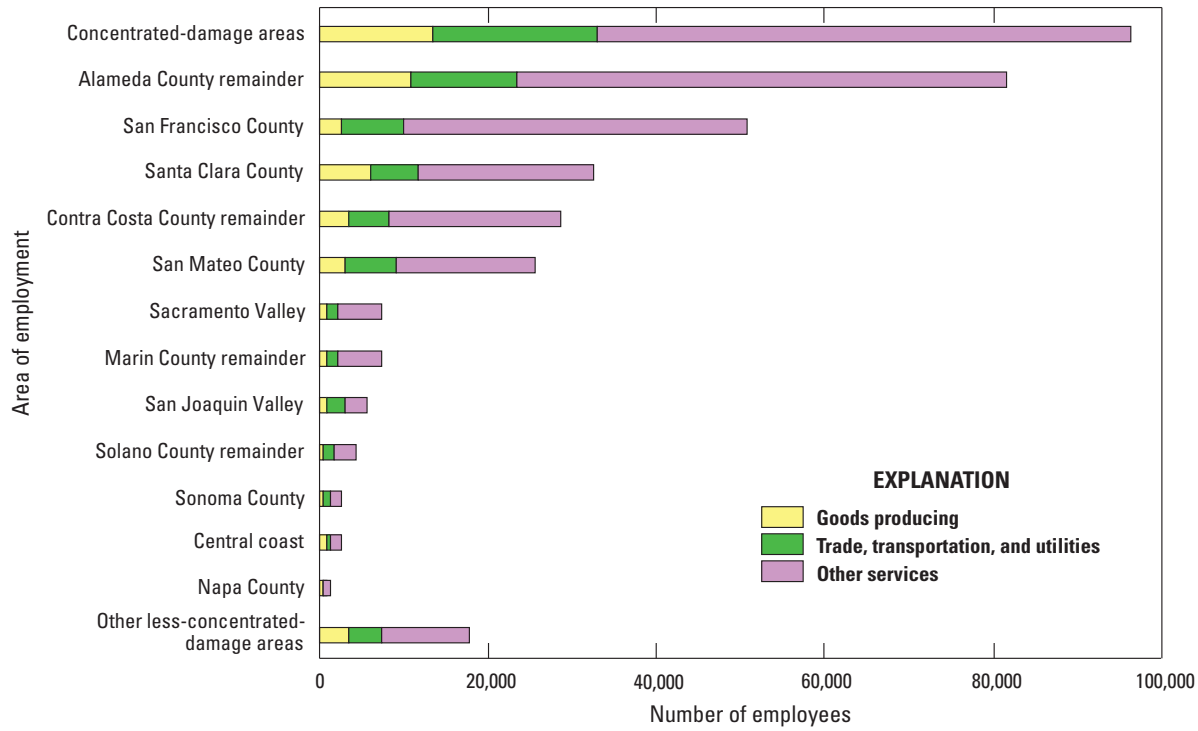


Figure 16. Bar chart showing job locations by employment segment of employed residents who live in concentrated-damage areas from all hazards (ground shaking, landslide, liquefaction, and fire following earthquake) resulting from the HayWired earthquake scenario in the San Francisco Bay region, California.

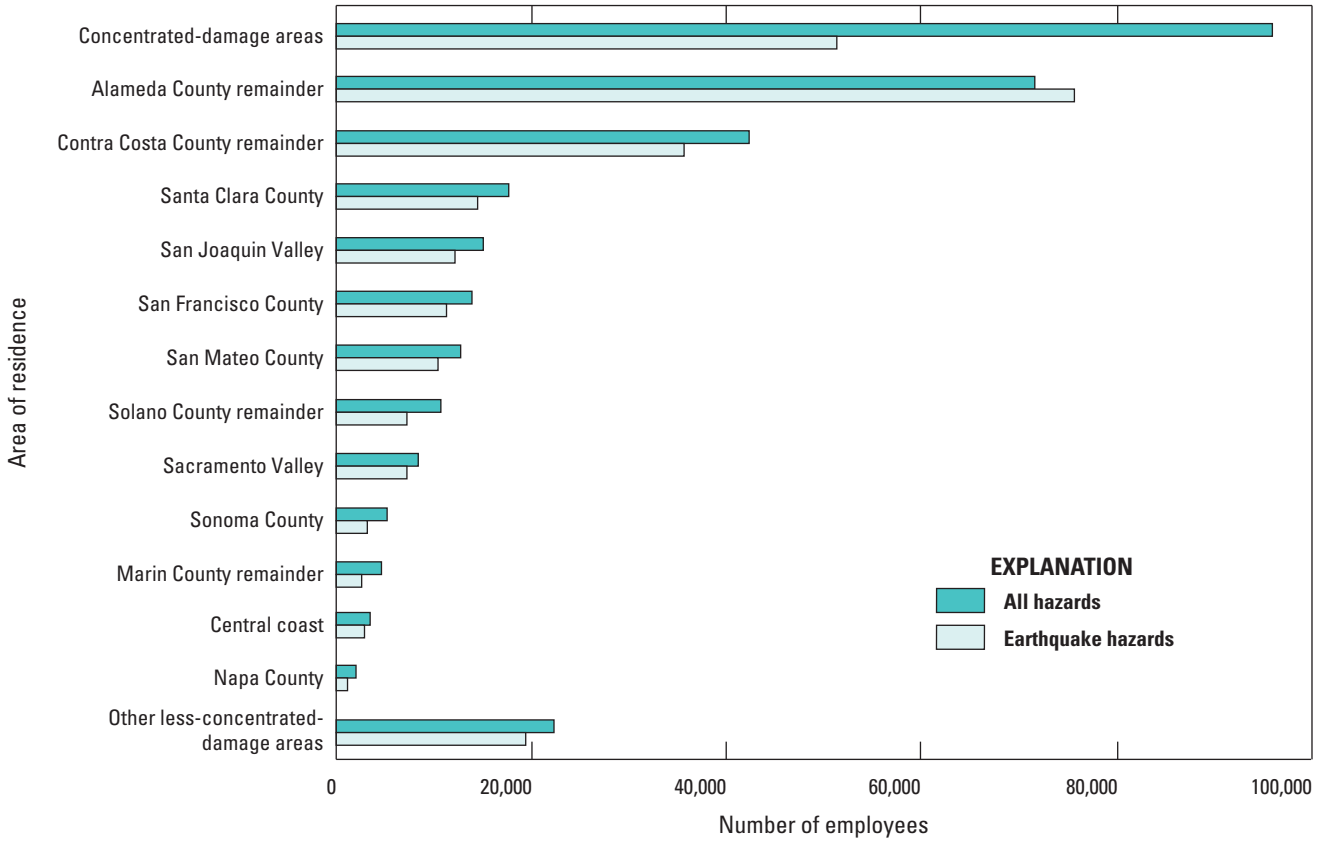


Figure 17. Bar chart showing residential locations of workers employed in concentrated-damage areas resulting from the HayWired earthquake scenario in the San Francisco Bay region, California. Results are shown for areas of concentrated damage from all hazards (ground shaking, landslide, liquefaction, and fire following earthquake) and earthquake hazards (ground shaking, landslide, and liquefaction).

Figure 18 shows where workers in concentrated-damage areas live, and what kinds of jobs they work, broken out into the three industry segments. Outside the concentrated-damage areas, workers mostly live in the remainder of Alameda and Contra Costa Counties. Workers living in the Alameda County remainder composed 21 percent of goods-producing workers, 17 percent of trade, transportation, and utilities workers, and 24 percent of other services workers. About 13 percent of workers employed in concentrated-damage areas in each segment live in the remainder of Contra Costa County. About 7 percent of both goods-producing and trade, transportation, and utilities workers live in Santa Clara County.

Although some of the workers living in less-impacted homes might have jobs that lend themselves to telecommuting, this may be a less-viable solution for the 124,000 people who work in the goods-producing and trade, transportation, and utilities segments that have low rates of working from home (U.S. Bureau of Labor Statistics, 2016).

This section emphasizes home-workplace relations of different industrial types and different subareas. The predominant flows are intra-county; homes and jobs are within or between county subareas that have concentrated-damage areas and the remainder of that county. Notably, most affected employees are commuting within the central Alameda County subarea or between this subarea and the remainder of Alameda County. These intra-Alameda County flows account for almost one-third of the affected home-workplace relations.

More than half of employed residents living in areas of concentrated damage in central Alameda County, approximately 226,500 people, are employed along Bay Area Rapid Transit (BART) routes and the major east bay highways in concentrated-damage areas, the remainder of Alameda County, and San Francisco. These commutes could be challenged (or impossible) if their routes were incapacitated for extended times (see Jones and others, this volume, for damage and restoration estimates of transportation systems, and Kroll and others, this volume, for economic impacts of disrupted commutes).

Other notable inter-county relations are illustrated in tables 3.5–3.8 of appendix 3 and can be summarized as follows:

- 25 percent of northern Alameda County and 19 percent of western Contra Costa County employed residents who live in concentrated-damage areas work in San Francisco.

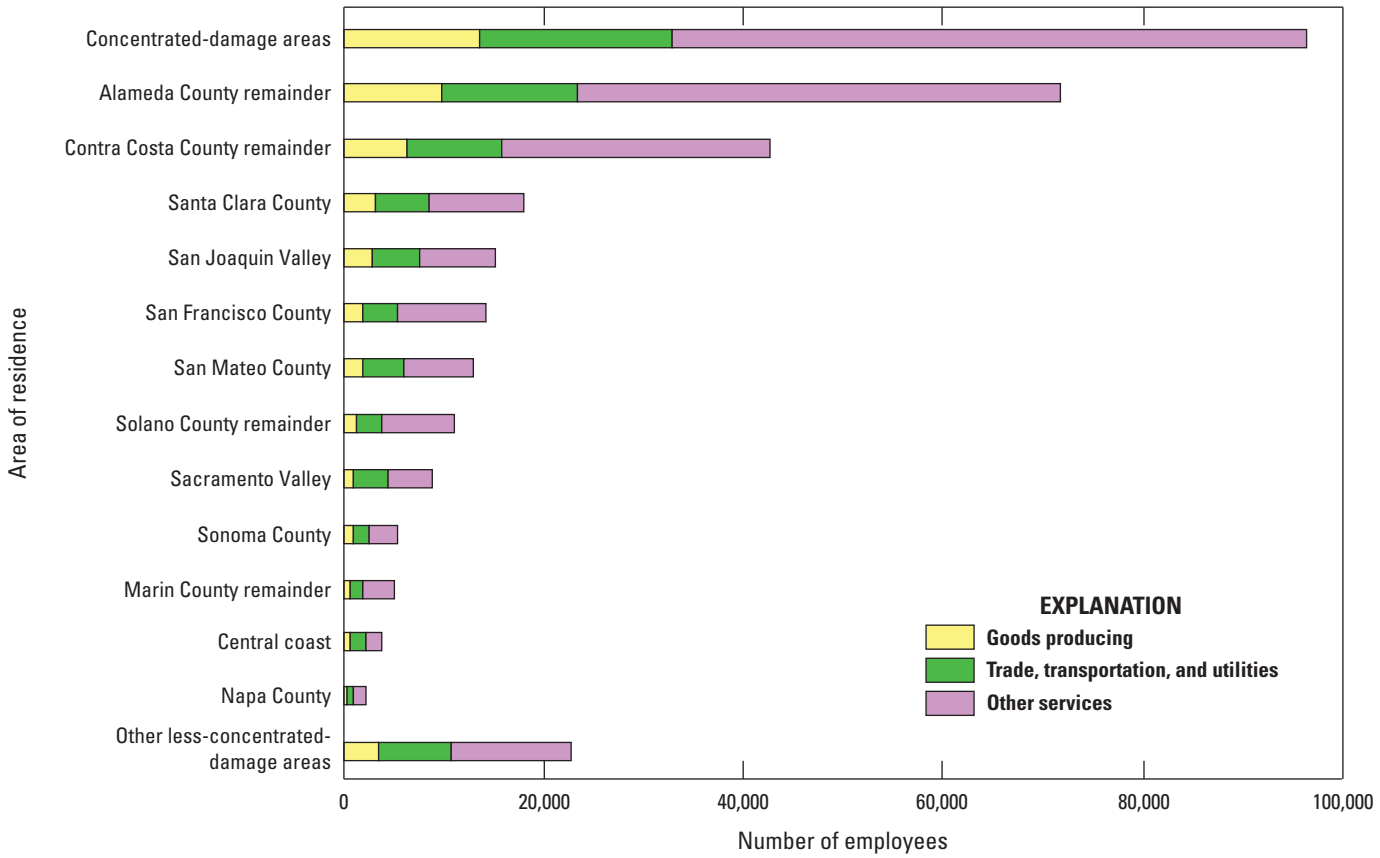


Figure 18. Bar chart showing residence locations of workers by employment segment in concentrated-damage areas from all hazards (ground shaking, landslide, liquefaction, and fire following earthquake) resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

- 31 percent of southern Alameda County and 16 percent of Dublin-Pleasanton employed residents who live in concentrated-damage areas work in Santa Clara County.
- 16 percent of northern Alameda County and 18 percent of Dublin-Pleasanton workers employed in concentrated-damage areas live in the remainder of Contra Costa County.

To illustrate the home-work commute relation, an example of commute flows for the areas of concentrated damage from all hazards in the central Alameda County subarea is provided below. Figure 19 shows, by subregion, how workers flow into the central Alameda County concentrated-damage areas. Figure 20 shows the inverse flow—how residents flow out of the central Alameda County concentrated-damage areas to commute to work. The commute flow of employees completely within the concentrated-damage areas of central Alameda County (the 54,463 people who both live and work in the same subarea) is represented by a circle where the flow arrows converge to (fig. 19) or diverge from (fig. 20).

Commute flow between the areas of concentrated damage from all hazards in central Alameda County and the remainder of Alameda County is the largest flow for both workers and employed residents. Comparing figures 19 and 20, however, it becomes obvious that more employed residents leave the concentrated-damage areas in central Alameda County to go to work than workers enter the same area. More employees commute into San Francisco and San Mateo County than vice versa, whereas the remainder of Contra Costa County sends more employees into the concentrated-damage areas in central Alameda County than the inverse.

Taking into account the distribution of industry segments, (tables 3.9 and 3.10 of appendix 3), we note several other observations.

- Other services workers with jobs in concentrated-damage areas are more likely to also be living in a concentrated-damage area or live in Alameda County remainder compared to workers in the goods-producing and trade, transportation, and utilities segment. However, residents employed in other services who have homes in concentrated-damage areas are less likely to have jobs in concentrated-damage areas compared to the other two industry segments.

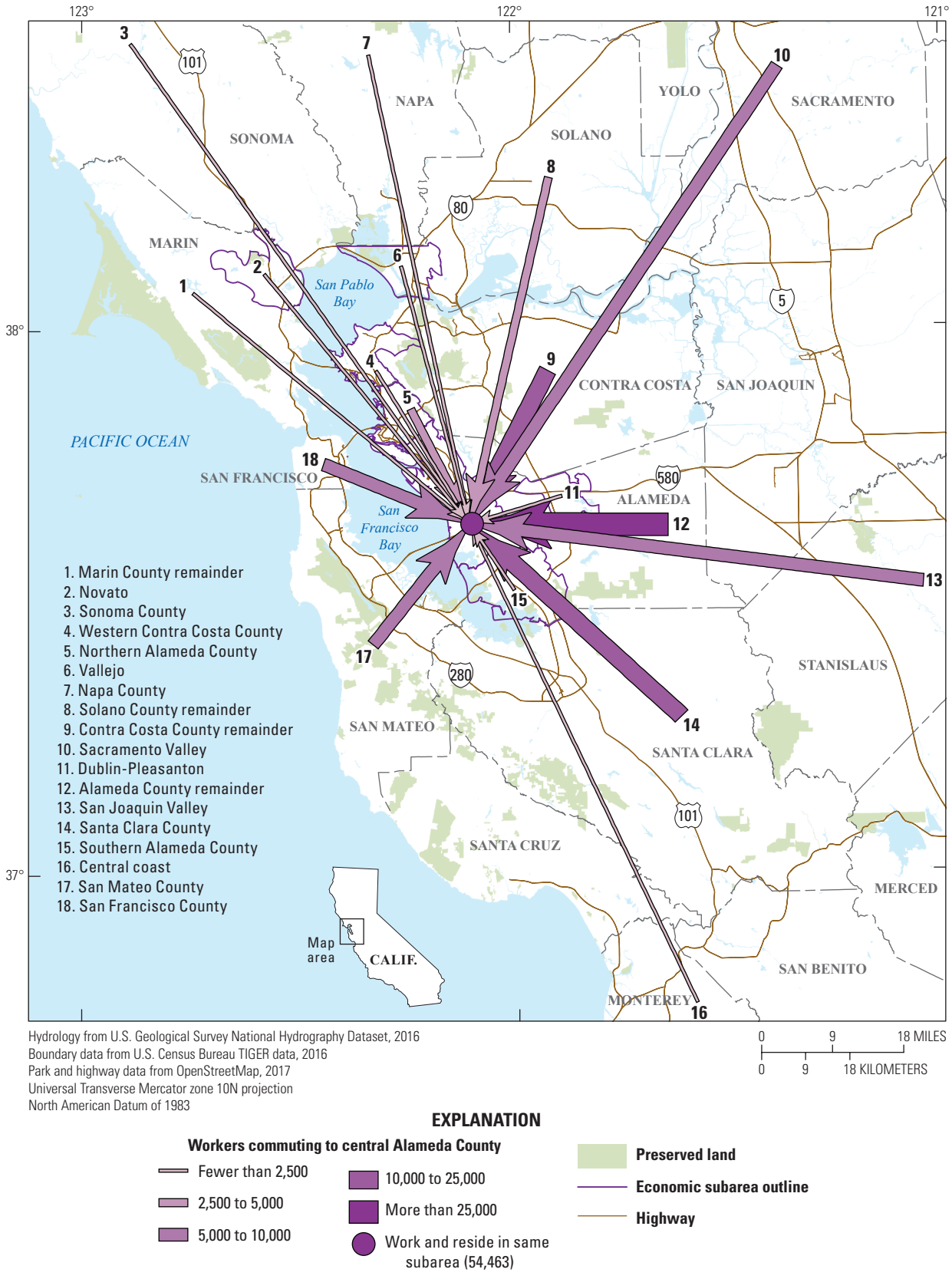


Figure 19. Map showing worker commute flow into areas of concentrated damage from all hazards in the central Alameda County subarea, San Francisco Bay region, California. All hazards refers to damages from all hazards considered for the HayWired earthquake scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Areas with "remainder" in the name are parts of counties outside the defined subareas, and other counties that do not have concentrated-damage areas are also included. More distant counties are aggregated into larger subregions: Sacramento Valley (Sacramento and Yolo Counties), San Joaquin Valley (Merced, San Joaquin, and Stanislaus Counties), and the central coast (Monterey, San Benito, and Santa Cruz Counties).

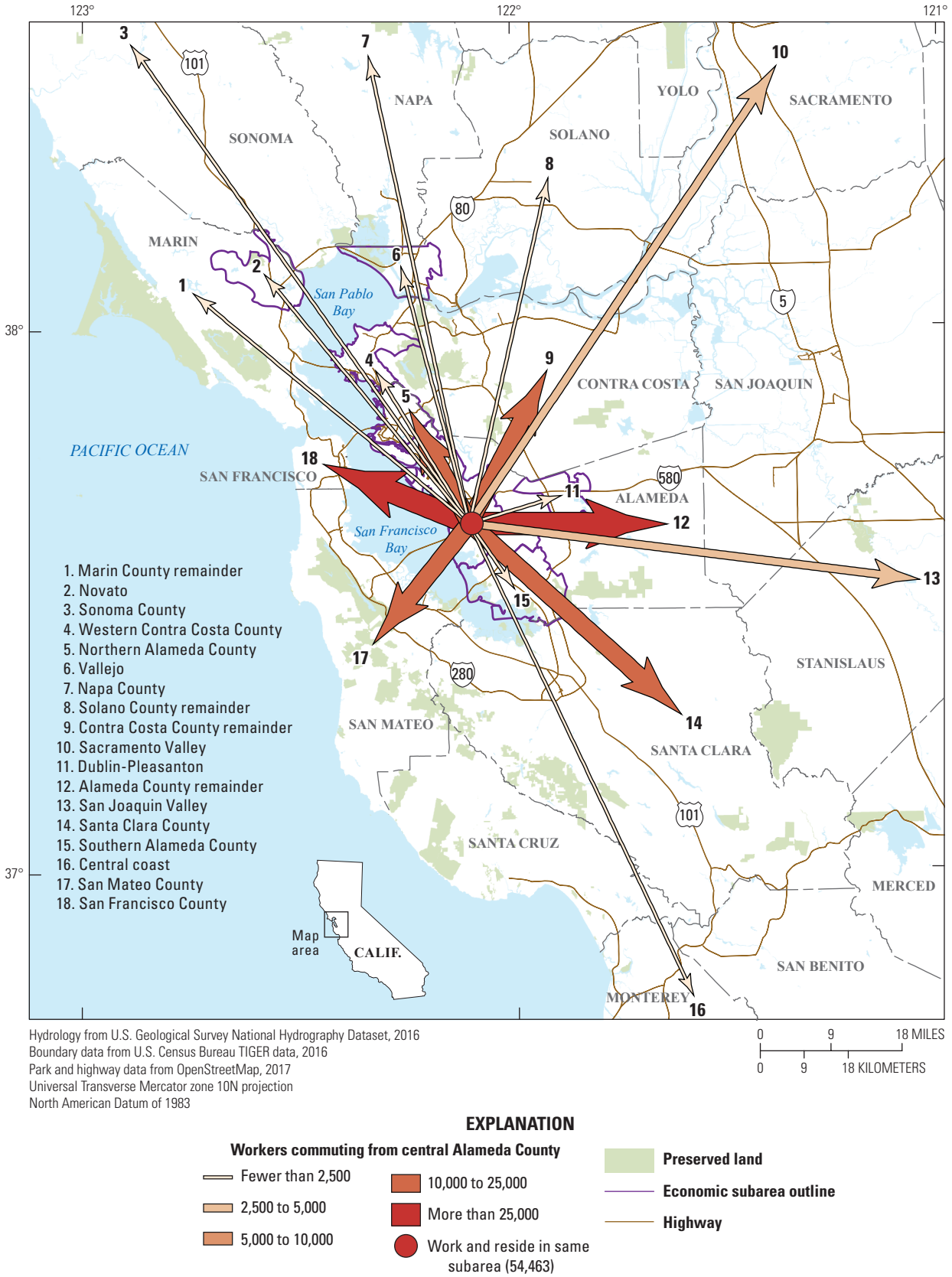


Figure 20. Map showing employed resident flow out of areas of concentrated damage from all hazards in the central Alameda County subarea, San Francisco Bay region, California. All hazards refers to damages from all hazards considered for the HayWired earthquake scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Areas with "remainder" in the name are parts of counties outside the defined subareas, and other counties that do not have concentrated-damage areas are also included. More distant counties are aggregated into larger subregions: Sacramento Valley (Sacramento and Yolo Counties), San Joaquin Valley (Merced, San Joaquin, and Stanislaus Counties), and the central coast (Monterey, San Benito, and Santa Cruz Counties).

- Residences of trade, transportation, and utilities and goods-producing workers with jobs in concentrated-damage areas are more dispersed than other services workers, including a large share of affected workers in Sacramento Valley and the central coast, where trade, transportation, and utilities workers' jobs almost equaled other services jobs in number.
- 13 percent of goods-producing employed residents living in concentrated-damage areas work in Santa Clara County; 11 percent of trade, transportation, and utilities employed residents living in concentrated-damage areas work in San Francisco.

Employee Well-Being

Employee productivity would likely decrease with stress. Employees could be stressed by displacement from their homes and neighborhoods, difficult living conditions, insurance and financial issues, commute disruptions, and business relocations. The enduring stress of aftershocks during the earthquake sequence could persist for all affected populations. Further productivity losses could result from declines in employee well-being because of the loss of loved ones or sustained injuries during the earthquake. Seligson and others (2018) estimate 800 fatalities, 500 life-threatening injuries, 3,000 major injuries, and 12,000 minor injuries that could affect the workforce.

Summary and Discussion

Macroeconomic impact analyses of building and infrastructure damage assessments provide an aggregate estimate of impacts the HayWired scenario could have on the regional economy (Sue Wing and others, this volume; Kroll and others, this volume). However, these analyses do not adequately capture the uneven spread of the HayWired scenario's impacts across the San Francisco Bay region. The spatial analysis discussed in this chapter provides a geographical examination of potential business disruption from concentrated damage and considers impacts on both employee workplaces (by industry group or segment) and homes (by single-family/duplex, multifamily, or group living type). Moreover, the spatial analysis reveals the potential spread of direct job impacts in concentrated-damage areas to the communities where those workers live, and the spread of home impacts in concentrated-damage areas to businesses where those residents are employed. This study follows the analytical framework of the communities at risk chapter by Johnson and others (this volume) and complements its examination of impacts of concentrated damages on housing and communities, potential population displacement, and long-term recovery challenges.

Following a summary of study findings, we draw deeper insights regarding industrial trends from regional studies of the San Francisco Bay region and published literature. We conclude with policy implications for earthquake mitigation, preparation, response, and recovery for emergency managers, businesses, communities, and (or) regional entities. Policies pertain to neighborhood effects of concentrated damage, disproportionate impacts on industrial/warehouse sectors, spread of impacts through home-workplace relations, and spatial economic demand shifts.

Summary of Study Findings

Concentrated Damages

As reported by Johnson and others (this volume), the total number of census tracts with areas of concentrated damage (where the percentage of extensive or complete damage across all building occupancy groups is greater than 20 percent) across the seven subareas used in this analysis for the all hazards case (ground shaking, landslide, liquefaction, and fire following earthquake) is 173. These 173 tracts make up about 11 percent of the total number of tracts in the nine-county region and are primarily located in Alameda and Contra Costa Counties with fire impacts in Marin and Solano Counties. Of these tracts, 115 (about 7 percent of the census tracts in the nine-county region) are in concentrated-damage areas for the earthquake hazards case (ground shaking, landslide, and liquefaction) within the two primary counties (Alameda and Contra Costa Counties).

A few concentrated-damage tracts correspond to downtown areas. The cities of Hayward and San Leandro have aging downtown cores with concentrations of vulnerable building stock that are heavily damaged in the HayWired scenario (fig. 1). Downtown Pleasanton also sustains concentrated damage from high intensity shaking. Downtown Oakland and San Francisco, which have some even older buildings, are spared from the most intense shaking in the HayWired scenario (but could be highly vulnerable in a different earthquake scenario).

Analyses of concentrated damage from the HayWired scenario show that the building square footage (and consequently businesses and residents at risk) in concentrated-damage areas ranges from more than double to nearly five times more than the square footage that is directly impacted by disruptive (extensive or complete) building damage.

Concentrated Damages and Building Occupancy

Industrial/warehouse, retail/commercial, and (or) multifamily buildings are most likely to contribute to neighborhood damage concentrations from all hazards.[10] The affordable housing crisis could be further distressed by the greater vulnerability of more

[10]Concentrated-damage areas are predominantly determined by industrial/warehouse and retail/commercial classes even before fire following earthquake impacts on residential areas are considered.

affordable housing (for example, aging multifamily housing) (Johnson and others, this volume).

Group-living housing, most prevalent in the northern Alameda County subarea, is also vulnerable to significant damage, but represents only a very small share of residential square footage. Offices and single-family/duplex buildings generally perform fairly well with respect to damage but may be more affected by their location in neighborhoods composed of more vulnerable buildings.

Household-serving industries are less affected by concentrated damages than other industries but are more closely tied to the households they serve. Household-serving industries could be affected if their customers—the households they serve—are displaced because of damage to multifamily residential buildings. Conversely, single-family/duplex residential neighborhoods would have trouble re-establishing themselves without household services (for example, schools) available (Johnson and others, this volume; Xiao and Nilawar, 2013).

Concentrated Damages and Employment

The 2015 workforce in concentrated-damage areas (from all hazards) represents 6 percent of the larger 17-county region, 9 percent of the nine-county region, and 24 percent of the four counties that contain concentrated-damage areas. In Alameda County (the most impacted county in the region), about one-quarter of the total county employment and 57 percent of central Alameda County subarea employment is in concentrated-damage areas. Nearly half of some city-based employment could be located in concentrated-damage areas in Contra Costa County.

Consistent with building occupancy results, industrial/warehouse employment is disproportionately located in concentrated-damage areas. Future work could delve deeper into income losses to employees affected by concentrated damages using more detailed sector data with income distributions or U.S. Bureau of Labor Statistics data. Effects on local expenditures could be estimated using an input-output analysis.

Home and Workplace Relations

Home and workplace relations are defined as one of the following: employees (1) live and work in concentrated-damage areas, (2) live in concentrated-damage areas but work in less-concentrated-damage areas, (3) work in concentrated-damage areas but live in less-concentrated-damage areas, or (4) live and work in less-concentrated-damage areas. About 15 percent of the nine-county San Francisco Bay region's employees are affected by one of the first three relations if all hazards are considered. Of the 96,000 employees who live and work in concentrated-damage areas, 70 percent do so in the same subarea, and 57 percent of these employees live and work in the central Alameda County subarea. The proximity of employee homes to workplaces in Alameda County is corroborated by lower vehicle miles traveled in Alameda County than in other counties in the region (Chapple and others, 2017).

With nearly 420,000 employees with a job or home in a concentrated-damage area in the nine-county region, job losses or relocation and residential population displacement have the potential to greatly widen business impacts. Approximately 81,000 people living in areas of concentrated damage from all hazards commute to jobs in less-concentrated-damage areas in Alameda County (referred to as Alameda County remainder). Further afield, around 51,000 people commute to San Francisco and about 32,000 commute to Santa Clara County. Employment districts, such as downtown San Francisco and some cities in Santa Clara County, could be adversely affected if many of the people who work in these locations are stranded on the day of the earthquake, lose their homes, utility services, and (or) community services (for example, schools are closed), are stressed by living conditions and home repairs, and (or) can no longer get to work because of transportation disruptions. Since fire following earthquake disproportionately affects residences, some businesses could struggle to fill jobs, as their preexisting and potential workforce no longer has housing accessible to jobs, similar to the outcome of the 2017 Santa Rosa fires (D. Guhin, Planning and Economic Development Director for the City of Santa Rosa, oral commun., 2018).

Of the 232,000 people working but not residing in concentrated-damage areas (from all hazards), half of these workers (114,000) are in residential neighborhoods in the remainder of Alameda and Contra Costa Counties. These workers could lose their jobs or be out of work for an extended period with no income, possibly leading to relocation. Such losses would be expressed as declines in spending (sales tax) in local communities and income taxes. Telework from home may be possible; office work generally has more flexibility for telework, but it is a less-viable option for some of the 90,000 employees living in less-concentrated-damage areas who work in goods-producing and trade, transportation, and utilities industry jobs located in concentrated-damage areas.

The movement within concentrated-damage areas and between concentrated- and less-concentrated-damage areas in central Alameda County, Alameda County remainder, San Francisco, and Santa Clara County shows, in addition, how challenging commutes would be if BART as well as the major highways in Alameda County were incapacitated for extended periods of time. The fourth home-workplace relation, between less-concentrated-damage areas, is also not immune to incapacitated major highways and BART lines that could disrupt commutes, especially given that commutes in 2019 were already encumbered in the San Francisco Bay region. Jones and others (this volume) present HayWired scenario transportation system disruptions, and Kroll and others (this volume) use this study with those disruptions to estimate economic impacts of commute disruptions.

Drawing Insights from other Regional Research and Experience

Regional results of concentrated damage from the HayWired scenario are largely driven by the results for the central Alameda County subarea and by industrial/warehouse and retail/commercial damages concentrated within. Industrial buildings in Alameda County are older than in many other parts of the region, with an average age of 60 years (Chapple and others, 2017). The prevalence of these older vulnerable buildings near the epicenter of the earthquake intensifies concentrated damage in the HayWired scenario. Industrial/warehouse and repair (included in our retail/commercial class) are already a focus in regional planning efforts for production, distribution, and repair (PDR) (Chapple and others, 2017, Roach and Chapple, 2018) and warehouse (da Silva and others, 2017) sectors. These studies provide insight into industrial and logistics trends that could influence job diversity, business survivability, and spatial economic demand shifts after a large earthquake on the Hayward Fault.

- The industrial/warehouse industry group that is widely affected by concentrated damage is a primary source of jobs with middle income wages that require fairly low levels of educational attainment (Chapple and others, 2017) and are significant sectors for retaining the region's economic diversity and options for middle-skill workers (Terplan and others, 2014). Significant damage to this building stock could result in eliminating many of these kinds of businesses/jobs in the San Francisco Bay region as businesses may choose to relocate permanently outside of the region, where land and construction costs are lower, and where housing prices for workers are lower.

- Half of the PDR industries in Alameda County are in decline and most are in decline in Contra Costa County (Chapple and others, 2017), particularly in a few manufacturing and construction sectors.[11] Using the employment distributions across counties and subareas (table 2.14 in appendix 2 and table 4.6 in appendix 4 of Wein, Haveman, and others, this volume), we calculate that 32 percent of San Francisco Bay region manufacturing and construction employment is located in Alameda and Contra Costa Counties. Manufacturing employment specifically is disproportionately larger in the subareas (containing all concentrated-damage areas), particularly in Alameda County and the central Alameda County subarea, than in the rest of the region. Construction employment is disproportionately larger in the western Contra Costa County subarea than in the rest of the region. Concentrated damages in these sectors, along with a shrinking share of San Francisco Bay region manufacturing and construction jobs, could exacerbate these trends.

- Concentrated damages could disrupt the efficiency of industrial clusters of manufacturing, research and development, corporate offices, and suppliers in the San Francisco Bay region (Chapple and others, 2017) for the high-tech sector. Many high-tech companies are moving towards manufacturing close to large office operations to enable quicker response time and more collaboration between design, production, and marketing teams (Chapple and others, 2017).

- Two trends are increasing demand for industrial/warehouse buildings in the areas more prone to concentrated damage: (1) the growing "maker movement," on-demand production, and productivity increases made possible by the Internet of Things (IoT), all of which create a demand for small industrial spaces that are in the urban core to be closer to customers; and (2) the rise of just-in-time delivery, which has increased the demand for small warehouses close to dense urban centers (Chapple and others, 2017). These two trends are more tightly coupling customers and suppliers geographically, which potentially intensifies these dependencies in areas of concentrated damage.

- Increased in-sourcing (of previously out-sourced industries) for more customized production and on-demand delivery is occurring in new buildings on the periphery of the urban core in less-developed areas because converting old buildings to modern manufacturing and distribution standards is prohibitively expensive (Chapple and others, 2017). This high-tech contract manufacturing allows companies to prototype products, protect intellectual capital, and decrease turnaround time relative to offshore operations (Chapple and others, 2017). These industries on the region's urban periphery may lose manufacturing customers located in the concentrated-damage areas of the urban core.

- Alameda County offers low rents for PDR production facilities, whereas headquarters might be in high rental areas, such as San Francisco (Chapple and others, 2017). This means that manufacturing will be sensitive to rent increases that occur in response to a scarcity of space from damages or competition with higher uses in mixed-use industrial lands. Businesses that do not own their land and buildings may experience rent increases and thus involuntary displacement. Even those that own their land and buildings may decide to profit from the conversion of their land and move away, in a process of voluntary displacement (Chapple and others, 2017). Headquarters, research and development, and suppliers in close proximity could also relocate from high-rent space in Santa Clara County and San Francisco to be close to the manufacturing facilities that move away.

[11]Industries in decline or losing jobs include boat building, black magnetic and optical recording, semiconductor, electrical instrument measuring, computer storage device, electronic computer manufacturing, drywall and installation contractors, commercial printing, specialty trade contractors, highway and bridge construction, and electric power distribution (Chapple and others, 2017).

- In the "Bay Area Plan 2040," there are some industrial land-use conflicts with priority development areas (PDAs), places identified by San Francisco Bay region communities as areas for investment, new homes, and job growth (Chapple and others, 2017). The industrial land use and PDA areas overlap in concentrated-damage areas along the BART line near the Port of Oakland. Damages to industrial buildings could accelerate the gradual displacement of PDR industries on industrial land with conversion of these lands to other high density uses, including housing.
- Goods-producing workers residing in the remaining areas of Contra Costa and Alameda Counties could be a post-earthquake factor in shifting manufacturing to the outer reaches of those counties if a damaged transportation network decreases access to the industrial concentrations on the eastern shore of San Francisco Bay. However, these areas may be competing for the employers located further from the earthquake impacts, either in neighboring counties or more distant locations.
- Although PDR employment has declined in the region, need for PDR space continues to grow to meet demand for more land for parking and loading. Recent expansion of manufacturing has occurred along Interstate 880 (as has one-third of new research and development activity) with the newest construction located in the southern part of Alameda County, which would be less impacted by the HayWired scenario and could be positioned to absorb more growth.
- Growing industries are mostly in wholesale, transportation, and logistics services (for example, electronic parts and equipment merchant wholesalers), sectors that use few workers per square foot of space. These types of small warehousing spaces close to the urban core enables just-in-time delivery to manufacturers as well as first/last mile delivery of consumer goods to online shoppers. New warehouse spaces are more evenly distributed than manufacturing in the San Francisco Bay region (Chapple and others, 2017). The small urban warehouse spaces work in tandem with large logistics facilities as demonstrated by warehouse growth in Stockton (California) and Reno (Nevada), which has outpaced that in the San Francisco Bay region (da Silva and others, 2017). If more warehousing is absorbed in Sacramento and other outlying areas after a large earthquake, increases in vehicle miles traveled would challenge just-in-time delivery and aggravate an environmental concern for regional planning (da Silva and others, 2017).
- Electronic shopping generates additional demand for large logistics and transportation industries and large e-commerce warehouses. These large entities have been locating on the periphery of the urban core for at least a decade (Chapple and others, 2017). A major earthquake could boost electronic shopping at the expense of more local retail stores at least temporarily, and possibly permanently.

In summary, in addition to the direct loss of jobs from damage and commuting disruption, concentrations of damage from a large earthquake on the Hayward Fault could: (1) accelerate the exit of declining industries; (2) exacerbate the already precarious position of specialized industrial clusters in old manufacturing buildings and move manufacturing to more affordable places, which would create ripple effects to suppliers, customers, research and development, and headquarter operations; and (3) accelerate the gradual conversion of industrial to higher uses in mixed land uses and PDAs, dislocating jobs.

Policy Implications

Learning from prior disasters and insights from regional studies, numerous policy implications are identified below. See Johnson and others (this volume) for other policy implications from the perspective of housing, communities, and local and regional governments affected by areas of concentrated damage.

Concentrated Damages

In areas with concentrated damages, businesses with a local customer base are at risk of losing customers that are displaced from their homes, deterred by physical damage in the business neighborhood, and (or) the loss of neighboring businesses. Where retail and household-serving businesses are already stressed and suffer permanent closure, this would make it harder to draw people back to the neighborhood. Reducing the impacts of neighborhood damage on business may include:

- More resilient businesses have broader customer bases and can more easily relocate, telework, and serve customers online. For businesses that are more dependent on local customers, adaptations would be critical and may even include temporary or permanent closure (for example, Hatton, 2015).
- Contingent business interruption insurance is important to cover losses from indirect causes, such as businesses that are inaccessible to customers (caused by cordons, checkpoints, or fear) resulting from concentrated damage (for example, Battisto and others, 2018).[12]
- Temporary and permanent business losses could potentially be reduced by post-disaster temporary installations of retail/commercial business space near customers. After the 1989 Loma Prieta earthquake, the City of Santa Cruz demonstrated how the provision of

[12]CoreLogic (2018) estimated that only 20 percent of commercial losses from damage would be insured for the HayWired scenario.

temporary retail space near customers can aid recovery (Kroll and others, 1990).

The neighborhood effects of concentrated damages indicate that disaster planning is as important for neighborhoods as it is for individual businesses:

- When a business invests in building retrofits or other mitigations, the action can benefit not just the business itself but also its neighbors (Xiao and Van Zandt, 2011; Johnson and others, this volume). Conversely, as seen in the 2014 South Napa earthquake, failure of one building spreads risk and impacts to the rest of a block or neighborhood of businesses and residences (Almufti and others, 2016).
- After Hurricane Sandy, grants to repair corridors of concentrated damage and market reopening aimed to bring back foot traffic to all the affected businesses (Battisto and others, 2018).
- Establishing links with neighboring establishments or businesses with similar production processes can provide a support network to call on after an event (for example, see Almufti and others, 2016; Stevenson and others, 2014).

In areas of concentrated damage, cordons may restrict access to blocks of businesses and residences for health and safety reasons because of infrastructure and building damage, aftershock risk, or environmental contamination—the first two conditions precipitated implementation of the central business district cordon following the February 2011 Christchurch earthquake (Chang and others, 2014). In the HayWired scenario, a few downtowns have concentrated damage, but not the dense downtowns of Oakland and San Francisco. The HayWired scenario is only one of many possible outcomes, just as an earthquake is only one of many possible damaging events. Lessons learned about cordons from recent earthquakes include:

- Businesses could improve their chances of survival should they find themselves located in a cordoned area if they bolster their preparedness beforehand to be able to quickly relocate, including moving critical records and supplies (for example, see Chang and others, 2014).
- Planning by emergency managers and building departments to manage a cordon prior to a disaster includes legal mechanisms for establishing a cordon and methods for determining the appropriate spatial extent, identified resources to secure the cordon, a communications plan, a system for deciding who gets access to the cordoned area and under what circumstances (to address the tension between safety and contents retrieval or business resumption), an arrangement for alternate sites where displaced businesses can relocate, and support for legal matters involving leases and civil liberties (Chang and others, 2014; Underwood and others, in press).
- Cordons around concentrations of damage can also be used to accelerate demolition, facilitate construction logistics, ensure that contractors meet professional standards, and enable greater debris sorting and waste management (Chang and others, 2014). Cordons could also increase the risk of long-term displacement to the original businesses and residents, especially if there is major redevelopment or upgrades to the aging building stock or infrastructure (Chang and others, 2014). Cities are cautioned to pursue such transformation opportunities only with full participation of stakeholders in the planning (Johnson and Olshansky, 2017).

When planning for neighborhood recovery from concentrated damages before and after a disaster, addressing both residential and business recovery needs are mutually beneficial to the recovery (Xiao and Van Zandt, 2011). Successful economic neighborhood revitalization lets businesses, property owners, and residents bring their resources to bear, weaving them together in support of a shared built vision and assessment of community needs (International Economic Development Council, 2015). Examples include:

- Efforts to address housing and household services in order to bring staff back to Tulane University (new Orleans) after the population displacement caused by Hurricane Katrina (Cowan, 2007).
- After the northern California wildfires in 2017, Sonoma County is developing a Renewal Enterprise District through a new county-wide joint power authority created to plan for and finance new housing in areas within walking distance of transit and shopping districts to help small businesses (Battisto and others, 2018).

Concentrated Damages by Industry Sector

Disproportionate building and concentrated damages in the industrial/warehouse industry group prompts consideration of resilience planning for these sectors:

- Collaborative resilience planning among industrial clusters would help prepare them for the impacts of concentrations of damage. This could be combined with broader planning for resilience of these clusters as described in the newly adopted Comprehensive Economic Development Strategy for the San Francisco Bay region (found at https://abag.ca.gov/sites/default/files/complete_ceds_with_all_appendices.pdf).
- Programs to protect disproportionate impacts to middle income jobs (particularly in the industrial/warehouse industry group) and training to develop skills to match jobs would be of regional concern. Programs could be developed as part of an economic action plan in support of the Comprehensive Economic Development Strategy.
- Regional agencies are developing a Priority Production Area program for "Plan Bay Area 2050" that identifies

geographies where measures are needed to preserve manufacturing, distribution and repair services, and middle wage jobs. The programs targeted to these areas could include consideration of resilience measures that would be helpful pre- and post-earthquake and integrate such measures into the Priority Production Area program.

Home-Workplace Relations Affected by Damage Concentrations

For business continuity planning, the home-workplace relation highlights the need for:

- Plans and resources for employee well-being in response to stress of displacement from their homes, difficult living conditions, or insurance and financial issues, and need for temporary accommodation; and
- Plans for telework and alternative work places if workplaces become inaccessible.

Many cities could lose jobs, residents, and (or) resident income. This has ramifications for the tax base when property tax revenues drop for distressed properties, sales tax revenues decline from reduced spending, and workplaces or homes are vacated. The most badly damaged cities are likely to experience the highest losses relative to total budget and have neither the insurance nor a reserve base large enough to deal with the cost required for recovery.

- State government and local jurisdictions may need to plan together to determine how the revenue losses of a widespread event should be shared and ensure that the local governments most in need of revenue for recovery have access to necessary resources. This could involve developing a reserve fund through contributions from state and local sources or an insurance program to cover lost revenues in impacted areas.

Spatial Economic Demand Shifts

Planning and resource allocations for spatial economic demand shifts would be a regional issue for the San Francisco Bay region and beyond. In the initial recovery, economic demand may shift spatially from slow growth in the damaged core to high growth outside. The nature of growth in areas near the core damaged area may change, with short-term "fixes" having long-term implications (for example, see Xiao and Nilawar, 2013; Brown and others, 2015). Various planning initiatives could need to be funded after a large earthquake in the east bay part of the San Francisco Bay region. These include:

- Leveraging current regional industrial and logistic planning discussions with respect to mitigating, preparing, responding, and recovering from an earthquake—for example, application of the criteria for industrial preservation and conservation, as proposed by Chapple and others (2017).
- Using major disruption of land use and routes as an opportunity to improve planning for greenhouse gas reductions. Regional and local jurisdictions would need to be prepared beforehand to launch a planning process that addresses the needs of local property owners and residents as alternative travel patterns, land uses, and land use intensity are considered.
- Considering earthquake impacts to supply chains (including the ports) in regional transportation planning. The Association of Bay Area Governments (ABAG), for example, funded a study on the role of airports in a disaster (Perkins, 2015) as part of a larger initiative reviewing vulnerabilities in transportation and utilities systems (available at http://resilience.abag.ca.gov/projects/transportation_utilities_2014/).
- Dove-tailing earthquake planning and policy making with the currently energized regional planning for climate change. East bay shoreline liquefaction hazards overlap with flood hazards and sea level rise as is recognized in the "Stronger Housing, Safer Communities" effort by ABAG (available at http://resilience.abag.ca.gov/projects/stronger_housing_safer_communities_2015/). The San Francisco Bay Area Planning and Urban Research Association (SPUR) promotes a regional strategy for improving resilience to multiple natural hazards (Tam and Johnson, 2020).
- Within the alternatives that will be considered for rebuilding after the earthquake, seizing opportunities for other parts of the 21-county northern California megaregion (Bellisario and others, 2016). Balancing relocation and rebuilding within the east bay with opening up megaregion opportunities will need to weigh resilient logistics, reduced risk of concentrated damage to vulnerable housing, and sustainable workplace-home relations against the risks of further supply chain disruptions should another earthquake occur. Substantial planning, infrastructure, and business network support might be needed to facilitate potential shifts in development of the megaregion, in circumstances where rebuilding the pre-earthquake business and community networks is not feasible.

Stakeholder Considerations

Our analysis of concentrated-damage areas raises considerations for various stakeholders:

- For emergency managers and building departments, considerations include preparing to manage many issues around neighborhood safety, demolition

efficiency, and business resumption in areas with concentrated damage where cordons may be necessary.

- For businesses, considerations include preparing for neighborhood effects on their business operations and critical infrastructure, impacts of employee living situations, work relocation plans with respect to their customers and employee residences, particular vulnerabilities of their sector, and their role in neighborhood resilience and recovery. This preparation could benefit from being done cooperatively with similar types of businesses and within the context of city or regionwide resilience plans, to be able to address the differing needs of businesses of different sizes and sectors.
- For communities and city and county jurisdictions, considerations include policies for effective mitigation of vulnerable neighborhoods, providing services to keep residents in their homes, identifying space and resources for business resumption, commitment to retaining PDR sectors, acquiring and coordinating resource allocations for recovery of residences and businesses in tandem, and planning for a reduced tax base after an earthquake through effects on employment and displaced employed residents.
- For regional scale government, considerations include mitigating, preparing for planning, and allocating resources to areas that lag in recovery, and to manage spatial economic demand shifts.
- For multiple levels of government and the private sector, considerations include exploring insurance mechanisms to respond to the fiscal consequences of a major earthquake, fire, and related damage (see Johnson and others, this volume).

Each of these stakeholders face budget and time constraints that may impede taking steps in advance to address the large but uncertain risks posed by a major earthquake along the Hayward Fault. However, budgeting for planning and mitigation efforts in advance of an event will allow more effective responses that address a broad range of stakeholders' needs when an event occurs. Much of the planning and preparation that is required to be prepared is also an investment that addresses the region's future more widely.

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Appendixes 1–3

Appendix 1. Correspondence Tables

Table 1.1. Building count correspondence from Hazus-MH 2.1.

[ft², square feet]

Hazus building occupancy	Description	Average size (ft²)
RES1	Single family	1,600
RES2	Mobile home	1,080
RES3A	Duplex	3,000
RES3B	Multifamily (3–4)	3,000
RES3C	Multifamily (5–9)	8,000
RES3D	Multifamily (10–19)	12,000
RES3E	Multifamily (20–49)	40,000
RES3F	Multifamily (50+)	60,000
RES4	Hotel/motel	135,000
RES5	Dormitories	25,000
RES6	Nursing home	25,000
COM1	Retail trade	110,000
COM2	Warehouse	30,000
COM3	Personal and repair services	10,000
COM4	Professional/technical services	80,000
COM5	Banks	4,100
COM6	Hospital	55,000
COM7	Medical office/clinic	7,000
COM8	Entertainment and recreation	5,000
COM9	Theaters	12,000
COM10	Parking	145,000
IND1	Industrial-Heavy	30,000
IND2	Industrial-Light	30,000
IND3	Industrial-Food/drugs/chemicals	45,000
IND4	Industrial-Metals/minerals processing	45,000
IND5	Industrial-High tech	45,000
IND6	Industrial-Construction	30,000
AGR1	Agriculture	30,000
REL1	Church/non-profit	17,000
GOV1	Government-General services	11,000
GOV2	Government-Emergency response	11,000
EDU1	Grade schools	130,000
EDU2	Colleges/universities	50,000

Table 1.2. LODES industry segment correspondence.

[LODES, LEHD Origin-Destination Employment Statistics; LEHD, Longitudinal Employer-Household Dynamics; NAICS, North American Industry Classification System]

LODES industry segment	NAICS sector	Industry description
Goods producing	11	Agriculture, forestry, fishing, and hunting
	21	Mining, quarrying, and oil and gas extraction
	23	Construction
	31–33	Manufacturing
Trade, transportation, and utilities	22	Utilities
	42	Wholesale trade
	44–45	Retail trade
	48–49	Transportation and warehousing
Other services	51	Information
	52	Finance and insurance
	53	Real estate and rental and leasing
	54	Professional, scientific, and technical services
	55	Management of companies and enterprises
	56	Administration, support and waste management, and remediation
	61	Education
	62	Health and social services
	71	Arts, entertainment, and recreation
	72	Accommodation and food
	81	Other services
	92	Public administration

Appendix 2. Building Damages

Table 2.1. Disruptive damage for nonresidential buildings by occupancy group in concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Occupancy group	Disruptive damage (ft^2)	Concentrated-damage areas (ft^2)	Percentage of occupancy group with disruptive damage	Percentage of total disruptive damage
All hazards				
Industrial/warehouse	27,599,713	62,921,624	44	17
Retail/commercial	24,030,474	60,025,720	40	14
Offices	10,479,760	29,497,195	36	6
Household serving	7,000,208	16,807,935	42	4
Agricultural uses	313,649	963,800	33	0.2
Total	**69,423,804**	**170,216,274**	**41**	**42**
Earthquake hazards				
Industrial/warehouse	25,492,796	58,552,397	44	23
Retail/commercial	19,636,682	47,598,063	41	18
Offices	8,744,959	23,699,591	37	8
Household serving	4,734,527	12,139,383	39	4
Agricultural uses	247,644	703,489	35	0.2
Total	**58,856,608**	**142,692,923**	**41**	**53**

Table 2.2. Disruptive damage for residential buildings by occupancy group in concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Occupancy group	Disruptive damage (ft^2)	Concentrated-damage areas (ft^2)	Percentage of occupancy group with disruptive damage	Percentage of total disruptive damage
All hazards				
Single family/duplex	65,198,410	301,216,785	22	39
Multifamily	28,022,305	64,907,344	43	17
Group living	3,121,621	8,086,883	39	2
Total	**96,342,336**	**374,211,012**	**26**	**58**
Earthquake hazards				
Single family/duplex	33,582,773	181,490,753	19	30
Multifamily	16,331,727	45,949,663	36	15
Group living	1,841,762	4,921,043	37	2
Total	**51,756,262**	**232,361,459**	**22**	**47**

Table 2.3. Total disruptive damage for nonresidential occupancy groups by subarea with concentrated damages resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Number of tracts with concentrated damage	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards					
Central Alameda County	106	46,319,962	100,977,993	46	67
Northern Alameda County	30	11,275,340	34,605,561	33	16
Western Contra Costa County	6	5,670,589	12,357,460	46	8
Dublin-Pleasanton	21	4,960,477	15,282,373	32	7
Southern Alameda County	1	497,914	1,796,104	28	1
Novato	5	408,909	2,413,169	17	1
Vallejo	4	290,613	2,783,614	10	0.4
Subarea total	**173**	**69,423,804**	**170,216,274**	**41**	**100**
Earthquake hazards					
Central Alameda County	72	41,187,231	91,392,743	45	70
Northern Alameda County	22	9,187,735	28,722,807	32	16
Western Contra Costa County	4	4,888,509	10,781,497	45	8
Dublin-Pleasanton	15	3,525,177	11,555,250	31	6
Southern Alameda County	2	67,956	240,626	28	0.1
Novato	0	0	0	0	0
Vallejo	0	0	0	0	0
Subarea total	**115**	**58,856,608**	**142,692,923**	**41**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.4. Industrial/warehouse occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	21,813,702	46,248,331	47	79
Northern Alameda County	3,023,652	8,644,377	35	11
Western Contra Costa County	955,275	2,095,403	46	4
Dublin-Pleasanton	1,532,181	4,167,978	37	6
Southern Alameda County	85,982	293,486	29	0.3
Novato	152,488	1,073,913	14	1
Vallejo	36,433	398,136	9	0.1
Subarea total	**27,599,713**	**62,921,624**	**44**	**100**
Earthquake hazards				
Central Alameda County	20,694,092	45,302,326	46	81
Northern Alameda County	2,689,719	7,709,791	35	11
Western Contra Costa County	839,733	1,899,985	44	4
Dublin-Pleasanton	1,248,444	3,566,292	35	5
Southern Alameda County	20,808	74,003	28	0.1
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**25,492,796**	**58,552,397**	**44**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.5. Retail/commercial occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	14,267,740	31,271,952	46	59
Northern Alameda County	4,200,828	12,931,928	32	18
Western Contra Costa County	3,212,139	7,016,672	46	13
Dublin-Pleasanton	1,908,605	5,962,536	32	8
Southern Alameda County	251,600	936,327	27	1
Novato	58,185	367,260	16	0.2
Vallejo	131,377	1,539,045	9	1
Subarea total	**24,030,474**	**60,025,720**	**40**	**100**
Earthquake hazards				
Central Alameda County	12,052,438	26,200,498	46	61
Northern Alameda County	3,703,925	11,610,384	32	19
Western Contra Costa County	2,722,179	5,874,397	46	14
Dublin-Pleasanton	1,125,075	3,800,296	30	6
Southern Alameda County	33,065	112,488	29	0.2
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**19,636,682**	**47,598,063**	**41**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.6. Offices occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	5,995,458	14,019,107	43	57
Northern Alameda County	2,304,512	8,283,010	28	22
Western Contra Costa County	819,714	1,846,762	44	8
Dublin-Pleasanton	1,184,326	4,049,269	29	11
Southern Alameda County	71,135	290,456	24	1
Novato	86,314	735,504	12	1
Vallejo	18,301	273,087	7	0.2
Subarea total	**10,479,760**	**29,497,195**	**36**	**100**
Earthquake hazards				
Central Alameda County	5,418,493	12,821,908	42	62
Northern Alameda County	1,624,274	5,681,359	29	19
Western Contra Costa County	734,480	1,710,149	43	8
Dublin-Pleasanton	957,318	3,444,364	28	11
Southern Alameda County	10,394	41,811	25	0.1
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**8,744,959**	**23,699,591**	**37**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.7. Household-serving occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	4,059,125	8,930,273	45	58
Northern Alameda County	1,716,836	4,631,949	37	25
Western Contra Costa County	639,340	1,295,490	49	9
Dublin-Pleasanton	285,386	918,117	31	4
Southern Alameda County	84,049	253,520	33	1
Novato	111,348	218,770	51	2
Vallejo	104,124	559,816	19	2
Subarea total	**7,000,208**	**16,807,935**	**42**	**100**
Earthquake hazards				
Central Alameda County	2,865,033	6,652,334	43	61
Northern Alameda County	1,144,831	3,621,353	32	24
Western Contra Costa County	551,822	1,203,011	46	12
Dublin-Pleasanton	169,152	650,361	26	4
Southern Alameda County	3,689	12,324	30	0.1
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**4,734,527**	**12,139,383**	**39**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.8. Agricultural uses occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	183,937	508,330	36	59
Northern Alameda County	29,512	114,297	26	9
Western Contra Costa County	44,121	103,133	43	14
Dublin-Pleasanton	49,979	184,473	27	16
Southern Alameda County	5,148	22,315	23	2
Novato	574	17,722	3	0.2
Vallejo	378	13,530	3	0.1
Subarea total	**313,649**	**963,800**	**33**	**100**
Earthquake hazards				
Central Alameda County	157,175	415,677	38	64
Northern Alameda County	24,986	99,920	25	10
Western Contra Costa County	40,295	93,955	43	16
Dublin-Pleasanton	25,188	93,937	27	10
Southern Alameda County	0	0	0	0
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**247,644**	**703,489**	**35**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.9. Total disruptive damage for residential occupancy groups by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damage from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	59,139,171	226,755,128	26	61
Northern Alameda County	15,091,522	61,039,246	25	16
Western Contra Costa County	11,837,609	45,582,106	26	12
Dublin-Pleasanton	3,228,128	16,439,482	20	3
Southern Alameda County	3,986,927	15,733,799	25	4
Novato	923,639	2,127,193	43	1
Vallejo	2,135,340	6,534,058	33	2
Subarea total	**96,342,336**	**374,211,012**	**26**	**100**
Earthquake hazards				
Central Alameda County	33,215,542	147,066,446	23	64
Northern Alameda County	9,213,063	36,576,990	25	18
Western Contra Costa County	6,790,192	33,997,751	20	13
Dublin-Pleasanton	1,504,494	10,218,553	15	3
Southern Alameda County	1,032,971	4,501,719	23	2
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**51,756,262**	**232,361,459**	**22**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.10. Single family/duplex occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	41,000,566	187,089,779	22	63
Northern Alameda County	8,745,996	41,706,938	21	13
Western Contra Costa County	7,778,963	37,106,849	21	12
Dublin-Pleasanton	2,668,035	14,721,031	18	4
Southern Alameda County	3,355,296	14,124,979	24	5
Novato	576,745	1,712,544	34	1
Vallejo	1,072,809	4,754,665	23	2
Subarea total	**65,198,410**	**301,216,785**	**22**	**100**
Earthquake hazards				
Central Alameda County	22,415,554	118,974,996	19	67
Northern Alameda County	4,818,541	22,402,794	22	14
Western Contra Costa County	4,250,551	27,080,846	16	13
Dublin-Pleasanton	1,228,508	9,129,562	13	4
Southern Alameda County	869,619	3,902,555	22	3
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**33,582,773**	**181,490,753**	**19**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.11. Multifamily occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	15,965,391	34,625,980	46	57
Northern Alameda County	5,748,605	17,265,910	33	21
Western Contra Costa County	3,832,968	7,862,251	49	14
Dublin-Pleasanton	514,768	1,579,560	33	2
Southern Alameda County	604,852	1,525,531	40	2
Novato	311,694	335,710	93	1
Vallejo	1,044,027	1,712,402	61	4
Subarea total	**28,022,305**	**64,907,344**	**43**	**100**
Earthquake hazards				
Central Alameda County	9,490,609	25,018,380	38	58
Northern Alameda County	4,040,679	12,924,281	31	25
Western Contra Costa County	2,374,904	6,378,633	37	15
Dublin-Pleasanton	266,941	1,045,300	26	2
Southern Alameda County	158,594	583,069	27	1
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**16,331,727**	**45,949,663**	**36**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 2.12. Group-living residential occupancy with disruptive damage by subarea with concentrated damage resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Disruptive damage is defined as extensive or complete damage according to Hazus analysis. All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake (these damages were added exclusively as complete damage). Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. ft^2, square feet]

Subarea	Disruptive damage (ft^2)	Concentrated-damage area (ft^2)	Percentage of disruptive damage in concentrated-damage areas	Percentage of total concentrated-damage areas[1]
All hazards				
Central Alameda County	2,173,214	5,039,369	43	70
Northern Alameda County	596,921	2,066,398	29	19
Western Contra Costa County	225,678	613,006	37	7
Dublin-Pleasanton	45,325	138,891	33	2
Southern Alameda County	26,779	83,289	32	1
Novato	35,200	78,939	45	1
Vallejo	18,504	66,991	28	1
Subarea total	**3,121,621**	**8,086,883**	**39**	**100**
Earthquake hazards				
Central Alameda County	1,309,379	3,073,070	43	71
Northern Alameda County	353,843	1,249,915	28	20
Western Contra Costa County	164,737	538,272	31	9
Dublin-Pleasanton	9,045	43,691	21	1
Southern Alameda County	4,758	16,095	30	0.3
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**1,841,762**	**4,921,043**	**37**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Appendix 3. Employed Residents and Workers

Table 3.1. Total employed residents and workers living or working in concentrated-damage areas from HayWired earthquake scenario mainshock hazards, San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction]

Subarea	Employed residents		Workers	
	Number	Percentage[1]	Number	Percentage[1]
All hazards				
Central Alameda County	226,648	62	186,191	57
Northern Alameda County	54,363	15	78,107	24
Western Contra Costa County	44,902	12	23,882	7
Dublin-Pleasanton	15,723	4	27,742	8
Southern Alameda County	14,035	4	2,375	1
Novato	3,035	1	5,703	2
Vallejo	4,858	1	4,145	1
Subarea total	**363,564**	**100**	**328,145**	**100**
Earthquake hazards				
Central Alameda County	151,183	64	157,000	61
Northern Alameda County	36,852	16	56,874	22
Western Contra Costa County	33,348	14	22,087	9
Dublin-Pleasanton	10,268	4	21,160	8
Southern Alameda County	4,183	2	389	0.2
Novato	0	0	0	0
Vallejo	0	0	0	0
Subarea total	**235,834**	**100**	**257,510**	**100**
Regional totals				
Alameda County	750,932	49	747,446	55
Contra Costa County	476,423	31	358,028	26
Marin County	104,987	7	111,746	8
Solano County	185,506	12	143,731	11
Counties with concentrated-damage areas	**1,517,848**	**30**	**1,360,951**	**26**
Nine-county study region	**3,498,141**	**70**	**3,708,216**	**72**
17-county study region	**5,033,129**	**100**	**5,169,136**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 3.2. Employed residents who work in concentrated-damage areas, by subarea, for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction]

Residence subarea	All hazards		Earthquake hazards	
	Number	Percentage[1]	Number	Percentage[1]
Central Alameda County	69,144	72	37,095	72
Northern Alameda County	12,105	13	6,638	13
Western Contra Costa County	9,396	10	5,852	11
Dublin-Pleasanton	2,975	3	1,397	3
Southern Alameda County	1,810	2	394	1
Novato	280	0.3	0	0
Vallejo	582	1	0	0
Total	**96,292**	**100**	**51,376**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 3.3. Workers who live in concentrated-damage areas, by subarea, for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction]

Work subarea	All hazards		Earthquake hazards	
	Number	Percentage[1]	Number	Percentage[1]
Central Alameda County	63,593	66	35,674	69
Northern Alameda County	20,827	22	9,792	19
Western Contra Costa County	5,849	6	3,668	7
Dublin-Pleasanton	4,447	5	2,117	4
Southern Alameda County	736	1	125	0.2
Novato	449	0.5	0	0
Vallejo	391	0.4	0	0
Total	**96,292**	**100**	**51,376**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 3.4. People who live and work in concentrated-damage areas in the same subarea for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction]

Residence/work subarea	All hazards		Earthquake hazards	
	Number	Percentage[1]	Number	Percentage[1]
Central Alameda County	54,463	80	30,920	81
Northern Alameda County	6,793	10	3,539	9
Western Contra Costa County	4,241	6	2,701	7
Dublin-Pleasanton	1,545	2	747	2
Southern Alameda County	345	1	98	0.3
Novato	166	0.2	0	0
Vallejo	233	0.3	0	0
Total	**67,786**	**100**	**38,005**	**100**

[1]Because of rounding, percentages may not sum to 100 percent.

Table 3.5. Employed residents living in concentrated-damage areas (from all hazards) with respect to their work locations in concentrated- and less-concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most employed residents working in them]

Place of work	Place of residence															
	Central Alameda County		Northern Alameda County		Western Contra Costa County		Southern Alameda County		Dublin-Pleasanton		Vallejo		Novato		Total for subareas	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees living and working in a concentrated-damage area																
Central Alameda County	54,463	24	4,670	9	2,096	5	1,106	8	1,075	7	138	3	45	1	63,593	17
Northern Alameda County	10,667	5	6,793	12	2,773	7	174	1	312	2	71	1	37	1	20,827	6
Dublin-Pleasanton	2,434	1	183	0	97	0	155	1	1,545	10	26	1	7	0	4,447	1
Western Contra Costa County	1,072	0	365	1	4,241	10	21	0	32	0	93	2	25	1	5,849	2
Southern Alameda County	340	0	28	0	12	0	345	2	10	0	1	0	0	0	736	0
Novato	100	0	48	0	108	0	7	0	0	0	20	0	166	5	449	0
Vallejo	68	0	18	0	69	0	2	0	1	0	233	5	0	0	391	0
Subtotal	**69,144**	**31**	**12,105**	**22**	**9,396**	**22**	**1,810**	**13**	**2,975**	**19**	**582**	**12**	**280**	**9**	**96,292**	**26**
Employees living in a concentrated-damage area and working in a less-concentrated-damage area																
Alameda County remainder	52,496	23	13,653	25	6,940	15	3,631	26	4,144	26	325	7	124	4	81,313	22
San Francisco County	25,667	11	13,372	25	8,706	19	912	6	1,026	7	445	9	535	18	50,663	14
Santa Clara County	20,944	9	2,721	5	1,727	4	4,305	31	2,581	16	177	4	96	3	32,551	9
San Mateo County	18,514	8	2,807	5	1,707	4	1,414	10	794	5	141	3	110	4	25,487	7
Contra Costa County remainder	14,022	6	3,602	7	7,423	15	421	3	2,150	14	611	13	136	4	28,365	8
Sacramento Valley	4,302	2	907	2	1,146	3	223	2	268	2	245	5	67	2	7,158	2
San Joaquin Valley	3,474	2	669	1	690	1	197	1	397	3	125	3	37	1	5,589	2
Marin County remainder	1,998	1	788	1	2,888	6	57	0	99	1	228	5	1,236	41	7,294	2
Solano County remainder	1,729	1	367	1	938	2	85	1	125	1	1,063	22	43	1	4,350	1
Central coast	1,591	1	326	1	287	1	102	1	115	1	26	1	11	0	2,458	1
Sonoma County	1,376	1	341	1	492	1	61	0	82	1	199	4	199	7	2,750	1
Napa County	519	0	137	0	278	1	22	0	23	0	420	9	30	1	1,429	0
Other	10,872	5	2,568	5	2,284	6	795	6	944	6	271	6	131	4	17,865	5
Subtotal	**157,504**	**69**	**42,258**	**78**	**35,506**	**78**	**12,225**	**87**	**12,748**	**81**	**4,276**	**88**	**2,755**	**91**	**267,272**	**74**
Total employed residents	**226,648**	**100**	**54,363**	**100**	**44,902**	**100**	**14,035**	**100**	**15,723**	**100**	**4,858**	**100**	**3,035**	**100**	**363,564**	**100**

Table 3.6. Workers living in concentrated-damage areas (from all hazards) with respect to their home locations in concentrated- and less-concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most workers residing in them]

Place of residence	Place of work															
	Central Alameda County		Northern Alameda County		Western Contra Costa County		Dublin-Pleasanton		Southern Alameda County		Novato		Vallejo		Total for subareas	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees working and living in a concentrated-damage area																
Central Alameda County	54,463	29	10,667	14	1,072	4	2,434	9	340	14	100	2	68	2	69,144	21
Northern Alameda County	4,670	3	6,793	9	365	2	183	1	28	1	48	1	18	0	12,105	4
Western Contra Costa County	2,096	1	2,773	4	4,241	18	97	0	12	1	108	2	69	2	9,396	3
Southern Alameda County	1,106	1	174	0	21	0	155	1	345	15	7	0	2	0	1,810	1
Dublin-Pleasanton	1,075	1	312	0	32	0	1,545	6	10	0	0	0	1	0	2,975	1
Vallejo	138	0	71	0	93	0	26	0	1	0	20	0	233	6	582	0
Novato	45	0	37	0	25	0	7	0	0	0	166	3	0	0	280	0
Subtotal	**63,593**	**34**	**20,827**	**27**	**5,849**	**24**	**4,447**	**16**	**736**	**31**	**449**	**8**	**391**	**9**	**96,292**	**29**
Employees working in a concentrated-damage area and living in a less-concentrated-damage area																
Alameda County remainder	38,969	21	21,876	28	2,238	9	7,468	27	793	33	238	4	137	3	71,719	22
Contra Costa County remainder	17,410	9	12,216	16	7,063	30	4,886	18	93	4	418	7	409	10	42,495	13
Santa Clara County	11,601	6	2,619	3	740	3	2,357	8	297	13	134	2	53	1	17,801	5
San Joaquin Valley	9,247	5	2,221	3	785	3	2,639	10	129	5	76	1	39	1	15,136	5
San Mateo County	8,473	5	2,701	3	589	2	762	3	85	4	151	3	23	1	12,784	4
San Francisco County	6,727	4	5,269	7	1,007	4	545	2	39	2	414	7	51	1	14,052	4
Sacramento Valley	5,163	3	1,502	2	821	3	908	3	29	1	112	2	116	3	8,651	3
Solano County remainder	4,177	2	1,939	2	1,871	8	464	2	19	1	300	5	2,042	49	10,812	3
Central coast	2,479	1	542	1	172	1	432	2	29	1	43	1	14	0	3,711	1
Sonoma County	2,129	1	897	1	532	2	305	1	18	1	1,099	19	315	8	5,295	2
Marin County remainder	1,112	1	1,382	2	652	3	125	0	10	0	1,542	27	43	1	4,866	1
Napa County	765	0	312	0	390	2	107	0	2	0	96	2	360	9	2,032	1
Other	14,346	8	3,804	5	1,173	5	2,297	8	96	4	631	11	152	4	22,499	7
Subtotal	**122,598**	**66**	**57,280**	**73**	**18,033**	**76**	**23,295**	**84**	**1,639**	**69**	**5,254**	**92**	**3,754**	**91**	**231,853**	**71**
Total workers	**186,191**	**100**	**78,107**	**100**	**23,882**	**100**	**27,742**	**100**	**2,375**	**100**	**5,703**	**100**	**4,145**	**100**	**328,145**	**100**

Table 3.7. Employed residents living in concentrated-damage areas (from earthquake hazards) with respect to their work locations in concentrated- and less-concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most employed residents working in them]

Place of work	Place of residence															
	Central Alameda County		Northern Alameda County		Western Contra Costa County		Dublin-Pleasanton		Southern Alameda County		Novato		Vallejo		Total for subareas	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees living and working in a concentrated-damage area																
Central Alameda County	30,920	20	2,741	7	1,220	4	550	5	243	6	0	0	0	0	35,674	15
Northern Alameda County	4,273	3	3,539	10	1,880	6	81	1	19	0	0	0	0	0	9,792	4
Dublin-Pleasanton	1,191	1	99	0	51	0	747	7	29	1	0	0	0	0	2,117	1
Western Contra Costa County	687	0	258	1	2,701	8	17	0	5	0	0	0	0	0	3,668	2
Southern Alameda County	24	0	1	0	0	0	2	0	98	2	0	0	0	0	125	0
Novato	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vallejo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**37,095**	**25**	**6,638**	**18**	**5,852**	**18**	**1,397**	**14**	**394**	**9**	0	0	0	0	**51,376**	**22**
Employees living in a concentrated-damage area and working in a less-concentrated-damage area																
Alameda County remainder	43,973	29	10,999	30	6,136	18	3,277	32	1,085	26	0	0	0	0	65,470	28
San Francisco County	17,164	11	9,213	25	6,493	19	691	7	289	7	0	0	0	0	33,850	14
Santa Clara County	14,335	9	1,776	5	1,294	4	1,784	17	1,309	31	0	0	0	0	20,498	9
San Mateo County	12,179	8	1,842	5	1,256	4	533	5	494	12	0	0	0	0	16,304	7
Contra Costa County remainder	9,199	6	2,378	6	5,689	17	1,265	12	149	4	0	0	0	0	18,680	8
Sacramento Valley	2,827	2	604	2	847	3	152	1	70	2	0	0	0	0	4,500	2
San Joaquin Valley	2,284	2	446	1	511	2	261	3	62	1	0	0	0	0	3,564	2
Marin County	1,362	1	533	1	2,081	6	63	1	16	0	0	0	0	0	4,055	2
Solano County	1,198	1	246	1	771	2	81	1	24	1	0	0	0	0	2,320	1
Central coast	1,058	1	209	1	195	1	60	1	27	1	0	0	0	0	1,549	1
Sonoma County	920	1	223	1	380	1	55	1	23	1	0	0	0	0	1,601	1
Napa County	333	0	86	0	195	1	14	0	8	0	0	0	0	0	636	0
Other	7,256	5	1,659	5	1,648	5	635	6	233	6	0	0	0	0	11,431	5
Subtotal	**114,088**	**75**	**30,214**	**82**	**27,496**	**82**	**8,871**	**86**	**3,789**	**91**	**0**	**0**	**0**	**0**	**184,458**	**78**
Total employed residents	**151,183**	**100**	**36,852**	**100**	**33,348**	**100**	**10,268**	**100**	**4,183**	**100**	**0**	**0**	**0**	**0**	**235,834**	**100**

Table 3.8. Workers in concentrated-damage areas (from earthquake hazards) with respect to their residence locations in concentrated- and less-concentrated-damage areas resulting from the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most workers residing in them]

Place of residence	Place of work															
	Central Alameda County		Northern Alameda County		Dublin-Pleasanton		Western Contra Costa County		Southern Alameda County		Novato		Vallejo		Total for subareas	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees working and living in a concentrated-damage area																
Central Alameda County	30,920	20	4,273	8	1,191	5	687	3	24	6	0	0	0	0	37,095	14
Northern Alameda County	2,741	2	3,539	6	99	7	258	1	1	0	0	0	0	0	6,638	3
Western Contra Costa County	1,220	1	1,880	3	51	0	2,701	12	0	0	0	0	0	0	5,852	2
Dublin-Pleasanton	550	0	81	0	747	10	17	0	2	1	0	0	0	0	1,397	1
Southern Alameda County	243	0	19	0	29	0	5	0	98	25	0	0	0	0	394	0
Novato	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vallejo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**35,674**	**23**	**9,792**	**17**	**2,117**	**22**	**3,668**	**17**	**125**	**32**	**0**	**0**	**0**	**0**	**51,376**	**20**
Employees working in a concentrated-damage area and living in a less-concentrated-damage area																
Alameda County remainder	47,021	30	19,847	35	6,510	15	2,533	11	114	29	0	0	0	0	76,025	30
Contra Costa County remainder	15,041	10	9,671	17	3,694	19	7,543	34	13	3	0	0	0	0	35,962	14
Santa Clara County	10,269	7	1,849	3	1,919	4	702	3	46	12	0	0	0	0	14,785	6
San Joaquin Valley	8,114	5	1,200	2	2,095	4	755	3	45	12	0	0	0	0	12,209	5
San Mateo County	7,436	5	1,981	3	613	15	551	2	15	4	0	0	0	0	10,596	4
San Francisco County	5,882	4	4,148	7	447	3	960	4	0	0	0	0	0	0	11,437	4
Sacramento Valley	4,739	3	1,186	2	722	1	790	4	2	1	0	0	0	0	7,439	3
Solano County	3,735	2	1,527	3	380	6	1,837	8	1	0	0	0	0	0	7,480	3
Central coast	2,186	1	416	1	325	2	164	1	3	1	0	0	0	0	3,094	1
Sonoma County	1,917	1	721	1	257	1	494	2	7	2	0	0	0	0	3,396	1
Marin County	924	1	1,179	2	106	1	606	3	2	1	0	0	0	0	2,817	1
Napa County	692	0	252	0	87	1	351	2	0	0	0	0	0	0	1,382	1
Other	13,370	9	3,105	5	1,888	6	1,133	5	16	4	0	0	0	0	19,512	8
Subtotal	**121,326**	**77**	**47,082**	**83**	**19,043**	**78**	**18,419**	**83**	**264**	**68**	**0**	**0**	**0**	**0**	**206,134**	**80**
Total workers	**157,000**	**100**	**56,874**	**100**	**21,160**	**100**	**22,087**	**100**	**389**	**100**	**0**	**0**	**0**	**0**	**257,510**	**100**

Table 3.9. Employed residents (who live in concentrated-damage areas) by place of work and LODES industry segment for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most employed residents from each LODES industry segment working in them. LODES, Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics]

Place of work	All hazards								Earthquake hazards							
	Total		Goods producing		Trade, transportation, and utilities		Other services		Total		Goods producing		Trade, transportation, and utilities		Other services	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees living and working in a concentrated-damage area																
Central Alameda County	63,593	17	10,008	21	14,050	21	39,535	16	35,674	15	6,378	21	8,638	20	20,658	13
Northern Alameda County	20,827	6	2,639	6	2,417	4	15,771	6	9,792	4	1,329	4	1,517	3	6,946	4
Western Contra Costa County	5,849	2	261	1	1,530	2	4,058	2	3,668	2	157	1	914	2	2,597	2
Dublin-Pleasanton	4,447	1	548	1	1,081	2	2,818	1	2,117	1	293	1	534	1	1,290	1
Southern Alameda County	736	0	52	0	139	0	545	0	125	0	14	0	1	0	110	0
Novato	449	0	62	0	46	0	341	0	0	0	0	0	0	0	0	0
Vallejo	391	0	9	0	32	0	350	0	0	0	0	0	0	0	0	0
Subtotal	**96,292**	**26**	**13,579**	**29**	**19,295**	**29**	**63,418**	**25**	**51,376**	**22**	**8,171**	**27**	**11,604**	**26**	**31,601**	**20**
Employees living in a concentrated-damage area and working in a less-concentrated-damage area																
Alameda County remainder	81,313	22	10,918	23	12,568	19	57,827	23	65,470	28	7,848	26	9,576	22	48,046	30
San Francisco County	50,663	14	2,424	5	7,433	11	40,806	16	33,850	14	1,582	5	4,993	11	27,275	17
Santa Clara County	32,551	9	6,110	13	5,517	8	20,924	8	20,498	9	3,867	13	3,495	8	13,136	8
Contra Costa County remainder	28,365	8	3,235	7	4,829	7	20,301	8	18,680	8	2,131	7	3,237	7	13,312	8
San Mateo County	25,487	7	3,208	7	6,045	9	16,234	7	16,304	7	2,020	7	3,843	9	10,441	6
Marin County remainder	7,294	2	731	2	1,353	2	5,210	2	4,055	2	447	1	776	2	2,832	2
Sacramento Valley	7,158	2	651	1	1,670	2	4,837	2	4,500	2	408	1	1,062	2	3,030	2
San Joaquin Valley	5,589	2	907	2	2,068	3	2,614	1	3,564	2	563	2	1,316	3	1,685	1
Solano County remainder	4,350	1	595	1	1,085	2	2,670	1	2,320	1	316	1	625	1	1,379	1
Sonoma County	2,750	1	385	1	698	1	1,667	1	1,601	1	193	1	446	1	962	1
Central coast	2,458	1	641	1	647	1	1,170	0	1,549	1	412	1	381	1	756	0
Napa County	1,429	0	314	1	265	0	850	0	636	0	138	0	121	0	377	0
Other	17,865	5	3,380	7	3,932	6	10,553	4	11,431	5	2,149	7	2,554	6	6,728	4
Subtotal	**267,272**	**74**	**33,499**	**71**	**48,110**	**71**	**185,663**	**75**	**184,458**	**78**	**22,074**	**73**	**32,425**	**74**	**129,959**	**80**
Total employed residents	**363,564**	**100**	**47,078**	**100**	**67,405**	**100**	**249,081**	**100**	**235,834**	**100**	**30,245**	**100**	**44,029**	**100**	**161,560**	**100**

Table 3.10. Employees (who work in concentrated-damage areas) by place of residence and LODES industry segment for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[All hazards refer to damages from all hazards considered for the HayWired scenario: ground shaking, landslide, liquefaction, and fire following earthquake. Earthquake hazards refer to damages from earthquake hazards: ground shaking, landslide, and liquefaction. Records are color coded from smallest (white) to largest (dark red) within each column for ease of identifying regions with the most workers from each LODES industry segment residing in them. LODES, Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics]

Place of residence	All hazards								Earthquake hazards							
	Total		Goods producing		Trade, transportation, and utilities		Other services		Total		Goods producing		Trade, transportation, and utilities		Other services	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Employees working and living in a concentrated-damage area																
Central Alameda County	69,144	21	10,540	23	14,308	18	44,296	22	37,095	14	6,497	16	8,722	13	21,876	15
Northern Alameda County	12,105	4	1,358	3	1,735	2	9,012	4	6,638	3	820	2	1,131	2	4,687	3
Western Contra Costa County	9,396	3	944	2	2,167	3	6,285	3	5,852	2	581	1	1,376	2	3,895	3
Dublin-Pleasanton	2,975	1	365	1	582	1	2,028	1	1,397	1	195	0	294	0	908	1
Southern Alameda County	1,810	1	304	1	355	0	1,151	1	394	0	78	0	81	0	235	0
Vallejo	582	0	42	0	100	0	440	0	0	0	0	0	0	0	0	0
Novato	280	0	26	0	48	0	206	0	0	0	0	0	0	0	0	0
Subtotal	**96,292**	**29**	**13,579**	**29**	**19,295**	**25**	**63,418**	**31**	**51,376**	**20**	**8,171**	**20**	**11,604**	**17**	**31,601**	**21**
Employees working in a concentrated-damage area and living in a less-concentrated-damage area																
Alameda County remainder	71,719	22	9,616	21	13,505	17	48,598	24	76,025	30	11,940	29	16,761	25	47,324	32
Contra Costa County remainder	42,495	13	6,069	13	9,560	12	26,866	13	35,962	14	5,672	14	9,009	13	21,281	14
Santa Clara County	17,801	5	3,056	7	5,406	7	9,339	5	14,785	6	2,824	7	4,710	7	7,251	5
San Joaquin Valley	15,136	5	2,851	6	4,653	6	7,632	4	12,209	5	2,583	6	4,076	6	5,550	4
San Francisco County	14,052	4	1,669	4	3,439	4	8,944	4	11,437	4	1,413	3	3,134	5	6,890	5
San Mateo County	12,784	4	1,745	4	4,161	5	6,878	3	10,596	4	1,589	4	3,676	5	5,331	4
Solano County remainder	10,812	3	1,277	3	2,545	3	6,990	3	7,480	3	1,139	3	2,059	3	4,282	3
Sacramento Valley	8,651	3	915	2	3,263	4	4,473	2	7,439	3	844	2	2,917	4	3,678	2
Sonoma County	5,295	2	701	2	1,668	2	2,926	1	3,396	1	404	1	1,382	2	1,610	1
Marin County remainder	4,866	1	552	1	1,107	1	3,207	2	2,817	1	292	1	880	1	1,645	1
Central coast	3,711	1	433	1	1,583	2	1,695	1	3,094	1	394	1	1,346	2	1,354	1
Napa County	2,032	1	215	0	503	1	1,314	1	1,382	1	173	0	404	1	805	1
Other	22,499	7	3,501	8	6,972	9	12,026	6	19,512	8	3,198	8	6,347	9	9,967	7
Subtotal	**231,853**	**71**	**32,600**	**71**	**58,365**	**75**	**140,888**	**69**	**206,134**	**80**	**32,465**	**80**	**56,701**	**83**	**116,968**	**79**
Total workers	**328,145**	**100**	**46,179**	**100**	**77,660**	**100**	**204,306**	**100**	**257,510**	**100**	**40,636**	**100**	**68,305**	**100**	**148,569**	**100**

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Chapter W

The HayWired Scenario—Earthquake Early Warning Forecast and Potential Hazard Mitigation Actions

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Abstract

The HayWired scenario is a hypothetical earthquake sequence that begins with a 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 region, California. In the mainshock, the Hayward Fault ruptures along 86 kilometers (km)—from beneath San Pablo Bay southeast to the City of Fremont—rattling the greater San Francisco Bay region during the 30 seconds of sustained shaking. Using this scenario, the impacts of earthquake early warning (EEW) information and triggered automated controls are explored. EEW is the rapid detection of earthquakes, real-time assessment of the shaking hazard, and notification of people before the seismic waves that cause shaking arrive at their location. To assess the utility and efficacy of EEW for a significant earthquake in the San Francisco Bay region, alert times were calculated for the mainshock of the HayWired scenario. EEW alert times throughout the bay region were estimated for the mainshock based on expected performance of the ShakeAlert system, then mapped against shaking intensities, and used to envision plausible responses and mitigation actions. Less than 15 km from the epicenter (for example, in the cities of Oakland and Berkeley), strong shaking would arrive before the alert. However, outside of this "no-warning zone," alerts could have widespread positive effects in the densely built urban environment. The most notable benefit for individuals is the possible reduction in injuries resulting from people having more time to take the self-protective "drop, cover, and hold on" (DCHO) actions. We summarize an initial estimate of the potential benefit of ShakeAlert and DCHO in the HayWired scenario, as well as assessments of elevator, transit, and hospital responses to highlight how prevention of cascading failures of lifeline infrastructure systems (such as highways, rail systems, telecommunications, and electric grids) is important for resiliency during and after the rupture. The HayWired scenario invites us to take a step back and assess both the built environment's possible response to disasters of this scale and our own preparedness in a situation where we might not be able to rely on the communication and other systems of our interconnected, "wired" world.

Introduction

The HayWired scenario is a hypothetical yet scientifically realistic depiction of an earthquake sequence that begins with a moment magnitude (M_w) 7.0 earthquake (mainshock) occurring on Wednesday April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of the San Francisco Bay region, California. The mainshock begins beneath the City of Oakland and ruptures 86 kilometers (km) of the fault—north to beneath San Pablo Bay and southeast to the City of Fremont. During the approximately 30 seconds of sustained shaking, people and structures throughout much of the greater San Francisco Bay region are rattled, and the fault in some places is offset by more than 2 meters (m), soils liquefy, and landslides occur. Afternoon rush hour in the bay region is in full swing by 4:00 p.m., and many people would be taking an elevator, sitting on a train, or on roads and bridges on their way home from work. Others would still be in their offices, at after-school activities, running errands, or at home. Family members could be in very different locations in the bay region during their afternoon commute times. This scenario allows readers to envision the physical, infrastructural, and societal consequences of the rupture.

Chapters in U.S. Geological Survey (USGS) Scientific Investigations Report (SIR) 2017–5013–A–H (v. 1) outlined the science behind the models used in the HayWired scenario and the implications to the ground, such as fault rupture, shaking intensities, landslides, and zones of liquefaction (areas where soils become liquid-like during shaking). Chapters in SIR 2017–5013–I–Q (v. 2) assessed ordinary building performance (Seligson and others, 2018), building code performance (Porter, 2018a), and tall-building performance (Almufti and others, 2018). Building codes are said to support "life safety," but there is a common misconception that this

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means buildings will also be habitable and useable in the aftermath of a design-level earthquake (Porter, 2018a). The reality is that many people and businesses will likely be displaced (Applied Technology Council, 2012; Johnson and others, this volume). Building codes aim to preserve the lives of those inside them, but perhaps we can do better than that in the future (Porter, 2016). New engineering designs and risk mitigation measures put in place now can increase resiliency and recovery.

USGS and a coalition of State and university partners are developing and testing an earthquake early warning (EEW) system called ShakeAlert (https://www.shakealert.org) to provide a few seconds of earthquake early warning to reduce risk and increase resiliency, not just for utilities and infrastructure, but also for people and organizations. The ShakeAlert system continues to evolve, and pilot groups, technology enablers, licensed operators, and stakeholders in the transportation, utility, healthcare, education, and emergency management sectors have been engaged in developing hazard-mitigation best practices and strategies in response to alerts of shaking. In the spirit of HayWired's focus on interconnectivity, and the authors' work with ShakeAlert stakeholders, this chapter is meant to outline possibilities for uses and benefits of the ShakeAlert system based on data researched for the scenario and priority focus areas from stakeholders. It is not intended as a rigorous cost-benefit assessment; the numbers of affected people or systems discussed should not be taken as absolutes. The discussion in this chapter is best used as a planning tool to probe the extent of what is possible for ShakeAlert.

We live in a "wired," interconnected world. When the first thorough cost-benefit study of the impacts of EEW was done in California (Holden and others, 1989), automated controls were not an accepted part of daily life. Now, we cannot imagine a world without machines helping with ordinary, daily tasks. In 1989, planning for the unknown was often a part of life, and distribution of goods and services was handled differently. For example, before the constant presence of cell phones, many families had a plan of where to meet if, say, people went to different stores in a mall. Emergency-response groups historically had access to warehouses of supplies in case of dire need. Now, businesses rely on just-in-time delivery to fill stores, and on-site inventories have been reduced. An earthquake can temporarily interfere with our constant interconnectedness, so having a plan in place before an earthquake strikes is even more crucial in today's world. The hypothetical ShakeAlert responses discussed in this chapter do not cover the full range of what is possible but instead give a rational flavor of what we could expect to unfold during an earthquake like the HayWired scenario mainshock and provide a framework to engender discussion on new strategies and responses. (For other resources, also see Allen and others, 2009; Fujinawa and Noda, 2013; Gasparini and others, 2007; Goltz and Flores, 1997; Heaton and others, 1985; Strauss and Allen, 2016.)

ShakeAlert Time Estimation for the HayWired Scenario

EEW provides an alert that an earthquake has occurred and may forecast the final magnitude and severity of shaking at a location. EEW has been deployed in at least eight countries—China, Japan, Mexico, Romania, Switzerland, Taiwan, and Turkey (National Research Council, 2011) and the United States, South Korea and Israel. Mexico began providing limited public alerts to certain cities within the country in 1993. Japan's nationwide system has provided alerts for the safety of the general public since 2007. Taiwan implemented nationwide public alerting in 2016.

EEW has been in active development in the United States since 2006 (Allen, 2011; Burkett and others, 2014), in a collaborative group including the USGS, the California Institute of Technology, the University of California at Berkeley, the University of Oregon, and the University of Washington. This public EEW system is called ShakeAlert and operates on the West Coast of the United States. The ShakeAlert group also works with State, public, and private partners to assess dissemination, resiliency and hazard mitigation, and implementation strategies that can make use of the advanced warnings that EEW can provide.

The ShakeAlert system, as currently designed, will generate public alerts (in the future) for earthquakes greater than magnitude (*M*) 4.5 and will deliver alerts to regions estimated to experience expected Modified Mercalli Intensities (MMI) greater than or equal to II (that is, felt shaking). The estimated regions are octagonal contours and thus provide an average intensity estimate for the area, so actual felt shaking could vary on a more local scale. Technical users, which could include transportation and utility sectors, could receive more detailed and lower magnitude threshold alerts, as well as alerts for lower magnitude earthquakes. California public alerting was activated just prior to publication of this chapter. Public alert dissemination began earlier in the Los Angeles region through the use of a cell phone application and will be tested in California by the end of 2019.

The ShakeAlert system uses a network approach, where the first seismic wave (the primary, or P-wave), which radiates from the earthquake hypocenter at speeds of 5–8 kilometers per second (km/s), is detected by nearby seismic sensors. Seismic sensors relay information about the P-wave to data centers, where algorithms compute the probable earthquake location and magnitude, and estimate the shaking intensities that will result. This information is used to generate an EEW alert for the impacted region that is sent to people and devices electronically. The goal is to distribute the alerts before the slower moving (3–5 km/s), yet generally stronger and more damaging, secondary wave (or S-wave) and following series of surface waves arrive at a given location. Because electronic communication travels much more rapidly than seismic energy, advanced warning

can be possible even in regions where critical infrastructure and population centers are located close to the rupturing fault (as is the case in the HayWired scenario).

ShakeAlert (Cochran and others, 2017; Given and others, 2018; Kohler and others, 2017) relies on an array of sensors throughout the West Coast that relay information back to a central site for analysis and alert distribution. The amount of warning provided depends on many factors, including the time it takes for the fault rupture to grow (large ruptures can take several to tens of seconds to grow), the shaking intensity threshold used to issue an alert, how often alerts are updated, time to detect the growing rupture, and time to distribute an alert to an end user or to engage an automated control, as well as the user's distance from the earthquake hypocenter. The amount of shaking a user experiences is related to their distance from the part of the fault that ruptures and site conditions at their location, whereas the amount of warning a user receives is based on their distance from the epicenter.

It is important to note that these local variations in shaking intensity can be large, and estimated shaking intensities can have large uncertainties. In general, P-waves induce vertical shaking, which has minimal impact on the built environment, because buildings are constructed to withstand the vertical force of gravity and less so for lateral motions from S-waves. However, that does not mean that high shaking intensities will only be experienced during the S-wave and later phases of an earthquake. The reader is encouraged to keep this in mind, as the estimated ShakeAlert warning times below are in reference to S-wave arrival.

It is estimated that ShakeAlert would issue its first alert 5.1 seconds (s) after the HayWired scenario mainshock begins (for details, see appendix 2 of Porter and Jones, 2018). This estimate is based on the system's performance during the M_w 4.0 Piedmont, California, earthquake on August 17, 2015. The Piedmont earthquake epicenter lies only 6 km from the epicenter of the HayWired scenario mainshock, and thus it is a reasonable proxy for our purposes here because the initial alert latency should be comparable. Initial alert latency (the alert time minus earthquake origin time) depends on the local seismic station density and the speed with which data is delivered to ShakeAlert processing centers. The station density has remained relatively constant in this region but upgrades to sensors and telemetry have improved data delivery since 2015. In the future, ShakeAlert will also continue to refine the algorithms to improve alert speeds. Full station buildout is complete in the bay region as of this writing. Buildout for the State of California is funded and expected to be completed in the coming years. The full West Coast of the United States will be built out sometime after that. Once all stations are contributing to the system, alert speeds will improve in areas where coverage is currently lacking.

The time between an EEW alert and the S-wave arrival at a particular location is what we call the EEW time. Different alert distribution methods used by various pilot implementations, such as public announcement systems, cellular applications, or radio communications, will increase latencies and result in shorter EEW times for end users. For the HayWired scenario mainshock, the distance traveled by S-waves during the 5.1 seconds (s) after the earthquake begins and the modeled distribution of the alert is approximately 15 km from the epicenter. This region defines a "no-warning zone," where S-wave shaking would arrive before or at the time of the published ShakeAlert. At distances greater than 15 km, a user of an EEW system could receive an alert before the arrival of S-waves. It should be noted that for large ruptures, the initial shaking intensity estimates are likely to be low and increase as a fault continues to rupture. Automated responses, outlined below, should take this into account when setting thresholds (Minson and others, 2018).

Table 1 catalogs the warning times and shaking intensities that ShakeAlert could provide for major cities affected by the M_w 7.0 HayWired mainshock using the assumptions outlined above and described in appendix 2 of Porter and Jones (2018) (fig. 1). Nearby regions situated about 0–65 km

Table 1. Estimates for earthquake early warning times, relative to secondary-wave (S-wave) arrival, and peak shaking intensities at select locations for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario in the San Francisco Bay region, California.

[MMI, Modified Mercalli Intensity]

City	Latitude (north)	Longitude (west)	Distance from epicenter, in miles	Distance from epicenter, in kilometers	Warning time, in seconds	Shaking intensity, MMI
Oakland	37.80	122.27	5	8	0.0	VIII
Berkeley	37.87	122.27	7	11	0.0	IX
Hayward	37.67	122.08	11	17	0.7	IX
San Francisco	37.78	122.42	13	21	1.8	VII
San Mateo	37.55	122.31	19	30	4.3	VII
Fremont	37.55	122.99	21	33	5.2	IX
Vallejo	38.11	122.24	21	35	5.8	VII
Redwood City	37.48	122.24	23	36	6.0	VII
San Rafael	37.97	122.53	23	36	6.0	VII
Livermore	37.68	122.77	24	39	6.9	VIII
San Jose	37.34	121.89	36	58	12.4	VIII

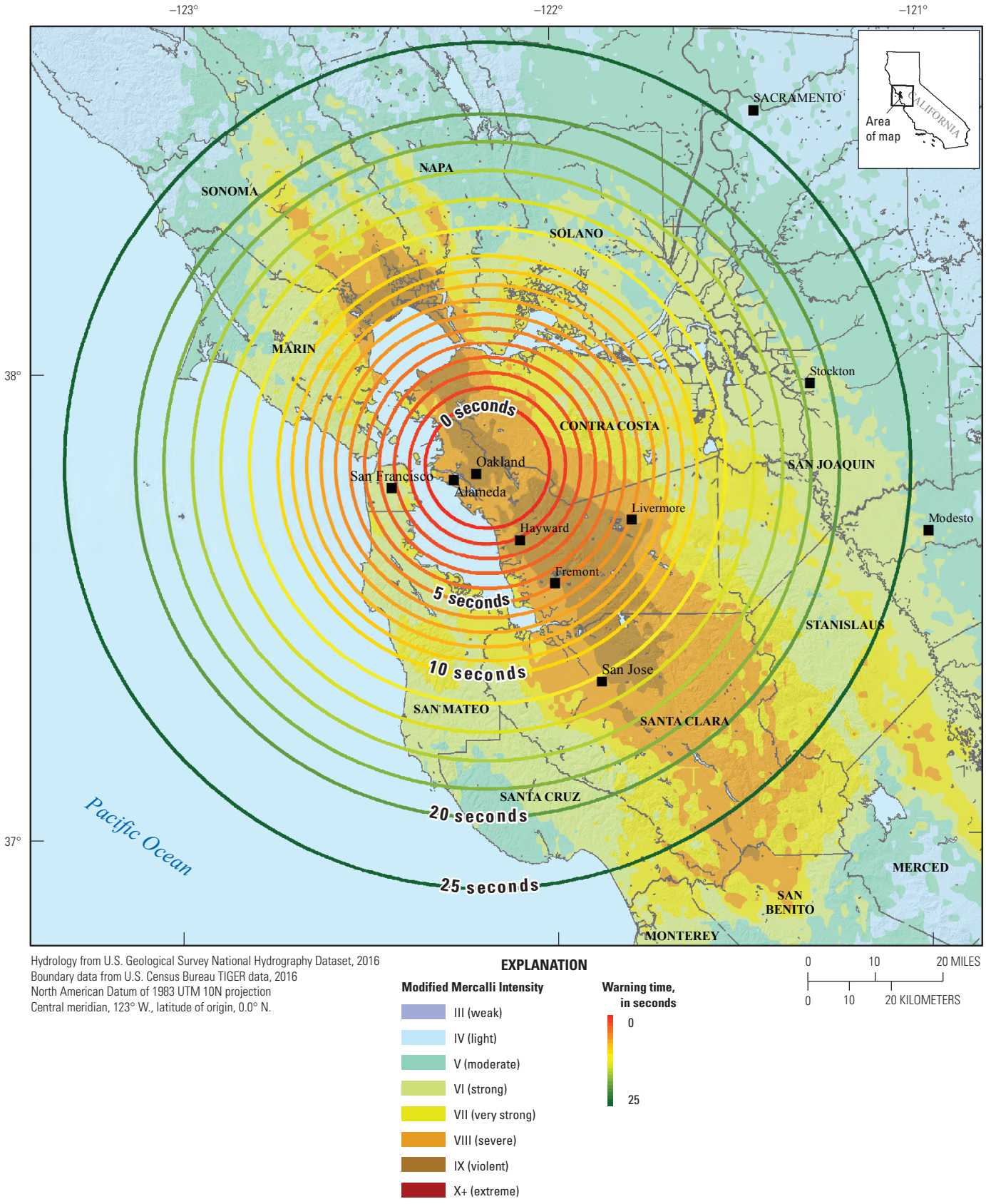


Figure 1. Map of the San Francisco Bay region, California, showing contours of earthquake early warning time estimates relative to secondary wave (S-wave) arrival for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault overlain on the instrumental intensity map for mainshock (intensity map modified from Aagaard and others, 2017a).

from the epicenter could receive advanced warnings ranging from 0 to 12.4 s and experience shaking intensities from VII to IX on the MMI scale. The MMI scale describes the very strong shaking level (MMI VII) as when people have difficulty standing during shaking. The next level up, severe shaking (MMI VIII), would not only prevent people from standing but could overturn heavy furniture, cause chimneys to collapse, and cause structural damage.

Discounting local site effects and amplification in basins and areas of liquefaction, which can locally increase shaking intensities, more intense shaking is usually experienced closer to the section of the fault that ruptures and falls off as a function of distance (Aagaard and others, 2017a). Inversely, greater early warning times are possible for locations farther from the epicenter of an earthquake. For large events (*M*7.0 and above), heavy shaking can be experienced far from the epicenter, because the rupture continues along the fault for some distance. Porter and Jones (2018, see appendix 2) suggest that MMI II or greater shaking would be felt as far as 250 km away from the epicenter of the HayWired mainshock. In such a case, people downstream of the event can receive larger warning times and still feel shaking.

For the HayWired scenario mainshock, many highly populated areas, such as San Jose, have warning times of more than 12 s and ground shaking intensities of MMI VIII (fig. 2), whereas San Francisco, which is closer to the epicenter, would only receive 1.8 s of warning time and experience lower shaking of MMI VII. People and businesses in Fremont could receive 5 s of warning of violent shaking. Further afield, people in the Central Valley could receive as much as 42 s of warning preceding severe shaking.

The HayWired mainshock rupture could be considered a worst-case scenario for the eastern part of the San Francisco Bay region, because the epicenter is right in the heart of an urban area, and the no-warning zone covers many affected people. Residents, businesses, and emergency responders in Oakland and Berkeley, less than 15 km from the epicenter, would be in this no-warning zone. That is, the S-wave would arrive before the warning did. The alert would not come in time for people in those cities to take advanced protective actions.

However, even in the no-warning zone, people who had been trained on how to use ShakeAlert warnings could have their minds and bodies "prompted" to remember their training to "drop, cover, and hold on" when an earthquake occurs, even if the warning came at the same time as or after the shaking. This is based on exemplification theory that tells us that:

> The use of exemplifying imagery, mostly as a complement to informative text, has emerged as a powerful means of creating risk consciousness and of motivating protective and corrective action (Zillmann, 2006).

The developers of ShakeAlert are working with social scientists to ensure that alerts can make use of this body of research to benefit the recipient by linking a situation with a response. This is why training in advance, like the annual ShakeOut drills (see https://www.shakeout.org), is important.

Of course, ShakeAlert warnings will not help with longer term decisions of constructing and retrofitting buildings for desired performance, nor can they prevent all impacts from heavy ground shaking. A few seconds of EEW is not enough time to take actions such as getting an earthquake kit together, contacting loved ones and deciding on a meeting place, securing heavy objects in a room, or stopping traffic over bridges. However, what a few seconds of EEW can do is allow people and organizations to implement mitigation and protective actions that were decided upon and put in place in advance of an earthquake. EEW is also a reminder that alerts and actions go hand in hand with preparedness (Allen and others, 2017). The process of planning strategies and actions for ShakeAlert can prompt people and organizations to also look at other protective actions in their environment that can be enacted well in advance of an earthquake. ShakeAlert is one tool in the resiliency toolbox, but one that requires prior planning to reach full potential. It should also be noted that the population affected by the no-warning zone for the HayWired scenario mainshock can, of course, benefit from warnings generated by earthquakes that occur in other parts of the San Francisco Bay region.

ShakeAlert Can Prompt Automated Controls

Automated controls are a key component for responding to the short warning times offered by ShakeAlert in the San Francisco Bay region. Automated responses eliminate the loss of precious time that a human would require to enact a process (such as opening fire station bay doors or slowing and stopping trains) that can aid in preventing cascading system failures. Cascading failures in this context are small failures that stack up together to have big impacts. Here, we outline some of the automated controls that ShakeAlert pilot users are working on, as well as those that were able to be directly investigated based on data provided as part of research for the HayWired scenario.

Many automated controls involve physical hardware and protocols to put specific equipment or systems into a safe mode. This is the case for elevator, door, and machinery type controls. There is also another approach that some groups are exploring to enable structural controls. These "smart civil structures" would be able to adapt building characteristics in real-time to more adequately brace a building for imminent earthquake shaking (Housner and Masri, 2000). A proof of concept using an EEW trigger to enact semiactive structural control capabilities was performed for a bridge in Southern California and shown to be effective at "reducing the response of the benchmark highway bridge for a wide variety of earthquake records" (Maddaloni and others, 2013). The analysis of structural controls is an interesting topic for further research but has not been integrated with EEW in the United States and is thus outside the scope of this chapter.

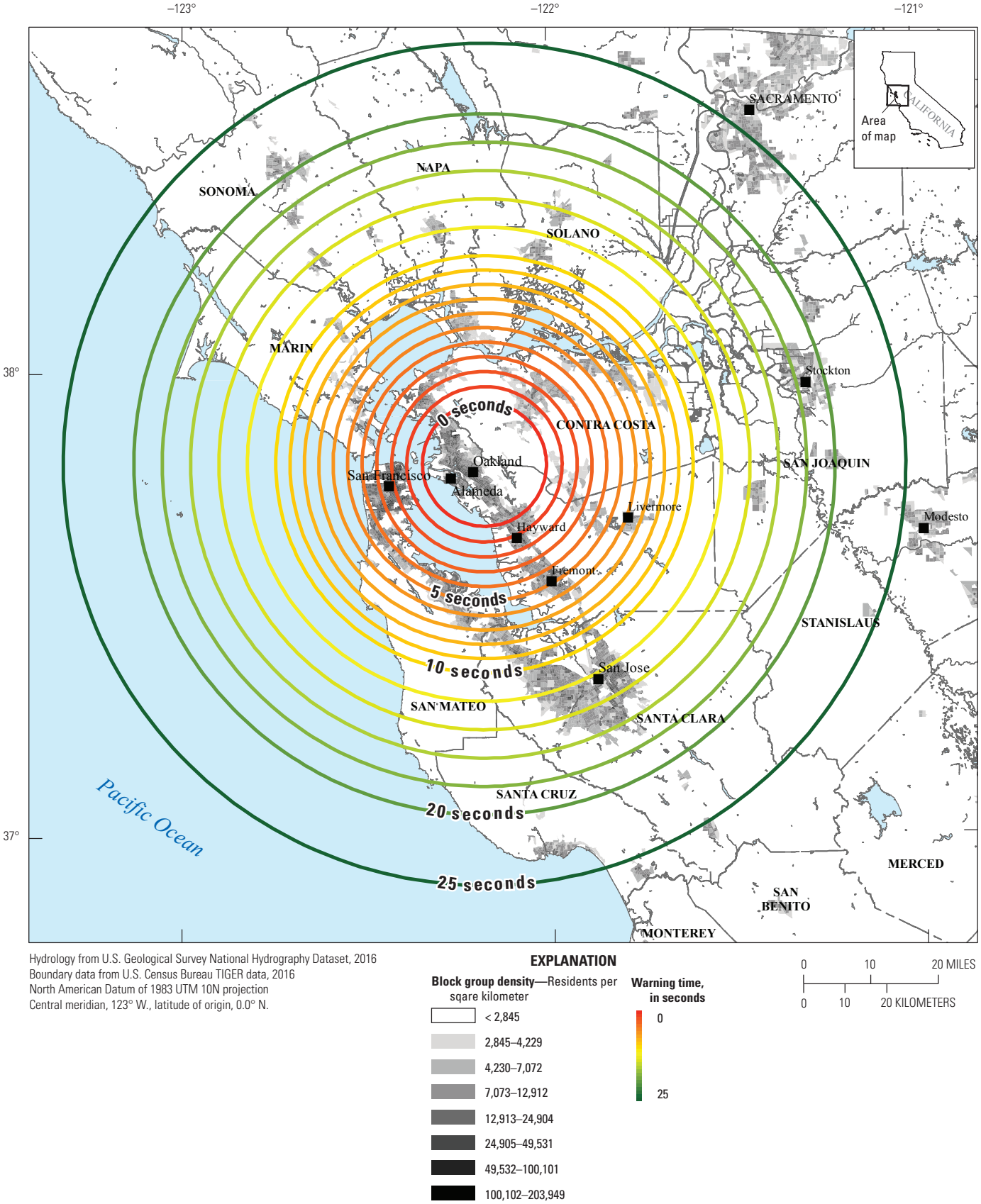


Figure 2. Map of the San Francisco Bay region, California, showing ShakeAlert (https://www.shakealert.org) earthquake early warning time estimates overlain with population density information for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault (also see fig. 2 in Porter and Jones, 2018). The geographically dispersed population experiences many different warning times in this scenario event.

Elevator Systems

Automated controls added to building elevator systems can prevent passengers from becoming trapped when an elevator car and its counterweight become misaligned during heavy earthquake shaking (in the absence of structural controls). Elevator systems with active response systems based on either EEW systems or threshold-crossing protocols for ground shaking held 16,700 occupants during the M_w 9.0 2011 Tohoku earthquake in Japan (Layne, 2011). All of these elevators were in the affected region and experienced shaking at a high enough level to cause the systems to trigger. Using such a system, elevators in the United States could be configured to send elevator cars to the ground floor or stop at the nearest floor and hold the doors open during a strong earthquake.

Currently, there are limitations on using EEW for elevator systems, because not all buildings are modern enough to permit retrofits with ShakeAlert EEW technology, and regulations affecting how ShakeAlert warnings can be transmitted to elevators would need to be modified. ShakeAlert pilot users have indicated that California regulations do not permit internet services to initiate an elevator stop. Recently, Pacific Gas and Electric Company installed on-site EEW in some of their elevators, which does not use the internet to initiate the stop as a workaround (BusinessWire, 2017). If State regulations were changed from a location-by-location strategy, this could result in a more realistic approach to building resiliency throughout the West Coast.

A detailed analysis of elevator entrapment owing to power outages can be found in Porter (2018b); we summarize the methodology and results here because we apply the same assumptions to show how ShakeAlert could reduce the risk of elevator entrapment in the region impacted by the HayWired scenario. Porter (2018b) assumed a national average of one elevator for every 334 people to estimate numbers of elevators. He removed an estimated proportion of elevators with emergency power and assumed 60 percent of the elevators are in use (for example, actually carrying people) at any instance during peak times, and of those elevators, 30 percent would be between floors when the HayWired mainshock occurred. On the basis of this approach, Porter (2018b) estimated 4,500 elevators in transit would be interrupted by power outages with the potential to trap as many as 22,000 people. This number is an upper limit estimation in that it assumes a widespread power outage occurs that affects all 10 million people living in the San Francisco Bay region and neighboring counties.

The following estimation of the number of people trapped in elevators represents ideal-world conditions where all elevators that could trap riders owing to shaking (that is, shaking that cuts power at the site or misaligns the elevator) have automated controls that do not add significant delay in response to a ShakeAlert. Also, we calculate percentages of elevators that could avoid entrapping riders where ShakeAlert conditions apply. Using the estimated ShakeAlert warning times for the HayWired mainshock that are a function of distance from the epicenter, we estimate the number of elevators in each warning-time band by invoking Porter's (2018b) assumption of one elevator for every 334 people. The numbers of people in each ShakeAlert warning-time band were calculated using population data (U.S. Census, 2016) and warning-time contours in a geographic information system (as shown in fig. 2). Similar to Porter (2018b), we removed percentages of elevators with emergency power, those not in use by riders, and those that would be at floors when the ShakeAlert is received.

We assume that given at least some ShakeAlert warning, elevators equipped with automated controls could be held at a floor and (or) stopped at the next floor with open doors for easy egress. For example, if elevators receive 2 s of warning of shaking that would trap riders, then those elevators that would have left a floor or would reach a floor in less than 2 s could be held before leaving a floor or stopped at the next floor, respectively. Hydraulic elevators, which according to Otis are "used extensively in buildings up to five or six stories high," have transit speeds of 150 feet per minute, requiring 3.2 s to get between floors (Otis, n.d.). Rounding the transit time to 4 s and assuming transit times are uniformly distributed at any one time, then elevators with approximately 1 s of warning (in the 1–2 s warning band) would allow one-quarter of riders to be held at a floor and one-quarter of riders to be stopped at the next floor. Similarly, half of riders might be held at a floor and the other half could be stopped at the next floor with about 2 s of warning (2–3 s warning band). If elevators can only be held or stopped, then three-quarters of riders might avoid entrapment with about 3 s of warning (3–4 s warning band). Beyond 4 s of warning, all riders would receive a warning in time to remain at a floor or stop at the next floor to avoid getting trapped.

With a ShakeAlert warning capable of only keeping elevators at a floor, about 9 percent of all riders receiving less than 2 s of warning could avoid entrapment (0 percent of elevator occupants in the area with less than 1 s of warning and 25 percent of elevator occupants in the area with 1 to 2 s of warning). About 40 percent of all riders receiving as much as 5 s of warning could avoid entrapment. This translates to about 1,600 elevators carrying about 8,000 riders and illustrates how a few seconds of warning could make a difference for elevator riders because elevators only take seconds to travel between floors. The hypothetical upper bound for ShakeAlert helping to avoid elevator entrapment in the HayWired scenario is 81 percent of elevator riders. If a ShakeAlert warning is able to stop elevators at the next floor, the results are the same because elevator transit is distributed uniformly. If a ShakeAlert warning can both hold departing elevators and stop elevators when they arrive at the next floor, then the numbers double for the first 1 s and 2 s of warning and cap at 87 percent of avoided entrapments or an upper bound of 19,600 riders in elevators in the region. See table 2 for the details of estimates of avoided entrapments. Elevators within the no-warning zone, within the 1-s warning zone, or in transit beyond the warning time could still benefit from existing mechanical earthquake sensor controls that are non-EEW-related.

Table 2. Number of elevators and percentage of riders in the San Francisco Bay region, California, that could use ShakeAlert to remain at a floor and (or) stop at the next floor to avoid entrapment of passengers in transit during power outage or damage at the site during the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario.

[Number of elevators is estimated using 2010 U.S. Census Bureau population data (U.S. Census Bureau, 2016) in the warning time areas. %, percent]

ShakeAlert warning-time bands	Estimate of the number of elevators in transit in warning-time band	Percent of riders avoiding entrapment with ShakeAlert capability to only hold elevators at a floor or only stop at the next floor	Percent of riders avoiding entrapment with ShakeAlert capabilities to both hold elevators at a floor and stop at the next floor
None	355	0	0
Less than 1 second	461	0	0
Less than 2 seconds	712	9	18
Less than 3 seconds	968	20	39
Less than 4 seconds	1,400	30	51
Less than 5 seconds	1,600	40	58
All warning-time bands in region, including areas receiving ≥5 seconds warning	4,500	81	87

Fewer people trapped in elevators would reduce the burden on 9-1-1 systems, which in turn could lessen the effects of cascading system and infrastructure failures. For example, in 2009, California experienced a 9-1-1 overload problem, which caused 26 percent of all wireless calls into the system to be "abandoned" (9-1-1 Industry Alliance, 2011). An example of how 9-1-1 overloads can lead to cascading failures involved a motorcycle accident on July 4, 2011, in Wichita, Kansas. Witnesses were unable to reach 9-1-1 to report the accident owing to the sheer volume of calls about fireworks clogging the lines (Finger, 2011). Paramedics were only reached after one witness bypassed 9-1-1 and directly contacted his father, who was an off-duty police officer. In light of this ongoing nationwide concern, California Governor's Office of Emergency Services created the Routing on Empirical Data (RED) project, to use locations from wireless devices to help reduce the number of busy signals—"shaving time and saving lives" (California Governor's Office of Emergency Services, 2014). This method involves "using historical empirical call data [to] determine the most efficient routing for wireless 9-1-1 calls" (California Governor's Office of Emergency Services, 2014).

Although the number of calls to 9-1-1 reporting trapped high-rise elevator occupants is not likely to ever reach the upper limit value of 3,900 calls represented by the number of elevators that could be held at a floor using ShakeAlert—in the HayWired scenario (87 percent of 4,500 elevators)—removing even some of these calls from the queue can have an impact on the volume of calls routed by 9-1-1 call centers.

Fire following earthquake is a major cause of postearthquake destruction (Scawthorn, 2018), so ShakeAlert's ability to reduce 9-1-1 calls from low-level injuries through drop, cover, and hold on (outlined later in this chapter) and by stopping elevators (and the use of other automated controls) in combination with the RED project, may enable more calls, like those for fire, to get through.

Transportation Systems

Bay Area Rapid Transit (BART) trains are a crucial transportation system for the San Francisco Bay region. BART has invested in structural retrofits, an earthquake safety program, and in using the ShakeAlert system to limit system vulnerabilities in the case of an earthquake. BART is a crucial lifeline in the San Francisco Bay area, and these actions work together to increase resiliency for the train network.

In the HayWired scenario, trains arriving and departing from the Fruitvale, Coliseum, San Leandro, Bay Fair, Hayward, and South Hayward stations intersect locations of high estimated shaking damage and areas with low to moderate liquefaction and (or) landslide probability (fig. 3). BART works with the ShakeAlert team and has implemented ShakeAlert warnings and their own local sensors, to slow and (or) stop the trains.

The BART system carries individual riders on more than 127 million trips annually (2015 data; Bay Area Rapid Transit, 2015). On Wednesdays at 4:18 p.m., there are on average 10,482 persons in motion on 40 trains and 2,021 patrons on 6 berthed trains (Kevin Copley, BART, written commun., 2015). Using timetables for each BART line passing through these six stations, we can construct a snapshot of train locations and directions along the track lines at 4:18 p.m. on a Wednesday afternoon (fig. 4) and envision how ShakeAlerts could impact the system. The following scenario is based on BART's late 2017 schedule.

Three trains (the Oakland International Airport and both Richmond line trains at Bay Fair) are berthed at the station platforms at 4:18 p.m. when the ShakeAlert alarm is received. Thus, approximately 1,011 passengers on the platforms and within the three trains would receive the command to hold position. Two trains on the Fremont-Daly City lines (both northbound and southbound) would be enroute between the South Hayward and Hayward stations at the time of the alarm.

Each train should receive 2 s of ShakeAlert warning in this scenario. BART receives alerts directly from ShakeAlert that do not pass through a third-party redistributor, so latency times are minimal from alert generation to alert receipt at BART. Two seconds is not enough time to slow and completely stop trains in motion; BART trains only can reduce speed 3 miles per hour per second. However, for the two trains in motion, which receive 2 s of warning before shaking, and the five trains in transit through the affected area, which would not receive an early enough warning, the automated controls still protect the system by not requiring slower human interventions to make decisions to begin slowing or stopping the trains. The trains would automatically begin slowing as a result of either the networked ShakeAlert warning or BART's own wayside track monitors. We should note that currently BART's Oakland International Airport to Coliseum leg does not yet have the benefit of automated reaction.

Other transportation systems, such as metered entrances to highways and toll bridges, could benefit from ShakeAlert. There are thousands of commuters on the road during rush

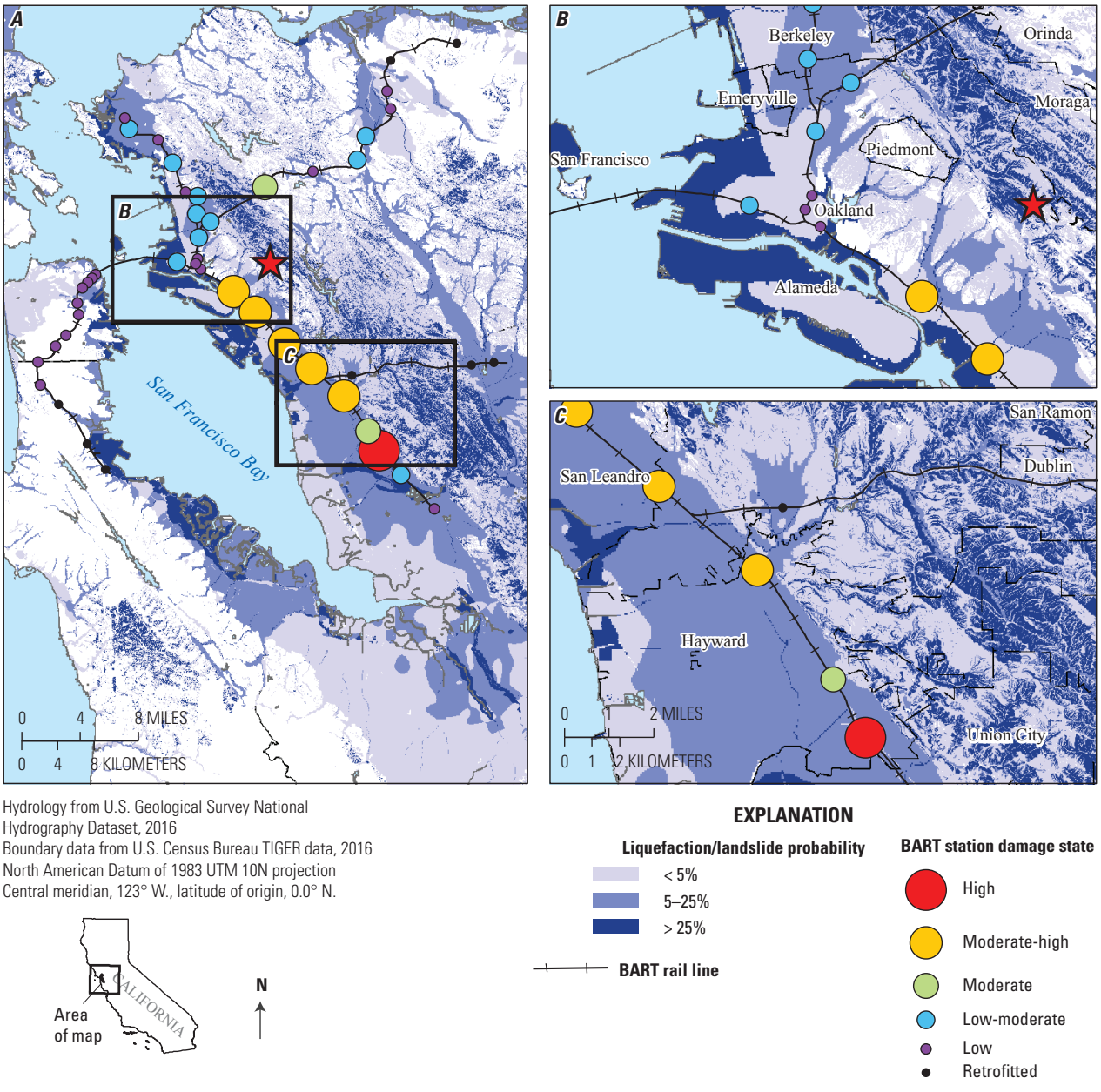


Figure 3. Maps of the San Francisco Bay region California, showing U.S. Geological Survey ShakeCast (see https://earthquake.usgs.gov/research/software/shakecast.php) shaking damage estimate for the Bay Area Rapid Transit (BART) system at the time of the hypothetical April 18, 2018, moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. *A*, Map showing the entire BART system; *B*, map showing BART stations near the mainshock epicenter (star) that are forecast to sustain moderate-high shaking damage, and *C*, map showing BART stations further south of the mainshock epicenter that are forecast to sustain moderate-high to high shaking damage.

hour in the San Francisco Bay region, with many crossing over the Richmond Bridge, Golden Gate Bridge, San Francisco-Oakland Bay Bridge, San Mateo-Hayward Bridge, Dumbarton Bridge, and other smaller spans to return home. During the M_w 6.9 1989 Loma Prieta earthquake, more than 80 bridges in the region sustained minor damage, 10 required temporary supports, and 10 were closed owing to major structural damage—including most notably, the San Francisco-Oakland Bay Bridge, whose upper level collapsed, causing one fatality. The Cypress Viaduct in the east bay catastrophically collapsed owing to amplified shaking of the underlying soft soils and was the locus of the vast majority of fatalities for the earthquake (Yashinsky, 1998). Today, the Bay Bridge has been retrofitted and a new eastern span has been put in place. The Cypress Viaduct was demolished, and a new connector between I–880 and I–80 was built nearby. Bridges in the region should now be safer to cross during heavy shaking, owing to the retrofitting and relocation, but halting traffic at freeway entrance metering lights and bridge toll booths in response to a ShakeAlert warning could lessen the number of cars entering these areas during peak shaking and further reduce potential risk.

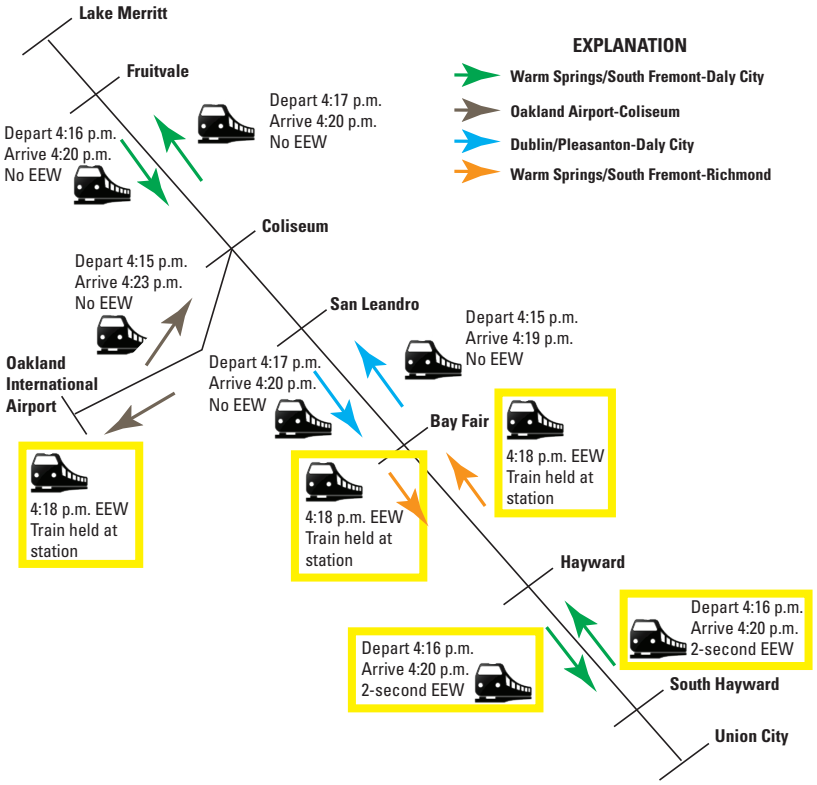


Figure 4. Schematic illustration of Bay Area Rapid Transit (BART) train locations along the systems tracks at the time of the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault in the San Francisco Bay region, California. Colored arrows represent the train direction of motion in the area of interest and yellow boxes indicate trains that receive earthquake early warning (EEW).

ShakeAlert Can Prompt Protective Actions

Hospitals and Injuries

Hospitals play a crucial role for society after an earthquake—responding not only to patients currently in their care, but also triaging incoming patients with injuries resulting from shaking. Horiuchi (2009) researched EEW capabilities in a hospital setting in Japan and found that within the hospital, EEW can play a role in securing patients during surgery to prevent errors, protecting equipment so it may be useable after shaking, and protecting staff so that they may be physically able to carry on their duties. Horiuchi (2009) found possible protective applications for EEW such as securing radiation sources (turning off X-rays) and detaching tubing that could become forcibly removed during shaking. Each hospital will need to identify their own best practices for EEW based on their own facility and seismic risk.

In discussions with hospital groups in the San Francisco Bay region, one theme that is often brought up is the impact that ShakeAlert could have on reducing a large influx of patients in the aftermath of an earthquake. As was seen when Hurricane Katrina struck the Gulf Coast in 2005, medical personnel were overwhelmed by the number of patients coming in and could only triage and provide basic first aid, leaving many critical patients unassisted owing to lack of supplies and resources (Franco and others, 2006). Reducing the sheer number of people who need to be triaged, in an earthquake's aftermath, could speed the triage process and allow hospitals to more nimbly respond to any severe trauma cases.

For the HayWired mainshock, this could be especially crucial in the east bay, where critical-care facilities are concentrated in a few city centers (fig. 5). This is in contrast to San Francisco Peninsula side of the bay, from San Francisco to the San Jose. There, warning times are larger, shaking is lower, and critical-care facilities are more evenly distributed geographically. If the roads and bridges are passable, facilities along the peninsula could perhaps help by providing extra medical services to east bay residents. However, roads and bridges may be difficult to navigate after a powerful earthquake on the Hayward Fault, so east bay residents could have difficulty reaching these other hospitals on their own. This could put stress on ambulances and other first responders. ShakeAlert could be used to reduce the number of injuries in an earthquake like the HayWired mainshock (see next section) and thus may be a helpful tool to reduce the demands on medical services.

Two hospitals in the Los Angeles region were running pilots of the ShakeAlert system during the 2019 Ridgecrest earthquake sequence. Alerts were received but no actions were taken at the facilities, even though people there experienced shaking, because the shaking at those locations did not reach pre-set thresholds for action. The hospitals are now considering lowering the thresholds, since people in the

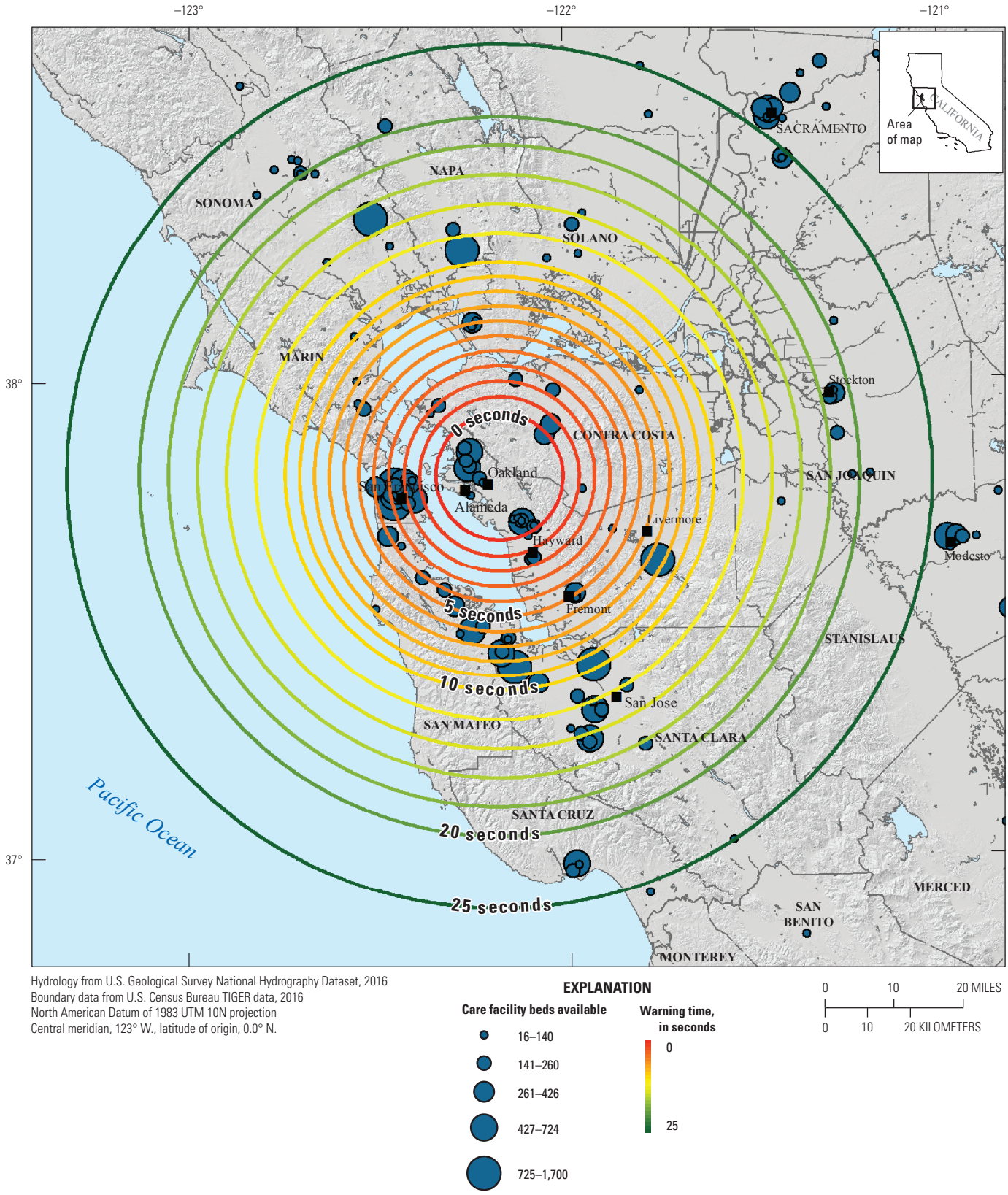


Figure 5. Map of the San Francisco Bay region, California, showing the location of critical-care facilities and the number of beds that they can accommodate (Doug Bausch, Federal Emergency Management Agency, written commun., 2014), overlain with earthquake early warning time estimates for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault.

building felt the earthquake and expected an alert (Margaret Vinci, California Institute of Technology, oral commun., 2019). Before considering the impact to injuries, it is important to keep in mind that giving people information about what they are experiencing is considered useful and desired.

Looking at past events, we can obtain a better picture of the prevalence of injuries. After the 1989 Loma Prieta earthquake, it was determined that more than 50 percent of the nonfatal incidents were caused by falls and falling hazards (Shoaf and others, 1998). This includes those caused by collapses of chimneys and porches, which were the most common structural collapse hazards. In the M_w 6.2 2011 Christchurch, New Zealand, earthquake, 70.4 percent of soft-tissue injuries were from trip or fall hazards (Lambie and others, 2017). Lambie and others (2017) used closed-circuit television footage to code responses during the earthquake and found that only a small number took self-protective actions—1.3 percent of people dropped and 26 percent held on to something. This is similar to the findings of Lindell and others (2016), where only 7.2 percent of people in Christchurch and 13.9 percent of people Hitachi, Japan, took cover during the 2011 Christchurch and Tohoku earthquakes, respectively. However, more than 30 percent of people froze in place (Lindell and others, 2016). Lindell also found that "lower levels of earthquake preparedness . . . produced higher levels of freezing in place." Getting a warning out to people is important, but so is educating people on what to do if they receive such an alert.

Drop, Cover, and Hold On

Training and education are crucial for populations to perform the most effective self-protective actions during an earthquake. The messages received from ShakeAlert can serve to improve and increase performance of protective actions by communicating the proper response to take (Drabek, 1986; Mileti and Fitzpatrick, 1991; Mileti and Sorensen, 1990; Sorensen, 2000). "Drop, cover, and hold on" (DCHO) is the recommended action to take when shaking is felt (provided it is safe to do so). EEW serves to augment the efficacy of this self-protective action by providing the person with advanced notice to be aware of the coming situation, remember their training, and take action.

As part of the HayWired scenario, Porter and Jones (2018) conducted a survey of people to assess response times to DCHO after a simulated earthquake alert. The survey results indicated a median time to complete DCHO at 8.8 seconds. The Federal Emergency Management Agency's Hazus-MH damage-estimation tool calculates 800 deaths and 18,000 nonfatal injuries from building and structural damage caused by ground shaking and liquefaction hazards from the HayWired mainshock in the San Francisco Bay region. They combined these data with the ShakeAlert warning-time contours for the HayWired mainshock to assess the number of people that could conceivably complete DCHO before heavy shaking began (S-wave arrival). Porter and Jones (2018) found that the population of the bay region that lives in areas receiving more than 8.8 seconds of EEW represents 8 percent of the total nonfatally injured population, or about 1,500 people, and they estimated that "The U.S. Government would value mitigation measures to avoid that number of nonfatal injuries at approximately $300 million (in 2015 [U.S. dollars])."

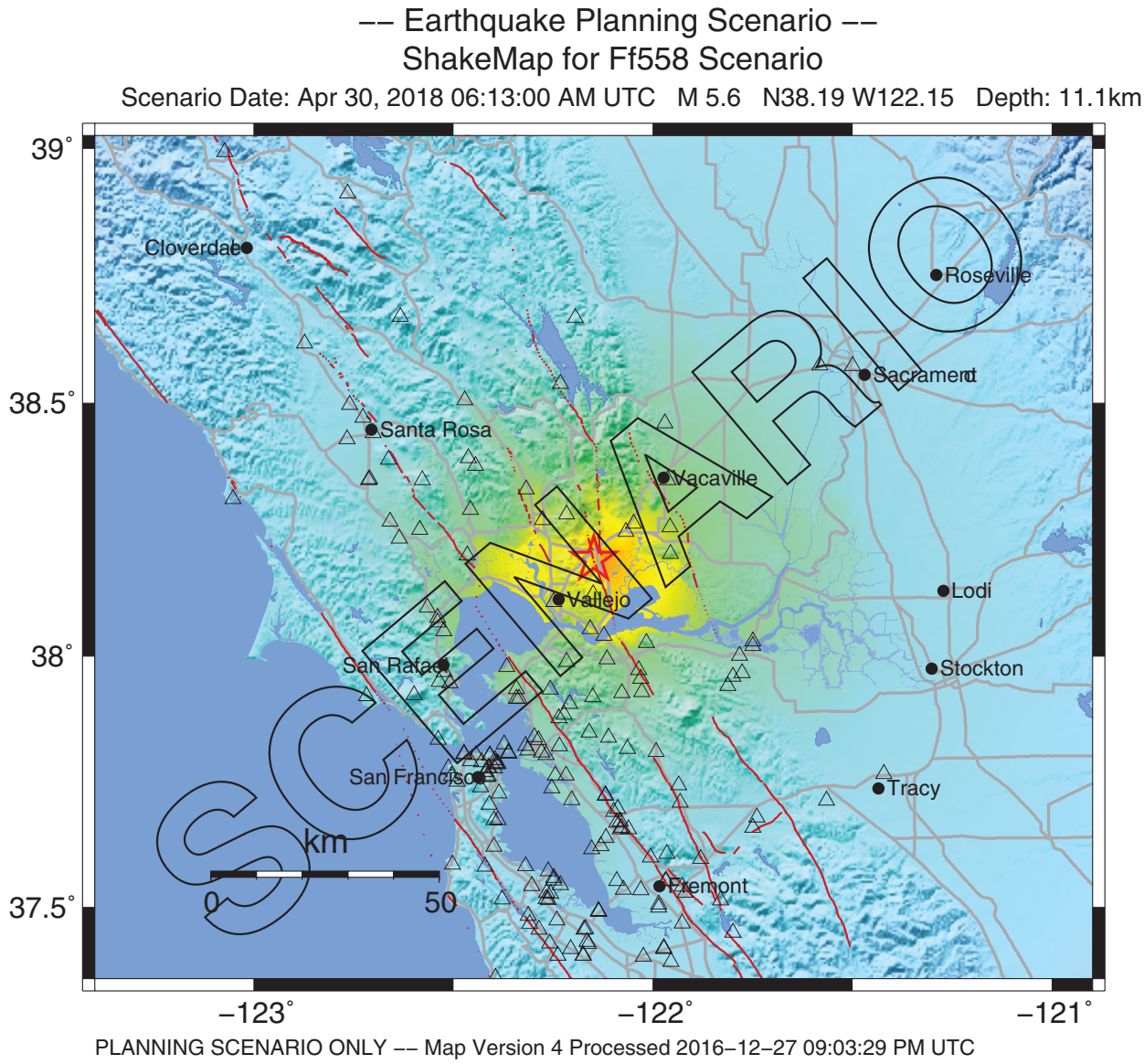
One should note that this number only represents subjects that fully completed DCHO before shaking began. Not every person may be able to fully complete DCHO in the population average time used for this study, but it is likely that DCHO may not need to be fully completed before the arrival of heavy shaking to have a benefit. As noted above, Lindell and others' (2016) Christchurch and Tohoku earthquake studies indicated that many injuries are trip and fall hazards. It therefore stands to reason that the "drop" part of DCHO is the most important step to prevent fall and trip injuries. Further studies could assess the benefits of "drop" or "hold" and the time required to complete these actions. DCHO is thought to be an effective strategy even in the absence of EEW, and a ShakeAlert warning message augments this strategy by providing the cognitive link between imminent earthquake shaking and the prescribed action to take. ShakeAlert messages could help increase the probability that DCHO will be performed.

Effective training should not be overlooked. A survey on EEW responses, outlined by Nakayachi and others (2019), suggests that "respondents seemed to place more value on mental preparation rather than reducing their chance of injury or death." People want an alert, but more social science research needs to be done to improve the incidence of DCHO responses within the short time frames provided by EEW and to reduce the time spent milling, that is, seeking confirmation and deciding what to do (Wood and others, 2017). This is supported by Nakayachi and others' (2019) observation that "the connection between receiving an EEW and swiftly moving through key psychological processes to undertake quick, deliberate protective actions has not yet been established."

ShakeAlert and Aftershocks

Aftershocks can occur following any earthquake. It should be noted that smaller aftershocks can vary in magnitude and can be more impactful than a mainshock in some areas, and a larger earthquake could also occur and become the new mainshock—as was the case in Japan in 2011, where a M_w 7.2 occurred offshore and was followed 2 days later by the M_w 9 Tohoku event. In the HayWired scenario, the M_w 7.0 mainshock is the beginning of an earthquake sequence in the San Francisco Bay region with aftershocks large enough to cause or aggravate damage and complicate emergency response and recovery (Wein and others, 2017).

Many aftershock sequences were generated by scientists for the Hayward fault rupture. We use a few earthquakes from the aftershock sequence selected for the HayWired scenario (Wein and others, 2017). The modeled HayWired aftershock sequence has 175 earthquakes of M_w 4 or larger that occur in



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based on Wald and others, 1999

Figure 6. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-5.6 Fairfield aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on April 29, 2018, at 11:13 p.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earthquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.

the 2 years following the mainshock, the largest of which is a M_w 6.4 event. We examine three of the larger aftershocks in this sequence and how recovery and ShakeAlert could work together (figs. 6–8). The selected aftershocks were chosen based on size, area of impact, and time of day, as well as elapsed time after the mainshock to assess a broad range of situations where EEW could be notable.

The analysis assumes that the ShakeAlert system continues to function and alerts are received by the public and organizations after the HayWired mainshock. ShakeAlert has redundant servers in three locations throughout the West Coast to ensure that even if one location experiences loss owing to shaking, other locations will still be able to push out alerts. Alerts would also be provided using multiple pathways (cellular, broadcast, and internet methods), which provide redundancy to increase the chances that alerts will get out. Physical damage to stations, communication lapses, or other effects could slow down alert delivery and result in shorter EEW times.

The first aftershock we consider is centered in Solano County near Fairfield, a M_w 5.6 event occurring 12 days after the mainshock on April 29, 2018, at 11:13 p.m. (fig. 6). For this event, the maximum expected shaking intensity is MMI VII. The area of strong shaking in this event does not overlap with the area of strong shaking during the mainshock, so there is an expectation that critical infrastructure in this area was likely not heavily damaged in the mainshock. We can also surmise that at 11:13 p.m. most people are at home and not working or commuting, so injuries sustained are likely to be fewer. We specifically highlight this aftershock to show that aftershocks can occur at some distance from the mainshock, especially to encourage organizations that use the HayWired scenario to construct or test resiliency plans to include contingencies for ShakeAlerts from such events. This also serves to remind readers that the no-warning zone of the mainshock will not always be the same for subsequent aftershocks. The EEW system is designed to help people in a broad region, not just those near the epicenter, so lifelines, businesses, and people could take this into consideration with their planning. The HayWired scenario mainshock is not likely to be the exact location of the next actual major earthquake on the HayWard Fault, so the covered populations could vary greatly.

The second aftershock we consider here is a M_w 5.4 event modeled to occur in Alameda County near Oakland on May 20, 2018, at 8:37 a.m. (fig. 7). At that time, 32 days would have passed since the mainshock. Infrastructure repairs would likely be ongoing in some areas because afterslip (fault movement after an earthquake) on the Hayward Fault of ~0.5–1.5 m (see Aagaard and others, 2017b) could continue to shift pipelines, roads, and utility conduits as the ground continues to move over time.

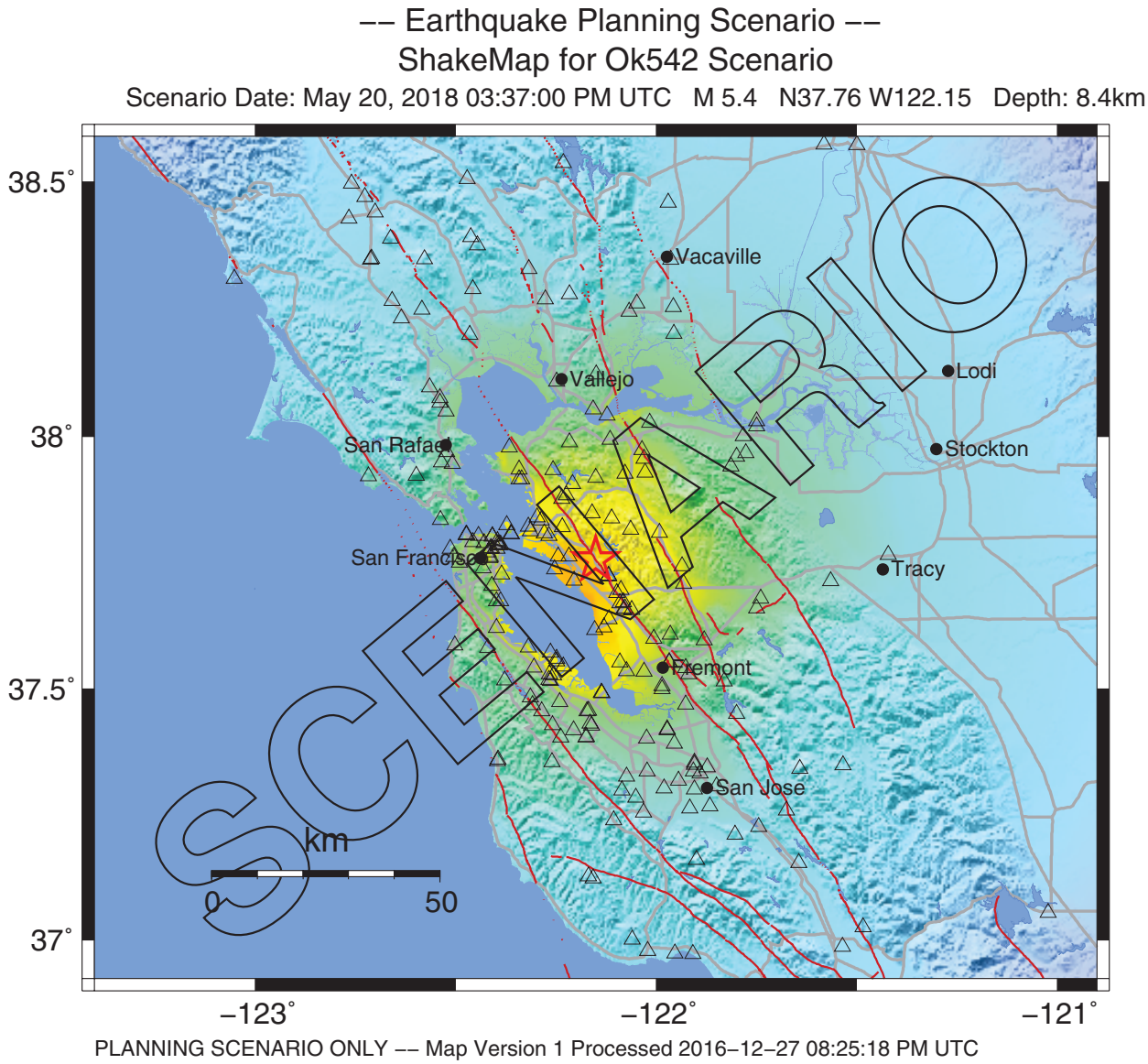
Land on the margins of the east bay side of San Francisco Bay that was already compromised by the mainshock and other aftershocks would be impacted by the strong shaking of this aftershock. In the Oakland area, those people at or heading to work, who were able to return to work since the mainshock, would be especially impacted by the shaking, as 8:37 a.m. is in the middle of morning rush hour. However, owing to the location and the less widespread heavy shaking, ShakeAlert may not be as effective for this area. Most of the heavily impacted locations with ongoing road repairs and unstable debris might be in the no-warning zone and may not receive sufficient warning for actions to be taken. This emphasizes the importance of restricting entry to dangerous areas. Repairs that were completed in the early weeks after the mainshock may now have to be redone.

Several of the larger HayWired aftershocks cluster in Silicon Valley (in the southern part of the San Francisco Bay region), hitting the area multiple times in the 2 years following the mainshock. This is a situation where (1) people will be continually rattled (as in Fairfield) and (2) multiple damaging earthquakes will wreak havoc on the recovery efforts. A M_w 6.4 aftershock in Santa Clara County near Cupertino on October 1, 2018, at 12:33 a.m. (fig. 8) follows close on the heels of a M_w 6.0 aftershock near Mountain View (also in Santa Clara County) 4 hours earlier. Although many repairs may not be underway during the night, response to the 8:16 p.m. M_w 6.0 event will have begun, and unstable debris and any repair work will likely be heavily shaken. In the M_w 6.4 aftershock, strong and very strong shaking would be felt over a large area of the south bay, so many people would receive a ShakeAlert warning. First responders activated in response to the earlier M_w 6.0 aftershock using ShakeAlert would know that another larger aftershock was on its way and might be more prepared to take self-protective actions. ShakeAlert could also help prioritize response to the aftershock before more detailed information is available.

The ShakeAlert warning could also help protect repair workers outside of the no-warning zone from unstable debris and other hazards caused by the M_w 6.0 aftershock. Bakun and others (1994) note that:

> Structures damaged in strong shaking are weakened and susceptible to additional damage and possible failure in subsequent shaking from aftershocks. More than 20 magnitude 4 and larger Loma Prieta aftershocks occurred in the month following the mainshock, each large enough to be widely felt in San Francisco and Oakland. Weeks after the shock, crews were still working in and near damaged structures in the Marina district of San Francisco and at the collapsed Cypress Street section of the 1-880 freeway in Oakland. The certainty of aftershocks in the weeks following the Loma Prieta earthquake posed a constant threat to the rescue and reconstruction crews working near weakened structures. Clearly the few tens-of-seconds warning of incoming strong shaking achievable in an early warning system provides a means to reduce this risk.

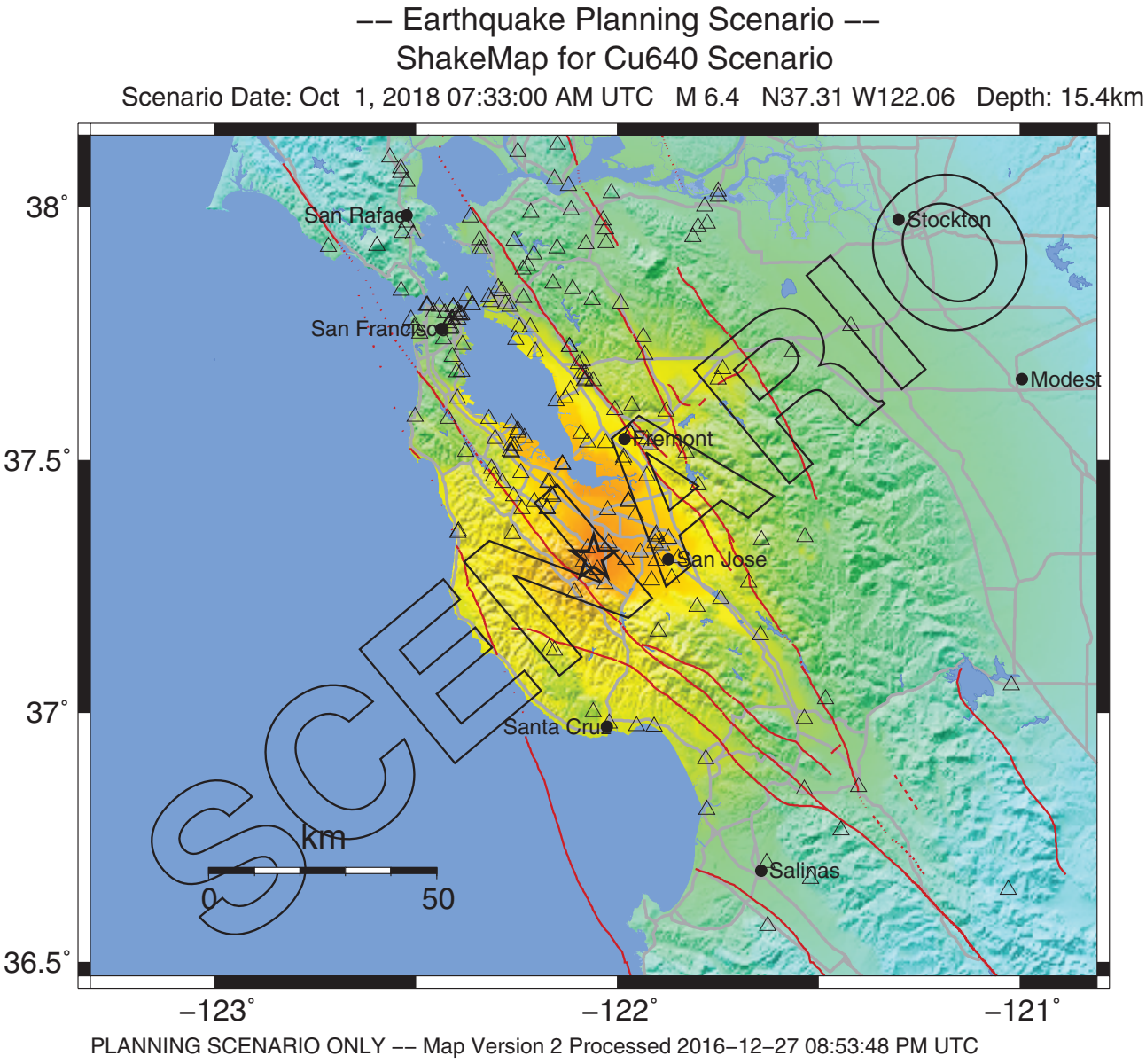
The damage done by continual aftershocks is not just to the built environment. A longitudinal study assessed the mental-health impact of the continuing aftershocks following the M_w 7.1 2010 Canterbury, New Zealand, earthquake



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based on Wald and others, 1999

Figure 7. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-5.4 Oakland aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on May 20, 2018, at 8:37 a.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earthquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based on Wald and others, 1999

Figure 8. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-6.4 Cupertino aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on October 1, 2018, at 12:33 a.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earthquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.

(Spittlehouse and others, 2014). The researchers found that there was an increased prevalence of major depressive disorder and bipolar disorder in the study cohort in the 18 months after the earthquake. They also found "scores significantly lower than the population norms in the mental health, vitality, social functioning and role-emotional subscales" (Spittlehouse and others, 2014). ShakeAlert would not be able to prevent the psychological repercussions of major earthquakes, as described by Mooney and others (2011) after the 2010 Canterbury earthquake. Although there is evidence that more people opt to use EEW than not (Ohara and others, 2012), and the benefits include increasing their awareness and preparedness to take protective actions (Allen and others, 2017; Ohara and others, 2012), psychological benefits from using ShakeAlert (for a damaging earthquake or during an aftershock sequence) is an open research question.

Actions Discussed Elsewhere in the Literature

EEW is in use in several countries worldwide, including Japan and Mexico, and is a proven technology for hazard mitigation (Fujinawa and Noda, 2013; Lee and Espinosa-Aranda, 2003; Shimamura and others, 2001; Allen and Melgar, 2019). An exhaustive list of self-protective actions to take in response to EEW was not attempted for this chapter and only a few are highlighted, and automated controls in response to ShakeAlert warnings are still under development. To encourage discussion of ShakeAlert among those who may use the HayWired scenario to inform hazard mitigation strategies, several overviews of EEW in the literature are worth noting. However, not all EEW actions performed in other countries will be applicable or practical to enact in the United States.

Heaton and others (1985) pioneered the idea of using computer-based automated controls in conjunction with EEW to increase resiliency. This idea took hold, and now many EEW systems are in place worldwide that are aided by automated technology. A summary of these systems and EEW use cases can be found in Allen (2011). A more specific demonstration of capabilities for both the prototypic U.S. ShakeAlert system and the Japan Meteorological Agency's approach to EEW are outlined by Burkett and others (2018), Fujinawa and Noda (2013), and Given and others (2014). Specific actions that can be taken to enhance the benefits of EEW include development of risk scenarios (for example, planned response protocols) in advance of an earthquake, such as described by Pittore and others (2014) and general-use case studies that include recovery and economic benefits as described by Strauss and Allen (2016).

Transportation systems can use EEW alerts to hold trains at station platforms and slow and stop trains that are enroute to reduce the chance of derailment and allow patrons and workers at stations to take protective actions, as discussed for the BART system in this chapter. Edwards and others (2015) extend this discussion beyond the San Francisco Bay region to look at transportation systems in Japan as well. Bridge and tunnel metering lights could be turned on to reduce the number of entering cars. Airports could make use of EEW alerts both inside and outside of terminals—baggage handlers can protect themselves before items fall, moving baggage carousels can be stopped to prevent damage, and alerts to patrons inside terminals could allow them to take self-protective actions.

Schools and hospitals both house vulnerable populations. EEW alerts in schools allow teachers and staff advanced warning to help their students to take DCHO actions and get to a safe space after shaking stops (Motosaka and Homma, 2009). Frequent drills help reinforce this training. In hospitals, surgeons can secure patients during surgery, delicate machinery like magnetic resonance imaging (MRI) machines can be put into a safe mode, and staff can take (as well as help patients take) self-protective action to ensure they are ready to respond once shaking ends (Horiuchi, 2009).

Fire following earthquake can be a large contributor to the postearthquake damage and is examined for the HayWired scenario by Scawthorn (2018). During the Northridge earthquake in 1994, many fire stations were seriously affected (Schneider, 1994). ShakeAlert triggers could be used to open firehouse doors before heavy shaking or loss of power occurs, enabling firefighters to exit with their equipment in a faster manner and more quickly respond to fires.

Work with ShakeAlert pilot groups in the water, gas, and electric distribution sectors, has shown that protecting both personnel and infrastructure with ShakeAlert will be a key to resiliency for a powerful earthquake. ShakeAlert warnings for utility workers in "cherry picker" lifts, out in the field, or in small tunnels are being assessed to ensure that these personnel are protected and services can get restored in a timely manner. Both water and gas systems could use ShakeAlert to trigger safety interlock systems for hazardous chemicals to reduce spills, fires, and explosions. Some groups are also exploring redirecting or securing certain sections of the utility grids.

Emergency responders help coordinate their disaster response and recovery efforts through incident command centers. Many in the San Francisco Bay region subscribe to the California Integrated Seismic Network Display to get accurate up-to-date information on earthquakes that have recently occurred. Groups in major cities and counties of the San Francisco Bay region are also piloting the ShakeAlert system through its UserDisplay (see https://www.shakealert.org/eew-research/caltech/shakealert-user-display/), which provides information on local shaking intensity, epicenter location, and event magnitude. ShakeAlert provides situational awareness to emergency responders so that they can more quickly and safely mobilize their teams and choose the best plan of action. Knowing right away where an earthquake epicenter is located and which areas likely experienced the most significant shaking can help the incident

command team marshal resources to the correct areas for damage assessment and provide information on likely mutual aid from outside areas that were not as affected. The importance of this was seen in the M_w 6.0 2014 South Napa, California, earthquake, when many local first responders initially assumed that the epicenter was near San Francisco. Had they been using ShakeAlert at the time, they would have known right away that mutual aid was likely coming their way and to prepare for that fact.

Conclusion

The HayWired earthquake scenario presents a framework to envision ShakeAlert's contribution to protecting local populations and infrastructure and reduce cascading failures in the aftermath of a major urban earthquake in the San Francisco Bay region. The most recent major earthquakes in this region—the M_w 6.0 2014 South Napa and M_w 6.9 1989 Loma Prieta earthquakes—are often reference points for people when they imagine what a Hayward Fault event could look like. Unfortunately for planning purposes, the South Napa earthquake was much smaller than the M_w 7.0 mainshock modeled in the HayWired scenario, and the epicenter of the Loma Prieta earthquake, although of similar magnitude, was not directly under a densely built urban environment. Thus, "tabletop" exercises using the HayWired scenario can better support proper planning and forecasting of risk reduction benefits, including those derived from ShakeAlert.

In closing, we would like to outline some limitations of ShakeAlert and the assumptions we made, as well as areas for future analysis. ShakeAlert is a tool for improving resiliency; however, building retrofits, improvements to building codes, and lifeline coordination will continue to be crucially important, even when a full public ShakeAlert system is in place. Fire following earthquake is a major source of loss in the HayWired scenario. Therefore, end users who use ShakeAlert in their critical facilities might consider assessing whether automated controls can be put in place that use the alerts to reduce ignition sources. As mentioned earlier, current regulations in California prohibit internet-distributed ShakeAlert warnings to trigger switches on elevators to cause them to remain open at the nearest floor. Changes to these regulations would need to be undertaken to permit these automated controls to be put into practice.

The ShakeAlert system will also need to explore a varied landscape of alert redistribution methods to ensure broad coverage and uptake of the system. Working with groups such as the Alliance for Telecommunications Industry Solutions will likely be needed to develop longer term alert delivery solutions so that future technologies can better serve the end user. As part of the 2018 limited public rollout of ShakeAlert, pilot users and technology enablers are exploring the landscape of options. Any policies on alert distribution need to also consider that notifications should be equitable and cover a number of different groups, including those with access and functional needs, people without access to cellular networks, and technical users who require more detailed information. The public will need to be made aware that broad alert distribution channels may cause them to be alerted when they may not personally feel shaking at their location. More technical users will also need to be made aware that the design of automated controls need to take this into consideration and not be precisely dependent on strict shaking values. A full public ShakeAlert system can have many benefits for people, including the possibility to begin the drop, cover, and hold on recommended action before shaking onset. However, public use of ShakeAlert will require an ongoing education and training campaign to be effective. The U.S. Geological Survey's Joint Committee for Communication, Education, and Outreach will need to work with State and local officials to develop a long-term strategy to engage the public. This will be especially necessary during times of low earthquake activity, so that preparedness remains fresh in the public's memory.

The HayWired scenario provides the first glimpse of ShakeAlert's role in resiliency and postearthquake recovery in the San Francisco Bay region. We envision a future where a broader landscape of automated responses and uses for ShakeAlert are identified and implemented. Organizations who use the information in this chapter should be aware that the solutions outlined here have not been fully developed or tested in the United States. Also, the epicenter for an actual large earthquake on the Hayward Fault may be in a different location with a different magnitude, so ShakeAlert times could geographically vary significantly from what is outlined here. Policymakers and end users would be best served by using this chapter about the potential immediate responses to ShakeAlert warnings in concert with longer term earthquake mitigation actions and planning.

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