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

Chapter T of

The HayWired Earthquake Scenario—Societal Consequences

Edited by Shane T. Detweiler and Anne M. Wein

Scientific Investigations Report 2017–5013–R–W

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
Jones, J.L., Wein, A.M., Schweikert, A.E., and Ballanti, L.R., 2019, Lifeline infrastructure and collocation exposure to the HayWired earthquake scenario—A summary of hazards and potential service disruptions, chap. T *of* Detweiler, S.T., and Wein, A.M., eds., The HayWired Earthquake Scenario—Societal Consequences: U.S. Geological Survey Scientific Investigations Report 2017–5013–R–W, 104 p., https://doi.org/10.3133/sir20175013V3.

ISSN 2328-0328 (online)

Contents

Figures

Tables

The HayWired Earthquake Scenario—Societal Consequences
Edited by Shane T. Detweiler and Anne M. Wein
Scientific Investigations Report 2017–5013–R–W
[Also see https://doi.org/10.3133/sir20175013]

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 (in prep.; planned to be published as part of 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, in prep. [planned to be published as part of 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.

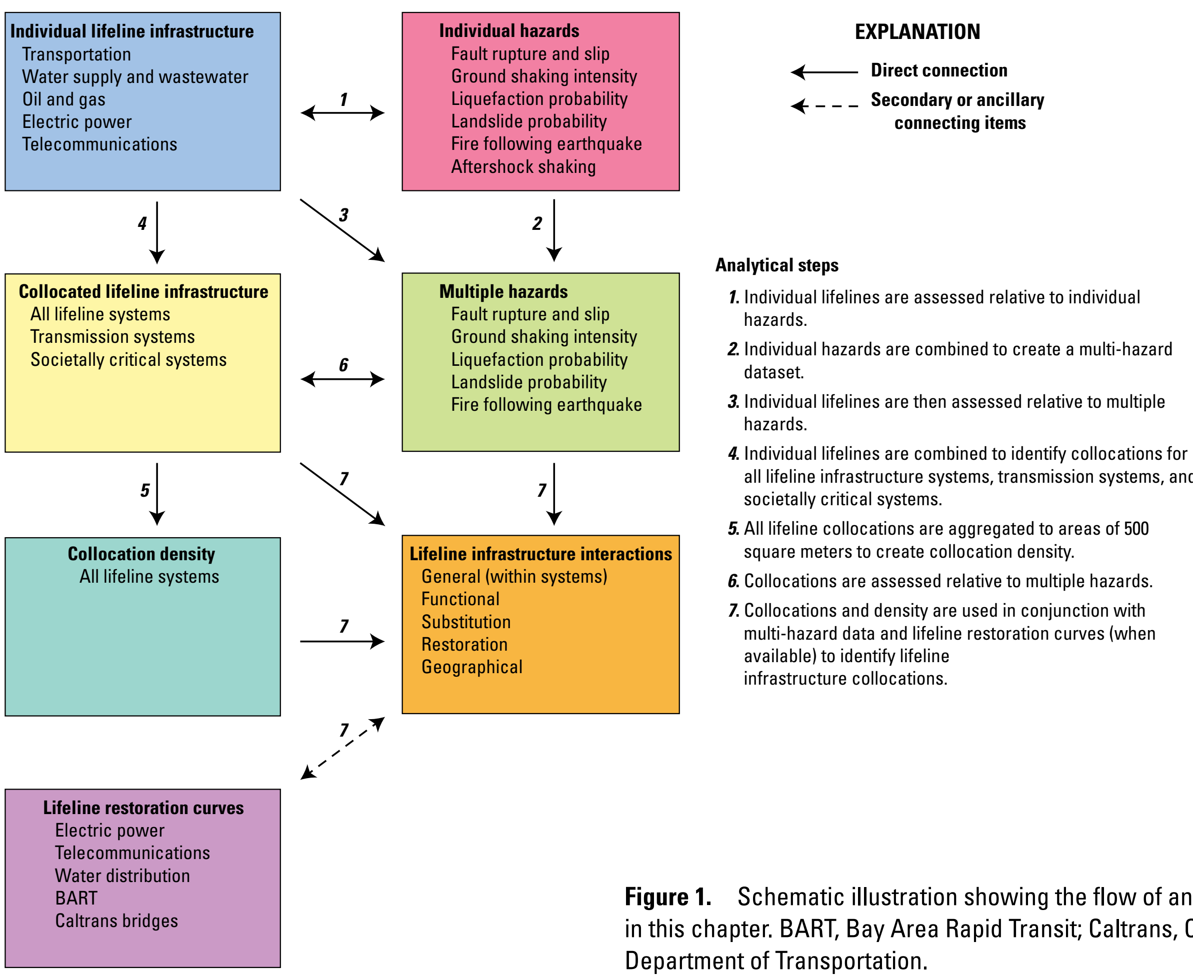


Figure 1. Schematic illustration showing the flow of analyses in this chapter. BART, Bay Area Rapid Transit; Caltrans, California Department of Transportation.

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,

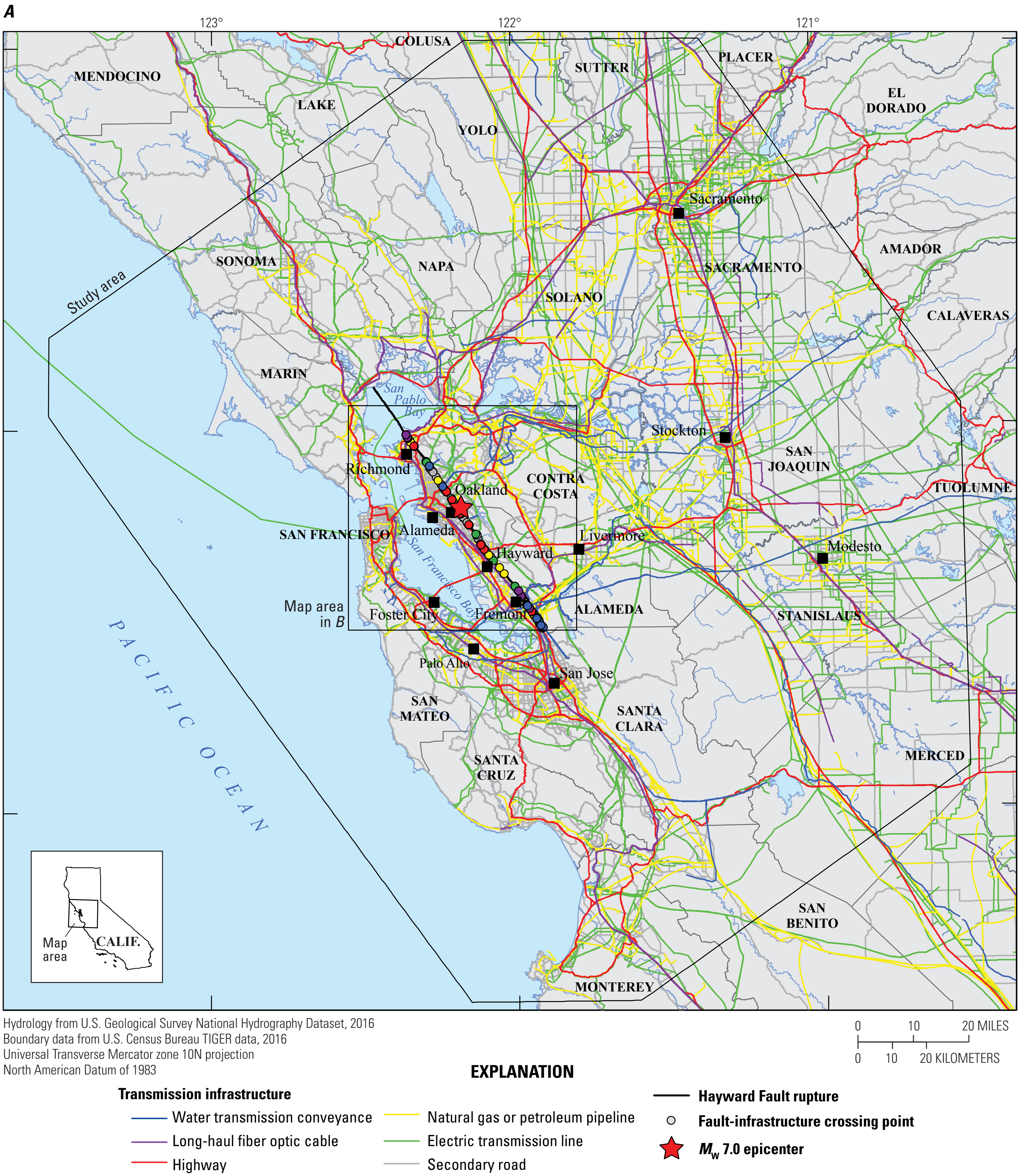


Figure 2 (pages 6–7). Maps of the San Francisco Bay region, California, showing transmission infrastructure relative to rupture of the Hayward Fault during the HayWired earthquake scenario mainshock. Many transmission infrastructure lifelines cross the fault, including natural gas and petroleum pipelines, 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.

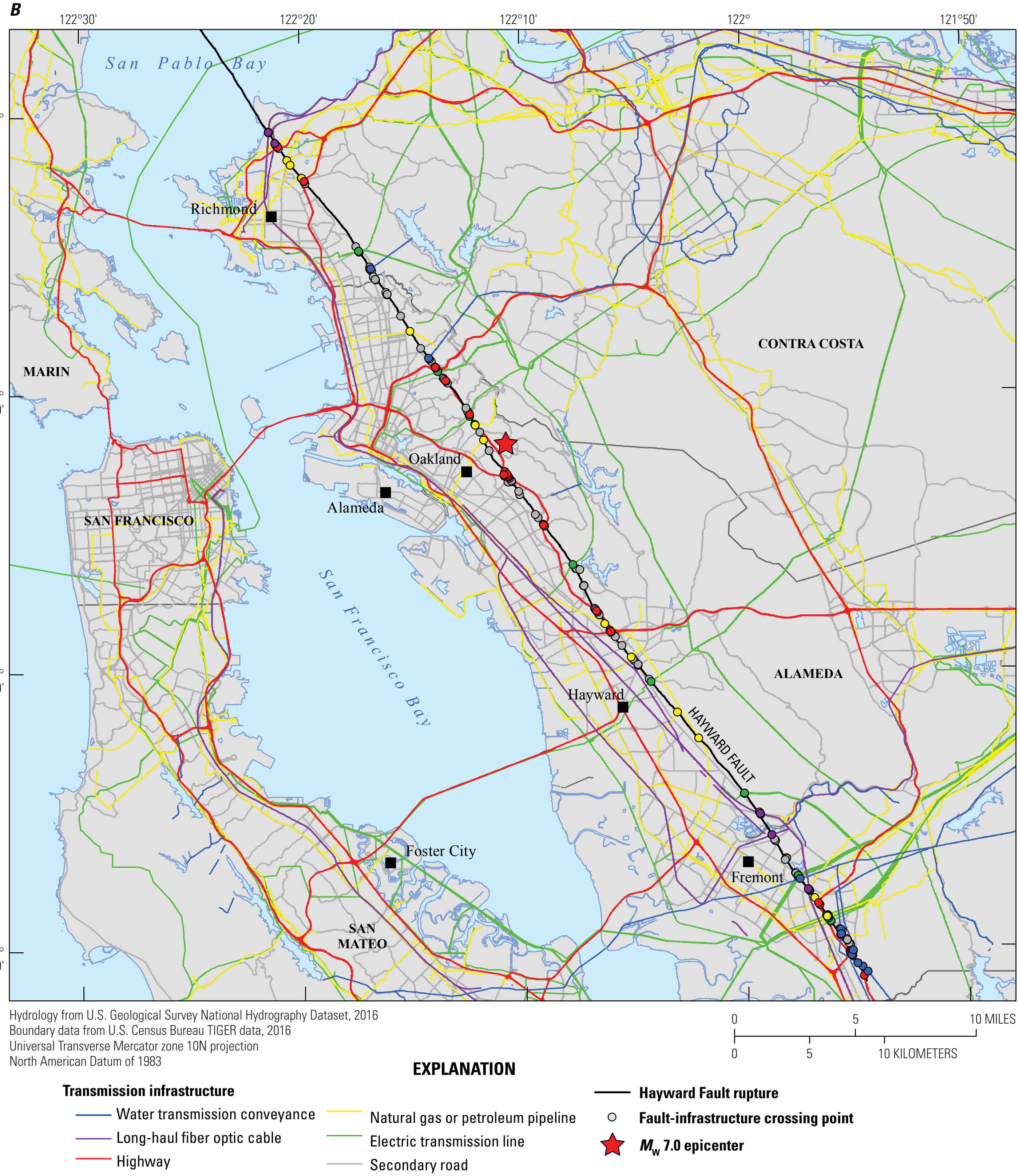


Figure 2 (pages 6–7).—Continued

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

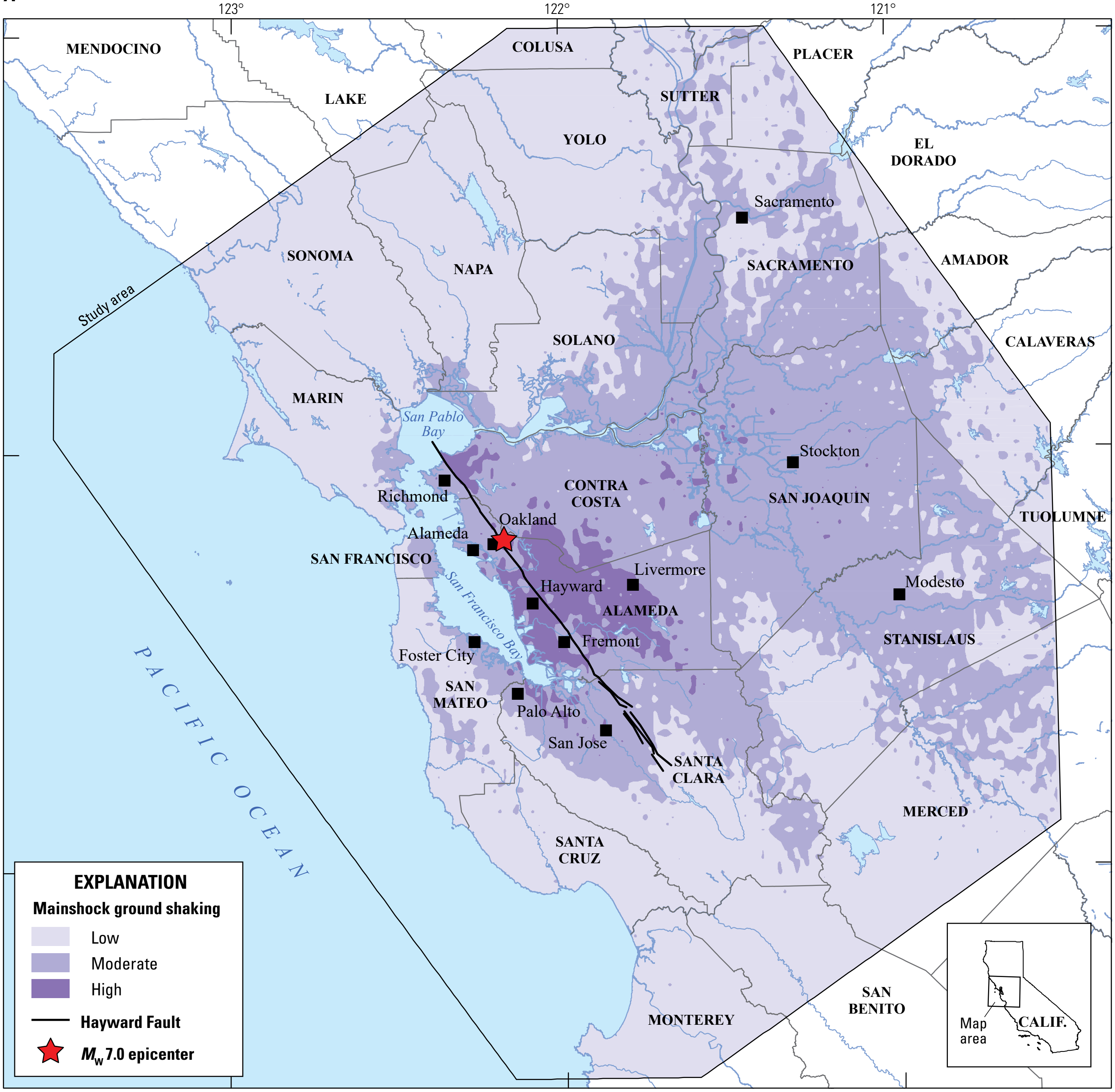
Table 2. Shaking-potential hazard intensity classification for the HayWired earthquake scenario mainshock in the San Francisco Bay region, California.

[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.

A



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

0 10 20 MILES
0 10 20 KILOMETERS

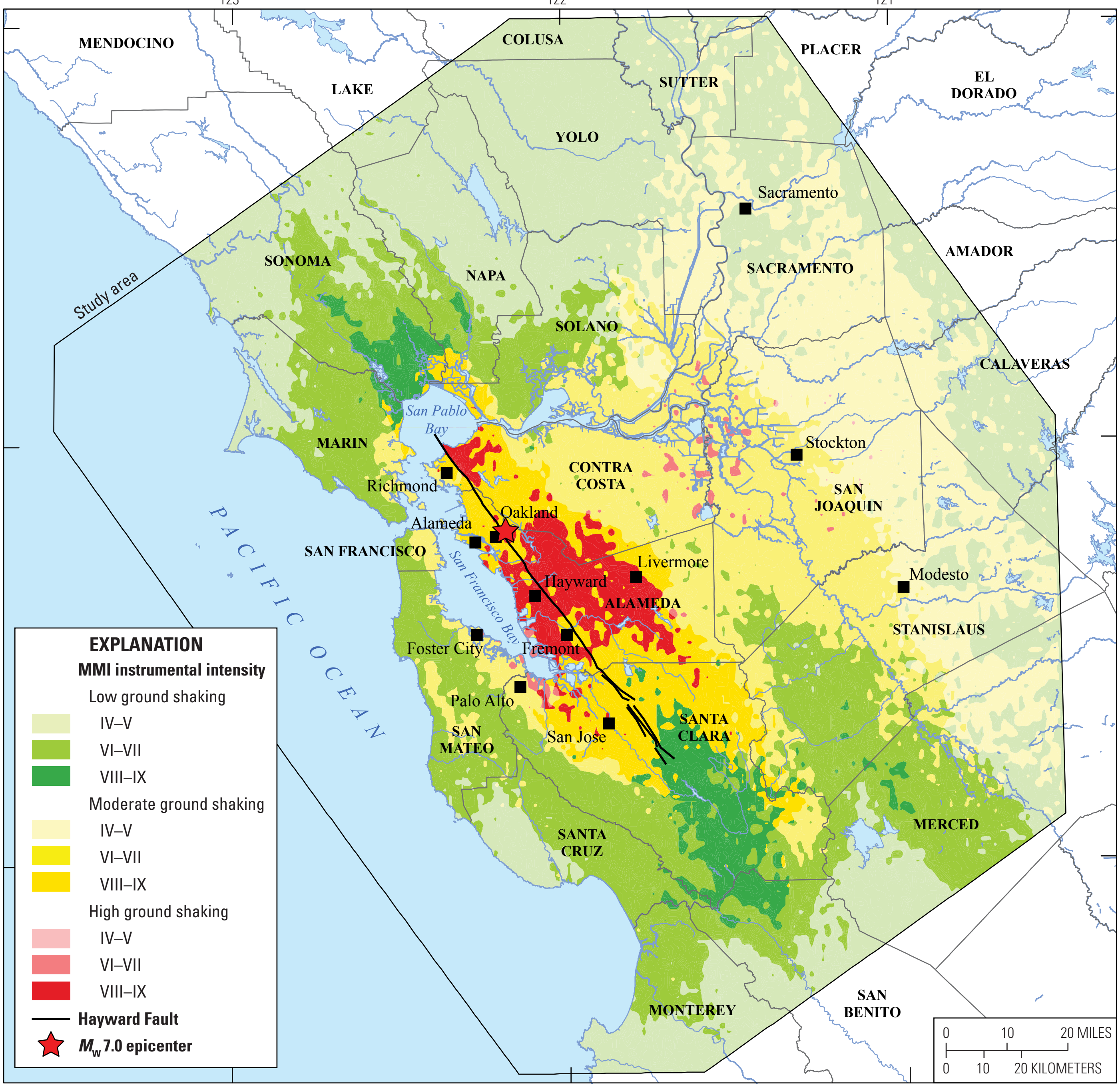
Figure 3 (pages 9–10). Maps of the San Francisco Bay region, California, showing ground shaking as a result of the HayWired earthquake scenario mainshock on the Hayward Fault. *A*, Ground-shaking classifications used in this chapter. *B*, Ground shaking classifications compared to ShakeMap Modified Mercalli 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

B



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 9–10). —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

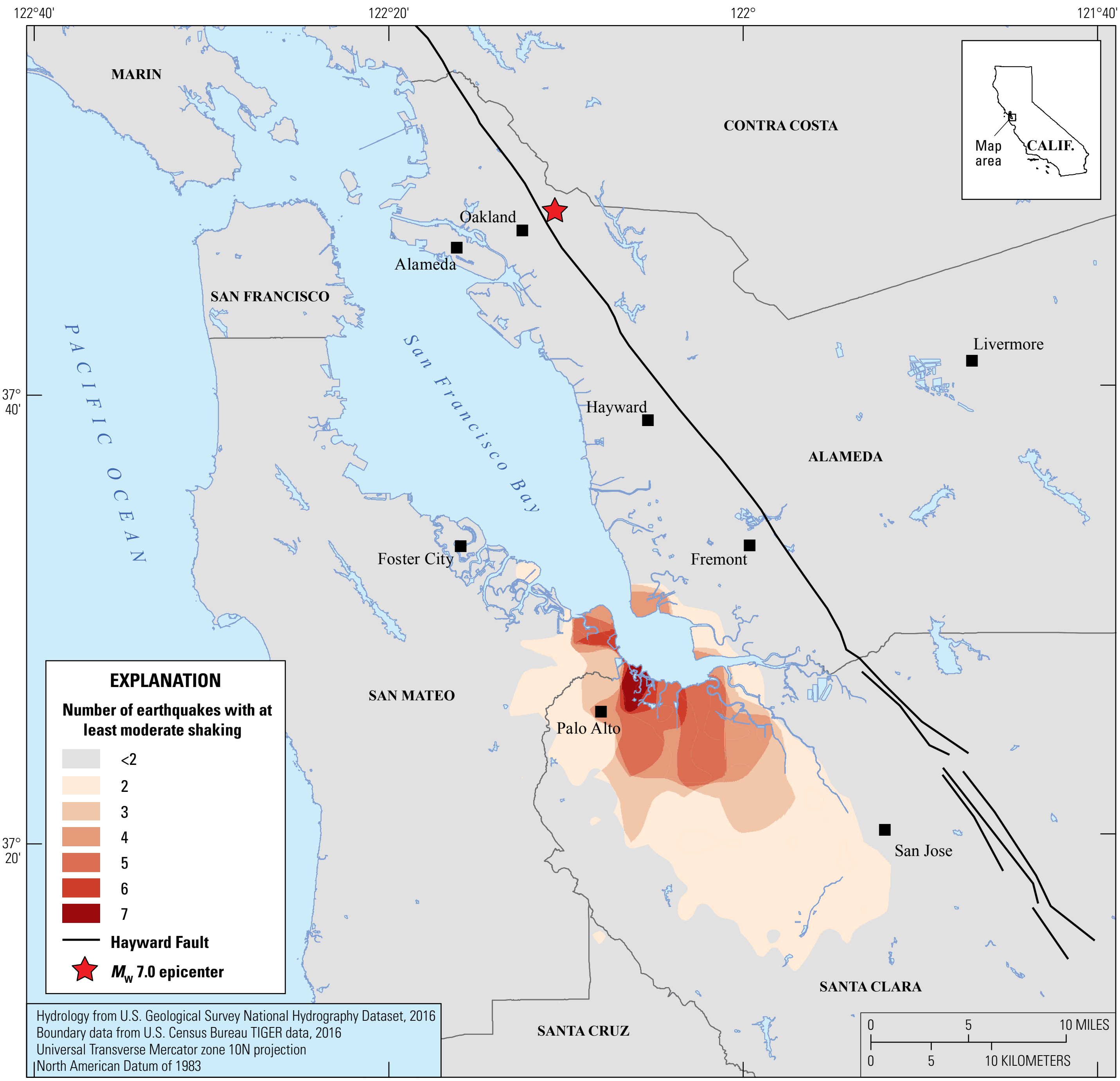


Figure 4. Map of the San Francisco Bay region, California, showing areas affected by overlapping aftershock ground shaking for the HayWired earthquake scenario. Some areas experience multiple aftershocks in addition to the mainshock, especially the bay side areas near Palo Alto, and some areas experience 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.

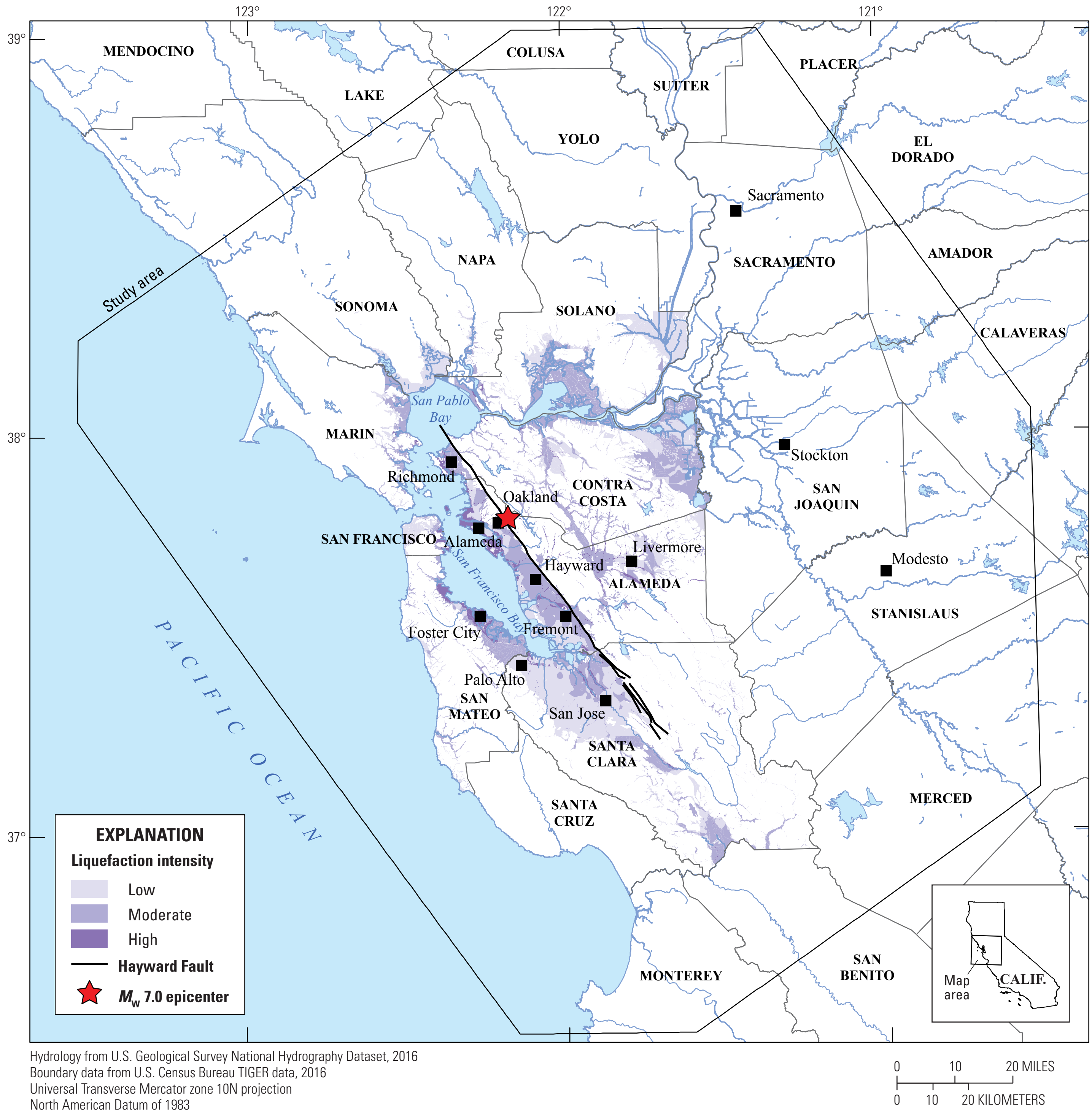


Figure 5. Map of the San Francisco Bay region, California, showing the liquefaction probability modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. Liquefaction probability is highest in the areas adjacent to San Francisco Bay and the creeks feeding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

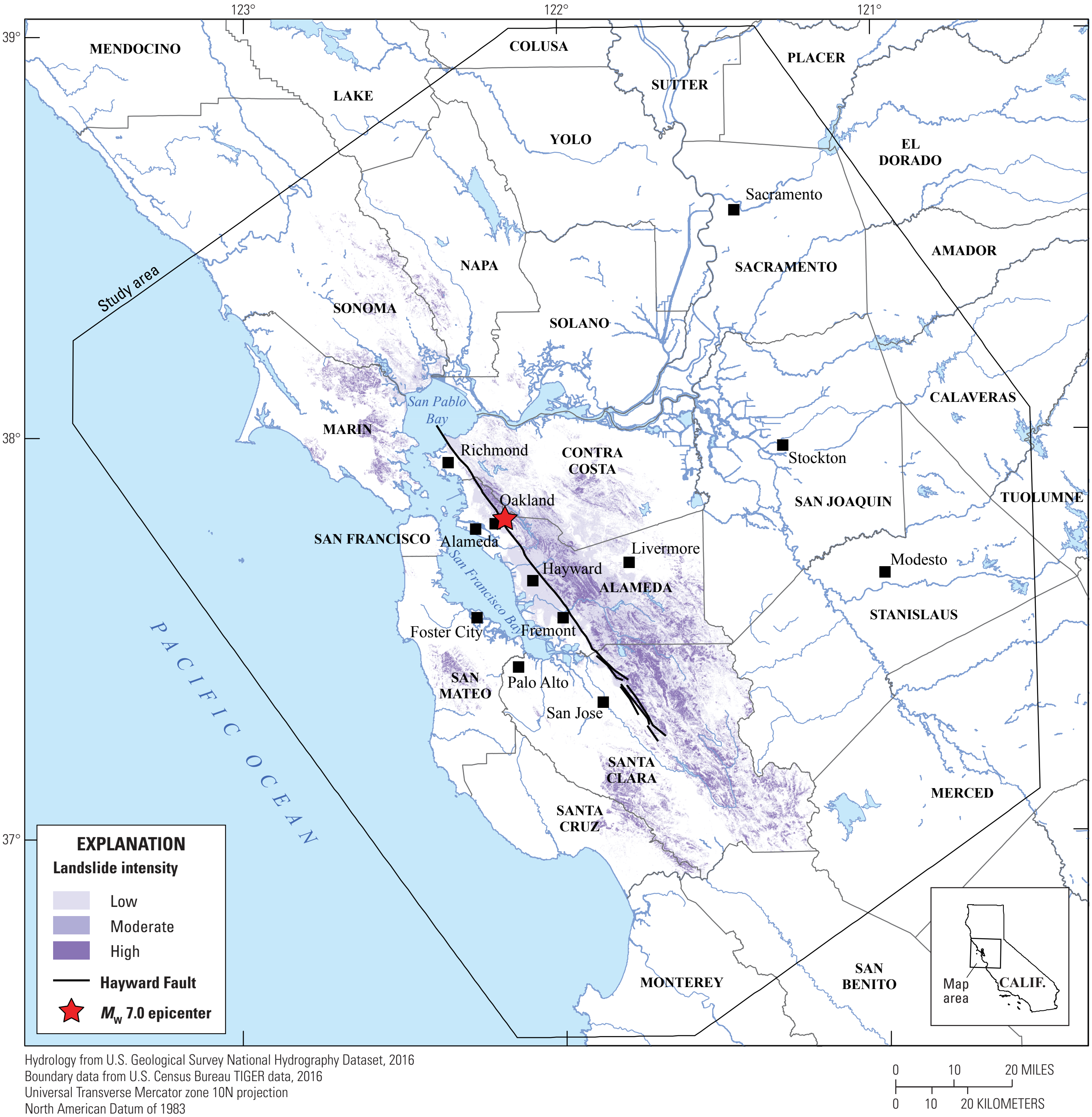


Figure 6. Map of the San Francisco Bay region, California, showing the landslide probability modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. Landslide probability is highest in the areas surrounding the fault rupture as well as on the northwest 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; %, percent]

Intensity classification	Fire density (%)	Estimated geographic extent (km^2)
Low	>0 to <0.85	994
Moderate	0.85 to <2.3	159
High	≥2.3	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.

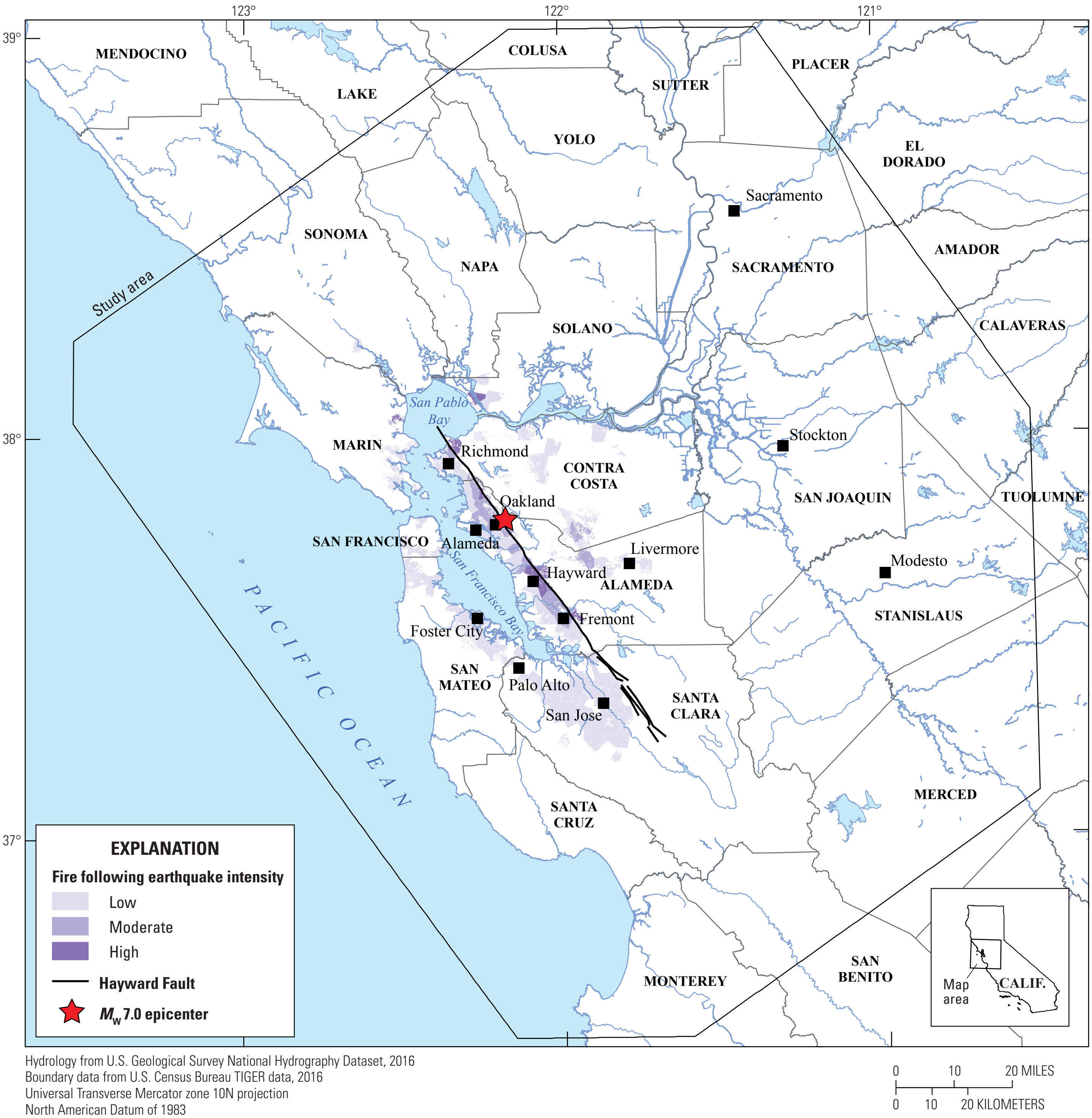


Figure 7. Map of the San Francisco Bay region, California, showing the fire-following-earthquake modeling extent and classification for the HayWired earthquake scenario mainshock on the Hayward Fault. The scale of analysis is determined by the location of each fire station. Analysis boundaries are drawn based on the closest distance to each fire station. Low, moderate, and high classifications are based on the percentage of developed land that is estimated to be burned. 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, in prep.; planned to be published as part of 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 (in prep.; planned to be published as part of 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).

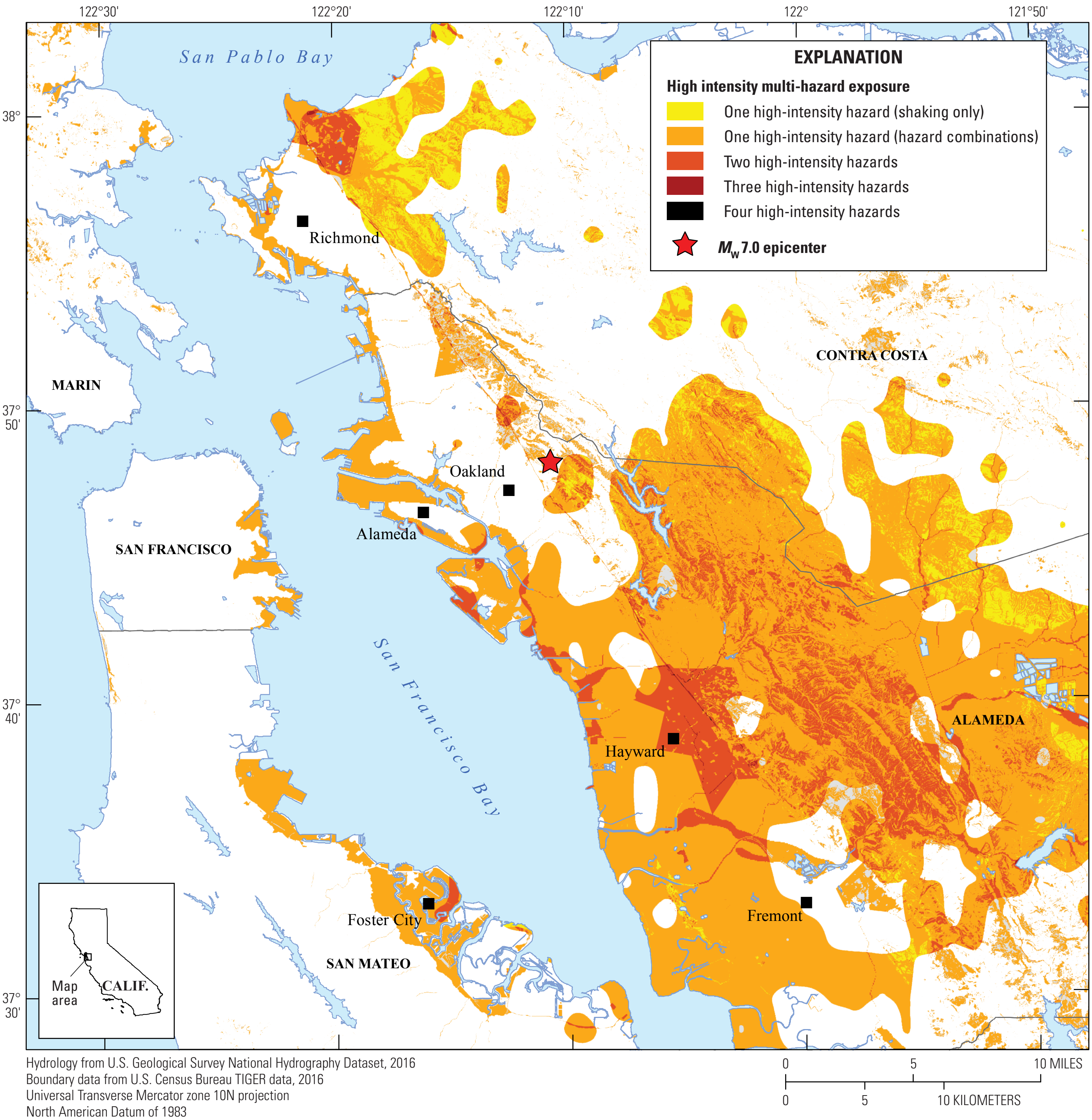


Figure 8. Map of the San Francisco Bay region, California, showing areas exposed to one or more high-intensity HayWired earthquake scenario mainshock hazards. Areas in dark red or black indicate exposure to multiple high-intensity hazards and are mostly found in the Hayward, Richmond, and Oakland urban 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

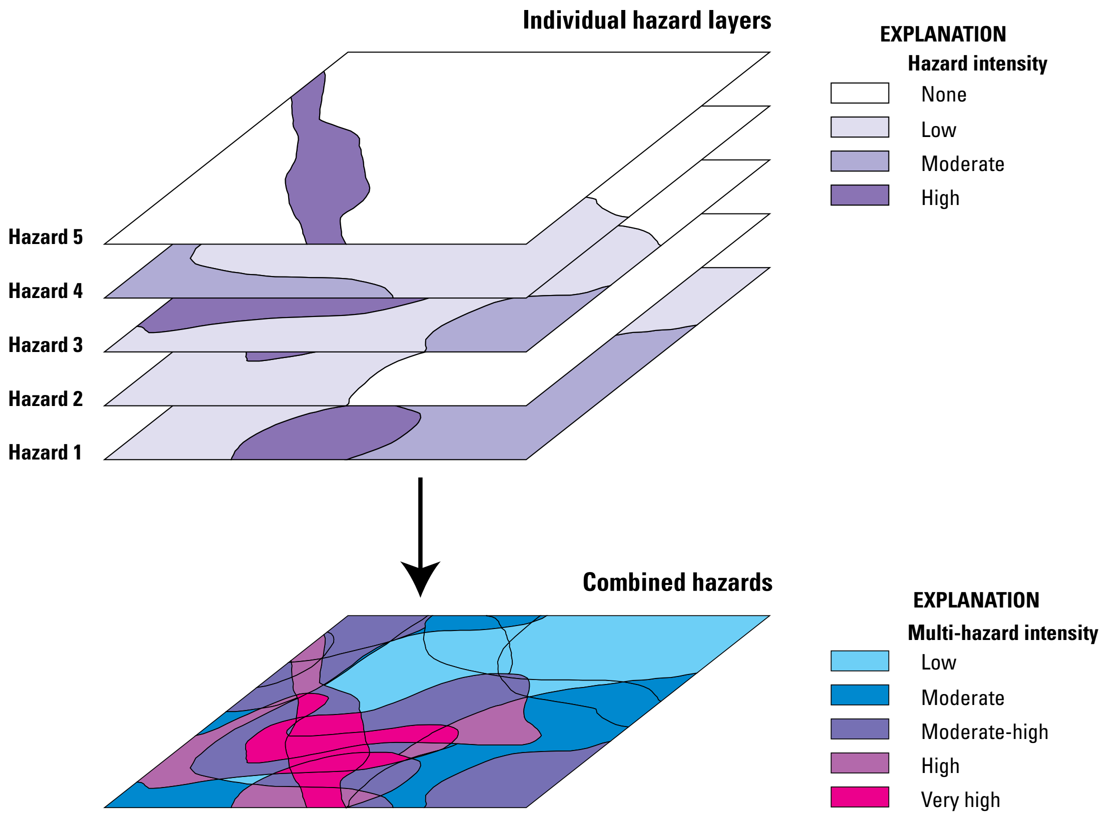


Figure 9. Schematic illustration showing how overlapping hazards are merged into one multiple hazard output. All individual hazards are combined into one dataset; the number and intensity of all overlapping hazards in a specific location are assessed in order to assign final multi-hazard values for each 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

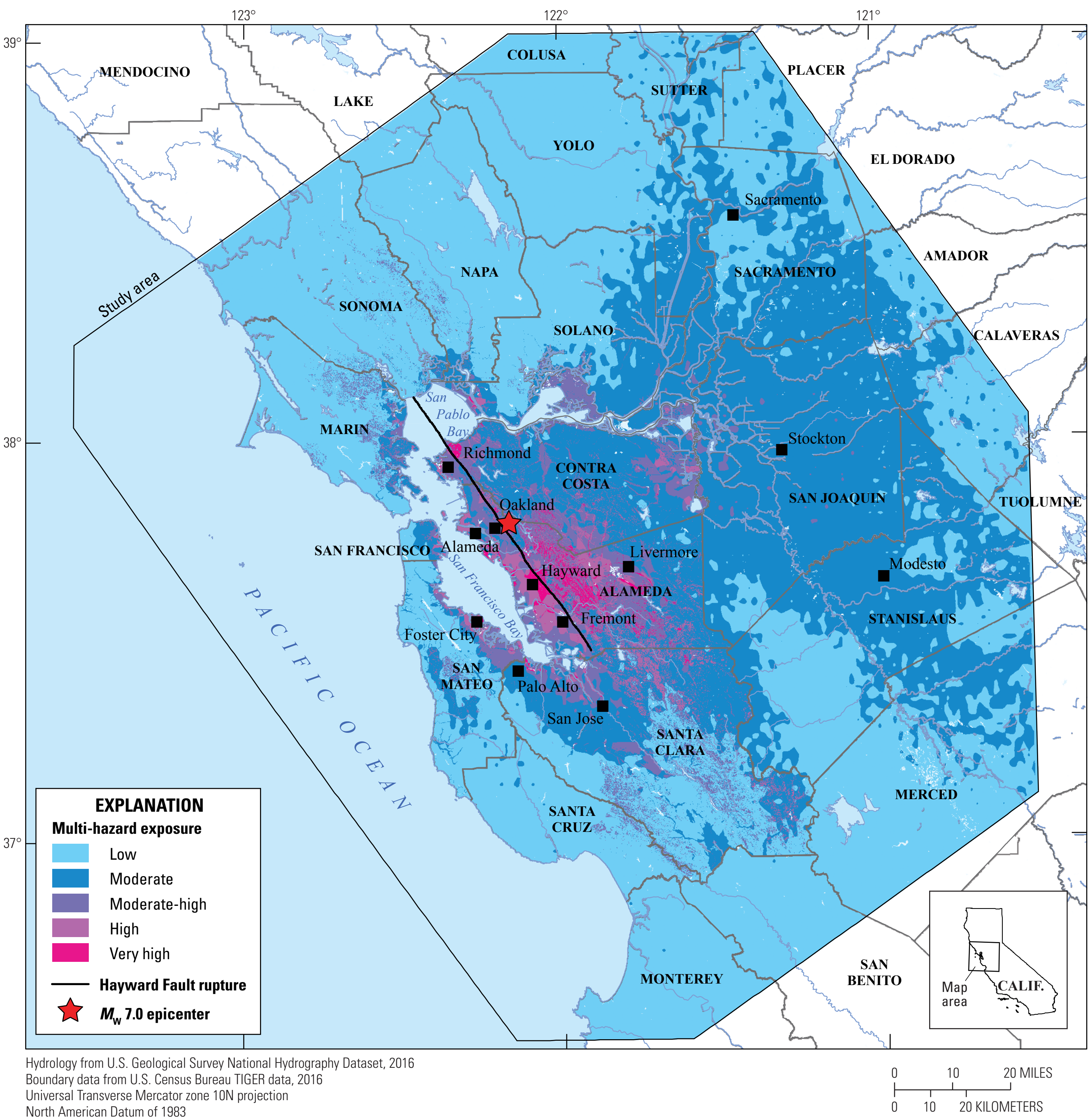


Figure 10. Map of the San Francisco Bay region, California, showing the composite multi-hazard exposure as a result of HayWired scenario mainshock hazards. For classifications of the multi-hazard layer, see table 10. M_w, moment magnitude.

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

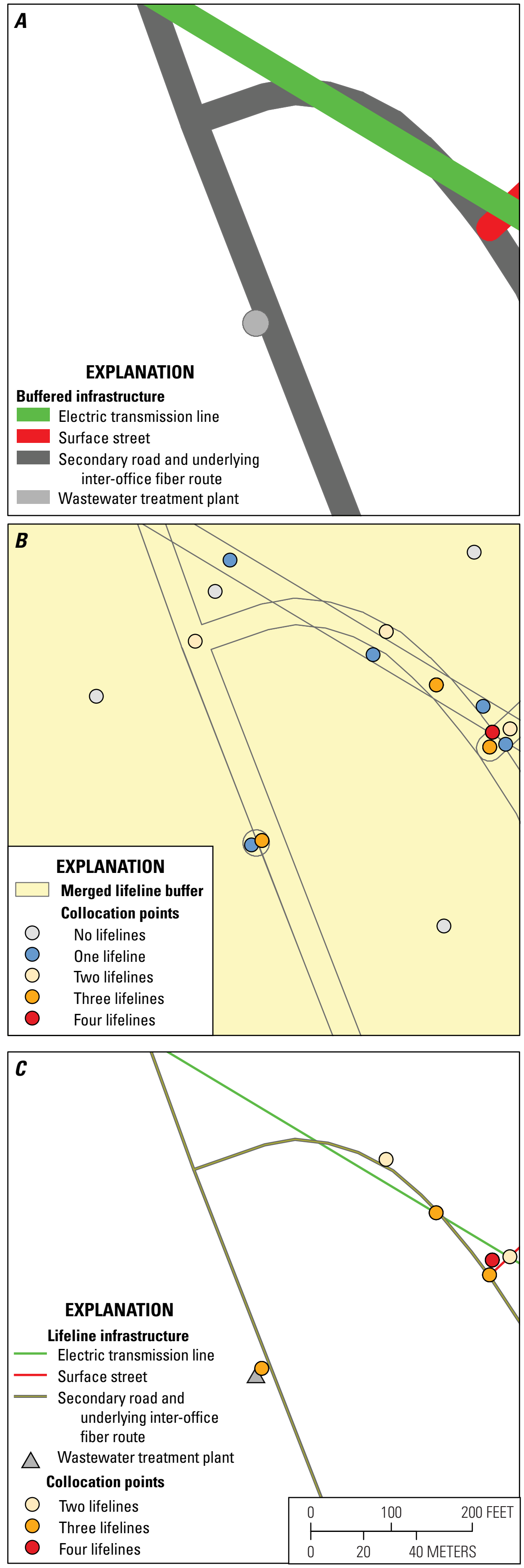


Figure 11. Simplified maps showing the steps of the process used to identify collocated lifeline infrastructure. *A*, Buffers of 5 meter width overlaid on top of each lifeline infrastructure system. *B*, Merged lifeline buffers and resulting polygon centroids used to determine final collocations. Note 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 m^2 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

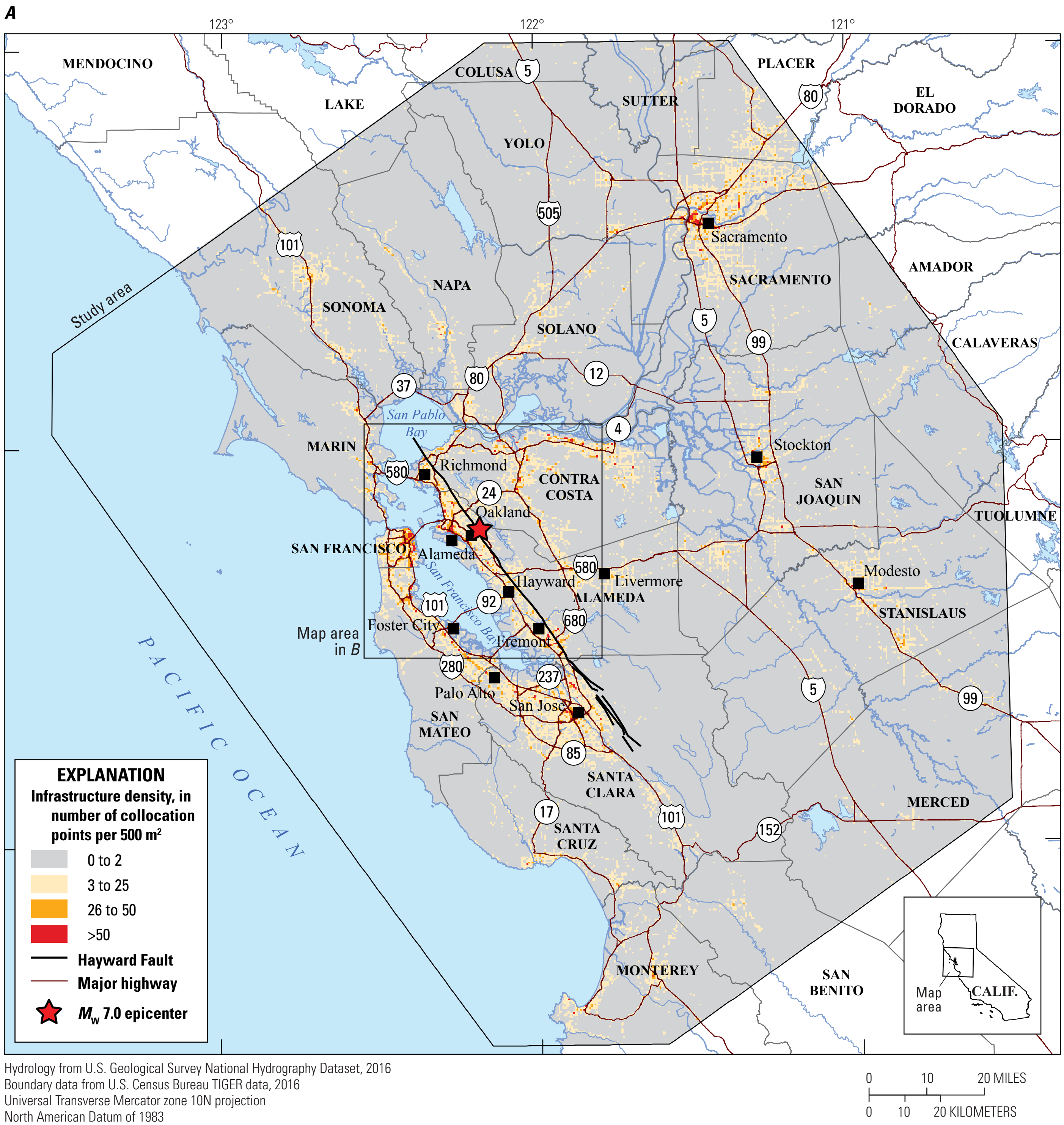


Figure 12 (pages 32–33). Maps of the San Francisco Bay region, California, showing a density assessment of collocated infrastructure per 500 square meters (m2). Red areas highlight exposure exceeding 50 unique collocation points and orange areas show 26–50 unique collocation points. This map is independent 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.

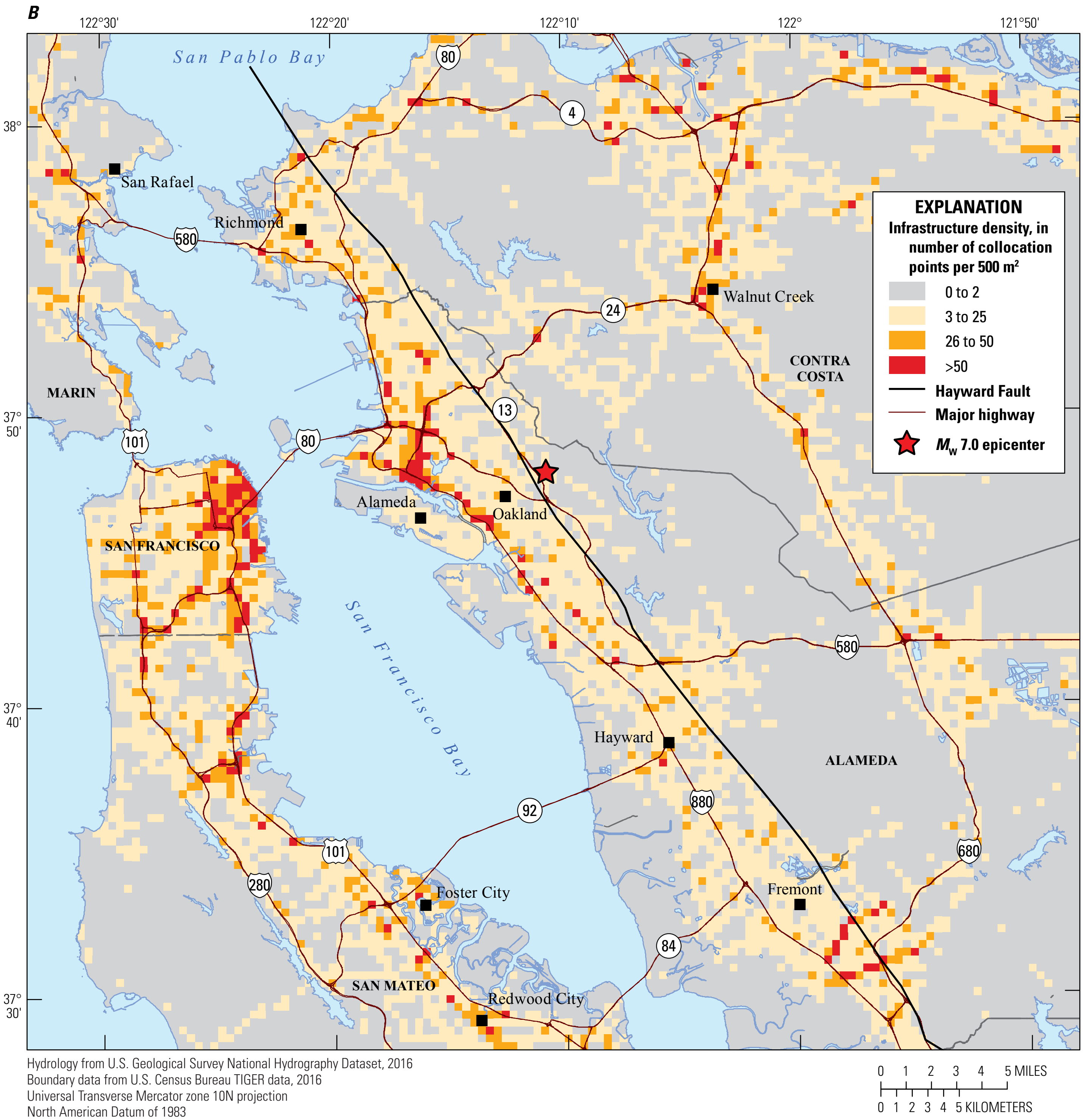


Figure 12 (pages 32–33).—Continued

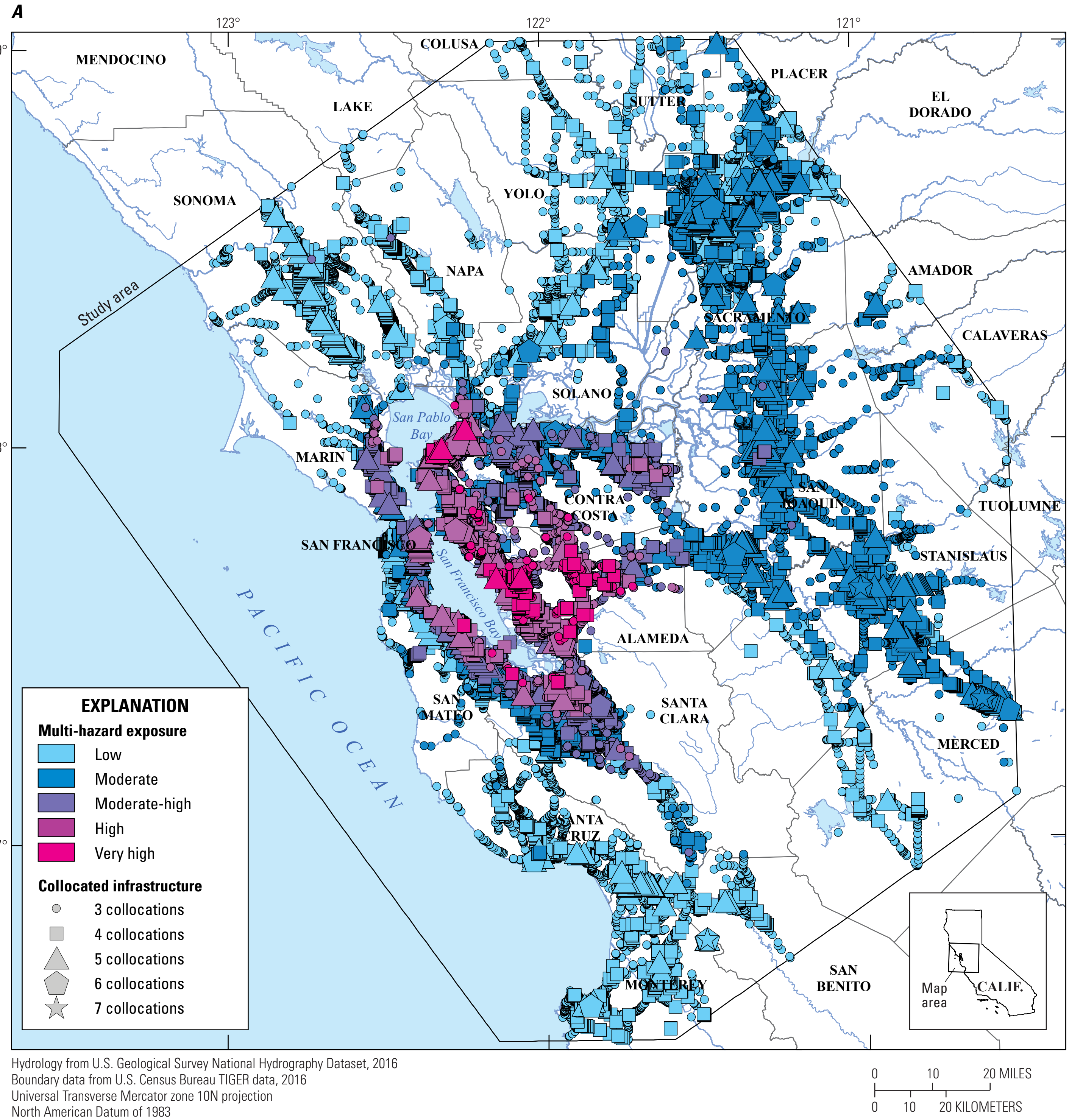


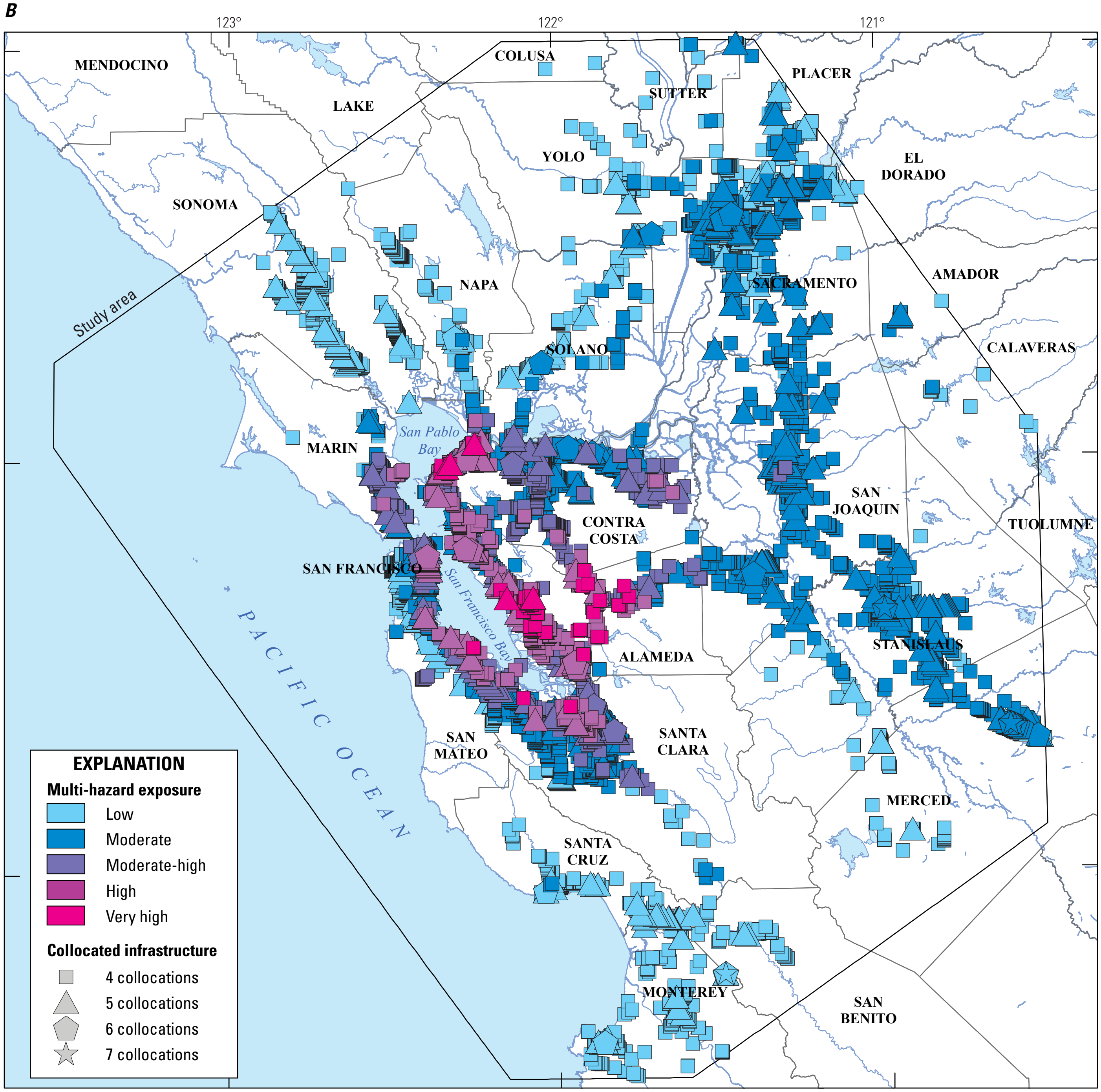
Figure 13 (pages 34–35). Maps of the San Francisco Bay region, California, showing collocated infrastructure points and exposure level to multiple HayWired earthquake scenario mainshock hazards (three or more collocated infrastructure assets only). The symbol shape corresponds to the number of infrastructure 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

B



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 34–35).—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.

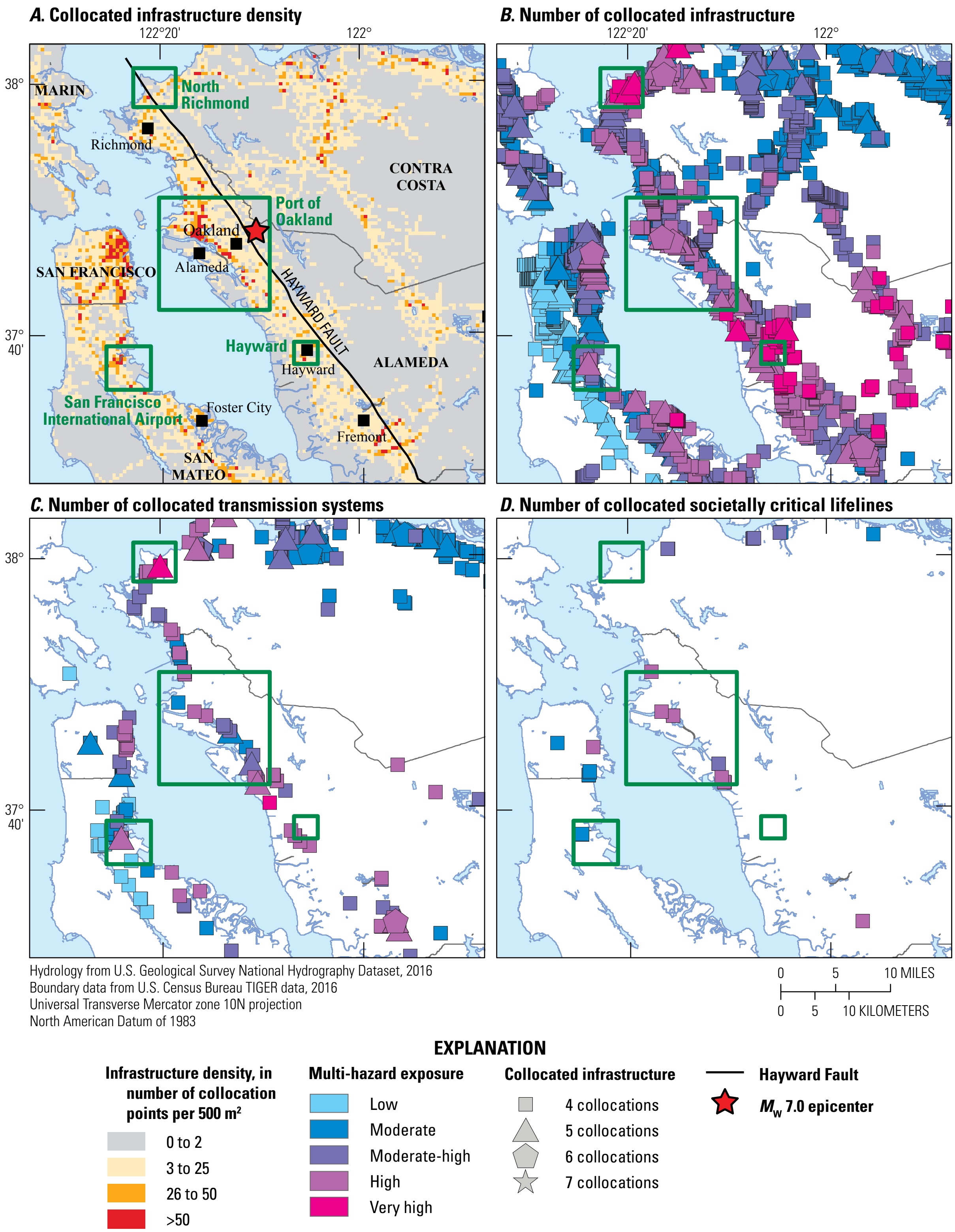


Figure 14. Maps of the San Francisco Bay region, California, showing lifeline infrastructure collocation analyses. Each panel was used to select different examples of lifeline infrastructure interactions. Boxes outline four lifeline interaction examples that are discussed in the text and table 16. *A*, 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, in prep. [planned to be published as part of 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, in prep.; planned to be published as part of 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, in prep.; planned to be published as part of 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, in prep. [planned to be published as part of 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, in prep. [planned to be published as part of 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, in prep.; planned to be published as part of 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, in prep.; planned to be published as part of 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

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.

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 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, in prep.; planned to be published as part of 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 (in prep.; planned to be published as part of 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 (in prep.; planned to be published as part of 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 (in prep.; planned to be published as part of this volume) and Kroll and others (in prep.; planned to be published as part of 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),

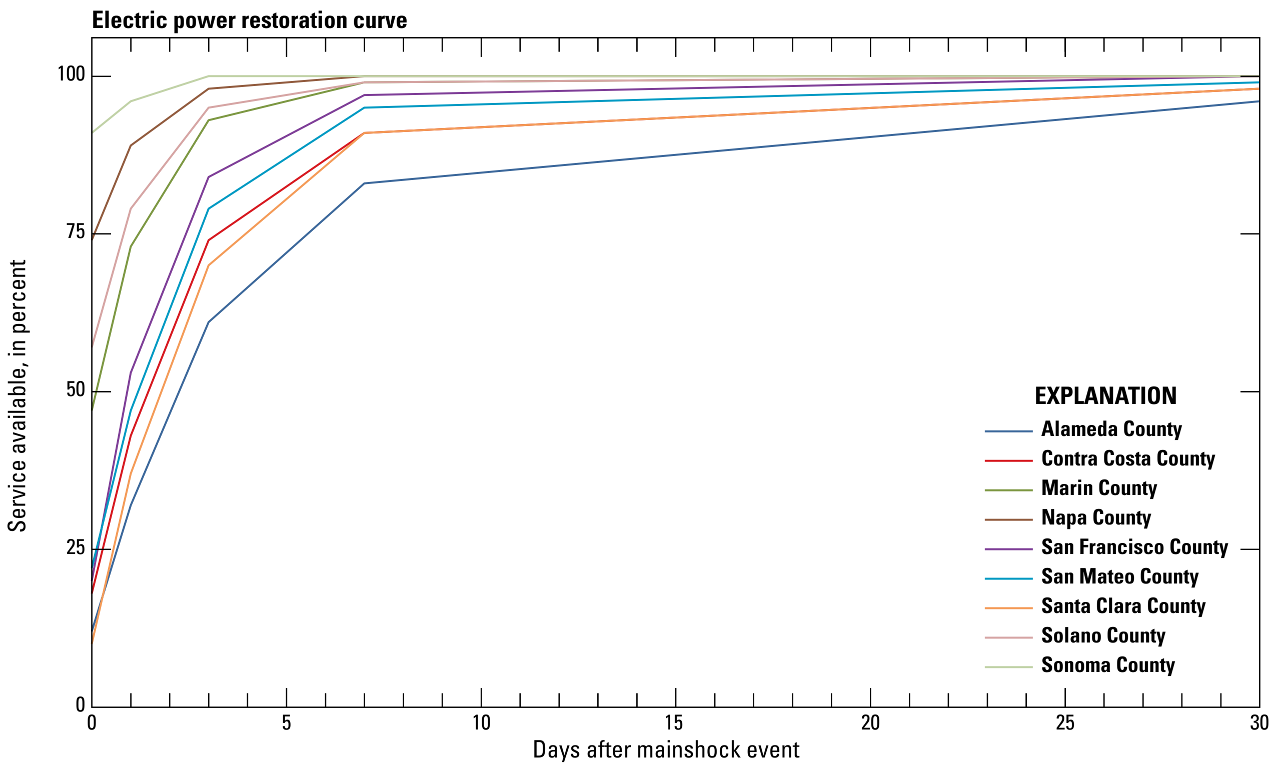


Figure 15. Line graph showing the electric power restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

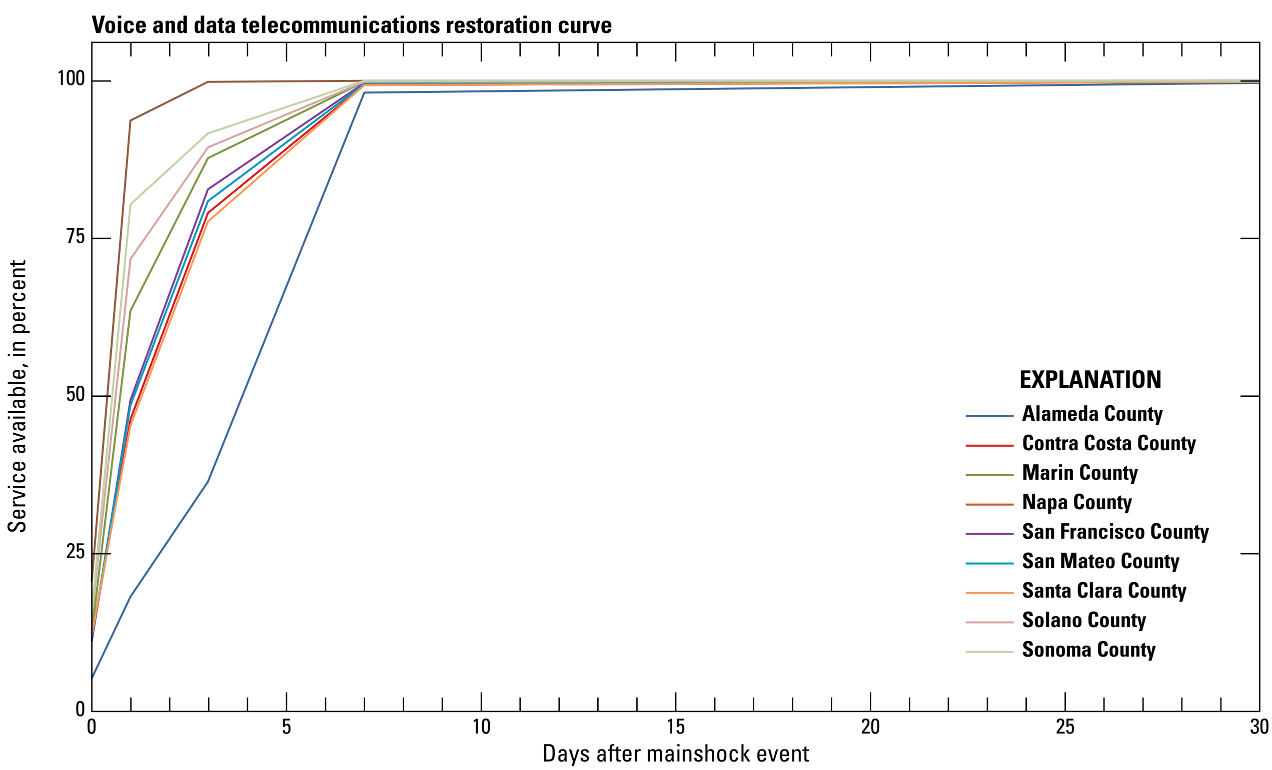


Figure 16. Line graph showing the voice and data telecommunications restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

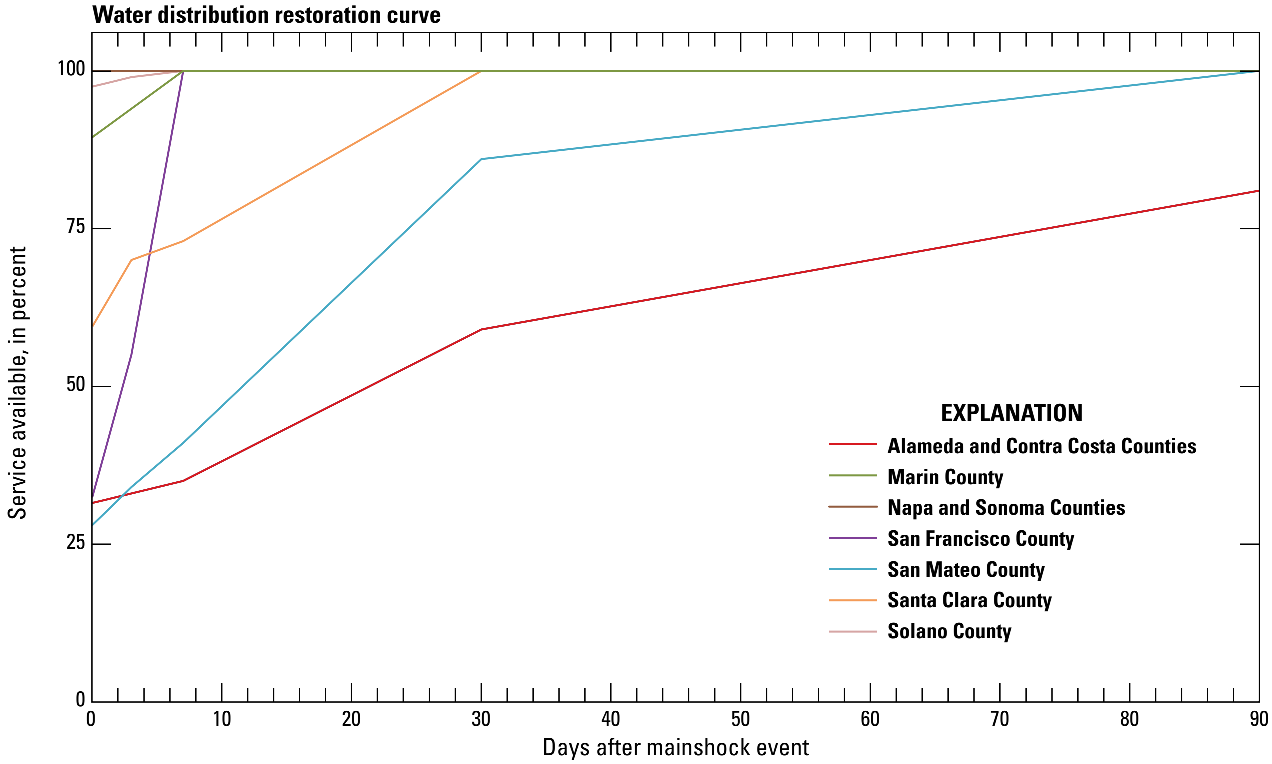


Figure 17. Line graph showing the water distribution restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California. Data originally from Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) and modified for Alameda, Contra Costa, and Santa Clara Counties by Porter (2018).

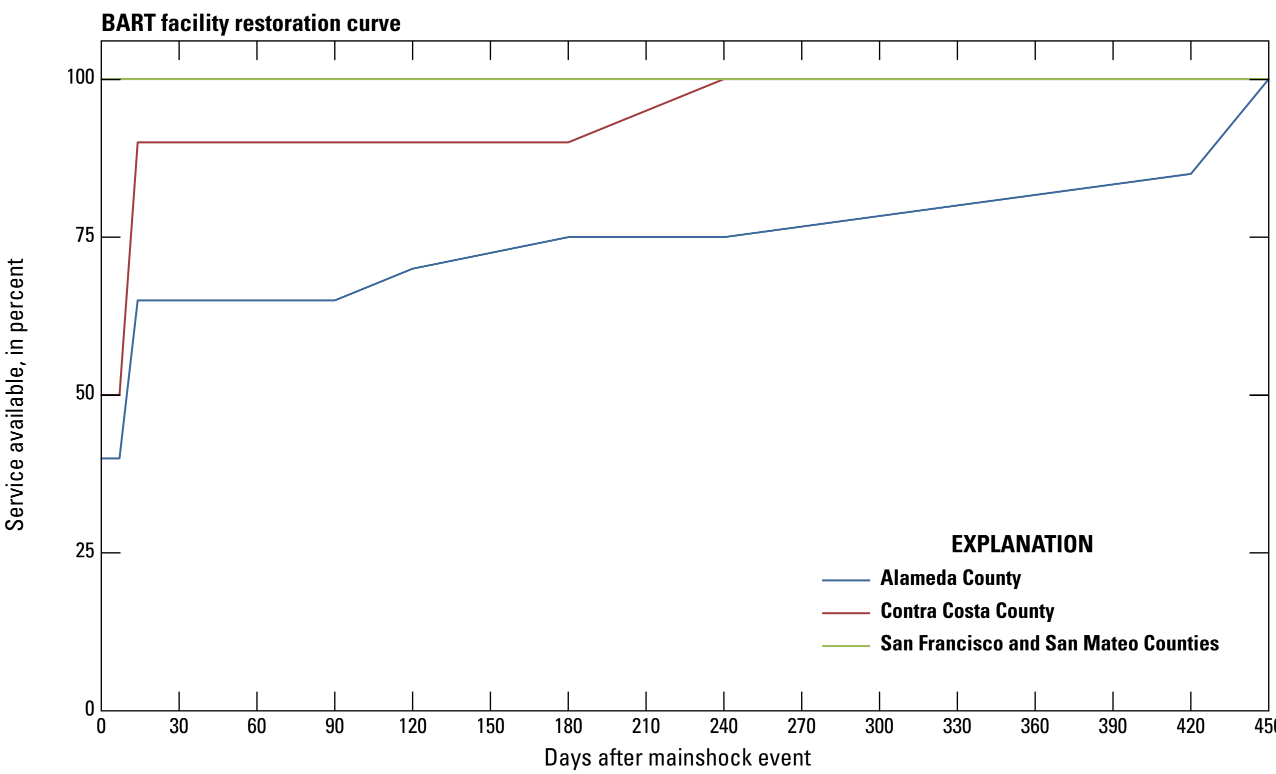


Figure 18. Line graph showing the Bay Area Rapid Transit (BART) facility restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California. Damage estimates only apply to stations in the original BART system (built between 1972 and 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).

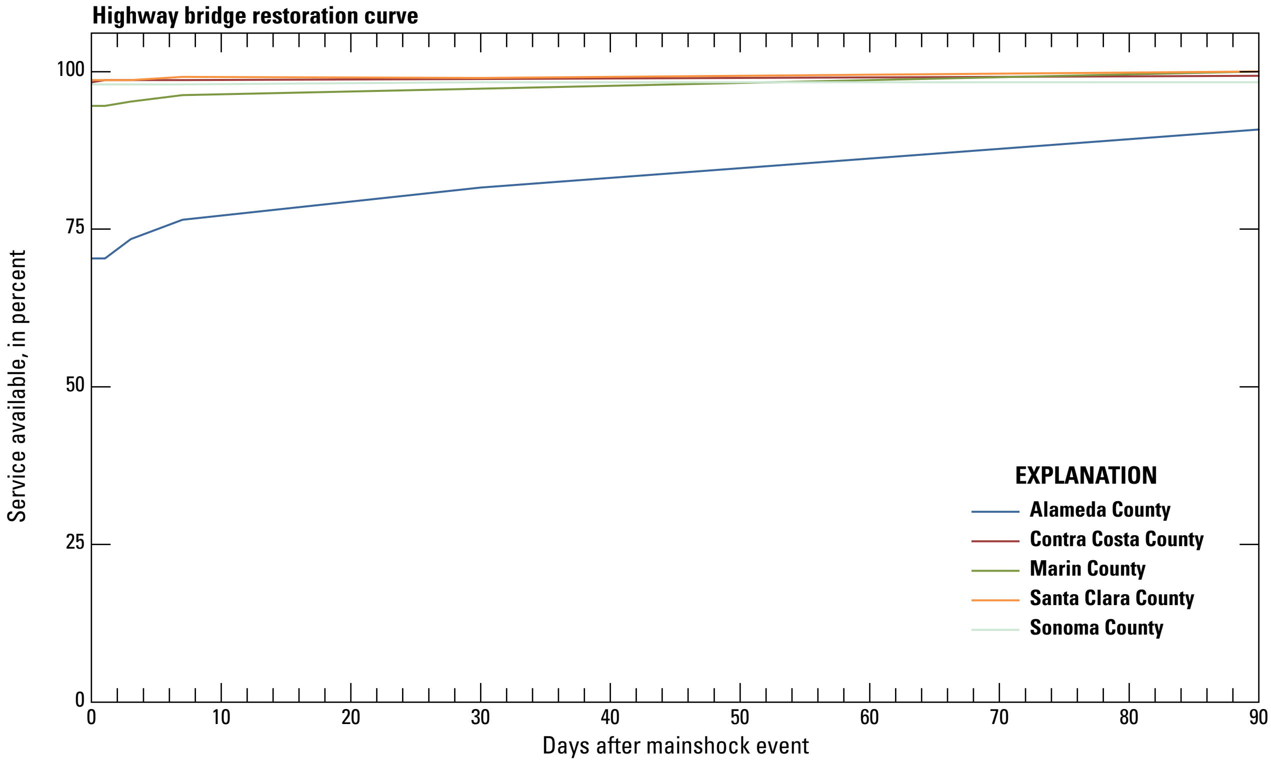


Figure 19. Line graph showing the California Department of Transportation highway bridge restoration curve by county for the HayWired earthquake scenario mainshock in the nine counties adjacent to San Francisco Bay, California.

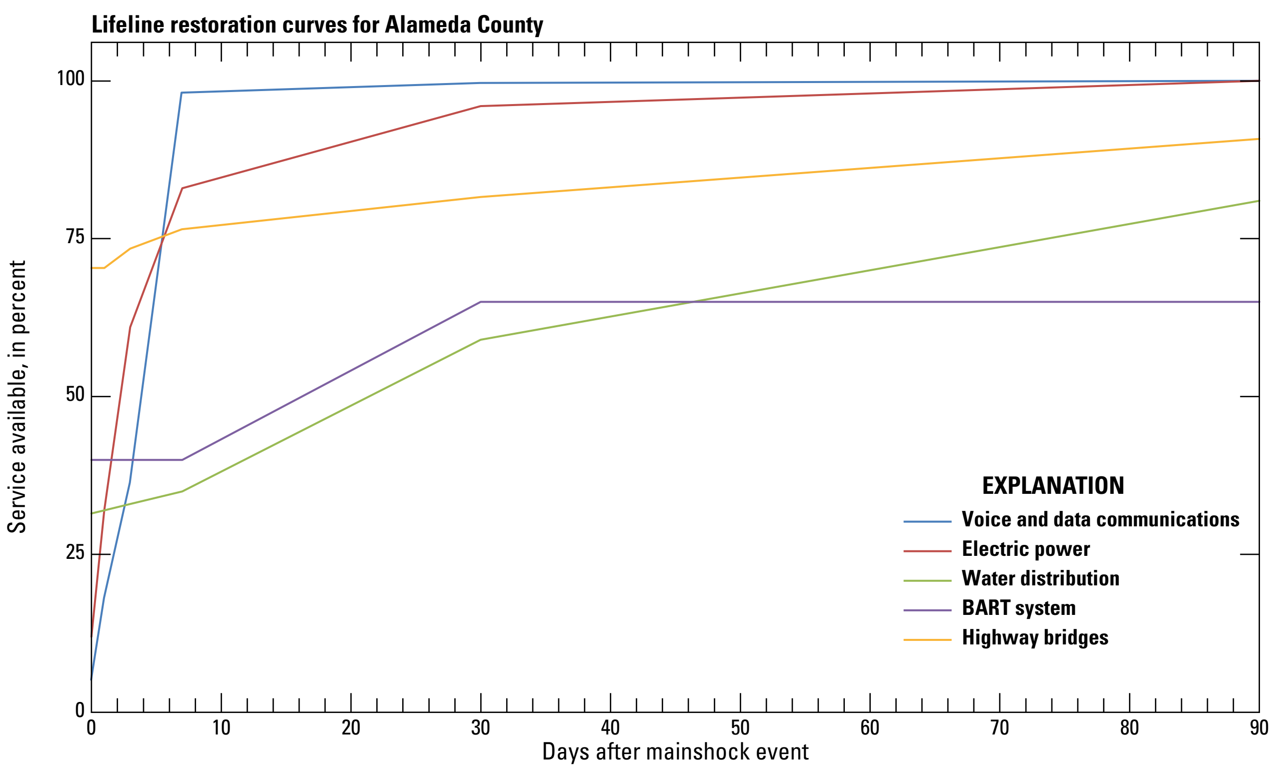


Figure 20. Line graph showing the lifeline restoration curves (electric power, voice and data, water distribution, Bay Area Rapid Transit [BART] service, and California Department of Transportation bridges) for Alameda County for the HayWired earthquake scenario mainshock in the nine counties adjacent 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, in prep.; planned to be published as part of 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).

Explorations of the infrastructure that are collocated 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 (in prep.; planned to be published as part of 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).

Acknowledgments

We could not have compiled lifeline infrastructure damage and restoration information without the valuable contributions from many organizations. We thank the following people for participating: Mark Salmon, Tom Horton, and Maria Blagg (Bay Area Rapid Transit); Loren Turner, Brian Chiou, Herby Lissade, and Dana Hendrix (California Department of Transportation); Greg Molnar, Evermary Hickey, and Stuart Nishenko (Pacific Gas and Electric Company); Gordon Schremp (California Energy Commission); and Keith Porter (University of Colorado at Boulder), who worked with water utilities. We appreciate the opportunity to test our analyses in a HayWired scenario exercise designed with Paula Scalingi (Bay Area Center for Regional Disaster Resiliency) for lifeline interdependency workshops. Monika Stoeffl (California Resilience Alliance) linked us to useful resources and relevant studies. Our work was improved by suggestions from several reviewers: Michael Germeraad (Metropolitan Transportation Commission and Association of Bay Area Governments); and Cherrie Black, Ryan Hruska, Shiloh Elliot, and Stefan Haus (Idaho National Laboratory).

References Cited

Aagaard, B.T., Boatwright, J.L., Jones, J.L., MacDonald, T.G., Porter, K.A., and Wein, A.M., 2017, HayWired scenario mainshock ground motions, chap. C *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.

Aagaard, B.T., Graves, R.W., Schwartz, D.P., Ponce, D.A., and Graymer, R.W., 2010, Ground-motion modeling of Hayward Fault scenario earthquakes, part I—Construction of the suite of scenarios: Bulletin of the Seismological Society of America, v. 100, no. 6, p. 2927–2944, https://doi.org/10.1785/0120090324.

Aagaard, B.T., Schwartz, D.P., Wein, A.M., Jones, J.L., and Hudnut, K.W., 2017, HayWired scenario mainshock coseismic and postseismic surface fault slip, chap. D *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.

Alameda County Flood Control and Water Conservation District, 2017, Cull Canyon and Don Castro reservoirs and dams: Alameda County Flood Control and Water Conservation District web page, accessed February 28, 2018, at https://www.acfloodcontrol.org/projects-and-programs/flood-control-projects/san-lorenzo-creek-watershed/cull-canyon-and-don-castro-reservoirs-and-dams/.

Applied Technology Council, 2016, Critical assessment of lifeline system performance—Understanding societal needs in disaster recovery: National Institute of Standards and Technology Report NIST CGR 16-917-39, 392 p., accessed October 20, 2017, at https://www.nist.gov/sites/default/files/documents/el/resilience/NIST-GCR-16-917-39-2.pdf.

Arellano, A.L.V., Cruz, A.M., Nordvik, J.-P., and Pisano, F., eds., 2003, Analysis of Natech (Natural Hazard Triggering Technological Disasters) disaster management—NEDIES workshop proceedings: European Commission Joint Research Centre, 198 p., accessed October 20, 2017, at http://www.preventionweb.net/files/1607_LBNA21054ENC002.pdf.

Association of Bay Area Governments, 2015, Loma Prieta 25 symposium policy agenda: Association of Bay Area Governments Resilience Program web site, accessed February 27, 2018, at http://resilience.abag.ca.gov/projects/loma-prieta-25-symposium/.

Bay Area Center for Regional Disaster Resiliency, [n.d.], RCISR InfoXchange: Bay Area Center for Regional Disaster Resilience web site, accessed December 15, 2017, at https://prod.i-info.com/dashboard/Layout/4380D6FBA4BA4861B42A9D14A4DCD1B0/about/aboutPublic/~rcisr_home.htm.

Bay Area Rapid Transit, 2017a, Ridership reports: San Francisco Bay Area Rapid Transit District web page, accessed October 23, 2017, at https://www.bart.gov/about/reports/ridership.

Bay Area Rapid Transit, 2017b, Earthquake safety program: San Francisco Bay Area Rapid Transit District web page, accessed October 23, 2017, at https://www.bart.gov/about/projects/eqs.

Bay Area Rapid Transit, 2017c, Projects: San Francisco Bay Area Rapid Transit District web page, accessed June 25, 2018, at https://www.bart.gov/better-bart/the-plan.

Bay Area Urban Areas Security Initiative, 2013, Regional catastrophic earthquake logistics response plan—Critical lifelines discussion workshops October 4, 7, and 11, 2013, summary report: California Governor's Office of Emergency Services, 30 p.

Bay Area Urban Areas Security Initiative, 2014, Regional catastrophic earthquake logistics response plan—Annex to the San Francisco Bay area regional emergency coordination plan: California Governor's Office of Emergency Services, 324 p., accessed October 18, 2018, at http://bayareauasi.org/sites/default/files/resources/Regional%20Logistics%20Response_February%202014.pdf.

Brocher, T.M., Gefeke, K., Boatwright, J., and Knudsen, K.L., 2018, Reported investments in earthquake mitigation top $73 to $80 billion in the San Francisco Bay Area, California, since the 1989 Loma Prieta earthquake: U.S. Geological Survey Open-File Report 2018–1168, 18 p., https://doi.org/10.3133/ofr20181168.

California Department of Conservation, 2017, Alquist-Priolo Earthquake Fault Zones: California Department of Conservation web page, accessed October 20, 2017, at http://www.conservation.ca.gov/cgs/rghm/ap.

California Department of Transportation, 1994, Bridge design details: Caltrans Division of Structures report, accessed December 6, 2017, at http://www.dot.ca.gov/des/techpubs/bdd.html.

California Department of Transportation, 2013, Caldecott Tunnel's new fourth bore set to open by Monday: California Department of Transportation press release, November 15, 2013, accessed April 11, 2019, at http://www.dot.ca.gov/hq/paffairs/news/pressrel/13pr103.htm.

California Department of Transportation, 2015, Bridges on the California state highway system: Caltrans Division of Maintenance web page, accessed October 27, 2017, at http://www.dot.ca.gov/hq/tsip/gis/datalibrary/Metadata/Bridges.html.

California Department of Water Resources, 2017, Dams within jurisdiction of the State of California: California Department of Water Resources Division of Safety of Dams report, 121 p., accessed August 24, 2018, at https://water.ca.gov/LegacyFiles/damsafety/docs/Dams%20by%20County_Sept%202017.pdf.

California Energy Commission, 2017, Total System Electric Generation: California Energy Commission web page, accessed October 20, 2017, at http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.

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.

Diablo Editors, 2013, Inside the fourth bore: Diablo Magazine, November 22, 2013, accessed April 11, 2019, at http://www.diablomag.com/December-2013/Inside-the-Fourth-Bore/.

Division of Research, Innovation, and System Information for the Division of Maintenance, California Governor's Office of Emergency Management, 2014, ShakeCast results for the "Haywired" earthquake scenario [unpublished report]: California Department of Transportation interim report, 18 p.

Eguchi, R.T., and Seligson, H.A., 1994, Lifeline perspective, chap. 5 *of* National Research Council, Practical lessons from the Loma Prieta earthquake: Washington, D.C., The National Academies Press, 288 p., https://doi.org/10.17226/2269.

Federal Emergency Management Agency, 1990, Earthquake resistant construction of electric transmission and telecommunication facilities serving the federal government report: Federal Emergency Management Agency Report 202, accessed June 20, 2018, at https://www.fema.gov/media-library-data/20130726-1505-20490-2834/fema-202.pdf.

Federal Emergency Management Agency, 2003, NEHRP recommended provisions for seismic regulations for new buildings and other structures–Part 2, Commentary: Federal Emergency Management Agency Report 450–2, accessed March 17, 2017, at https://www.fema.gov/media-library-data/20130726-1532-20490-7602/fema_450_2_commentary.pdf.

Federal Emergency Management Agency, 2006, Designing for earthquakes—A manual for architects: Federal Emergency Management Agency Report 454, accessed July 26, 2018, at https://www.fema.gov/media-library-data/20130726-1556-20490-5679/fema454_complete.pdf.

Federal Emergency Management Agency, 2009, NEHRP recommended seismic provisions for new buildings and other structures: Federal Emergency Management Agency Report P–750, accessed November 16, 2017, at https://www.fema.gov/media-library-data/20130726-1730-25045-1580/femap_750.pdf.

Federal Emergency Management Agency, 2012, Hazus multi-hazard loss estimation methodology, earthquake model, Hazus®-MH 2.1 technical manual: Federal Emergency Management Agency, Mitigation Division, 718 p., accessed July 18, 2017, at http://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf.

Germeraad, M., Mieler, D., and Brechwald, D., 2014, Cascading failures—Earthquake threats to transportation and utilities: Association of Bay Area Governments Publication P14001EQK, 52 p., accessed October 20, 2017, at http://resilience.abag.ca.gov/wp-content/documents/Cascading_Failures/InfrastructureReport_2014.pdf.

Grain, D., 2014, Critical infrastructure security and resilience national research and development plan—Final report and recommendations: National Infrastructure Advisory Council, 69 p., accessed October 20, 2017, at https://www.dhs.gov/sites/default/files/publications/NIAC-CISR-RD-Plan-Report-508.pdf.

Holzer, T.L., Noce, T.E., and Bennett, M.J., 2008, Liquefaction hazard maps for three earthquake scenarios for the communities of San Jose, Campbell, Cupertino, Los Altos, Los Gatos, Milpitas, Mountain View, Palo Alto, Santa Clara, Saratoga, and Sunnyvale, northern Santa Clara County, California: U.S. Geological Survey Open-File Report 2008–1270, 29 p., 3 plates, and database, https://pubs.usgs.gov/of/2008/1270/.

Holzer, T.L., Noce, T.E., and Bennett, M.J., 2010, Predicted liquefaction in the greater Oakland area and northern Santa Clara Valley during a repeat of the 1868 Hayward Fault (M6.7–7.0) earthquake: Proceedings of the Third Conference on Earthquake Hazards in the Eastern San Francisco Bay Area October 22–24, 2008.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information: Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345–354, accessed December 15, 2016, at http://www.asprs.org/a/publications/pers/2015journals/PERS_May_2015/HTML/files/assets/basic-html/index.html#345/z#noFlash.

Hudnut, K.W., Brocher, T.M., Prentice, C.S., Boatwright, J., Brooks, B.A., Aagaard, B.T., Blair, J.L., Fletcher, J.B., Erdem, J.E., Wicks, C.W., Murray, J.R., Pollitz, F.F., Langbein, J., Svarc, J., Schwartz, D.P., Ponti, D.J., Hecker, S., DeLong, S., Rosa, C., Jones, B., Lamb, R., Rosinski, A.M., McCrink, T.P., Dawson, T.E., Seitz, G., Rubin, R.S., Glennie, C., Hauser, D., Ericksen, T., Mardock, D., Hoirup, D.F., and Bray, J.D., 2014, Key recovery factors for the August 24, 2014, South Napa earthquake: U.S. Geological Survey Open-File Report 2014–1249, 51 p., https://doi.org/10.3133/ofr20141249.

Jacobs Associates and G&E Engineering Systems, 2014, BART Berkeley Hills tunnels—Seismic retrofit feasibility study: Bay Area Rapid Transit Earthquake Safety Program report, 122 p.

Jones, J.L., 2019, Results of individual and collocated lifeline exposure to hazards (and associated hazard and multi-hazard exposure surface data) resulting from the HayWired scenario earthquake sequence for counties and cities in the San Francisco Bay area, California: U.S. Geological Survey data release, https://doi.org/10.5066/P94HDTD8.

Jones, J.L., Knudsen, K.L., and Wein, A.M., 2017, HayWired scenario mainshock—Liquefaction probability mapping, chap. E *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., 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 2001–1150, 308 p., https://doi.org/10.3133/ofr20081150/.

Karagiannis, G.M., Chondrogiannis, S., Krausmann, E., and Turksezer, Z.I., 2017, Power grid recovery after natural hazard impact: Joint Research Centre publication JRC108842, 58 p., accessed March 1, 2018, at http://publications.jrc.ec.europa.eu/repository/bitstream/JRC108842/jrc108842kjna28844enn.pdf.

Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000, Preliminary maps of Quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California—A digital database: U.S. Geological Survey Open-File Report 00–444, 21 p., https://doi.org/10.3133/ofr00444.

Lienkaemper, J.J., 2007, Digital database of recently active traces of the Hayward Fault, California: U.S. Geological Survey Data Series 2006–177, https://pubs.usgs.gov/ds/2006/177/.

Lienkaemper, J.J., DeLong, S.B., Domrose, C.J., and Rosa, C.M., 2016, Afterslip behavior following the 2014 M6.0 South Napa earthquake with implications for afterslip forecasting on other seismogenic faults: Seismological Research Letters, v. 87, no. 3, https://doi.org/10.1785/0220150262.

McCrink, T.P., and G. Perez, F.G., 2017, HayWired scenario mainshock—Earthquake-induced landslide hazards, chap. F *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.

National Protection and Programs Directorate, 2017, Dams—Functionality, interdependencies, and project demands: Department of Homeland Security Office of Cyber and Infrastructure Analysis, 46 p.

Newman, M.E.J., 2005, Power laws, Pareto distributions, and Zipf's law: Contemporary Physics, v. 46, no. 5, p. 323–351, https://doi.org/10.1080/00107510500052444.

Noyes, D., 2014, I-Team investigates AT&T center after Napa quake: ABC7 News, August 27, 2014, accessed October 20, 2017, at http://abc7news.com/news/i-team-investigates-at-t-center-after-napa-quake/284302/.

Perkins, J.B., and Hutchings, D., 2010, Taming natural disasters—Multi-jurisdictional local hazard mitigation plan for the San Francisco Bay area: Association of Bay Area Governments Publication P09001EQK, 104 p., accessed October 20, 2017, at http://resilience.abag.ca.gov/wp-content/documents/ThePlan-Chapters-Intro.pdf.

Porter, K.A., 2017, HayWired scenario three-dimensional numerical ground-motion simulation maps, chap. H *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.

Porter, K.A., 2018, A new model of water-network resilience, with application to the HayWired scenario, chap. N *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.

Radke, J.D., Biging, G.S., Roberts, K., Schmidt-Poolman, M., Foster, H., Roe, E., Ju, Y., Lindbergh, S., Beach, R., Maier, L., He, Y., Ashenfarb, M., Norton, P., Wray, M., Alruheili, A., Yi, S., Rau, R., Collins, J., Radke, M., Coufal, M., Marx, S., Gohar, A., Moanga, D., Ulyashin, V., and Dalal, A., 2018, Assessing extreme weather-related vulnerability and identifying resilience options for California's interdependent transportation fuel sector: California's Fourth Climate Change Assessment, California Energy Commission Publication CCCA4–CEC–2018–012, 353 p., accessed February 22, 2019, at http://www.climateassessment.ca.gov/techreports/docs/20180827-Energy_CCCA4-CEC-2018-012.pdf.

Scalingi, P., ed., 2015, Workshop on interdependent lifelines, risk and regional resilience—The South Napa earthquake lessons learned and priority actions for the "Big One": Bay Area Center for Regional Disaster Resilience workshop proceedings, 16 p., accessed October 20, 2017, at http://www.bayareacrdr.org/BACRDR-images/Resources/Event-Summaries-and-Other-Reports/Summary-of-Workshop-on-Interdependent-Lifelines-Risk-and-Regional-Resilience-South-Napa-Earthquake-Lessons-Learned.pdf.

Scawthorn, C., 2018, Fire following the HayWired scenario mainshock, 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.

Scawthorn, C., 2019, Fire following the M_w 7.0 HayWired earthquake scenario: U.S. Geological Survey data release, https://doi.org/10.5066/P9LMGHRV.

Schiff, A.J., Lund, L., Markowitz, J., O'Rourke, T.D., Strand, C., Bettinger, R., Laverty, G., Cornell, H., Guerrero, A.R., Ballantyne, D., Pickett, M., Cassaro, M., and Godschak, A., 1990, Lifelines: Earthquake Spectra, v. 6, no. S1, p. 239–338, https://doi.org/10.1193/1.1585606.

Schremp, G., 2015, California fuel overview and emergency fuels set-aside program: Presentation to the 2015 California Utilities Emergency Association Annual Conference, Mather, C.A., June 18, 2015, 39 slides, accessed February 22, 2019, at https://www.cueainc.com/documents/CaliforniaFuelSetAsideProgramGordonSchremp-Final20150618.pdf.

Stronger Christchurch Infrastructure Rebuild Team, 2017, Forward Works Viewer: Stronger Christchurch Infrastructure Rebuild Team web site, accessed January 9, 2018, at https://scirtlearninglegacy.org.nz/story/forward-works-viewer.

The Lifelines Council, 2014, Lifelines interdependency study report: The City and County of San Francisco, 56 p., accessed October 20, 2017, at http://sfgov.org/esip/sites/default/files/Documents/homepage/LifelineCouncil%20Interdependency%20Study_FINAL.pdf.

Theoharidou, M., Kotzanikolaou, P., and Gritzalis, D., 2009, Risk-based criticality analysis, chap. 3 *of* Palmer, C., and Shenoi, S., eds., Critical infrastructure protection III—IFIP Advances in Information and Communication Technology: Springer, Berlin, Heidelberg, v. 311, 257 p., https://doi.org/10.1007/978-3-642-04798-5_3.

U.S. Department of Homeland Security, 2018, Infrastructure interdependency assessment—Puerto Rico: U.S. Department of Homeland Security report, 214 p., accessed February 22, 2019, at http://www.camarapr.org/Camara-en-Accion-18-19/17-nov-8/gob/PR-Infrastructure-Interdependency-Assessment-Report-Sept-2018.pdf.

Wein, A.M., Felzer, K.R., Jones, J.L., and Porter, K.A., 2017, HayWired scenario aftershock sequence, chap. G *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.

Werner, S.D., Taylor, C.E., Moore III, J.E., Walton, J.S., and Cho, S., 2000, A risk-based methodology for assessing the seismic performance of highway systems: Multidisciplinary Center for Earthquake Engineering Research Technical Report MCEER-00-0014, 269 p., accessed October 27, 2017, at http://mceer.buffalo.edu/pdf/report/00-0014.pdf.

Wilson, M.L., Corbet, T.F., Baker, A.B., and O'Rourke, J.M., 2015, Simulating impacts of disruptions to liquid fuels infrastructure: Sandia National Laboratories report SAND2015–2696, 58 p., accessed February 21, 2019, at https://www.energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20Simulating%20Impacts%20of%20Disruptions%20to%20Liquid%20Fuels%20Infrastructure.pdf.

Yao, B., Xie, L., and Huo, E., 2004, Study effect of lifeline interaction under seismic conditions: 13th World Conference on Earthquake Engineering Proceedings, Vancouver, B.C., Canada, August 1–6, 2004, 12 p., accessed March 1, 2018, at http://www.iitk.ac.in/nicee/wcee/article/13_3152.pdf.

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.

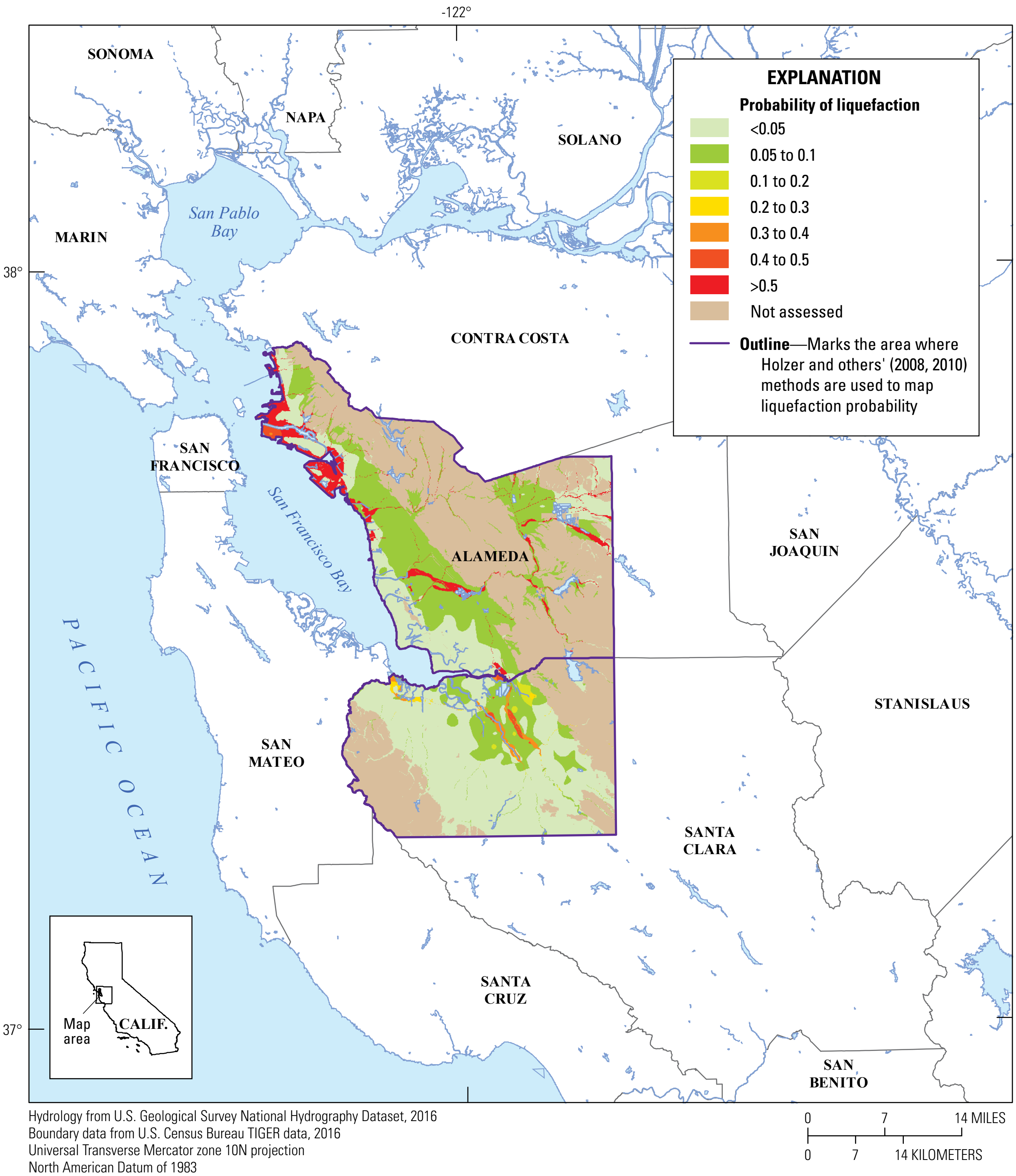


Figure 1.1. Map of the San Francisco Bay region, California, showing liquefaction probability results modeled by Jones and others (2017).

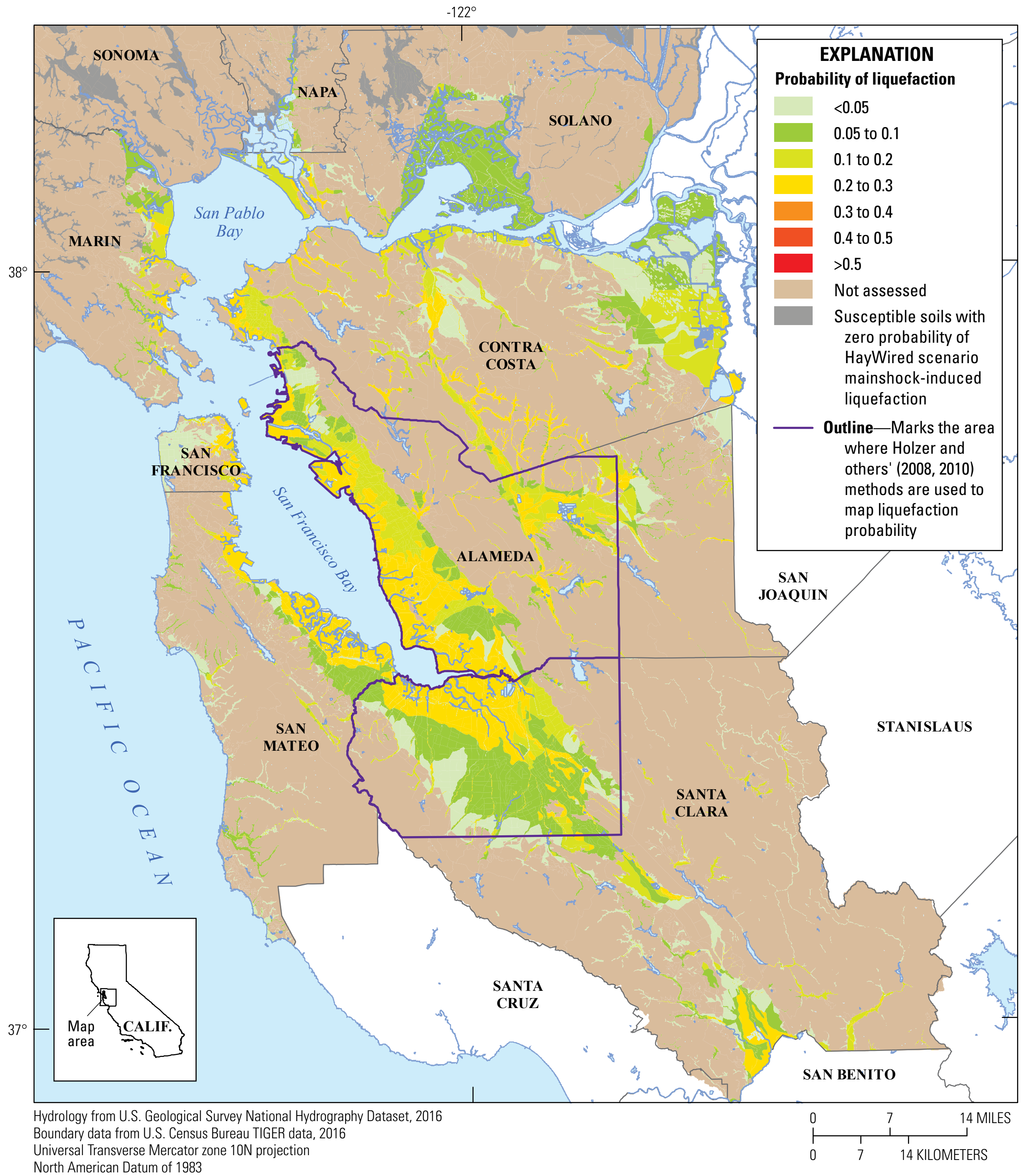


Figure 1.2. Map of the San Francisco Bay region, California, showing liquefaction probability results modeled using Hazus-MH 2.1 (Federal Emergency Management Agency, 2012); modified using methods described in this appendix.

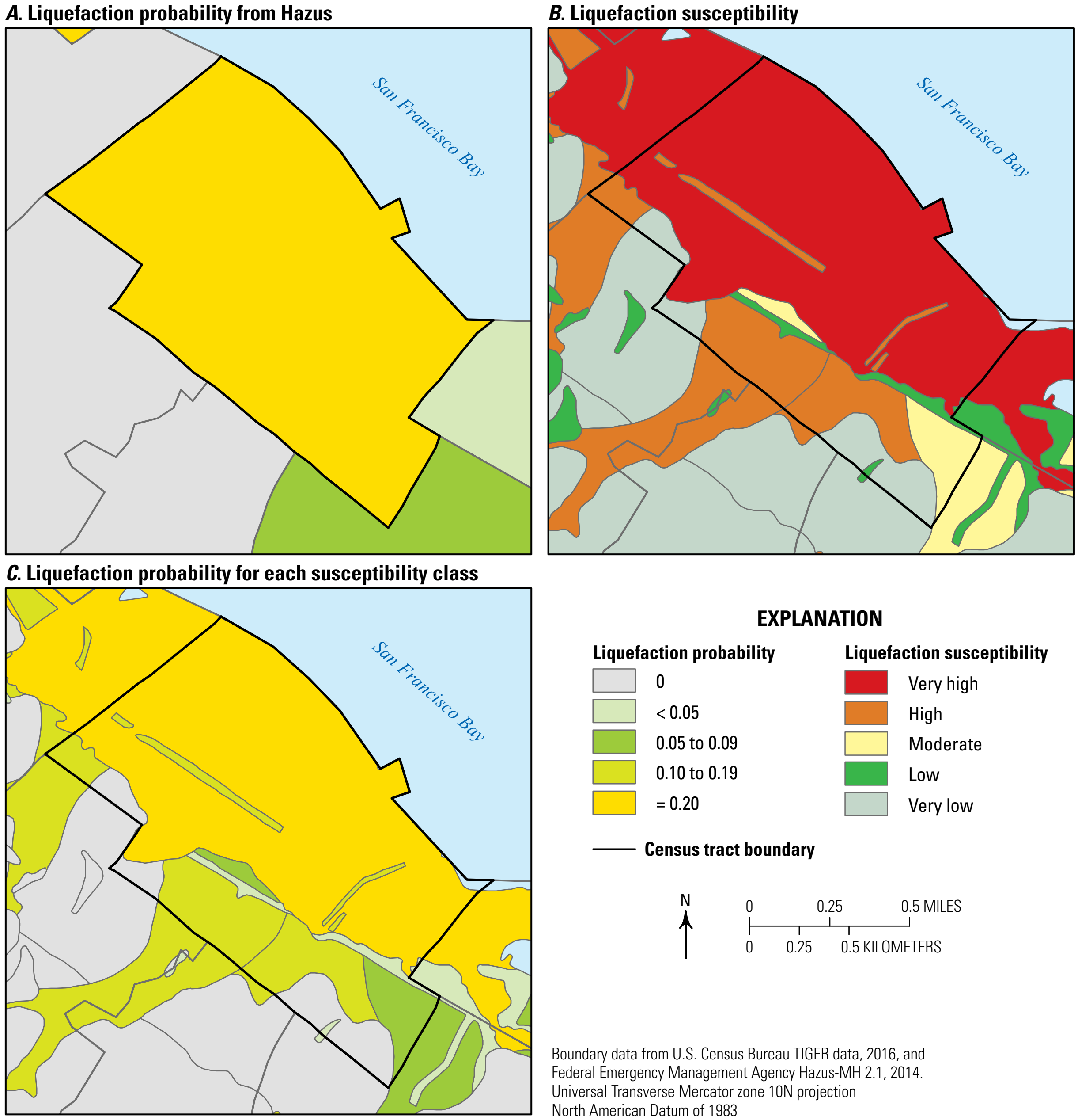
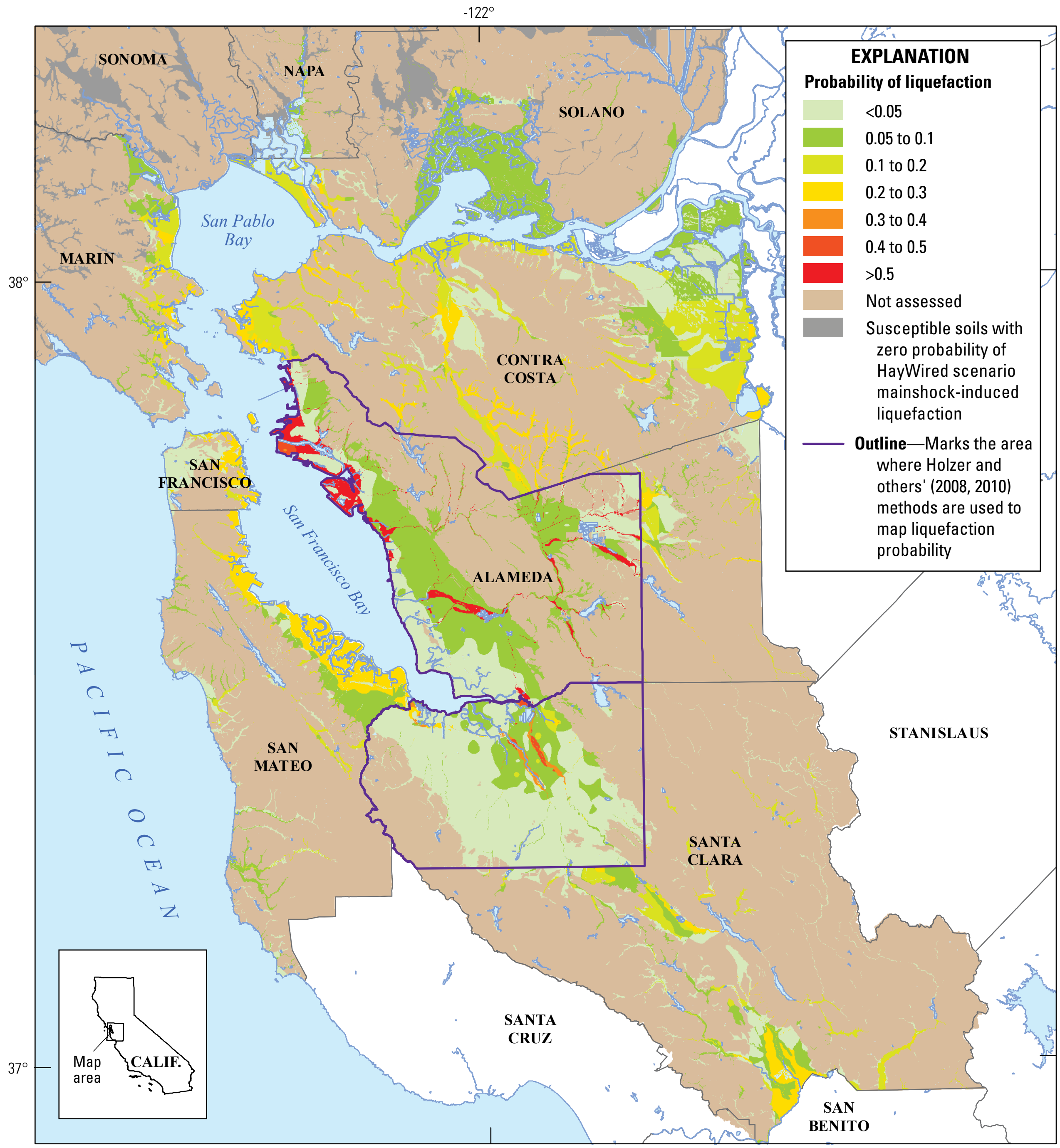


Figure 1.3. Series of simplified maps showing how census tract-level liquefaction probability data (from Hazus-MH 2.1 [Federal Emergency Management Agency, 2012]) were downscaled to sub-census-tract level susceptibility class areas within a single census tract. *A*, Original census-tract liquefaction 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.



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 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

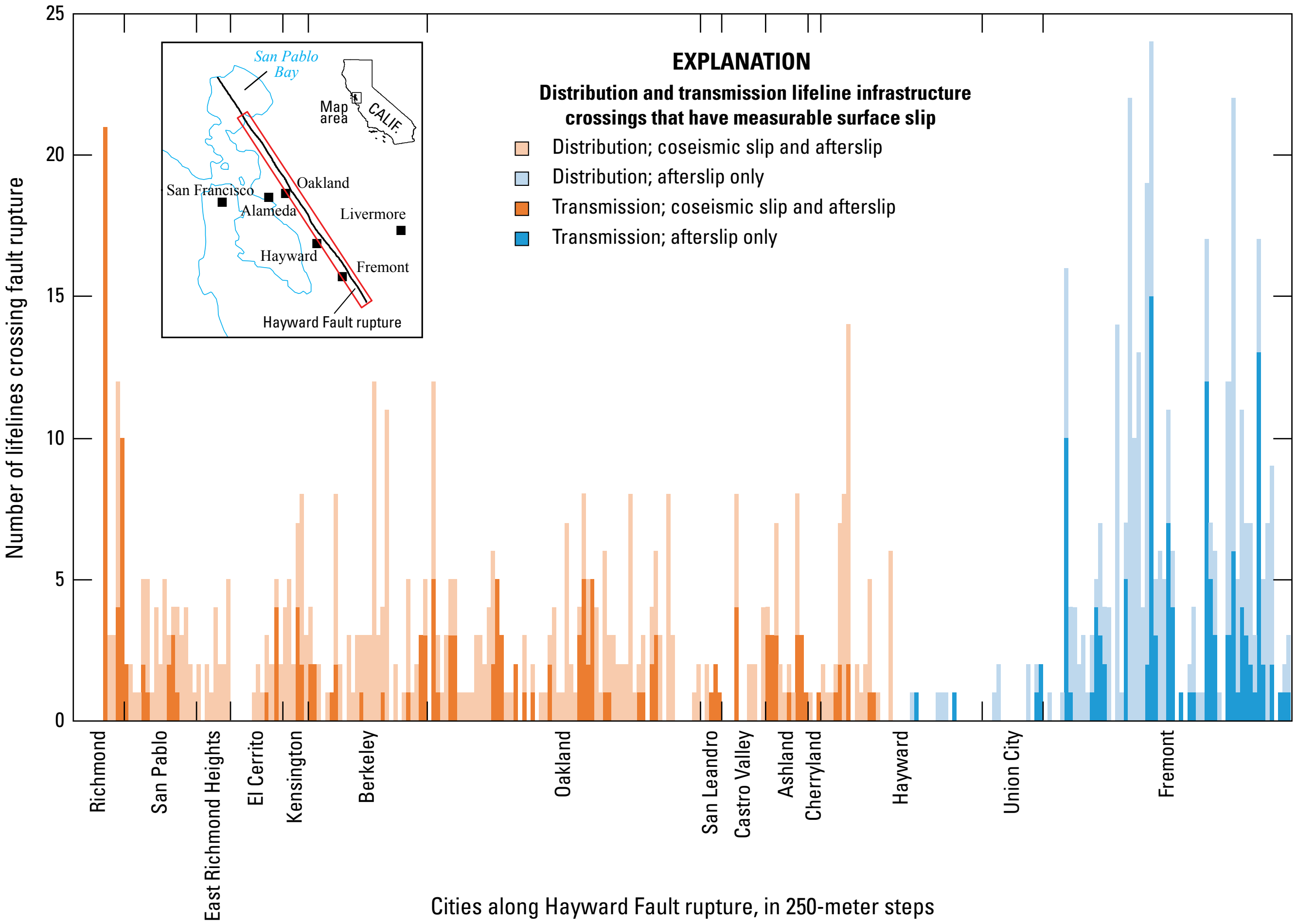


Figure 2.1. Schematic illustration showing the number of lifelines that cross the ruptured length of the Hayward Fault within the HayWired scenario in the San Francisco Bay region, California. Lifelines are shown in 250-meter segments. The chart reads from San Pablo Bay at the northwestern edge of the 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 M6.2 event with a hypocenter in Palo Alto on May 28, 2018, at 4:47 a.m., a M5.7 event with a hypocenter in Palo Alto on May 28, 2018, at 11:53 p.m., a M5.2 event with a hypocenter in Palo Alto on June 23, 2018, at 8:27 p.m., and a M5.3 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 M5 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 M6.0 event with a hypocenter in Mountain View on September 30, 2018, at 8:16 p.m., a M6.4 event with a hypocenter in Cupertino on October 1, 2018, at 12:33 a.m., and a M5.4 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
Region total	3,393,325	60	82	94	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

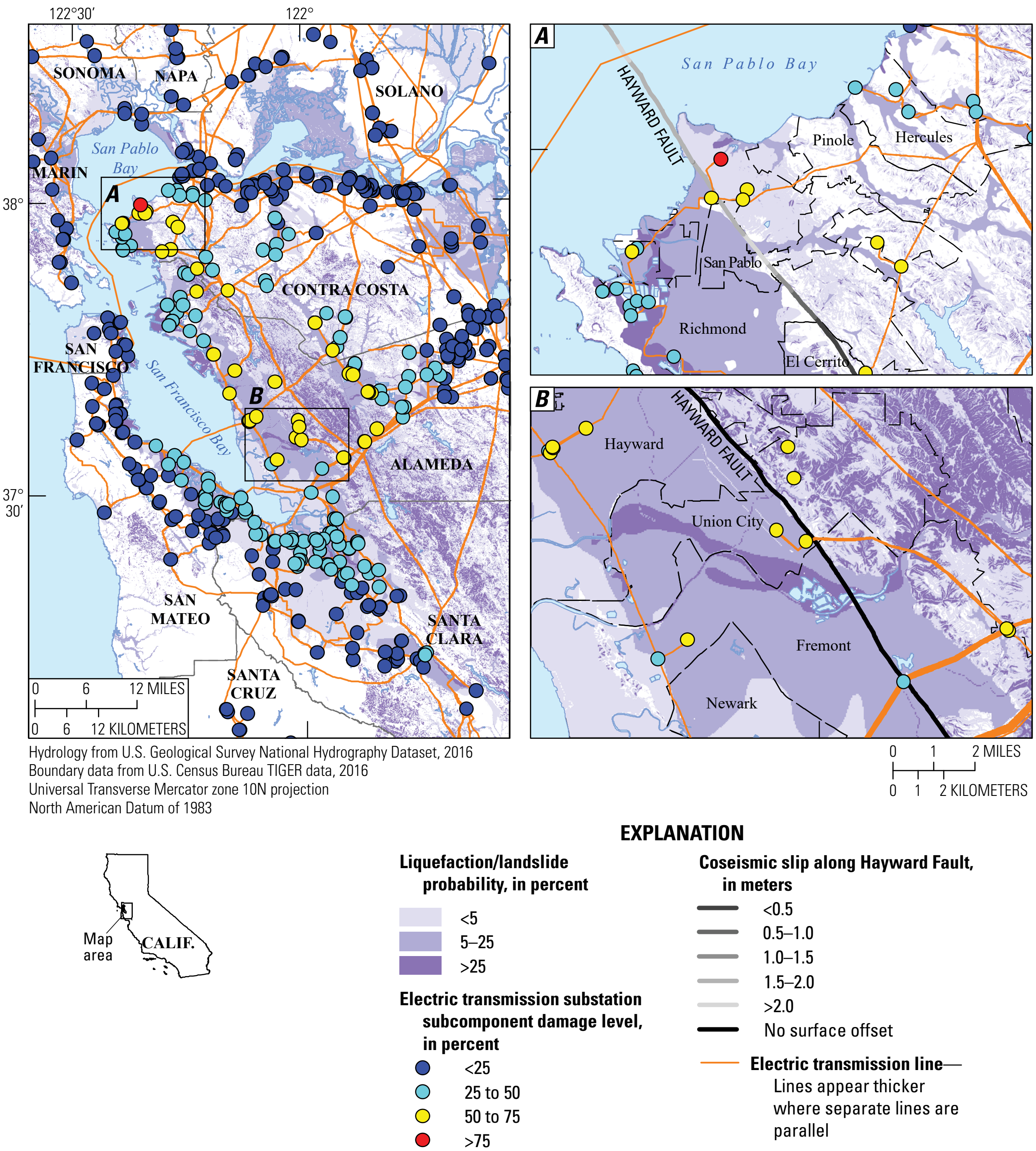


Figure 3.1. Map of the San Francisco Bay region, California, showing the ground failure (coseismic slip, landslide, and liquefaction) exposure of the electric transmission system (electric transmission lines and substations) relative to the electric transmission substation subcomponent damage level estimated by Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) for the HayWired earthquake scenario.

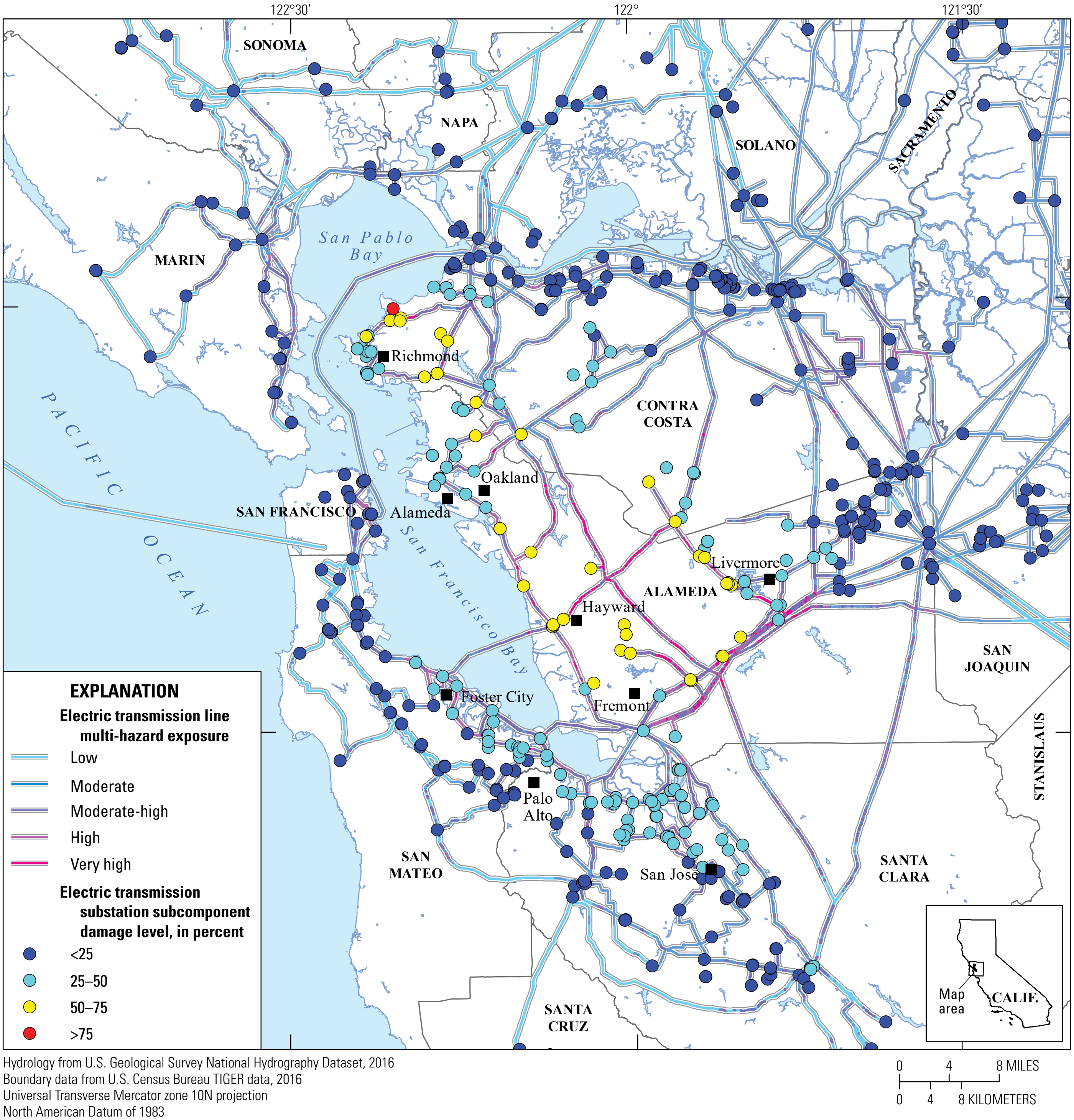


Figure 3.2. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the electric transmission system (electric transmission lines and substations) relative to the electric transmission substation subcomponent damage level estimated by Hazus-MH 2.1 (Federal Emergency Management 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

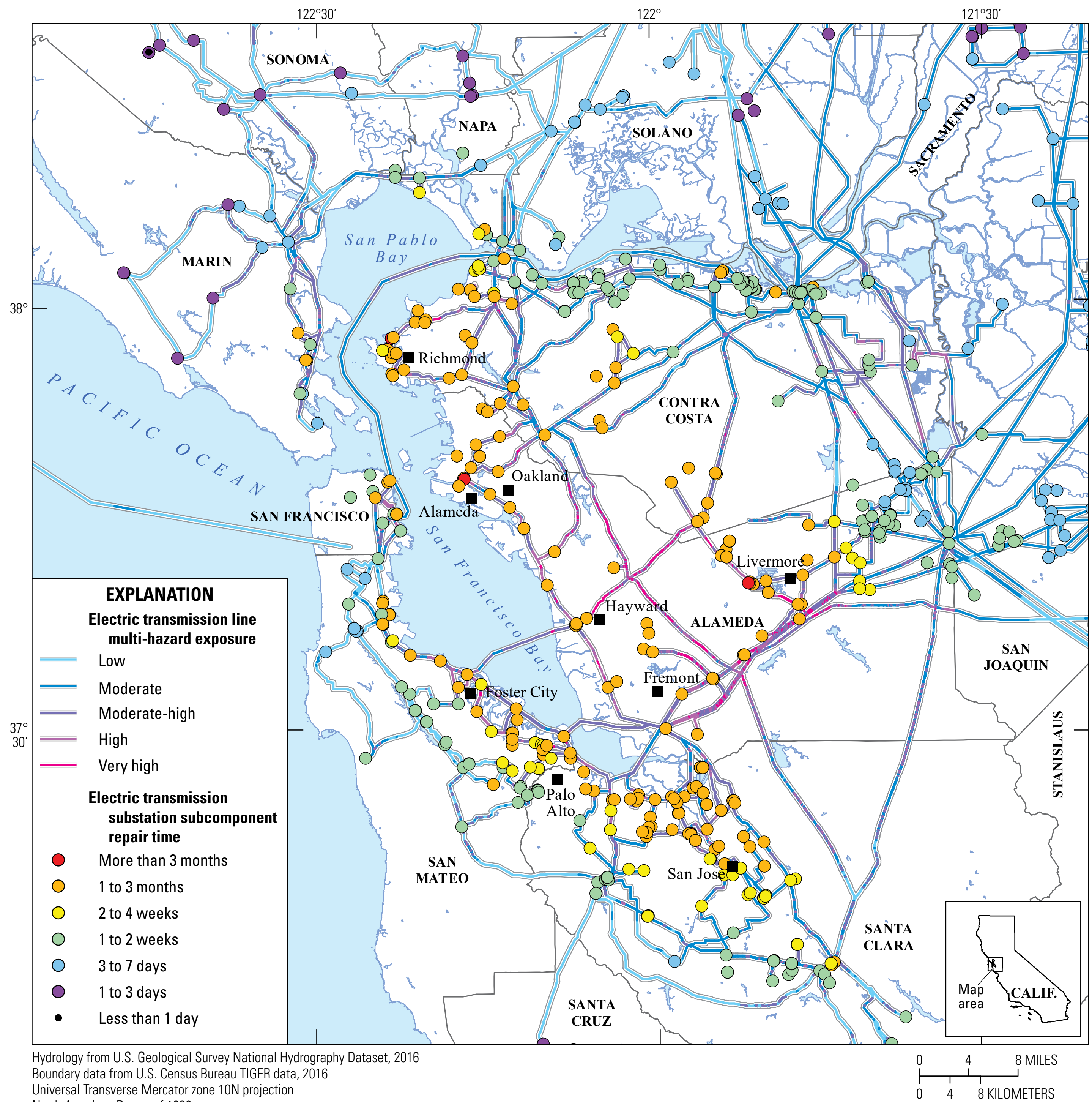


Figure 3.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the electric transmission system (electric transmission lines and substations) relative to the transmission substation repair time estimated by Hazus-MH 2.1 (Federal Emergency Management Agency, 2012) for 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).

[1] Bay Area Rapid Transit.

[2] U.S. Geological Survey.

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.

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

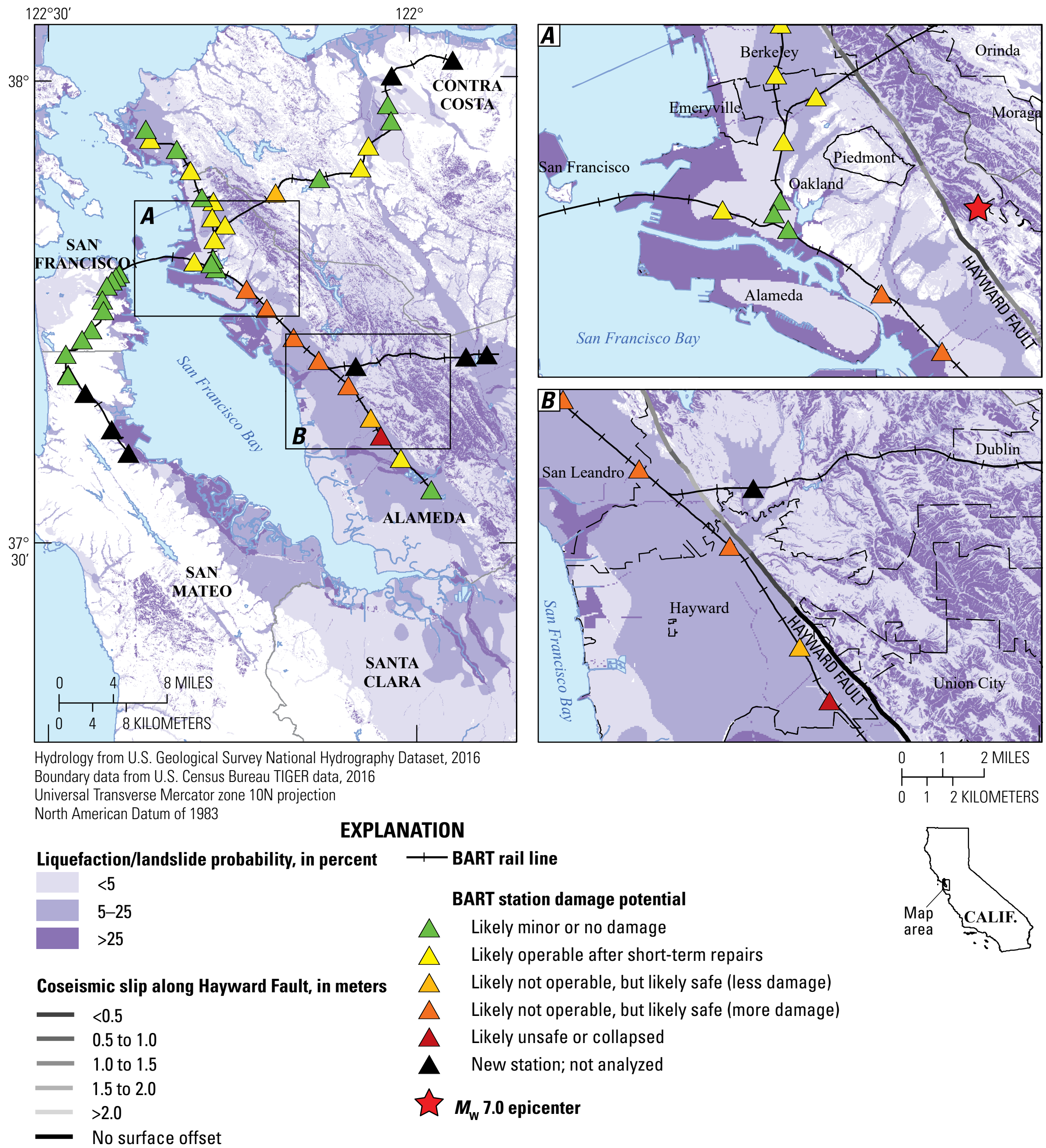


Figure 4.1. Map of the San Francisco Bay region, California, showing the ground failure (coseismic slip, landslide, and liquefaction) exposure of the Bay Area Rapid Transit (BART) system relative to the BART estimated shaking damage potential for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 extensions to Milpitas and Berryessa.

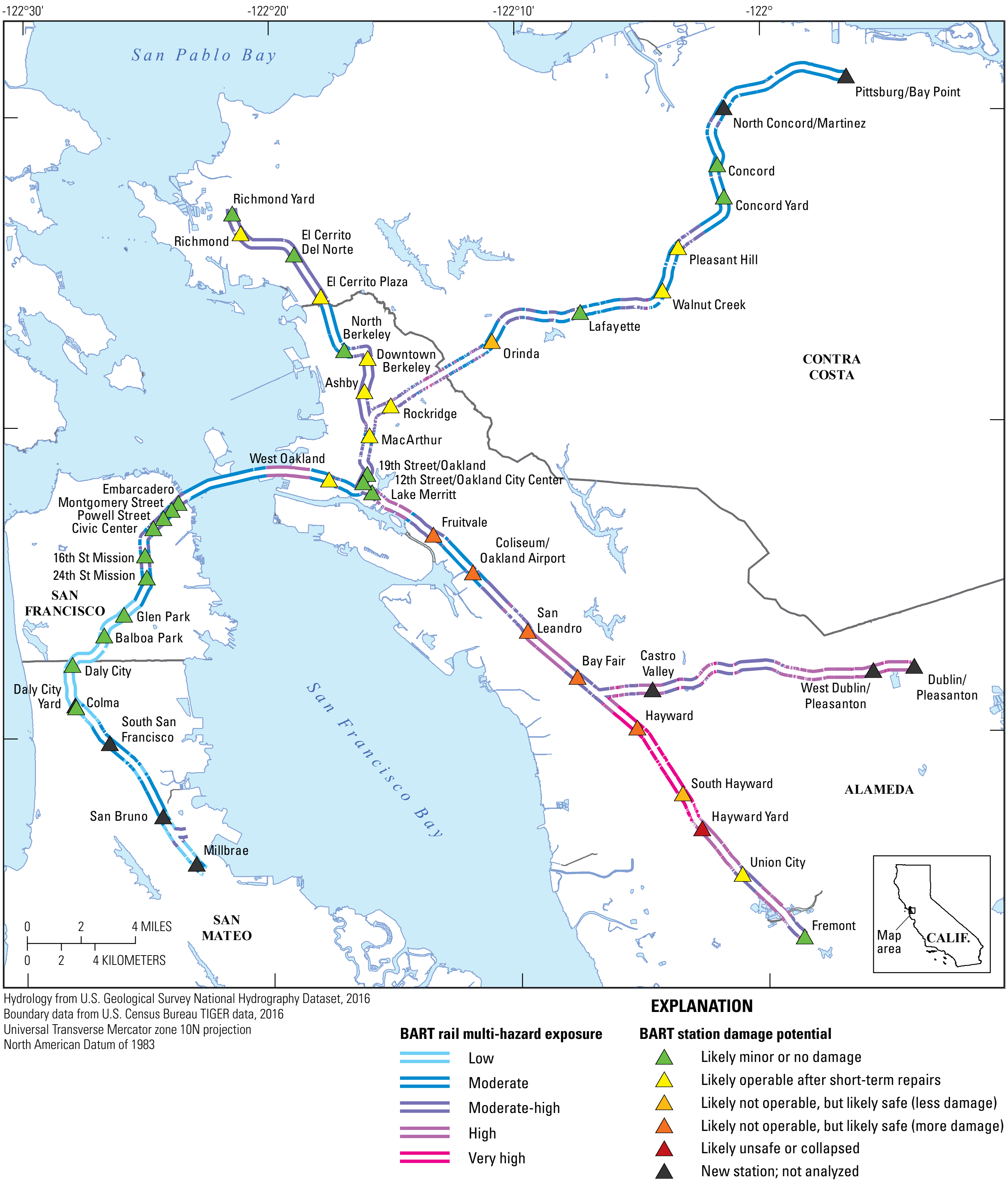


Figure 4.2. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the Bay Area Rapid Transit (BART) system relative to the BART-estimated shaking damage potential for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 extensions to Milpitas and Berryessa.

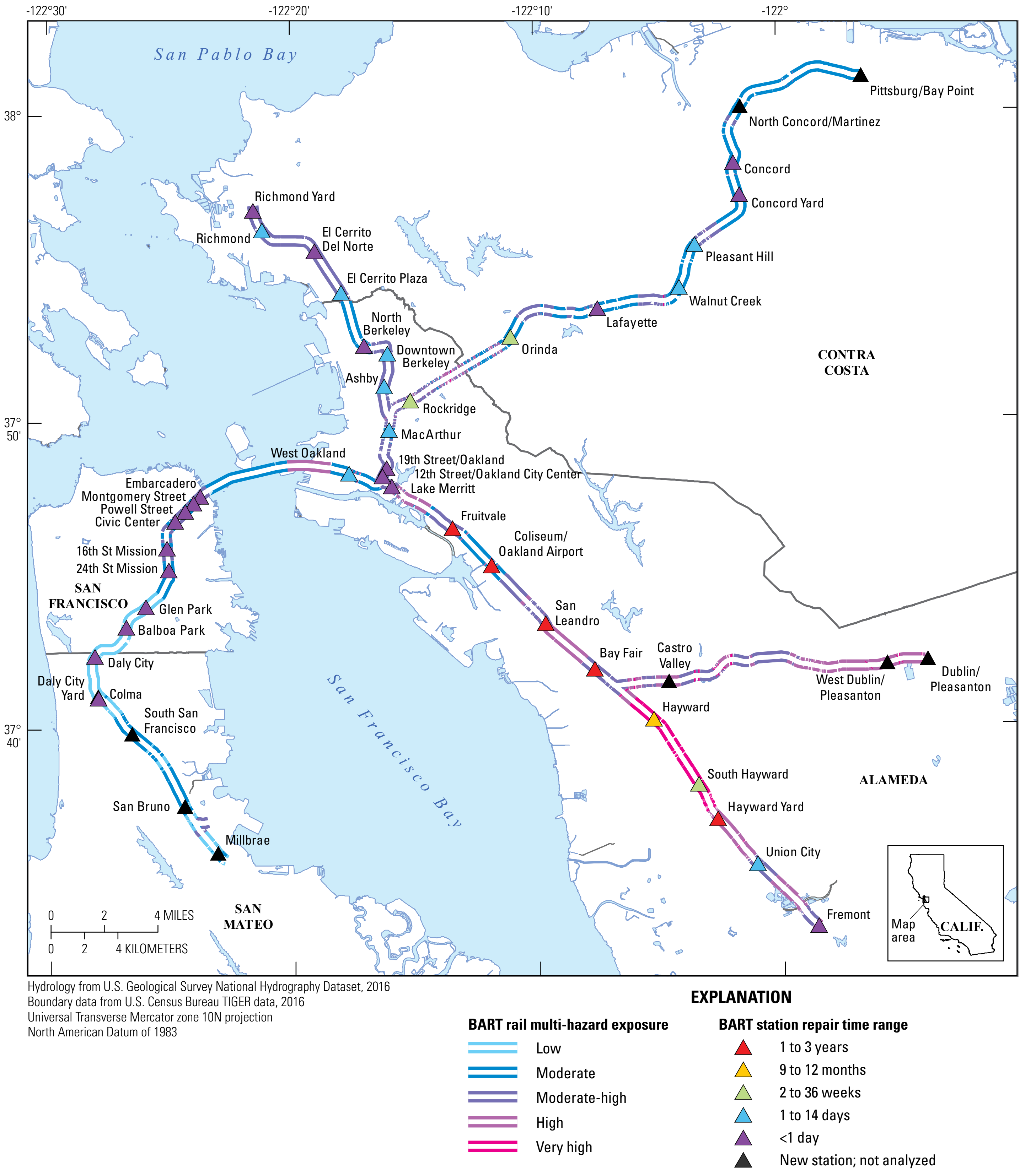


Figure 4.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of the Bay Area Rapid Transit (BART) system relative to BART-estimated facility repair duration for the HayWired earthquake scenario. Map does not include the 2017 extension to Warm Springs or the planned 2019 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.

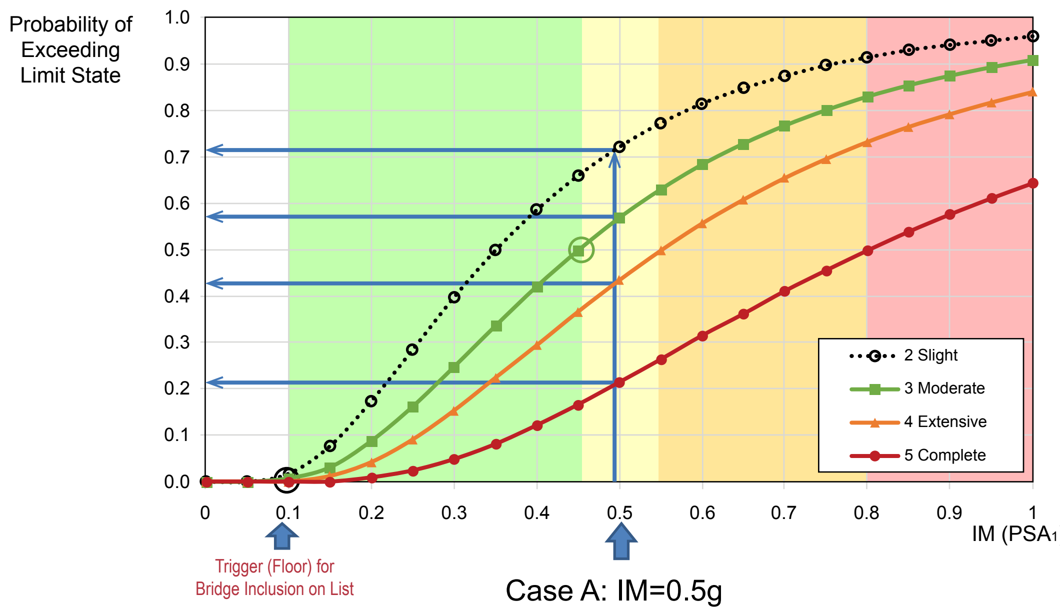


Figure 5.1. Chart showing an example of one set of potential impact curves for a highway bridge in the San Francisco Bay region, California (reproduced here with slight modification from Division of Research, Innovation, and System Information for the Division of Maintenance, California Governor's Office 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. Replace fallen deck span, replace bearings, and repair or replace damaged substructure.	3-span bridge: 3–6 months 4-span bridge: 4–8 months 5-span bridge: 5–10 months 3–6 months	Closed during bridge reconstruction Closed during bridge repair and replacement.	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)

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.

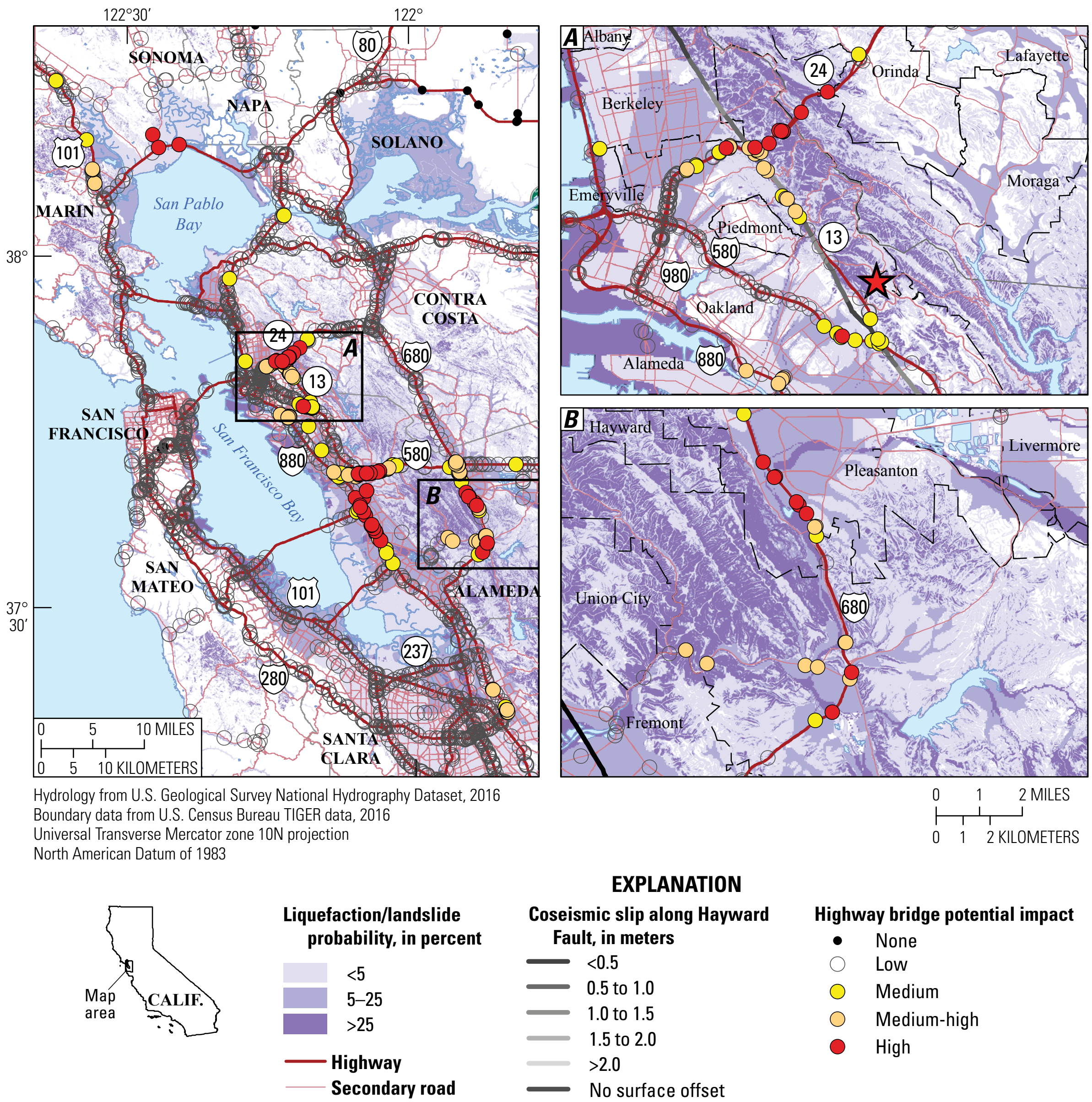


Figure 5.2. Map of the San Francisco Bay region, California, showing highway bridge potential impacts generated by California Department of Transportation's ShakeCast assessment relative to the HayWired scenario mainshock ground-failure hazards (coseismic slip, landslides, and liquefaction). Most bridges 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.

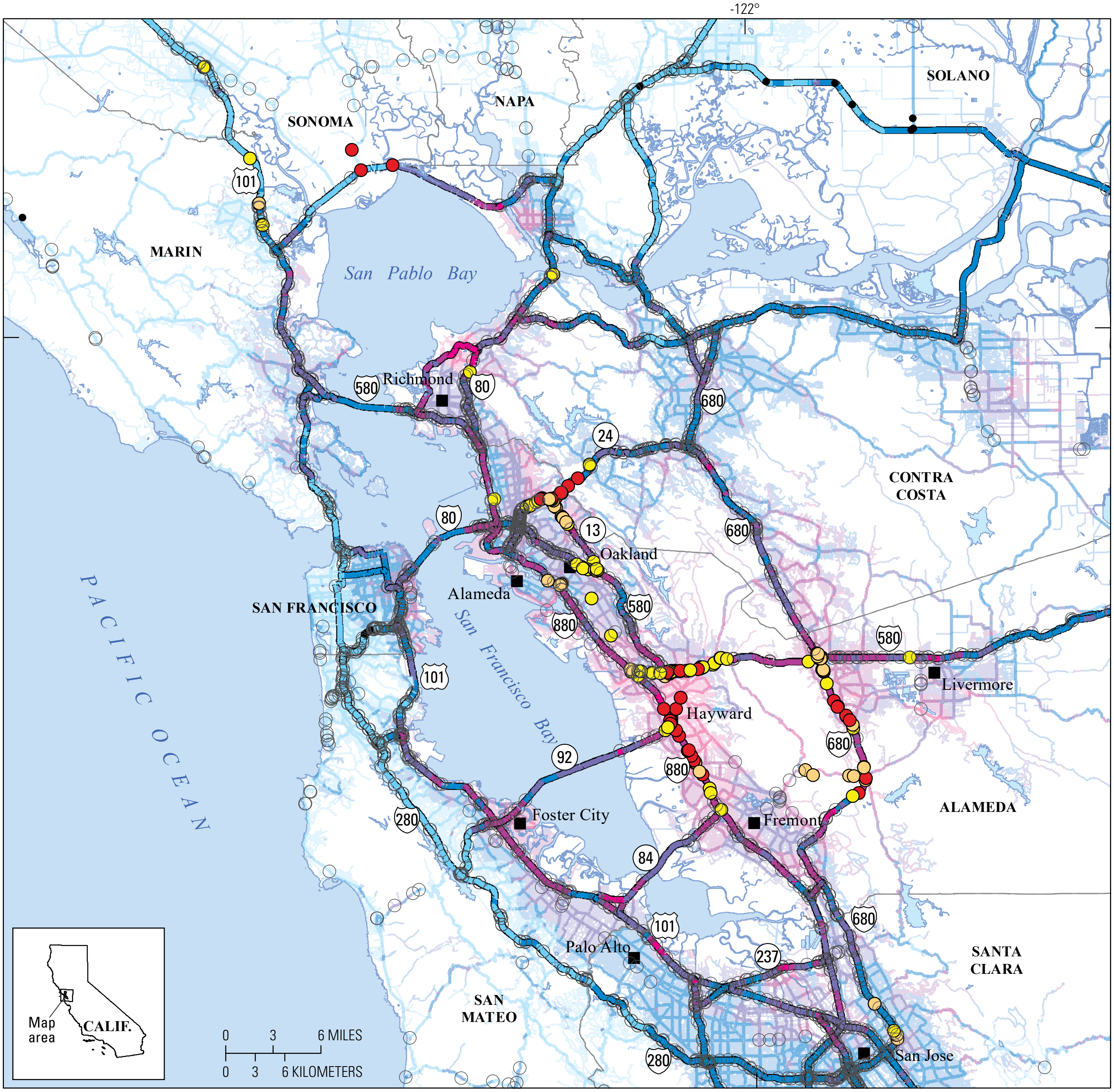
[Values are number of bridges]

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



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

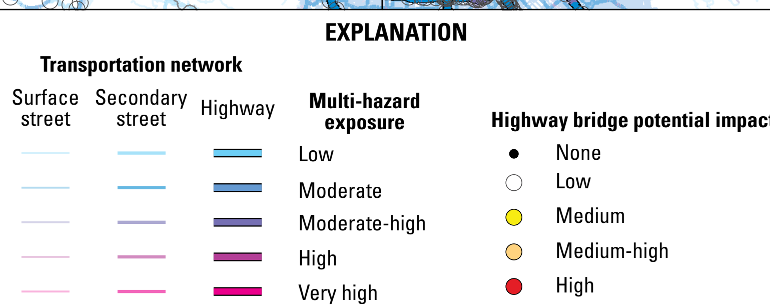


Figure 5.3. Map of the San Francisco Bay region, California, showing the multi-hazard exposure of roadways and potential impacts to California Department of Transportation highway bridges in the HayWired earthquake scenario.

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.

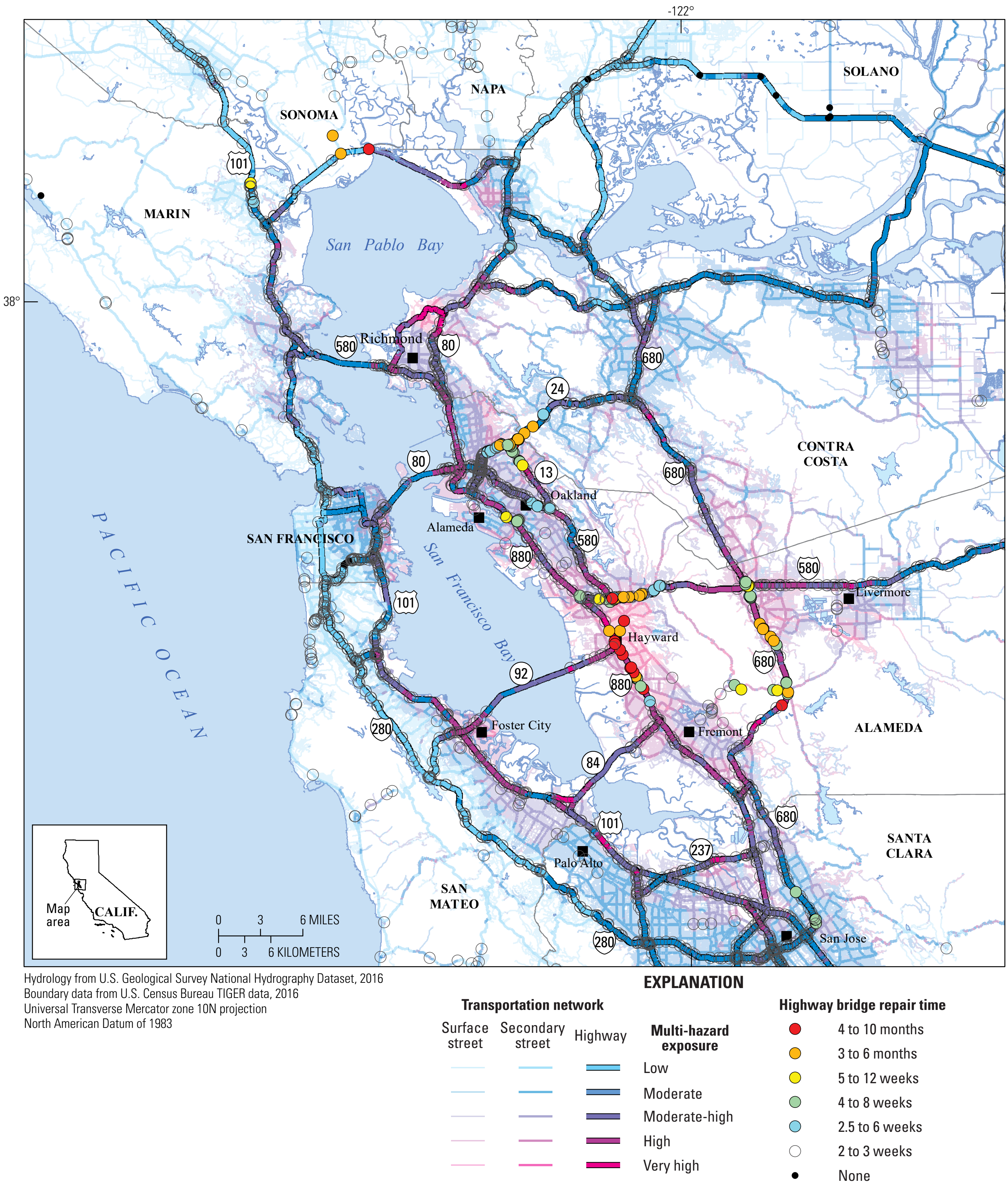


Figure 5.4. Map of the San Francisco Bay region, California, showing repair times for highway bridges as determined by the California Department of Transportation relative to multi-hazard exposure in the HayWired earthquake scenario.