Overview of the HayWired Scenario Societal-Consequences Volume

By Anne M. Wein

Chapter R of

The HayWired Earthquake Scenario—Societal Consequences

Edited by Shane T. Detweiler and Anne M. Wein

Scientific Investigations Report 2017–5013–R–W

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Abbreviations and Acronyms

ABAG	Association of Bay Area Governments
ATC	Applied Technology Council
BART	Bay Area Rapid Transit
COVID-19	Coronavirus Disease 2019
EEW	earthquake early warning
GRP	gross regional product
GSP	gross state product
ICT	information and communications technology
km	kilometer
M_w	moment magnitude
SIR	Scientific Investigations Report
USGS	U.S. Geological Survey

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Chapter R

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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.

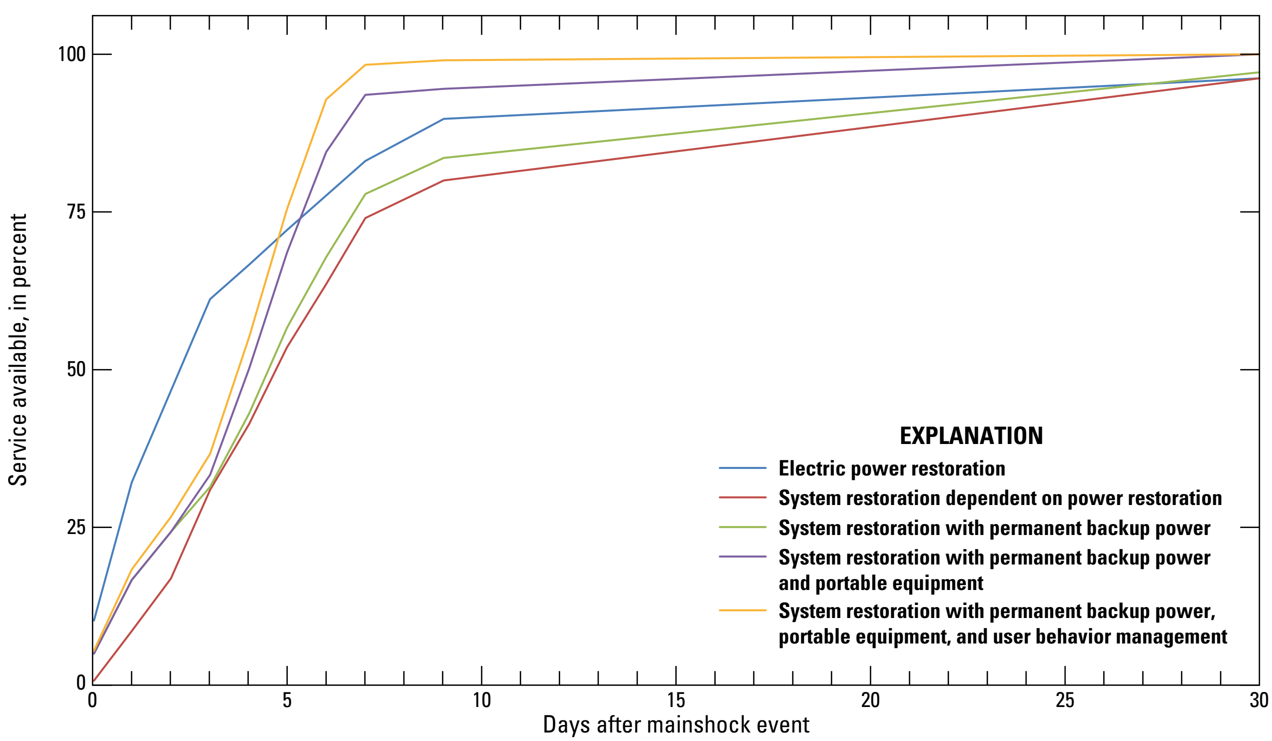


Figure 1. Line graph showing the percentage of demand for voice and data services served and electric power restoration curves for Alameda County after the HayWired scenario earthquake mainshock in the San Francisco Bay region, California. The base case (red line) assumes that telecommunications are 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

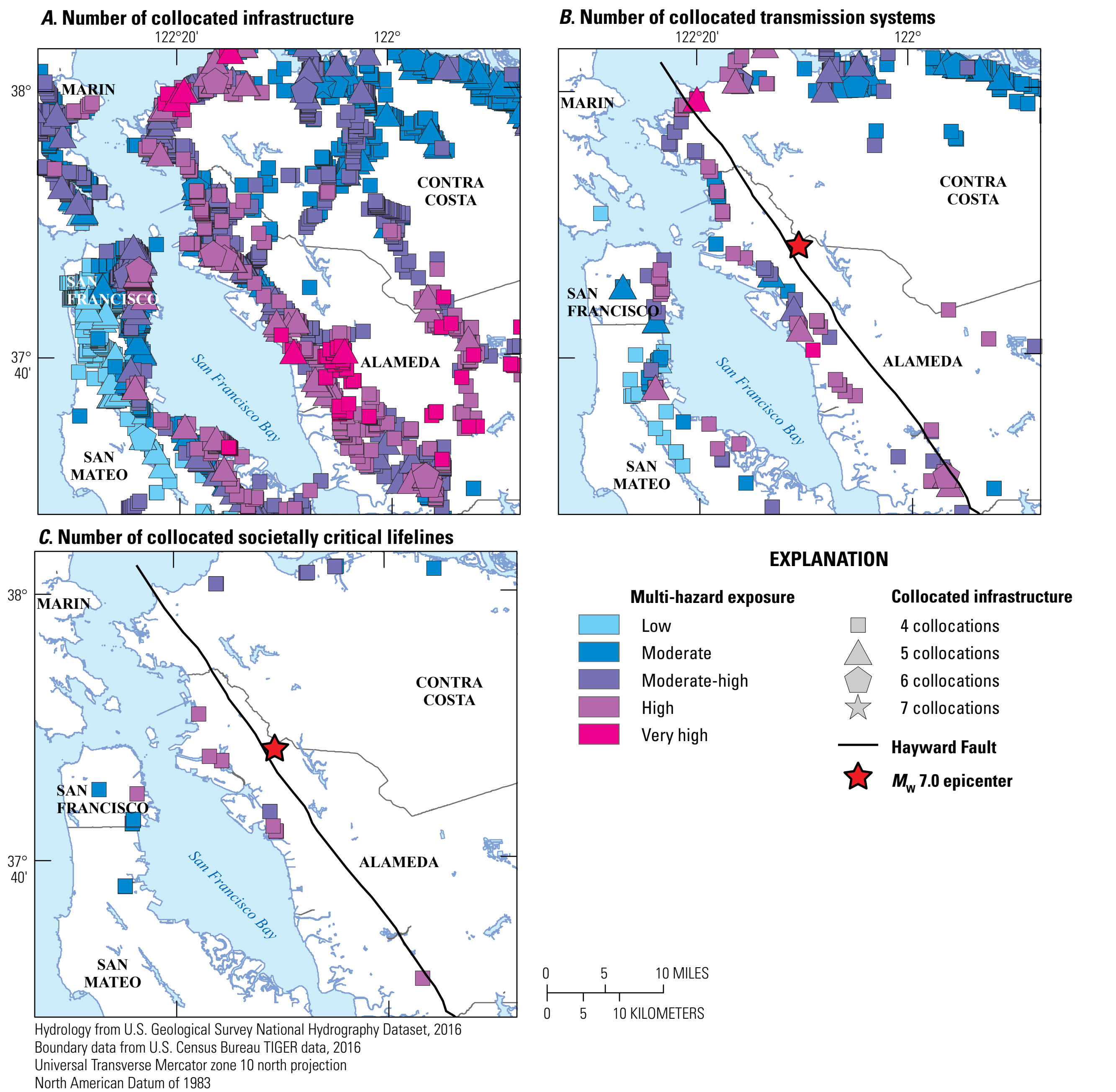


Figure 2. Maps of the San Francisco Bay region, California, showing exposure of lifeline infrastructure collocations to multi-hazards. Three examples are: *A*, Collocations for all lifeline infrastructure systems, showing points with four or more collocated lifelines. *B*, Collocations for transmission 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.

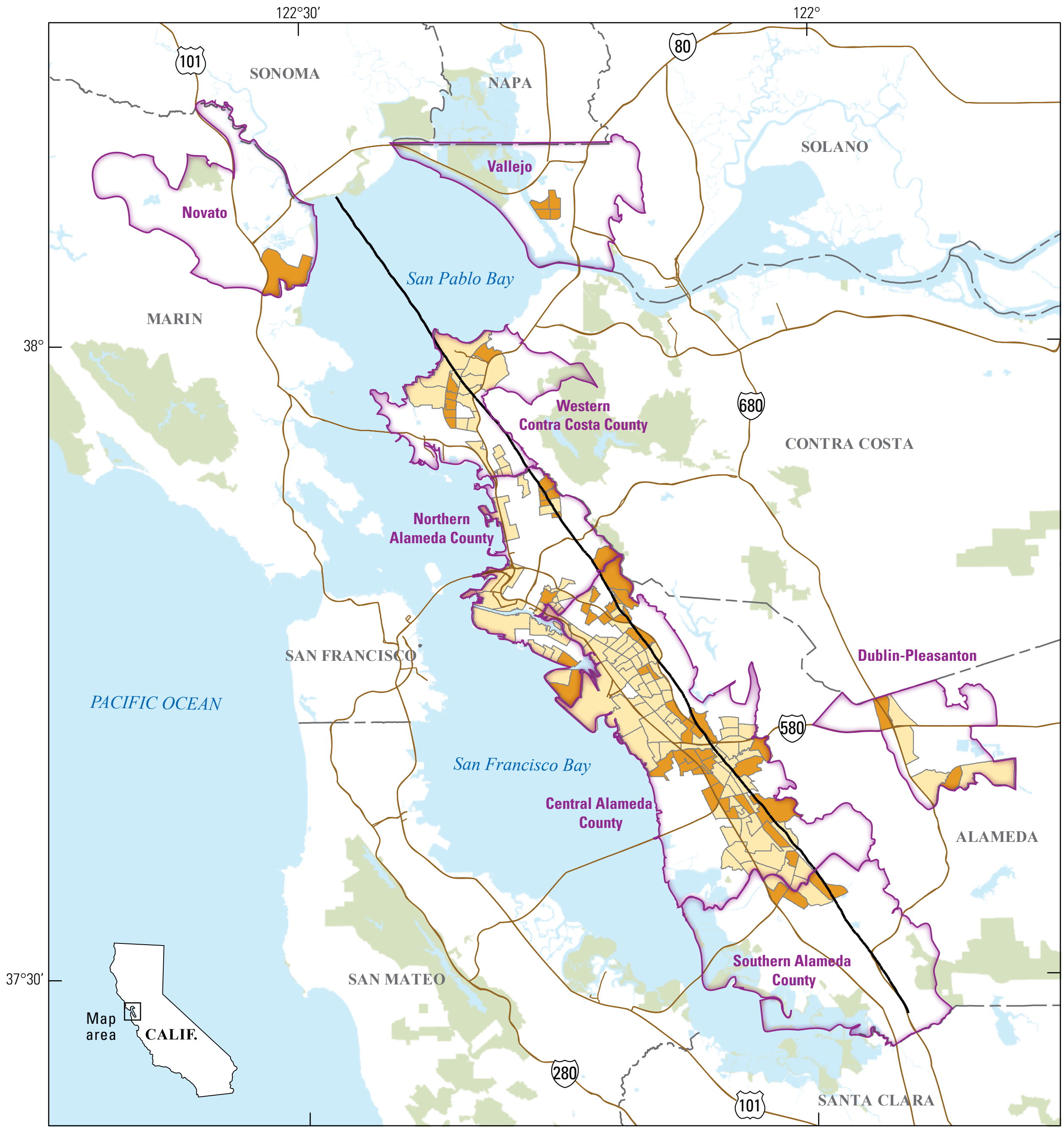
Communities at Risk

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).



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
Universal Transverse Mercator zone 10N projection
North American Datum of 1983

0 4 8 MILES
0 4 8 KILOMETERS

EXPLANATION

- **Tract with concentrated building damage from earthquake hazards**
- **Additional tract with concentrated building damage from fire**
- **Preserved land**
- **Economic subarea outline**
- **Hayward Fault rupture**
- **Highway**

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

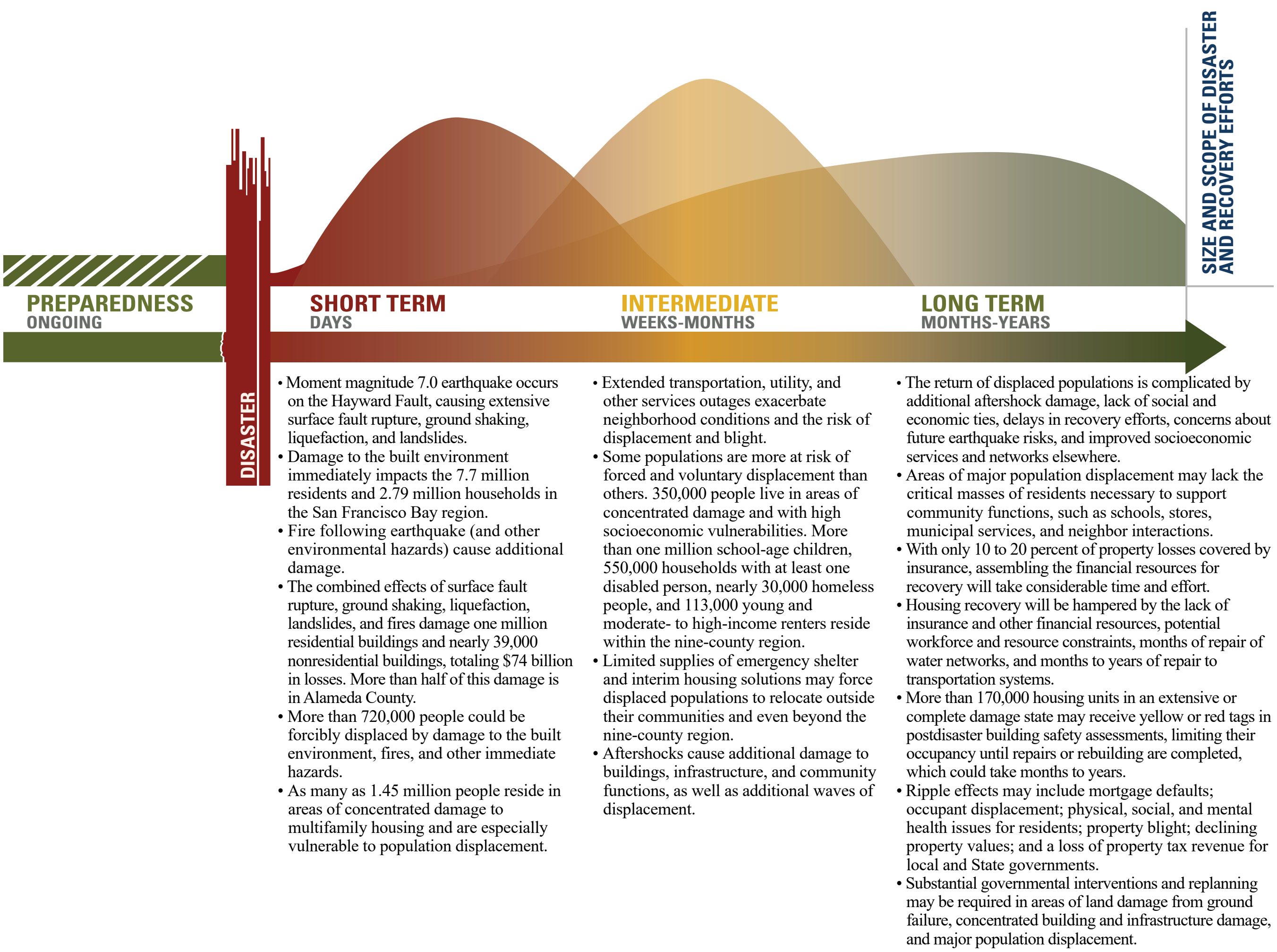


Figure 4. Schematic diagram showing major themes and estimates emerging from the analysis of communities at risk in the HayWired scenario in the San Francisco Bay region, California, with respect to the "disaster recovery continuum" timeline developed by the Federal Emergency Management Agency (2016).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

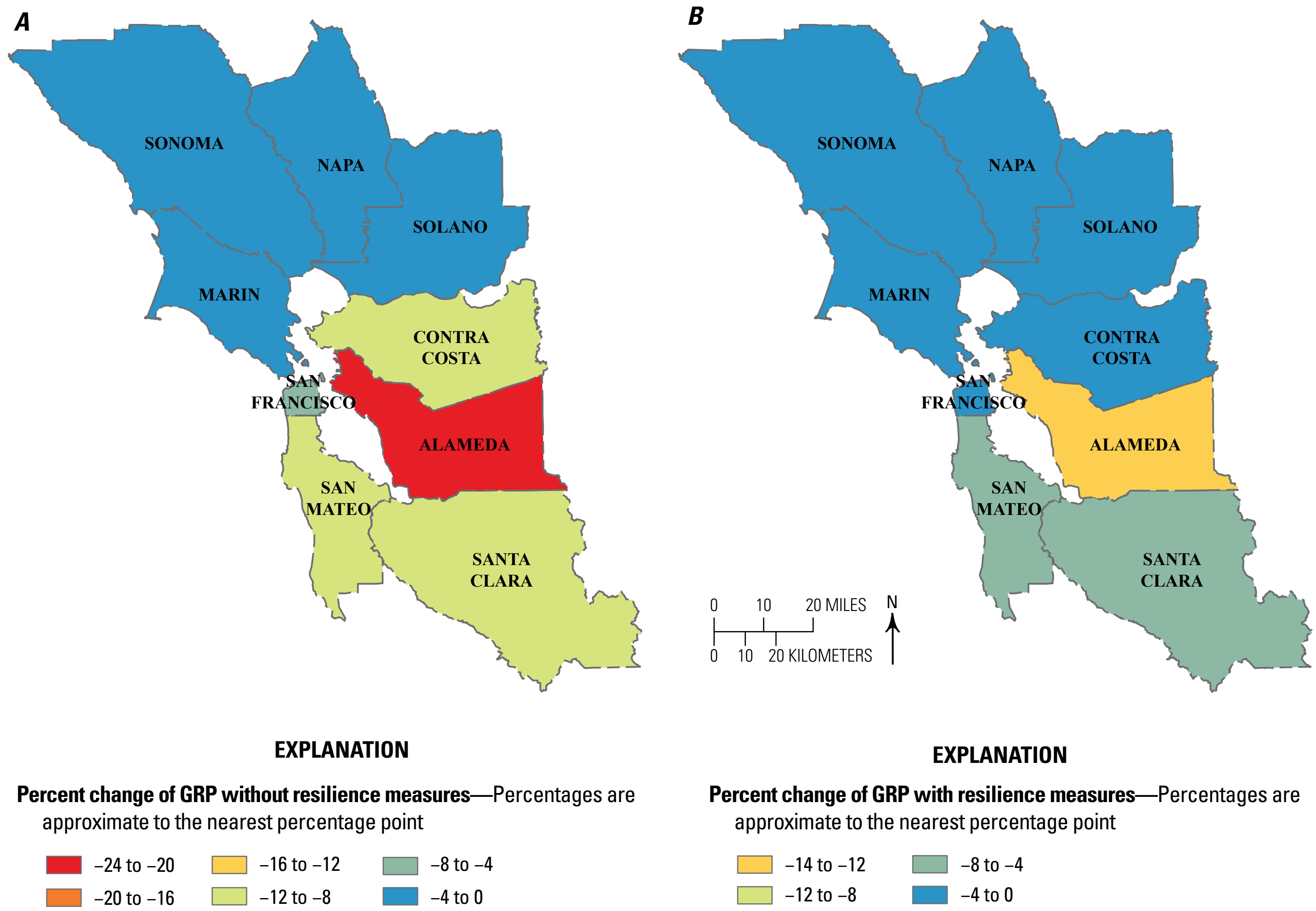


Figure 5. Maps showing the percentage of gross regional product (GRP) change in the first 6 months after the HayWired earthquake from property damages and water, electricity, and telecommunications service disruptions by county in the San Francisco Bay region. *A*, Base case without microeconomic resilience 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.

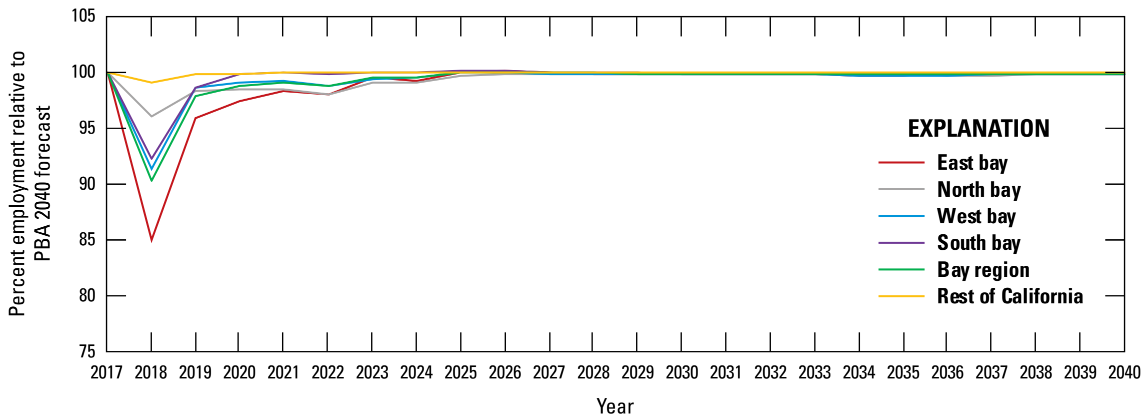


Figure 6. Line graph showing the employment difference resulting from the HayWired earthquake scenario in the San Francisco Bay region, California, by subregion compared to Association of Bay Area Governments (ABAG) regional and statewide projections. PBA 2040 is the ABAG Plan Bay Area 2040 forecast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

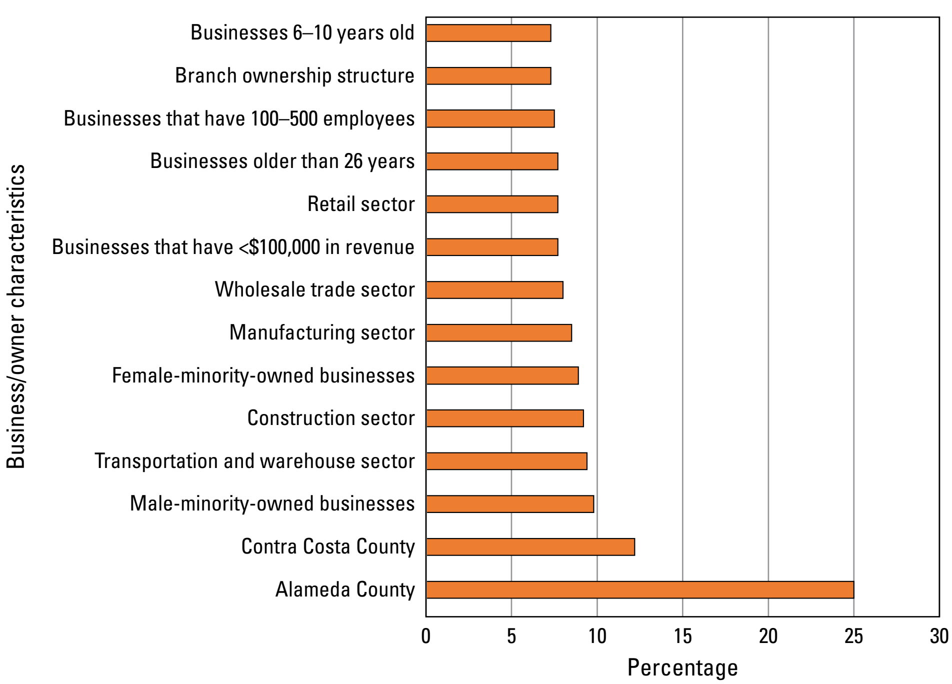


Figure 7. Plot showing business characteristics with average and larger risk of disruptive building damage from earthquake hazards in the HayWired scenario in the San Francisco Bay region, California. Figure from Levy and others (this volume).

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.

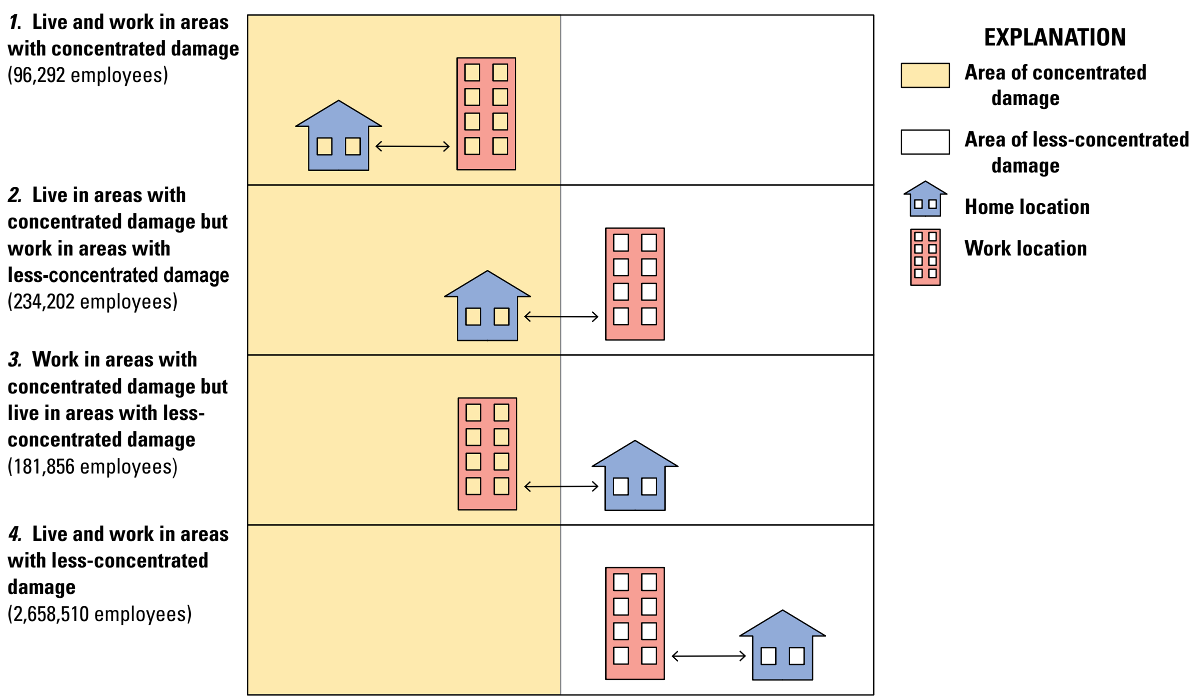


Figure 8. Cartoon showing possible home-workplace relations associated with areas of concentrated and less-concentrated damage resulting from the HayWired scenario mainshock in the San Francisco Bay region, California. Figure from Wein, Belzer, and others (this volume).

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

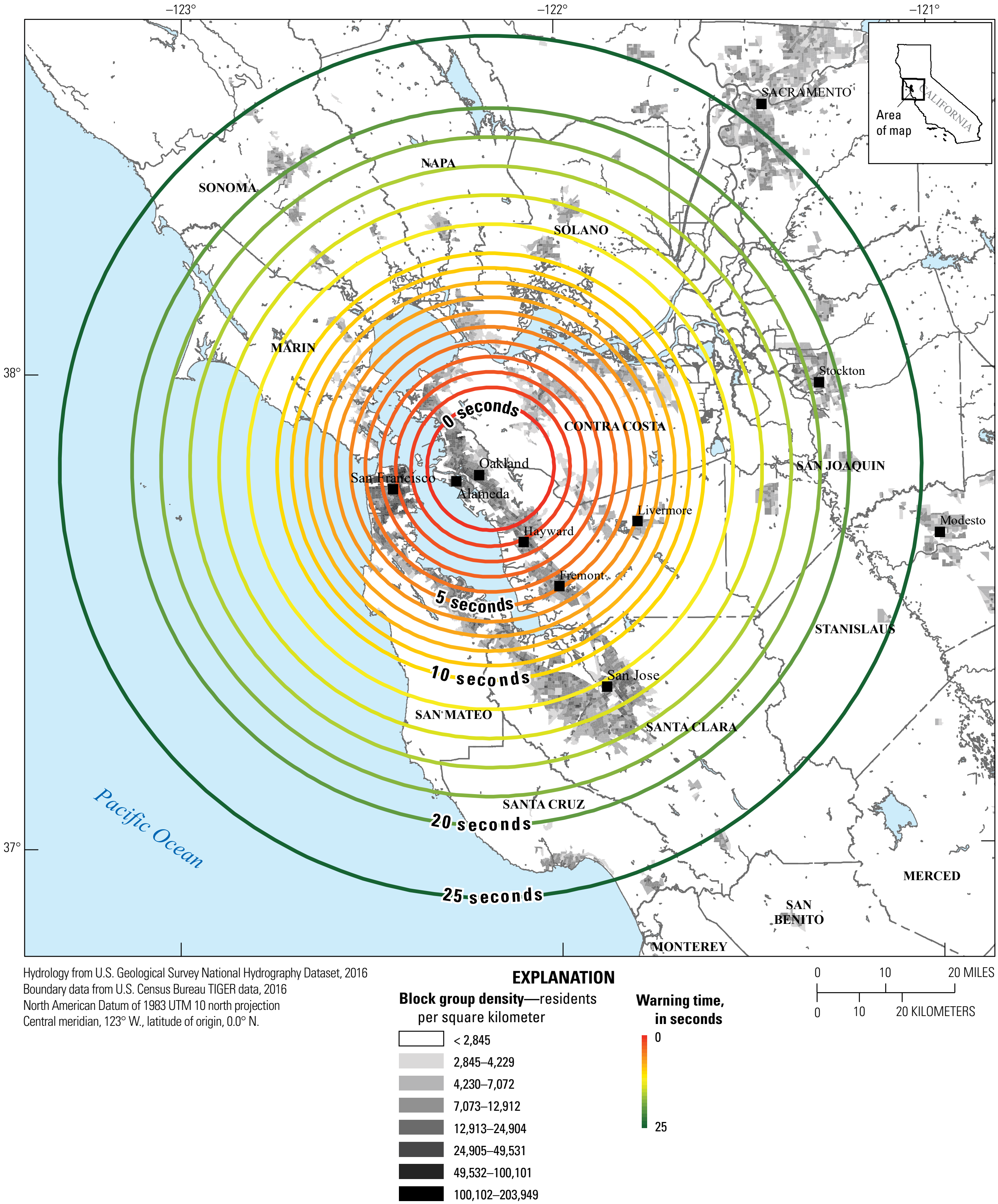


Figure 9. Map of the San Francisco Bay region, California, showing ShakeAlert (https://www.shakealert.org) earthquake early warning time estimates overlain with population density information for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. 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.

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References Cited

Applied Technology Council, 2016, Critical assessment of lifeline system performance—Understanding societal needs in disaster recovery: Applied Technology Council Grant/Contractor Report 16-917-39, 392 p., accessed April 1, 2021, at https://nvlpubs.nist.gov/nistpubs/gcr/2016/NIST.GCR.16-917-39.pdf.

Association of Bay Area Governments and Metropolitan Transportation Commission, 2020, Resilient and equitable strategies for the bay area's future: Association of Bay Area Governments and Metropolitan Transportation Commission final report, 99 p., accessed May 18, 2021, at https://mtc.ca.gov/sites/default/files/Horz_Futures_Report.web_.pdf.

Association of Bay Area Governments Planning and Research Department, 2016, Regional forecast for Plan Bay Area 2040: Association of Bay Area Governments, 25 p.

City and County of San Francisco, 2020, Lifeline Restoration Performance Project (Mieler, D., preparer): City and County of San Francisco, 284 p., accessed May 18, 2021, at https://onesanfrancisco.org/sites/default/files/inline-files/Lifelines%20Restoration%20Performance%20Report%20Final-03-02-21.pdf.

CoreLogic, Inc., 2018, Financial implications of the HayWired scenario: CoreLogic, Inc., Special Report, accessed February 11, 2019, at https://www.corelogic.com/downloadable-docs/corelogic_haywired-scenario_r5.pdf.

Costa, R., Haukaas, T., and Chang, S.E., 2020, Predicting population displacements after earthquakes: Sustainable and Resilient Infrastructure, v. 1, no. 4, 19 p., https://doi.org/10.1080/23789689.2020.1746047.

Detweiler, S.T., and Wein, A.M., eds., 2017, The HayWired earthquake scenario—Earthquake hazards: U.S. Geological Survey Scientific Investigations Report 2017–5013–A–H, 126 p., https://doi.org/10.3133/sir20175013v1.

Detweiler, S.T., and Wein, A.M., eds., 2018, The HayWired earthquake scenario—Engineering implications: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q, 429 p., https://doi.org/10.3133/sir20175013v2.

Federal Emergency Management Agency [FEMA], 2016, National disaster recovery framework (2d ed.): Federal Emergency Management Agency, accessed September 10, 2021, at https://www.fema.gov/emergency-managers/national-preparedness/frameworks/recovery.

Grant, A.R.R., Wein, A.M., Befus, K., Finzi Hart, J., Frame, M.T., Volentine, R., Barnard, P., and Knudsen, K., in press, Changes in liquefaction severity in the San Francisco Bay area with sea-level rise: Geo-Extreme 2021 Conference Proceedings.

Grossi, P., and Zoback, M.L., 2013, 1868 Hayward earthquake—145-year retrospective: Risk Management Solutions, Inc., Special Report, 26 p., accessed February 13, 2019, at https://forms2.rms.com/rs/729-DJX-565/images/eq_1868_hayward_eq_retrospective.pdf.

Gupta, A., Wein, A.M., and Haveman, J., 2020, Variability of business characteristics exposed to building damages from earthquakes in the San Francisco Bay area: Earth and Space Science Open Archive, American Geophysical Union, 2019 Fall Meeting [poster presentation], San Francisco, 1 p., https://doi.org/10.1002/essoar.10501861.1.

Hudnut, K.W., Wein, A.M., Cox, D.A., Perry, S.C., Porter, K.A, Johnson, L.A., and Strauss, J.A., 2017, The HayWired scenario—How can the San Francisco Bay region bounce back from or avert an earthquake disaster in an interconnected world?, chap. A *of* Detweiler, S.T., and Wein, A.M., eds., The HayWired earthquake scenario—Earthquake hazards: U.S. Geological Survey Scientific Investigations Report 2017–5013–A–H, 126 p., https://doi.org/10.3133/sir20175013v1.

Jones, L.M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J., and Wein, A., 2008, The ShakeOut scenario: U.S. Geological Survey Open-File Report 2008–1150 [also released as California Geological Survey Preliminary Report 25], 312 p. and appendixes, https://doi.org/10.3133/ofr20081150.

Markhvida, M., Walsh, B., Hallegatte, S., and Baker, J., 2020, Quantification of disaster impacts through household well-being losses: Nature Sustainability, v. 3, p. 538–547, https://doi.org/10.1038/s41893-020-0508-7.

Porter, K.A., and Jones, J.L., 2018, How many injuries can be avoided in the HayWired scenario through earthquake early warning and drop, cover, and hold on?, chap. Q *of* Detweiler, S.T., and Wein, A.M., eds., The HayWired earthquake scenario—Earthquake implications: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q, 429 p., https://doi.org/10.3133/sir20175013v2.

Plumlee, G.S., Alpers, C.N., Morman, S.A., and San Juan, C., 2016, Anticipating environmental and environmental-health implications of extreme storms—ARkStorm scenario: Natural Hazards Review, v. 15, no. 4., 11 p., https://doi.org/10.1061/(ASCE)NH.1527-6996.0000188.

Porter, K., Byers, W., Dykstra, D., Lim, A., Lynett, P., Ratliff, J., Scawthorn, C., Wein, A., and Wilson, R., 2013, The SAFRR tsunami scenario—Physical damage in California, chap. E *of* Ross, S.L., and Jones, L.M., eds., The SAFRR (Science Application for Risk Reduction) Tsunami Scenario: U.S. Geological Survey Open-File Report 2013–1170, 168 p., https://doi.org/10.3133/ofr20131170E.

Scawthorn, C., 2018, Fire following the HayWired earthquake scenario, chap. P *of* Detweiler, S.T., and Wein, A.M., eds., The HayWired earthquake scenario—Engineering implications: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q, 429 p., https://doi.org/10.3133/sir20175013v2.

Seligson, H.A., Wein, A.M., and Jones, J.L., 2018, HayWired scenario—Hazus analyses of the mainshock and aftershocks, chap. J *of* Detweiler, S.T., and Wein, A.M., eds., The HayWired earthquake scenario—Engineering implications: U.S. Geological Survey Scientific Investigations Report 2017–5013–I–Q, 429 p., https://doi.org/10.3133/sir20175013v2.

Vargas, P., Zsarnóczay, A., Wein, A., Esnard, A-M., and Johnson, L., 2019, Understanding earthquake impact on communities through structural building damage and social vulnerability metrics: Earth and Space Science Open Archive, American Geophysical Union, 2019 Fall Meeting [poster presentation], San Francisco, 1 p., http://doi.org/10.13140/RG.2.2.33444.22400.