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Economic Consequences of the HayWired Scenario—Digital and Utility Network Linkages and Resilience

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Chapter V2 of

The HayWired Earthquake Scenario—Societal Consequences

Edited by Shane T. Detweiler and Anne M. Wein

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Chapter V2

Economic Consequences of the HayWired Scenario—Digital and Utility Network Linkages and Resilience

By Ian Sue Wing,[1] Dan Wei,[2] Adam Z. Rose,[2] and Anne M. Wein[3]

Abstract

The HayWired scenario examines a hypothetical earthquake (mainshock) with a moment magnitude (M_w) of 7.0 occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region. This study evaluates the economic impacts of the HayWired earthquake scenario on the greater San Francisco Bay region's economy using a detailed multiregional static computable general equilibrium model for 6 months following the event and a simpler, multiregional intertemporal partial equilibrium simulation model for the dynamic recovery in the 17 years thereafter. Economic impacts are measured by the estimated reduction in the bay region's gross regional product (GRP), the standard economic measure of the total value of final goods and services produced. The major hazards that cause property (buildings and contents) damages (or capital stock losses) are ground shaking, liquefaction, landslides, and fire following earthquake. Economic impacts in terms of GRP (or business interruption losses) caused by both capital stock losses and water and electricity utility and telecommunications-service disruptions from the HayWired earthquake sequence are estimated and are primarily caused by capital stock damages. The most vulnerable industry sectors are heavy manufacturing and service industries, such as education and healthcare. The hardest hit county (in absolute and relative terms) is Alameda County, followed by Santa Clara County. In the 6 months following the earthquake, total GRP losses are estimated to be $44.2 billion (4.2 percent of California's projected baseline gross state product [GSP] over the period), but this result could be reduced by about 43 percent to $25.3 billion after factoring in microeconomic resilience tactics, which promote the efficient use of remaining resources.

The most effective resilience tactic for businesses that experience property damages and power-service disruptions is production recapture (using overtime or extra shifts to catch up on lost production after necessary facilities and equipment have been repaired or replaced and power services have been restored). The most effective resilience tactic for water-service or data- and voice-service outages is production isolation (making greater use of processes that do not need these services). Production isolation combined with the use of portable equipment by telecommunication carriers to fast track data- and voice-service restoration can effectively reduce GRP losses below those imposed by power outages that are the greatest cause of data- and voice-service disruptions.

Information and communications technology (ICT) sectors, which are the core of the digital economy, include internet publishing and broadcasting; telecommunications; data- processing, hosting, and related services; and other information services. GRP losses (in percent) in the ICT sectors show a strong correspondence with property damages, although internet publishing and broadcasting show a consistent pattern of GRP losses exceeding capital losses in counties less directly affected by the earthquake (San Mateo and San Francisco Counties) and counties that export 80 percent of these services (Marin, Solano, and Santa Cruz Counties). Internet publishing not only suffers direct economic damage but also suffers from smaller supplies of data-processing and telecommunications inputs, whose prices increase significantly.

A simple, dynamic recovery model illustrates that initially, relative to "business as usual," capital stocks in the largely unaffected remainder of the bay region and the rest of California decrease owing to reallocation of investment toward the most severely damaged counties. Eventually, counties with less damage gain from picking up the slack of lost capacity in the core of the damaged region and also provide valuable inputs to all affected counties by producing their goods and services during the recovery process.

Introduction

Earthquakes and other natural disasters affect regional and national economies by disrupting inputs to the production of goods and services. These inputs include primary factors of production, such as land that provides natural resources,

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capital that provides productive capacity, and labor that provides human resources, as well as intermediate inputs such as processed goods and utility services.

The HayWired scenario examines a hypothetical earthquake (mainshock) with a moment magnitude (M_w) of 7.0 occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of California's San Francisco Bay region. For such an urban earthquake, the primary economic concern is the damage to capital such as buildings and contents and critical infrastructure. Severely damaged buildings would be unavailable for use, and damages to critical infrastructure would cause utility-service outages (for example, electric, gas, water), interruptions to data and voice services, and disruption to transportation systems (for example, roadways, rail lines, airports, and seaports) (Porter, 2018; Jones and others, this volume; Wein, Witkowski, and others, this volume). Furthermore, damages to buildings and infrastructure could ignite fires that spread owing to limited fire-suppression resources, and damages to critical infrastructure (for example, communication systems, roadways, and water-supply systems) could increase emergency-response times (Scawthorn, 2018). This study focuses on the economic impacts from capital losses (property or building and content damages) and water-, power-, and data- and voice-service disruptions. The latter refers to a major theme of the HayWired scenario—today's wired and wirelessly connected world. Therefore, we also analyze the digital economy, centered around the information and communications technology (ICT) industry sectors, which play a vital role in the regional economy. For the HayWired scenario, economic impacts from earthquake damages to transportation infrastructure are considered in Kroll and others (this volume).

This study estimates the regional economic impacts of property damages and utility-service disruptions on the San Francisco Bay region economy from the HayWired scenario using a multiregional computable general equilibrium (CGE) model. The model consists of industrial sectors and institutions (for example, households and government sectors) and simulates their interaction through production functions and market linkages (for example, the output of one sector becomes an input to another sector or itself). This means that the effects of earthquake damages to one sector may be direct (production is affected by property damages and utility outages) or indirect (production is affected by disruptions to its supplier and customer chains). The latter are sometimes referred to as ripple, multiplier, or general equilibrium effects.

The equilibrium solution of the CGE model computes the prices and quantities of goods and production factors that equalize supply and demand in all markets in the economy. The economic impacts are measured by the estimated reduction in the bay region's gross regional product[4] (GRP), the standard economic measure of the total value of final goods and services produced. Within this model some sectors may lose, whereas others may gain. Where production decreases, prices increase owing to scarcity and thus drive a reallocation of scarce resources to highest marginal value uses. The analysis assumes capital to be fixed, but labor resources are somewhat mobile among sectors, and factors of production can substitute for each other. These flexibilities in the economy are a form of inherent economic resilience that effectively reduces GRP losses that otherwise would be incurred.

Economic resilience refers to the ability of the economy to use remaining resources efficiently and to recover from or adapt at an accelerated pace to damages and disruptions caused by adverse events. It can be measured as the capability to reduce potential negative effects on GRP (Rose, 2009, 2017). At the micro (business) and meso (sector/market) levels of the economy, resilience—sometimes termed "business continuity" practices—enables enterprises to reduce their revenue losses, typically termed "business interruption" (BI) losses. In this study, these practices are referred to as static inherent and adaptive resilience tactics and include conserving scarce resources, using existing inventories of materials, substituting for disrupted supplies and services, temporarily relocating business activities, telecommuting, and the ability to make up lost production time by people working overtime or extra shifts. Wein and Rose (2011) compiled and categorized (in economic resilience terms) many tactics that were identified as having the potential to reduce BI during the development of the 2008 ShakeOut southern San Andreas Fault earthquake scenario. In this study, the effectiveness of resilience tactics is evaluated by modifying inputs and outputs of the CGE model to demonstrate their relative potential effectiveness in reducing BI losses measured in terms of GRP.

We begin by reviewing literature on economic impact assessments of previous disasters and estimates of disaster scenarios. The scenario assessments include our own work

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[4]In this report, we refer to several indicators of economic activity at the macroeconomic level. *Gross domestic product* (GDP) refers to the value of all final goods and services produced in an economy (less imports). It is the sum of consumption, investment, government spending, and exports, minus imports. *Gross regional product* (GRP) is the counterpart for subnational areas. Note that even though the term "gross" is used, it is only because the concept includes depreciation. It is otherwise considered a "net" concept, because it does not include intermediate goods (goods used to produce other goods). GRP is an indicator from the production side and is approximately equivalent to value added, which reflects the income and depreciation counterpart.

Gross output is also a production measure but one that includes the value of intermediate goods (which results in a great amount of double counting, so it is not as popular among economists). However, it is an indicator of significant interest to the business community because it is equivalent to sales revenue. In general, GRP is about 60 percent of gross output.

The term *direct gross output losses* refers to lost production at the sites of businesses directly affected by the HayWired mainshock (either through property damage or utility service disruptions). The term *total gross output losses* includes various "higher-order" effects. In input-output modeling this includes indirect and induced effects resulting from quantity interdependence through supply chains and in CGE modeling refers to general equilibrium effects (essentially indirect and induced effects but with the consideration of responses to prices and inclusion of input substitutions).

All of the above convey different aspects of the commonly used term *business interruption* (BI). The term BI is used at the levels of the individual business, sector, and economy as a whole, as is the term *gross output*. However, GRP is typically only used at the macroeconomic level, although its counterpart—value added—is used at all three levels. (See Rose [2004a] for more information.)

that has established techniques to model the economic impacts for the three previous U.S. Geological Survey (USGS) scenarios—the Southern California Shakeout earthquake (Rose and others, 2011), the California ARkStorm severe winter storm (Sue Wing and others, 2016), and a California tsunami generated by an earthquake offshore of the Alaska Peninsula (Rose and others, 2016). Next, we establish a foundation for this analysis with a description of the San Francisco Bay region economy and the composition of the largest industry sectors. We also define the ICT sectors, the core of the digital economy, and what sectors they depend on and serve. The detailed description of the CGE model is then provided, followed by the discussion of formal definitions and measures of economic resilience.

The analysis of economic impacts proceeds in several steps. First, estimates are constructed for the direct economic impacts to industry sectors resulting from physical damage to buildings and contents caused by the mainshock shaking, liquefaction and landslides, aftershocks, fire following the mainshock, and utility-service disruptions. Second, the total economic impacts (consisting of both direct and indirect effects) are estimated by simulating lost production in upstream and downstream sectors through market adjustments along the supply chain, using a multiregional CGE model. The economic impacts on sectors and the economy are first calculated without the consideration of microeconomic resilience tactics (apart from the resilience already incorporated in the CGE model's baseline structural representation of supply, demand, and market interactions[5]). The economic impacts are then estimated with various types of additional inherent and adaptive resilience tactics. The bottom-line measure of the economic impacts on the bay region economy of the HayWired earthquake scenario during the following 6 months are estimated as the reduction in GRP, in both absolute and percentage terms. To complement the short timeframe of the analysis, a simpler multiregional intertemporal partial equilibrium simulation model demonstrates a dynamic recovery for 17 years following the mainshock.

Literature Review of Economic Impact Analysis of Earthquake Events or Scenarios

The literature review focuses on the estimation of total economic impacts stemming from business interruption losses. The M_w 6.7 1994 Northridge, California, earthquake remains the costliest earthquake in U.S. history in terms of GRP reduction ($75 billion, in 2018 dollars) and property damage ($31 billion, in 2018 dollars). Based on empirical survey data collected from more than 1,000 firms in the cities of Los Angeles and Santa Monica, Tierney (1997) investigated the disaster preparedness, response, and recovery of businesses. Although structural and nonstructural damages caused substantial economic losses, a large number of firms suffered from extensive BI owing to other disaster-related problems, including utility service disruption, transportation network disruption, and a decrease in customer demand. The results also elucidate the cost-reducing potential of various resilience tactics adopted by businesses. For example, nearly 30 percent of the study respondents had stored fuel or batteries, and more than 35 percent had stored water prior to the earthquake. However, only 5.2 percent of respondents indicated that they had arrangements to move a business to an alternative location in case of a disaster. (See also Rose and Lim, 2002, and papers reviewed below for further analysis of resilience to electricity-service disruptions using Tierney's data.)

The series of earthquakes in 2010 and 2011 in Canterbury, New Zealand, resulted in an estimated $15 billion in rebuild costs, which is about 10 percent of New Zealand's annual gross domestic product (GDP) (Parker and Steenkamp, 2012). Insured losses, covering both property damage and business interruption losses, exceeded U.S. $25 billion (Parker and Steenkamp, 2012). The Canterbury economy exhibited reasonable resilience—agriculture and manufacturing sectors were only slightly affected, and merchandise exports remained strong owing to the rapid recovery of the capacity of seaports and airports. However, international tourism and student enrollment dropped significantly, which greatly affected service sectors such as retail, education, accommodation, and hospitality (Parker and Steenkamp, 2012).

Kajitani and others (2013) performed an economic impact analysis of the M_w 9.1 2011 Tohoku, Japan, earthquake, tsunami, and subsequent nuclear accident based on observed time-series data on economic activities before and after the disaster. The study revealed significant economic impacts beyond the direct damage of $211 billion. Indirect economic impacts include supply-chain disruptions, decrease in retail trade and tourism because of curtailed consumption, and fear of radiation. Japan's GDP decreased by 1.32 percent and 1.63 percent, respectively, in the first two quarters after the disaster. Despite these substantial losses, several resilience mechanisms were identified, including, for example, a collective energy conservation effort that successfully averted blackouts after the reduction of power generation capacity owing to nuclear power units being offline.

Using a time series-based input-output table for the City of Kobe, Okuyama (2014) applied a combined approach of structural-decomposition analysis (SDA) and shift-share analysis to analyze the long-term economic structural change and the corresponding economic impacts of the M_w 6.9 1995 Kobe earthquake. The four factors included in the SDA were changes in regional purchase coefficients, changes in production technological coefficients, changes in final demand, and changes in exports. Reduced final demand (caused by loss of lives and [or] out-migration) was found to be the largest contributor to total output losses. The study also identified how impacts varied across industries, with three service

[5]This includes inherent resilience of the economy through the price system in the form of input and locational substitution embedded in the CGE model's equations (see appendix 2 for details).

sectors (port-related transportation, other transportation, and public services) and the food and kindred products sector experiencing the largest negative effects.

Rose and Liao's (2005) pioneering study of economic resilience provided a rigorous definition of static economic resilience and demonstrated methods for incorporating key resilience tactics into a CGE modeling framework. The two tactics modeled were adaptive conservation (for example, recycling water) and adaptive input substitution (for example, finding new substitutes for piped water services, such as bottled or trucked water), and they were incorporated by altering constant elasticity of substitution (CES) production function productivity parameters and elasticities of substitution, respectively, based on Tierney's (1997) data. The model was applied to simulate a major Pacific subduction zone magnitude 6.1 earthquake affecting the Portland, Oregon, water system, resulting in a 48-percent reduction in service delivery over 4 weeks of recovery time, with direct and indirect losses of more than $1 billion (or 4.6 percent of gross output). The two resilience tactics described above yielded potential reductions in business interruption losses of 33 percent.

A CGE modeling study by Rose and others (2007a) of the resilience of the Los Angeles water system to a 2-week shutdown stemming from a terrorist attack indicated that these two resilience tactics could have a much smaller impact because of differences in the structure of the economies being modeled, the larger impacts to the water system, and the shorter period over which producers and consumers could engage in substitution. However, the additional resilience tactics of water storage, input isolation, and production recapture (see definitions below) increased the potential loss reductions to more than 90 percent. Rose and others (2007b) derived similar estimates for all of these resilience tactics combined to recover from a hypothetical shutdown of the Los Angeles electricity system caused by terrorist attack.

Rose and others (2011) simulated the economic impacts of an earthquake on the Verdugo Fault, north of Los Angeles, by coupling a CGE model with a water system fragility model. Base case results indicated a gross output loss of nearly $1 billion—or a nearly 5-percent loss of gross output over a 2-week recovery period, but resilience potential is estimated to be in excess of 90 percent. However, the authors cautioned that the moderation of losses in the real-world economy could be much smaller because of obstacles to implementation of the various resilience tactics (this applies to previous studies by the authors as well). A novel feature of that analysis relates to water prices, which are typically set by local government authorities rather than by the market and, therefore, do not adjust in the face of shortages. If water prices are allowed to rise with scarcity, curtailment of 24 percent of baseline supply triggers a 30-percent increase in the equilibrium price of water, but the consequent reallocation of water among users reduced business interruption losses by only 2 percent, in part because of the limited substitution possibilities among water and other inputs, even modeling the effect of additional measures that would have the effect of increasing the substitutability of other inputs for water.

Mackenzie and others (2012) used a multiregional input-output (I-O) model to estimate the total economic impacts of the 2011 Tohoku tsunami. As with the CGE framework, I-O models characterize the economy as a set of interconnected supply chains linking the activities of economic sectors. The key finding is that more than 90 percent of the potential BI losses could be avoided by a combination of inventories held by domestic producers and expanding input supplies through increased imports from abroad. Although the analysis did not explicitly consider issues of timing, some of this offset is implicitly contributed by production recapture.

In 2015, a multidisciplinary initiative was funded by the National Institute of Standards and Technology to develop a comprehensive set of modeling tools to better assess the likely impact of natural disasters on local communities, understand the factors affecting community resilience, and develop cost-effective strategies to optimize the recovery of communities (Ellingwood and others, 2016). A dynamic spatial CGE model was developed by Cutler and others (2016) to estimate the economic impact of damages to building stocks and transportation infrastructure caused by a simulated magnitude 7.8 earthquake in the Centerville Virtual Community, one of the community resilience testbeds of the initiative. The study also takes the dynamic impacts of changes in firm and household behavior into consideration. Alternative degrees of substitutability between capital and labor for the producing sectors and various rates of precautionary savings for households are analyzed to examine their effects on the long-run economic and social impacts of the disaster.

Thematically, the study that is closest to this report is the economic consequence analysis of the ShakeOut earthquake scenario—a hypothetical magnitude 7.8 southern San Andreas Fault earthquake centered near Palm Springs, California (Rose and others, 2011). That investigation used an I-O rather than a CGE model, which likely resulted in overstatement of the BI losses, because the former modeling approach omitted substitution among the various inputs to individual sectors and interregional substitution among the sources of supply of commodity inputs to production and consumption. Hazus and other geotechnical estimation methods were used to estimate property damage from ground shaking, supplemented by a fire-damage estimation methodology, yielding loss estimates of $113 billion—more than half accounted for by fire damage. The total BI losses (without resilience tactics) were estimated at $204 billion, stemming from as much as a 6-month disruption to the regional water system, which accounted for more than 35 percent of the total. The sole resilience option considered was production recapture, which was estimated to reduce BI losses by 67 percent to $68 billion.

San Francisco Bay Region Economy

The San Francisco Bay region consists of nine counties: Marin, Sonoma, Napa, Solano, San Francisco, San Mateo, Contra Costa, Alameda, and Santa Clara. In the past 15 years, the economy of the bay region experienced a 37-percent growth in gross regional product (GRP)—the measure of the total value of final goods and services produced in a region, which for the bay region was about 14 percent greater than the average growth rate for the United States (Kroll and others, 2017).[6] Based on I-O data from IMPLAN (short for impact analysis for planning), of which we have aggregated the 9-county bay region economy into 46 industry sectors (see appendix 1 for details), the GRP for the bay region in 2012 was $579 billion (IMPLAN, 2014). This accounted for nearly 30 percent of the total gross State product (GSP) of California, which was $2,050 billion in 2012. Table 1 shows the top five industry sectors in terms of GRP, and table 2 shows the top five industry sectors in terms of employment (including both full- and part-time jobs).[7] The top five sectors listed in these two tables account for nearly 50 percent of the total GRP and total employment, respectively, of the economy of the bay region.[8]

One theme of the HayWired scenario is the effects of wired and wireless technology in today's world. Therefore, we focus on the digital economy through the ICT sectors that play a vital role in the bay region's economy. Based on the 9-county 46-sector bay region I-O table (see appendix 1 for details), the 3 sectors that provide ICT services in the model are (1) telecommunications (such as Verizon, AT&T, T-Mobile, Comcast, Spectrum); (2) internet publishing and broadcasting and web-search-portal services (such as Netflix and Amazon as video broadcast sites, Google and Yahoo as internet search portals, and Facebook and Twitter as internet social networking sites); and (3) data processing, hosting, and related services (such as Amazon, Microsoft, and Google for providing computer data-storage services and Google, Microsoft, and Apple for providing application hosting). The GRPs of these three sectors were $11.19, $7.39, and $4.26 billion, respectively, in 2012, and the employment in these sectors was 30,700, 30,400, and 15,900, respectively, in 2012.

Tables 3 to 5 show the top 10 sectors that depend on—that is, purchase the largest quantities of the outputs of—the three ICT service sectors in the bay region economy, both in total dollar terms and as a percentage of the purchasing sectors' gross output. The three ICT sectors themselves are major users of their own outputs as inputs in production. Apart from this, the top sectors using ICT are service sectors such as finance, insurance, real estate, and leasing; professional, scientific, and technical services; business services; and publishing, motion pictures, and broadcasting.

Tables 6 to 8 show the top 10 sectors from which the ICT service sectors purchase inputs to produce their services, both in total dollar terms and as a percentage of the respective ICT sectors' gross output. Consistent with that shown in tables 3 to 5, the three ICT services use large amounts of their own outputs as inputs in production. Apart from this, the top supplier sectors to ICT service sectors are professional, scientific, and technical services; finance, insurance, real estate, and leasing; business services; light industry; publishing, motion picture, and broadcasting; semiconductor and related device manufacturing; and computer systems design and related services.

Table 1. Five largest industry sectors (gross regional product basis) in the nine-county San Francisco Bay region, California (data from IMPLAN, 2014).

Computable general equilibrium model sector	Billions of 2012 dollars
33. Finance, insurance, real estate, and leasing	$86.45
36. Other professional, scientific, and technical services	$43.26
46. Government and non-NAICS[1]	$42.90
35. Computer systems design and related services	$36.27
16. Semiconductor and related device manufacturing	$28.74

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 2. Five largest industry sectors (employment basis) in the nine-county San Francisco Bay region, California (data from IMPLAN, 2014).

Computable general equilibrium model sector	Jobs
33. Finance, insurance, real estate, and leasing	560,300
46. Government and non-NAICS[1]	409,000
19. Retail trade	403,700
41. Arts, entertainment, and recreation	390,700
36. Other professional, scientific, and technical services	369,100

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

[6]This includes the five Metropolitan Statistical Areas defined by the U.S. Department of Commerce's Bureau of Economic Analysis in the San Francisco Bay region, which also includes San Benito County in addition to the nine counties listed above.

[7]The three major datasets used by IMPLAN for employment estimates are the Bureau of Labor Statistics (BLS) Census of Employment and Wages (CEW), the Census Bureau County Business Patterns (CBP), and the Bureau of Economic Analysis (BEA) Regional Economic Accounts (REA) data. IMPLAN employment estimates are usually larger than the employment data provided by government agencies (such as the California Employment Development Department [EDD]) because IMPLAN employment includes not only full-time and part-time wage and salary employment (typically small business and professional practices) but also proprietor employment. The latter is not included in the EDD employment estimates.

[8]The discussions of the San Francisco Bay region economy in this section and the economic impact model to be discussed in the next section are based on IMPLAN data for the year 2012. These represent the latest data that could be obtained when we started working on the HayWired economic impact study in 2014. Based on IMPLAN data obtained in 2018, the GRP and employment of the 9-county bay region were $804 billion and 5.293 million thousand jobs (full-time and part-time) in 2016. The top sectors in terms of GRP and employment remained the same as in 2012.

Table 3. Top industry-sector purchases of internet-publishing and broadcasting services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Internet publishing and broadcasting	1,219	Internet publishing and broadcasting	11.37
Food, drug, and chemicals	278	Other mining	6.13
Other professional, scientific, and technical services	267	Couriers and messengers	3.22
Other business services	220	Primary metal manufacturing	1.07
Light industry	216	Heavy industry	0.67
Heavy industry	157	Other business services	0.57
Finance, insurance, real estate, and leasing	148	Light industry	0.53
Publishing, motion pictures, and broadcasting	132	Food, drug, and chemicals	0.51
Telecommunications	83	Sightseeing transportation	0.48
Computer systems design and related services	75	Telecommunications	0.44

Table 4. Top industry-sector purchases of telecommunications in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Telecommunications	2,299	Telecommunications	12.28
Other professional, scientific, and technical services	936	Coal mining	4.95
Publishing, motion pictures, and broadcasting	795	Publishing, motion pictures and broadcasting	2.45
Finance, insurance, real estate, and leasing	673	Repair and maintenance	1.70
Other business services	390	Other professional, scientific, and technical services	1.53
Government and non-NAICS[1]	375	Electricity generation/transmission/distribution	1.23
Construction	299	Accommodations	1.08
Light industry	259	Rail transportation	1.02
Semiconductor and related device manufacturing	182	Other business services	1.01
Computer systems design and related services	175	Construction	0.97

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 5. Top industry-sector purchases of data processing, hosting, and related services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Industry sector	Input as percentage of gross output
Other professional, scientific, and technical services	328	Other mining	1.56
Finance, insurance, real estate, and leasing	241	Telecommunications	1.21
Telecommunications	227	Other information services	0.90
Other business services	159	Accommodations	0.74
Publishing, motion picture, and broadcasting	127	Transit and ground passengers	0.55
Computer systems design and related services	95	Other professional, scientific, and technical services	0.54
Light industry	93	Air transportation	0.50
Government and non-NAICS[1]	44	Other business services	0.41
Arts, entertainment, and recreation	42	Publishing, motion picture, and broadcasting	0.39
Accommodations	35	Data processing, hosting, and related services	0.38

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 6. Top industry-supplier sectors to internet-publishing and broadcasting services in the San Francisco Bay region, California (data from IMPLAN 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of internet-publishing and broadcasting services
Internet publishing and broadcasting	1,219	11.37
Food, drug, and chemicals	278	2.59
Other professional, scientific, and technical services	267	2.49
Other business services	220	2.06
Light industry	216	2.02
Heavy industry	157	1.47
Finance, insurance, real estate, and leasing	148	1.38
Publishing, motion picture, and broadcasting	132	1.23
Telecommunications	83	0.78
Computer systems design and related services	75	0.70

Table 7. Top industry-supplier sectors to telecommunications in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of telecommunications
Telecommunications	2,299	12.28
Other professional, scientific, and technical services	936	5.00
Publishing, motion picture, and broadcasting	795	4.25
Finance, insurance, real estate, and leasing	673	3.60
Other business services	390	2.08
Government and non-NAICS[1]	375	2.00
Construction	299	1.60
Light industry	259	1.38
Semiconductor and related device manufacturing	182	0.97
Computer systems design and related services	175	0.93

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Table 8. Top industry-supplier sectors to data processing, hosting, and related services in the San Francisco Bay region, California (data from IMPLAN, 2014).

Industry sector	Input in millions of 2012 dollars	Input as percentage of gross output of data processing, hosting, and related services
Other professional, scientific, and technical services	328	5.54
Finance, insurance, real estate, and leasing	241	4.06
Telecommunications	227	3.83
Other business services	159	2.68
Publishing, motion picture, and broadcasting	127	2.14
Computer systems design and related services	95	1.60
Light industry	93	1.57
Government and non-NAICS[1]	44	0.75
Arts, entertainment, and recreation	42	0.70
Accommodations	35	0.58

[1]NAICS stands for North American Industry Classification System (U.S. Census Bureau, 2017). Non-NAICS sector includes all sectors in IMPLAN (2014) that are not defined by the NAICS code.

Economic Impact Estimation Model—Computable General Equilibrium Modeling

A computable general equilibrium (CGE) model is a stylized computational representation of the circular flow of the economy (see, for example, Sue Wing, 2009, 2011; Sue Wing and Balistreri, 2018). It solves for the set of commodity and factor (intermediate inputs used to produce other goods and services rather than for final consumption, as well as labor and capital) prices and the set of activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy. The model developed for this study divides California's economy into 18 areas (the 17 counties in the region affected by the HayWired mainshock—Alameda, Contra Costa, Marin, Merced, Monterey, Napa, Sacramento, San Benito, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Stanislaus, and Yolo—and the remainder of the State). Each economy consists of 46 industry sectors and households in nine different income categories and is linked to the other regions through trade.

The industry aggregation (see appendix 1) is matched to the occupancy classes in Hazus, the Federal Emergency Management Agency's (FEMA) expert loss estimation system (Federal Emergency Management Agency, 2012), which was used by other HayWired team members to calculate the building and content losses caused by the earthquake's physical impacts (Seligson and others, 2018). Each sector is modeled as a representative firm that produces a single good or service using production technology characterized by a CES cost function denominated over combinations of intermediate commodity and primary factor inputs. The households in each income group are modeled as a single representative agent with a constant marginal propensity to save and invest out of income and preferences characterized by a CES expenditure function denominated over final consumption of commodities. Government is represented in a simplified fashion, because its role in the circular flow of the economy is passive—collecting taxes from industries and passing some of the resulting revenue to households as lump-sum transfers, in addition to purchasing commodities to create a composite government good that is consumed by households. Two primary factors of production are represented within the model—labor, whose endowment is fixed but whose allocation among sectors responds to changes in the wage rate, and capital, which is treated as sector-specific and immobile among industries or regions during the 6-month postearthquake recovery horizon. Factors are owned by the representative agents, who rent them out to the firms in the agents' county of residence in exchange for factor income. Each region is modeled as an open economy that engages in trade with the rest of California, the rest of the United States, and the rest of the world according to an assumption, whereby imports from other counties, States, and the rest of the world are imperfect substitutes for goods produced locally (Armington, 1969) and also modeled using CES functions.

The basic model is static, computing the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments, over a single period of 6 months duration.[9] The economic impacts of the earthquake are modeled as exogenous reductions in endowments of sector-specific capital in the sectors sustaining direct physical damage and negative shocks to the aggregate (that is, the sum of domestic and imported) supply of utility lifelines to each region. The model is formulated as a mixed complementary programming problem using the Mathematical Programming System for General Equilibrium analysis (MPSGE) subsystem for the General Algebraic Modeling System (GAMS) software (Brooke and others, 1988; Rutherford, 1999) and is solved using the PATH solver (Ferris and Munson, 2000). A more detailed and technical description of the model is given in appendix 2. The model is calibrated using an IMPLAN social accounting matrix for the State of California for the year 2012 (IMPLAN, 2014). The key parameters of the model are summarized in appendix 2. Earlier variants of the model were used to analyze the effects of other disaster scenarios, such as a San Francisco Bay region earthquake cutting off water supplies from the California Aqueduct to Los Angeles County (Rose and others, 2011), the USGS California ARkStorm severe winter storm scenario (Sue Wing and others, 2016), and the USGS Science Application for Risk Reduction project (SAFRR) tsunami scenario (Rose and others, 2016).

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[9]The shortest timeframe on which the assumptions of Walrasian general equilibrium (market clearance, zero profit, and income balance) that underpin the construction and operation of a CGE model can be said to hold is the timeframe of several weeks to months that corresponds to Alfred Marshall's "short-period" over which price signals bring supply and demand in line with one another but the endowment of productive factors does not adjust (see Helm, 2008). Intermediate and final goods markets clear on about the timeframe over which work-in-process and finished goods inventories are drawn down. However, labor markets can remain far out of full employment equilibrium for periods of several years. Our selection of a 6-month simulation horizon for our comparative statics CGE analysis attempts to strike a balance between the duration of damaging aftershocks and the shortest period on which Marshallian quasi-rents (above-normal profits generated by idiosyncrasies of location or specialized fixed factors such as human capital) are eroded by competitive entry firms into the economy's various markets and prices equilibrate in the postdisaster regime. Consumers tend to rapidly adjust the composition of expenditures if they experience appropriately weighted disequilibrium aggregate marginal expenditures that exceed their marginal utility (for example, shifting away from luxury goods and toward staple items in a postdisaster environment). However, the timeframe over which households can continue to undertake expenditures in excess of their income is determined by their pool of savings and (or) remittances, as well as borrowing constraints. These facilitating factors are unlikely to operate over periods longer than a few months, which will tend to bring households' spending into line with their income. Because most households' primary source of income is labor remuneration, but wages adjust slowly and job search and matching takes time, household adjustment is more likely to occur on the expenditure side rather than on the income side in the short run.

Economic Resilience

Researchers and decision makers in the disaster field are split on the definition of economic resilience. One group uses the concept to refer to any action taken to reduce disaster losses. This group, with a large representation of engineers, focuses primarily on mitigation to reduce the frequency and magnitude of disaster stimuli and strengthening property to reduce damage (see, for example, Bruneau and others, 2003). This broad definition has also been adopted and applied across the board by major panels of experts assessing resilience research and practice, such as the National Research Council, which defines resilience as “The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events” (National Research Council, 2012, p. 16).

Another group, with a large representation of social scientists (Tierney, 2007; Rose, 2017; Cutter, 2016), but with increasing representation by engineers in relation to utility lifelines (National Research Council, 2017), focuses primarily on actions implemented after the disaster strikes. This group takes the meaning of resilience more literally, referring to its Latin language root, whose definition is “to rebound.” They also acknowledge that resilience is a process, whereby steps can be taken before the disaster to build resilience capacity, but resilient actions do not take place until after a disaster. Examples would include emergency drills, purchase of back-up electricity generators, and lining up alternative suppliers of critical inputs. In each case, the action serves no benefit before a disaster takes place but lowers the interruption of key business services when a disaster takes place. Here the focus is not on property damage, which has already taken place, but rather the reduction in the loss of the flow of goods and services emanating from property or capital stock. The former is often measured in terms of GRP and employment and is typically referred to as business interruption (Tierney, 1997). BI begins at the point when the disaster strikes and continues until the system has recovered or reached a “new normal,” which is typically considered a “sustainable” level of activity (meaning a healthy economy). Measuring BI losses is thus much more complicated, because it involves matters of the duration and time-path of recovery, both of which are strongly affected by the behavioral responses of public and private decision makers (Rose, 2015).

Defining Economic Resilience

There are many definitions of resilience, but Rose (2009) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them up with definitions that capture the essence of economic considerations. Following Rose (2004b, 2009), we distinguish two major categories of resilience.

In general, static resilience refers to the ability of the system to maintain a high level of functioning when shocked (Holling, 1973). Static economic resilience is the efficient use of remaining resources at a given point in time. It refers to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.

In general, dynamic resilience refers to the ability and speed of the system to recover (Pimm, 1984). Dynamic economic resilience is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to reestablish productivity in the future. Static economic resilience does not restore damaged capacity and is therefore not likely to lead to complete recovery.

Note that economic resilience can take place at three levels of analysis:

- Microeconomic (operation of individual businesses, households, and government agencies; for example, conservation of or substitution for critical inputs, use of inventories or excess capacity, relocation, and production rescheduling)
- Mesoeconomic (operation of industries and markets; for example, the resource-allocating mechanism of the price system)
- Macroeconomic (operation of the economy; for example, supply-chain adjustments, importation of critical inputs, and fiscal and monetary policy)

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Tierney, 2007; Cutter, 2016). Inherent resilience refers to resilience capacity already built into a system or capacity that can be enhanced before the disaster strikes, such as the ability to use more than one fuel in an electric-power generating unit, substituting domestically disrupted goods and services with imports, the workings of the market system in offering price signals to identify scarcity and value, and established government policy levers. Adaptive resilience is exemplified by normal or improvisational actions after a disaster strikes, such as undertaking conservation that was not previously thought possible, changing technology, devising market mechanisms where they might not have previously existed, and (or) devising new government postdisaster assistance programs. It is important to realize that a great deal of resilience is already embodied in the economy at various levels (for example, a firm’s ability to substitute inputs and market signals for reallocating resources) and that policies could be designed to capitalize rather than obstruct or duplicate this capacity. At the same time, benefits can accrue from policy that is geared to rewarding both general categories of resilience.

Economic resilience can also be defined from both the customer-side and supplier-side (Rose, 2009, 2017). Customer-side resilience primarily refers to demand-side resilience tactics, by which the businesses and households cope with the disruption (quantity and timing) of the delivery of intermediate production inputs or final goods and services, respectively, using resilience tactics such as conservation, input substitution, import substitution, use of inventories, and production recapture. In other words, it pertains to ways to use remaining resources available as effectively as possible (static resilience). In contrast, supplier-side resilience is concerned with delivering outputs to customers and could include the establishment of system redundancy in the production process (a form of static resilience); it also involves the repair or reconstruction of critical inputs (that is, dynamic resilience). Repair of the capital stock, or supplier-side efforts, are the domain of the sectors that provide production inputs (including services) to other (customer) sectors and are for the most part a separate matter from customer-side resilience.[10]

An Operational Economic Resilience Metric

The next step is to translate these definitions into something we can measure. For static resilience, this can be done in terms of the amount of BI losses prevented by the implementation of a given resilience tactic or set of tactics comprising a resilience strategy. For dynamic resilience, the metric would be the reduction in recovery time in addition to the reduction in BI losses, although the former influences the latter. In both cases, one needs to establish a reference point or baseline to perform the measurement. For static resilience, this would be the maximum potential BI losses in the absence of the resilience tactic, whereas for dynamic resilience it would be the duration and time-path of economic activity in the absence of resilience in relation to investment in repair and reconstruction.

Several studies have measured resilience using this and related metrics in addition to the studies reviewed above. Rose and others (2009) found that potential BI losses were reduced by 72 percent by the rapid relocation of businesses following the September 11, 2001, terrorist attacks on the World Trade Center. Rose and Wei (2013) found that a reduction in potential BI losses from a 3-month closure of a major U.S. seaport could be as great as 66 percent from the implementation of several types of static resilience, most notably ship rerouting, use of inventories, and production rescheduling. Xie and others (2018) estimated that dynamic resilience in the form of increase in and acceleration of the timing of investment funds in the aftermath of the M_w 7.9 2008 Sichuan (Wenchuan), China, earthquake reduced BI losses by 30 percent and recovery time by 1 year.

Other studies have found extensive potential of economic resilience. Kajitani and Tatano (2009) found extensive resilience possibilities among Japanese manufacturing firms in response to utility-service disruptions caused by disasters. Specialized studies have developed methodologies for examining the potential of specific resilience strategies, such as use of inventories (Barker and Santos, 2009).

[10]There are tradeoffs in the level of implementation of customer-side and supplier-side resilience in that an increase in resilience expenditures by one side reduces the need for expenditures by the other.

Inputs into the Economic Impact Model

There are three types of inputs into the HayWired scenario economic impact model. First, the percentage of property damages (capital stock losses) incurred in each sector are calculated by county. The direct economic impacts of these capital losses for each sector are expressed as a percentage of their baseline gross output. Second, digital and utility service disruptions are another source of business interruption and the percentage of baseline services provided are estimated by county. Third, resilience adjustments to these service disruptions are identified on both the supplier-side and customer-side. In addition to these resilience strategies on the input-side of the CGE analysis, we also explain how production recapture and relocation of production activities are applied to the CGE modeling output to ameliorate the impacts of property damage and digital- and utility-service disruptions.

Property Damage

The percentage of property damage (capital stock losses) incurred in each industry sector is calculated from building and content damages caused by the HayWired mainshock and aftershocks estimated using Hazus[11] (Seligson and others, 2018). Indirect, or ancillary, property damages from fire following earthquake are also estimated (see Scawthorn, 2018) and integrated with the Hazus damage assessment (see Johnson and others, this volume). Cumulative property damages are inputs to the CGE model for the evaluation of the total economic impacts of the HayWired scenario as follows:

1. Building and content exposure value (dollar) loss from HayWired mainshock shaking, liquefaction, and landslide hazards.
2. The above with additional building and content losses from fire following the mainshock.
3. The above with additional building and content losses from HayWired aftershocks.

Mainshock Earthquake Hazards

For building and content damages caused by the mainshock hazards, the following steps were followed to compute the percentage property damages for occupancy classes in each county:

1. Compute the percentage of building damage for each occupancy class in each county by dividing the

[11]One caveat is that the custom Hazus mapping schemes of construction used in the HayWired scenario were developed in 2006 to reflect the distribution across various vintages, and the building codes under which they were designed (vintage 2000). Although new buildings were constructed since then in the bay region, regional building stock is still dominated by older buildings, and “new” buildings represent only a small fraction of the current inventory. Since “new” buildings that comply with more current building codes are expected to perform better than “old” buildings, the property damage estimates generated by Hazus can be considered conservative.

Hazus “BldgLoss” of that occupancy class in the county by the corresponding Hazus “BldgVal”; and similarly, compute the percentage of content damage for each occupancy class in each county by dividing Hazus “ContentLoss” by Hazus “ContentsVal.”

2. Determine the percentage of building damage and percentage of content damage for each CGE sector in each county based on the bridging table between the Hazus occupancy classes and the CGE sectors (see appendix 1, table 1.1).

3. In the case of one CGE sector corresponding to more than one Hazus occupancy class, we calculate the percentage of building damage (or percentage of content damage) for the CGE sector as a weighted average of the percentage of damage of all the relevant occupancy classes. The average is weighted by building value of the Hazus sectors.

The percentages of building damage and content damage are shown in appendix 3, tables 3.1 and 3.2, respectively. The county that suffers the greatest property damages, in percentage terms, is Alameda (ranging from 14.4 percent building and content damages of primary metal manufacturing to 44 percent for the mining sector and for the food, drug, and chemicals manufacturing sector), followed by Contra Costa (ranging from 7.2 percent for the imputed rental value for owner-occupied dwellings sector to 18.3 percent for the education services sector), Santa Clara (ranging from 3.7 percent for the imputed rental value for owner-occupied dwellings sector to 7.6 percent for the light industry), and San Mateo (ranging from 3.4 percent for the imputed rental value for owner-occupied dwellings sector to 6.5 percent for the mining sector and for the food, drug, and chemicals manufacturing sector).

Mainshock Earthquake and Fire Following Earthquake Hazards

Additional property damages are caused by fire following the HayWired mainshock. The additional percentage of buildings that are completely damaged from fire are computed, eliminating the potential double counting for the buildings that have already been completely damaged by shaking. (The integration of fire damage with direct earthquake hazard damages is described in section A of Johnson and others [this volume]). Appendix 1, table 1.1, is also used to map the percentage of this property damage by occupancy class to the corresponding CGE sectors. Appendix 3, table 3.3, shows the percentages of additional property damage (including both buildings and contents) caused by fire following the HayWired mainshock by county and by CGE sector. Appendix 3, table 3.4, shows the percentage of property damage caused by mainshock and fire combined. The three most damaged counties in terms of property damage are again Alameda (from 17 percent to 47 percent), Contra Costa (from 10.2 percent to 26.4 percent), and Santa Clara (from 5.1 percent to 9.7 percent).

Mainshock Earthquake Hazards, Fire Following Earthquake Hazards, and Aftershock Shaking Hazards

The property damage from aftershocks is also estimated. Appendix 3, table 3.5, shows the additional percentage of building and contents damages caused by aftershocks. It is assumed that the building and content losses for the mainshock and the aftershocks are additive. In other words, the total percentage of building and contents damage shown in appendix 3, table 3.6, represents a simple sum of the mainshock (including fire) losses and aftershock losses. Some of the damages could be double counted because Hazus assumes that the buildings are as they were before the mainshock in the simulations for each aftershock. Therefore, some of the buildings that have already been extensively or completely damaged by the mainshock may be “damaged” again by the aftershocks in the simulations. This leads to an overestimate of the building damages. Conversely, Hazus does not allow for structures that are slightly or moderately weakened by the mainshock to be more fragile to subsequent shaking, and this leads to an underestimation of damage to these buildings by aftershocks. The potential double counting (overestimation) of damages to buildings that are extensively or completely damaged by the mainshock and the underestimation of damages to weakened (slightly or moderately damaged) buildings by the mainshock offset each other to some extent when we compute the combined impacts of the mainshock and aftershocks. The total property damages for the three most impacted counties are 24.3 percent to 51.3 percent for Alameda, 10.5 percent to 26.9 percent for Contra Costa, and 8.8 percent to 16.6 percent for Santa Clara.

Gross Output Losses

To compare the baseline economy with direct economic impacts of property damages, the sector percentages of these capital losses are applied to baseline sector capital inputs in the model to obtain the direct impacts in terms of sector gross output. These are divided by baseline sector gross output to produce the percentages of gross output losses in figure 1. The figure summarizes the aggregate direct effects of the mainshock and aftershock shaking and fire at the level of sectors within each county. (The total economic impact result for this case is shown in table 18, line 4.) The figure indicates that, although direct adverse effects on the internet publishing and broadcasting sector are modest (losses on the order of 2–3 percent of baseline output), related and supporting sectors whose outputs are used intensively as inputs to that industry (for example, telecommunications, electric power, data processing, hosting and related services, computer storage device manufacturing, electronic computer manufacturing, and other information services) are on average among those that are most directly affected, with average losses of 5 to 10 percent of baseline output. However, these gross output reductions induce changes in the CGE model simulation which account for the price and substitution responses in markets throughout California’s economy.

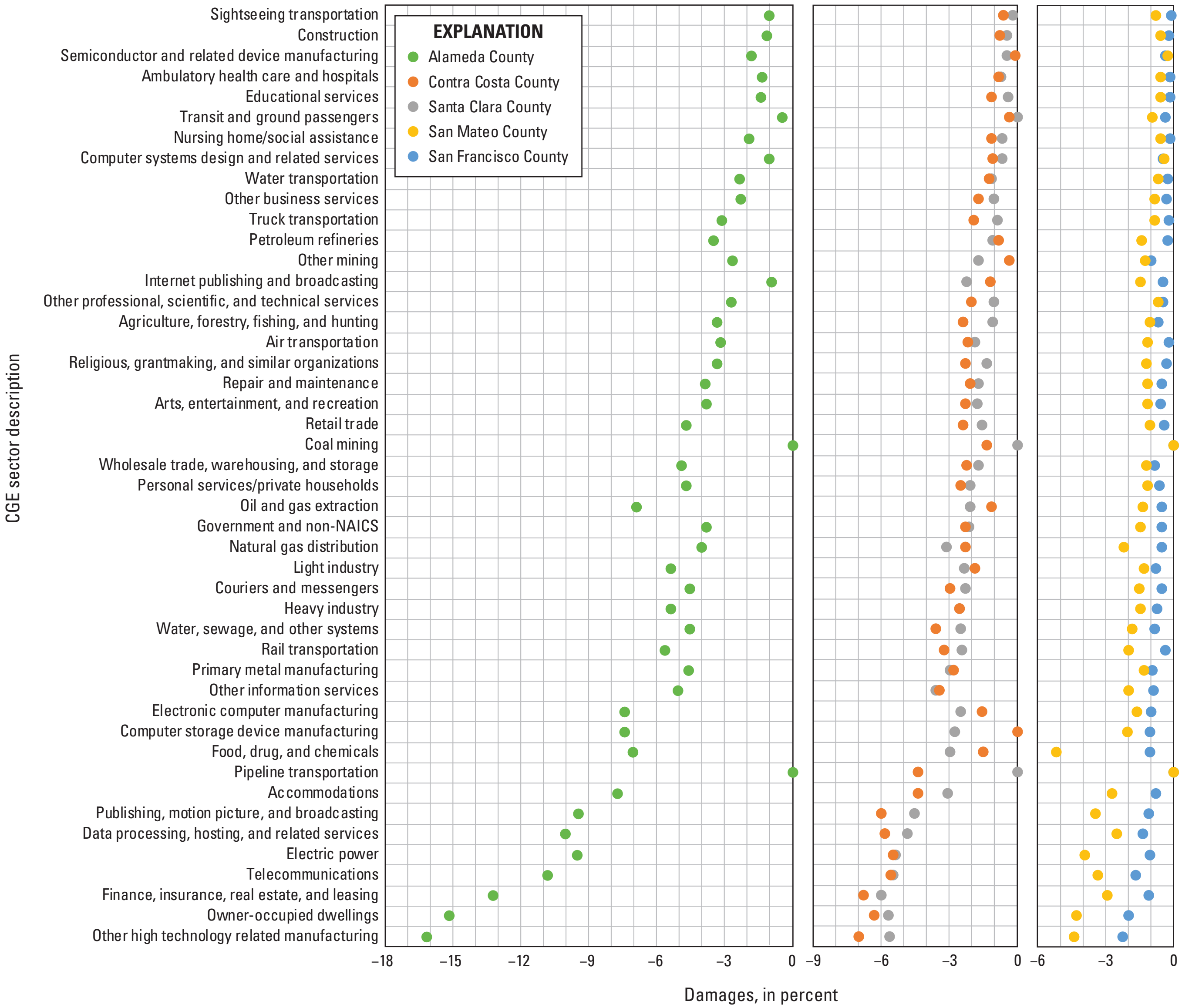

Figure 1. Aggregated mainshock, fire, and aftershock damages directly sustained by sectors in affected counties in the San Francisco Bay region, California, expressed as a percentage of a sector's gross output. CGE, computable general equilibrium.

Digital and Utility-Service Disruptions

Like all large urban earthquakes, the HayWired mainshock and aftershocks would damage the utility systems that supply water, electricity, and other essential services. To check equipment, repair damage, and reroute or restore service can take days to months. As recounted in Porter (2018) and Jones and others (this volume, appendix 3), all the water- and electricity-service damage envisioned in the HayWired scenario is eventually repaired and all the service is eventually restored. In San Francisco Bay region locations farthest from the mainshock epicenter these services are restored fastest or never disrupted at all. Closer to the mainshock, it would take days or weeks to restore electricity service and as long as 7 months to restore water service. Until service is restored, economic production in workplaces suffers as described in this chapter. Households also suffer from the significant inconvenience costs caused by the service disruptions detailed in appendix 7. CGE models, like nearly all macroeconomic models, focus on goods and services, and their value, transacted through market or delivered by governments. Therefore, household costs need to be evaluated outside the models by "nonmarket valuation" methods as presented in this section and appendix 4.

We summarize the base cases for the utility-service disruptions for water and electric power supply in the HayWired scenario. In the next section we will recognize resilience tactics that reduce the direct and total economic impacts of service disruptions. Inconvenience costs of water and power outages to households (that are not part of the larger economic impact analysis) are treated separately.

Water-Service Disruptions

Water service is evaluated in terms of a preplan scenario (as-is conditions) by Porter (2018) and is expected to be restored within 30 days in most counties. However, it is estimated that 100 percent restoration of water service in San Mateo County will take 90 days, and the full restoration in Alameda and Contra Costa Counties will take as long as 7 months. In table 9, utility-service disruption model inputs in percentage terms are shown by county and by 6-month period in the second through fourth columns. The percentage of water-service disruption is calculated for the first 6-month (or 182-day) horizon of the analysis using the CGE model. For example, if 50 percent of water service is disrupted for 7 days, the percentage of water-service disruption in the 182-day period is 50 percent × 7/182 = 1.92 percent. The same approach is used in the calculation of other utility-service disruptions.

However, for many households, loss of water service is an inconvenience that comes with a cost. In the HayWired scenario, almost 3 million people lose water service to their homes for more than 3 days. The average household in the study area loses water service for 16 days, and in Alameda and Contra Costa Counties, the average is 54 days. Between the mainshock and all the aftershocks of M_w 5.0 or greater, households lose just over 57 million service-days of water, that is each day of lost water supply to a household equates with one service day. Households without water service must rely on bottled water and portable toilets. To bathe, residents must travel to someplace outside the home that has a functioning water supply and shower facilities, all of which have inconvenience costs. The cost for bottled water, rental of portable toilets (assuming enough stock exists nationwide to supply the need), and the inconvenience cost of traveling for showers is estimated to cost $90 per household per day. The total inconvenience cost of disrupted water service to residences is conservatively estimated to be $5.2 billion (appendix 4). Using other sources examined in appendix 4, the figure could be as high as $33 billion.

Table 9. Percentage of customers experiencing utility-service disruptions in the first 6 months following the HayWired mainshock, by county in the San Francisco Bay region, California.

County	Water disruption	Electric power disruption	Data and voice disruption
	Percentage of customers		
Alameda	32.34	3.93	5.05
Contra Costa	32.34	2.52	3.60
Marin	0.54	0.74	1.39
Merced	0.20	0.29	0.60
Monterey	0.00	0.18	0.52
Napa	0.00	0.29	0.60
Sacramento	0.00	0.07	0.46
San Benito	0.05	1.02	1.16
San Francisco	3.68	1.31	1.86
San Joaquin	0.00	0.58	0.76
San Mateo	11.05	1.82	2.33
Santa Clara	2.80	2.69	3.67
Santa Cruz	0.00	0.41	0.67
Solano	0.11	0.60	1.27
Sonoma	0.00	0.09	0.99
Stanislaus	0.00	0.00	0.00
Yolo	0.00	0.00	0.00

Power-Service Disruptions

Power-service disruptions were estimated using Hazus (see appendix 3 in Jones and others, this volume). They are estimated to last a shorter duration than water-service disruptions in all counties. By Day 7, all counties are expected to have more than 90 percent of power service back. The only exception is Alameda County, which would have 83 percent power service restored. By Day 30, the only counties that still experience power-service disruptions are Alameda, Contra Costa, San Mateo, and Santa Clara, but the disruptions are all less than 4 percent of electric power services. Compared to water supply restoration, some counties initially have lower power than water services owing to the widespread nature of the electric power outage.

For households, while electricity is out, freezers thaw and refrigerators warm, food spoils, and people must rely on their emergency supplies. Approximately 1.4 million households lose power long enough that, once the electricity is restored, they must replace the spoiled food at a cost of approximately $325 per average household, for a total cost of $450 million (appendix 4). Other inconveniences, such as eating cold meals from emergency supplies and inability to charge devices, are real but not quantified here in dollar terms. Using a FEMA standard value, one can estimate the value lost as $3.9 billion.

Data- and Voice-Service Disruptions

In Wein, Witkowski, and others (this volume), data and voice service restoration curves are first derived for a base case that assumes full dependence on electric power such that service restoration lags behind power restoration. The base case also assumes a surge in demand, from customers communicating about the earthquake, that overloads networks. The surge decreases with time after the crisis subsides as the need to communicate with family, friends, and first responders and seek information lessens. The percentages of customer demand for data and voice services in the base case are in appendix 6, table 6.1.

Resilience Adjustments

As explained above, the CGE model implements economic resilience primarily at the meso (sector or market) and macro (entire regional economy) scale. At the micro scale, businesses can take other actions to reduce business interruption. Many of these resilience tactics are beyond normal business and market behavior. Although resilience can be enhanced before the disaster strikes by investments that increase its capacity (for example, increasing stockpiles of critical inputs, purchasing backup generators), the various tactics are implemented only after the earthquake has occurred.

We model most of these effects by adjusting the inputs to the CGE model (discussed in detail in the subsection on Summary of Property Damage and Utility-Service Disruptions by Sectors) or by adjusting the GRP losses—the output of the CGE modeling (discussed in subsection on Resilience Adjustments). In particular, the resilience tactics are as follows:

1. Supplier-side resilience tactics that restore services faster:

A. Input substitution, such as fixed back-up power (batteries and generators) and fuel management plans in case of an electric power outage.

B. Inventories of portable equipment to temporarily replace power sources and add capacity.

These reductions in disruption are modeled by adjusting the restoration curves upward accordingly and then input into the CGE model.

2. Customer-side resilience tactics work around the supplier disruption to maintain production of goods and services. In general, these include the following:

A. Conservation is to produce goods or services using fewer critical inputs and to conserve critical inputs that could become scarce owing to indirect effects.

B. Input substitution replaces an unavailable good or service by a different available good or service.

C. Production isolation refers to the portions of a production process that are insulated from lifeline services, and hence are not affected by service disruptions (for example, much of agricultural production does not require electricity).

The reductions in disruptions are modeled as equivalent utility input (the base case utility-service disruption percentages adjusted downwards for each individual resilience tactic) to represent the production of goods and services that are attained by other means. The equivalent utility inputs are adjusted for each sector and used in the CGE model. However, we cannot account for the additional "upstream" effects to suppliers of the additional equivalent input.

3. Customer-side resilience tactics that use capacity of capital beyond normal use. Two examples are as follows:

A. Production recapture (rescheduling) is the ability of businesses to recoup lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs and employees are available. This is a viable option for short-run disruptions, where customers are less likely to cancel orders from their standard suppliers.

B. Relocation of businesses, including teleworking from other locations (for example, shared workplaces or homes).

These reductions in disruption are applied to the outputs of the CGE model to reduce total BI losses for sectors. However, the upstream effects from additional production are not accounted for.[12]

Resilience Adjustments on Input Side of CGE Modeling

Water-Service Disruptions with Resilience

Two customer-side resilience tactics applied to water supply restoration are

- Water conservation of 2 percent can be reasonably achieved by means such as water recycling.
- Production isolation from water inputs are derived from utility "Importance" factors by sector (Applied Technology Council, 1991) in appendix 5, table 5.1. The portion of production processes that can be isolated from water services is one minus the percentages shown in column 2.

Note that input substitution refers to the use of other products, such as bottled and trucked water, other beverages, and possibly even chemicals, in place of disrupted water input. Some of these substitutions are inherent in the economy and modeled through the ordinary elasticities of substitution between water and other inputs in the CES production functions in the CGE model. We lack information, however, on adaptive input substitution that could emerge under stressful conditions.

Note that Porter (2018) provided three cases: (1) base case ("no fuel management plan or mitigation" in Porter, 2018), (2) supplier-side fuel management plan to keep permanent generators running during power outages ("postplan" in Porter, 2018), and (3) both mitigation (brittle pipe replacement) and resilience (power source management plan for pumping) ("ideal world" in Porter, 2018). The effects of customer-side resilience (conservation, production isolation, or both) on the base case water-service disruption are shown in table 10. Table 11 shows water-service disruption percentages for the postplan and ideal-world scenarios.

Power-Service Disruptions with Resilience

Customer-side resilience tactics for power-service disruptions include 2-percent conservation and production isolation (similarly, derived from appendix 5, table 5.1). Again, input substitution is assumed to be already accounted for in the CGE model. Table 12 shows power-service disruptions by county for conservation and production isolation both separately and combined.

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[12]We note that Porter (2018) also offers a water-disruption analysis for the mitigation action of replacing old brittle pipes that will reduce damages, and therefore disruption.

Table 10. Percentage of customers experiencing water-service disruptions in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics for preplan scenario in the San Francisco Bay region, California.

[Combined resilience is conservation and production isolation]

County	Water disruption with conservation	Water disruption with production isolation	Water disruption with combined resilience
	Percentage of customers		
Alameda	31.69	12.65	12.40
Contra Costa	31.69	13.11	12.85
Marin	0.53	0.16	0.15
Merced	0.19	0.09	0.09
Monterey	0.00	0.00	0.00
Napa	0.00	0.00	0.00
Sacramento	0.00	0.00	0.00
San Benito	0.05	0.02	0.02
San Francisco	3.61	1.04	1.02
San Joaquin	0.00	0.00	0.00
San Mateo	10.83	3.86	3.78
Santa Clara	2.75	1.49	1.46
Santa Cruz	0.00	0.00	0.00
Solano	0.11	0.05	0.05
Sonoma	0.00	0.00	0.00
Stanislaus	0.00	0.00	0.00
Yolo	0.00	0.00	0.00

Table 11. Percentage of customers experiencing water-service disruption in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics for postplan and ideal-world scenarios in the San Francisco Bay region, California.

[Postplan is conservation and production isolation; ideal world is conservation and production isolation]

County	Water disruption with resilience for postplan scenario	Water disruption with resilience for ideal world scenario
	Percentage of customers	
Alameda	10.59	5.11
Contra Costa	10.98	5.30
Marin	0.05	0.05
Merced	0.06	0.06
Monterey	0.00	0.00
Napa	0.00	0.00
Sacramento	0.00	0.00

Table 11—Continued.

County	Water disruption with resilience for postplan scenario	Water disruption with resilience for ideal world scenario
	Percentage of customers	
San Benito	0.02	0.02
San Francisco	0.34	0.34
San Joaquin	0.00	0.00
San Mateo	3.16	3.16
Santa Clara	1.46	0.89
Santa Cruz	0.00	0.00
Solano	0.01	0.01
Sonoma	0.00	0.00
Stanislaus	0.00	0.00
Yolo	0.00	0.00

Table 12. Percentage of customers experiencing power-service disruptions in the first 6 months following the HayWired mainshock, by county, after adjustment for resilience tactics in the San Francisco Bay region, California.

[Combined resilience is conservation and production isolation]

County	Power disruption with conservation	Power disruption with production isolation	Power disruption with combined resilience
	Percentage of customers		
Alameda	3.85	3.31	3.24
Contra Costa	2.47	2.29	2.24
Marin	0.73	0.62	0.61
Merced	0.28	0.22	0.21
Monterey	0.17	0.13	0.13
Napa	0.28	0.23	0.23
Sacramento	0.07	0.06	0.06
San Benito	1.00	0.84	0.82
San Francisco	1.29	1.10	1.07
San Joaquin	0.57	0.46	0.45
San Mateo	1.79	1.54	1.51
Santa Clara	2.63	2.45	2.41
Santa Cruz	0.40	0.33	0.33
Solano	0.59	0.51	0.50
Sonoma	0.09	0.07	0.07
Stanislaus	3.85	3.31	3.24
Yolo	2.47	2.29	2.24

Data- and Voice-Service Disruptions with Resilience

Resilience tactics for data and voice services are examined in Wein, Witkowski, and others (this volume). They include supplier- and customer-side tactics as well as customer behavior management.

Supplier-Side Resilience Tactics

Supplier-side resilience tactics for data and voice services include:

- Input substitution for power—using permanent backup batteries and generators—by the telecommunication providers to maintain the function of the residual data and voice infrastructure capacity that would otherwise depend on electric power. The assumption is that half the cellular sites are fitted with batteries that will drain on the first day and half the sites have a generator with fuel for three days.
- Inventories of portable gensets (for example, a diesel generator, which is a combination of diesel engine and electric generator) for cell sites lacking a functioning generator and mobile cell sites on wheels or light trucks (COWs or COLTs) to temporarily restore service capacity. Depending on the level of impact, the first trucks deliver and install portable equipment within a week after the earthquake.

The percentages of customer demand for data and voice services met for each of these resilience tactics with the base case are in appendix 6, tables 6.2 and 6.3. The service disruption estimates for customers during the first 6 months for these and subsequent resilience tactics are shown in table 13.

Customer Behavior Management

Wein, Witkowski, and others (this volume) suggest that data and voice bandwidth can be conserved through managing customer behavior on the supplier and (or) customer sides. Efficient use of bandwidth includes using text rather than voice and radio rather than news streaming to reduce the surge in demand for communication services immediately after the earthquake. Assuming the surge in customer demand is reduced by 10 percent, appendix 6, table 6.4, shows the percentages of demand for data and voice service met by county. The potential to benefit from customer behavior management decreases with reductions in demand as the crisis surge subsides.

Table 13. Percentage of customers experiencing data- and voice-service disruptions in the first 6 months following the HayWired mainshock for base case and after adjustment for resilience tactics, by county, in the San Francisco Bay region, California.

[Combined resilience is supplier permanent backup power and portable equipment, supplier and customer behavior management, and customer input substitution and production isolation]

County	Data and voice disruption in the base case	Data and voice disruption with supplier permanent backup power	Data and voice disruption with supplier portable equipment	Data and voice disruption with supplier/customer behavior management	Data and voice disruption with customer input substitution	Data and voice disruption with customer production isolation	Data and voice disruption with combined resilience
	Percentage of customers						
Alameda	5.05	4.42	2.96	4.66	2.79	2.11	0.78
Contra Costa	3.60	3.06	1.68	2.79	1.91	1.12	0.29
Marin	1.39	1.27	1.25	1.17	0.91	0.77	0.37
Merced	0.60	0.52	0.56	0.59	0.46	0.20	0.14
Monterey	0.52	0.48	0.50	0.51	0.44	0.22	0.17
Napa	0.60	0.52	0.56	0.59	0.46	0.22	0.15
Sacramento	0.46	0.45	0.46	0.45	0.42	0.21	0.19
San Benito	1.16	1.26	0.82	1.16	0.69	0.37	0.18
San Francisco	1.86	1.62	1.48	1.67	1.25	1.03	0.47
San Joaquin	0.76	0.58	0.67	0.75	0.53	0.31	0.17
San Mateo	2.33	1.93	1.57	2.15	1.36	1.14	0.44
Santa Clara	3.67	3.08	1.73	2.88	1.99	1.36	0.36
Santa Cruz	0.67	0.55	0.61	0.67	0.47	0.29	0.18
Solano	1.27	1.15	1.16	1.04	0.79	0.42	0.19
Sonoma	0.99	0.97	0.98	0.73	0.58	0.42	0.20

Customer-Side Resilience

Customer-side resilience tactics to cope with the data and voice service disruptions include additional considerations that we describe in more detail below.

Input Substitution

Various input substitution options given in Rose and Miller (2017), including using paper records and people processes (personal conversations and couriers) rather than telecommunications, are estimated to prevent 20 percent to 35 percent of the loss of productivity from direct data- and voice-service disruptions. To be conservative, we increase the base case percentage of demand for data and voice services met (table 13, column 2) by 20 percent to represent an equivalent availability of data and voice service to customers who substitute inputs for the loss of data and voice services (see appendix 6, table 6.5).

Production Isolation

Production isolation refer to the portion of business operations that can continue without data and voice services. The "importance factors" of telephone services (Applied Technology Council, 1991) are shown in appendix 5, table 5.1, column 4. In appendix 6, table 6.6, we made further adjustments to the Applied Technology Council "importance factors" based on the dependence of individual sectors' operations on internet services. Appendix 6, table 6.7, shows the equivalent data and voice service availability after considering production isolation in the absence of data and voice service.

Combined Supplier-Side and Customer-Side Resilience

After simulating the effects of each of the supplier-side and customer-side resilience tactics to data- and voice-service disruption separately, we combine the effects of all of them together. The tactics are applied in a logical order of permanent backup power and use of portable equipment first; then customer behavior management followed by other customer-side resilience tactics (including input substitution and production isolation) (see estimates in appendix 6, table 6.8, which are in turn used as input to the CGE modeling).

Resilience Adjustments on the Output Side of CGE Modeling

To reflect unusual uses of capital after an earthquake, adjustments for production recapture and telework are applied to the CGE modeling results to reduce GRP losses by sector.[13]

Production Recapture

Production recapture entails employees working overtime and extra shifts after equipment and facilities have been repaired or replaced and employees and critical inputs become available. "Recapture factors" that lead to potential percent reductions in GRP losses for sectors have been used in economic analyses for 20 years (see, for example, FEMA, 2012; Rose and Lim, 2002). We adjust the factor values downward by 50 percent owing to obstacles to efficient implementation such as lack of excess capacity and customers cancelling their orders.[14] The adjusted production recapture factors in appendix 5, table 5.2, are applied directly to reduce GRP losses by sector.

The capability of the businesses to recapture lost productions diminishes over time, because more customers would cancel their orders and seek alternative suppliers as the length of disruption extends. Building recovery time increases with Hazus property damage states of slight, moderate, extensive, and complete damage. Therefore, using Hazus data, we computed the weighted average production recapture factor for each Hazus occupancy class in each county and applied it to the base case GRP losses.[15]

Relocation (Inter-County Shift in Economic Activity)

The multiregional CGE model automatically includes a form of business relocation through inherent substitution (shifts) of production across counties. This need not represent the actual physical move of a damaged operation to another location, but simply production entities in other counties picking up the slack if they have the capacity to do so. A related additional consideration, not taken into account by the CGE model (and discussed further below), is the potential for telework, relocation of good- and service-producing activities to other sites. The major source to estimate the telework potential is the Bureau of Labor Statistics (BLS) (2017) data on the percentage of workers working at least one day at home for different types of occupations. In appendix 6, we further adjusted the BLS data, with considerations of workers' readiness to go back to work after a major disaster, data- and voice-service restoration, and cloud-backup data availability.

[13]The evaluation of the effects of the various resilience tactics assumes that the businesses aim to return to "business as usual" conditions. In practice, businesses will reposition or redefine themselves and find new efficiency, as was reported after the Christchurch earthquakes (Chang and others, 2014; Stevenson and others, 2014; Brown and others, 2015).

[14]Note that most of these factors become more important as the disruption duration increases, but they are still pertinent in a short-run case.

[15]Note that for production recapture of BI losses stemming from property damages, we only have data on the distribution of property damages over damage states for the mainshock. For each occupancy class in each county, we assume that the weighted average recapture factor calculated based on the mainshock distribution of building damage states can be applied to aftershocks as well. The underlying assumption is that the distribution of building damage by severity state for each occupancy class for aftershocks is similar to the distribution for the mainshock. This would be a conservative assumption in terms of the potential of production recapture. This is because the aftershocks are less impactful than the mainshock except in a few localized areas. Since we assume that the damage distribution of the aftershocks is towards the more impactful category (as in the mainshock), on average the corresponding repair and reconstruction time of the buildings would be longer, so that the weighted average production recapture factor we calculate would be small.

Total Economic Impacts

Total economic impacts are estimated using the CGE model with inputs for the base case, with inputs for the various resilience cases, and by adjusting the outputs for production recapture and telework.

Base Case Without Resilience Tactics

Table 14 summarizes the total economic impacts of the HayWired scenario, elaborating on the effects on the bay region and broader California economies in terms of GRP losses resulting from business interruption caused by the HayWired scenario property damage and utility-service disruptions. The base case only includes inherent resilience in the CGE model relating to factor and locational substitution and price adjustments; it does not include the impacts of any other inherent or adaptive resilience tactics addressed subsequently.[16]

By far the greatest BI losses (measured in GRP losses) are caused by the initial mainshock, propagated via the destruction of structures (and, to a lesser extent, their contents) owing to shaking and ground failure. This impact pathway accounts for more than three quarters of the statewide economic loss in the 6-month postearthquake period, which totals $44.2 billion, or 4.2 percent of the State's projected baseline GSP over the period. In table 14 and other tables and figures to follow

[16]Note that the base case results presented in table 14 and the resilience results presented below are primarily based on CGE modeling results. However, adjustment needs to be made for the impacts of water and electricity service disruptions. The readers are referred to appendix 7 for detailed discussions on the adjustments we made.

Table 14. Base-case gross regional product (GRP) change in the first 6 months following the HayWired mainshock in San Francisco Bay region counties and the rest of California.

[Percent change with respect to 6-month benchmark GRP shown in parentheses]

Loss category	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Mainshock	−10.6	−3.4	−2.1	−2.1	−7.4	−1.7	−4.7	**−31.9**
	(−19.7)	(−10.7)	(−3.3)	(−4.8)	(−6.4)	(−1.3)	(−0.7)	**(−3.0)**
Shaking: buildings	−6.5	−2.2	−1.4	−1.3	−4.1	−0.9	−2.9	**−19.2**
	(−12.0)	(−6.9)	(−2.3)	(−3.0)	(−3.5)	(−0.7)	(−0.5)	**(−1.8)**
Shaking: contents	−2.4	−0.8	−0.5	−0.6	−2.0	−0.4	−1.2	**−7.9**
	(−4.3)	(−2.7)	(−0.9)	(−1.3)	(−1.7)	(−0.3)	(−0.2)	**(−0.7)**
Fire	−1.4	−0.32	−0.1	−0.2	−1.2	−0.3	−0.5	**−4.1**
	(−2.5)	(−1.0)	(−0.2)	(−0.5)	(−1.1)	(−0.3)	(−0.1)	**(−0.4)**
Aftershocks	−1.1	−0.16	−0.3	−1.5	−5.5	−0.4	−1.5	**−10.5**
	(−2.1)	(−0.5)	(−0.6)	(−3.3)	(−4.7)	(−0.3)	(−0.2)	**(−1.0)**
Shaking: buildings	−0.7	−0.1	−0.2	−0.9	−3.6	−0.2	−1.0	**−6.8**
	(−1.3)	(−0.3)	(−0.4)	(−2.1)	(−3.1)	(−0.2)	(−0.2)	**(−0.6)**
Shaking: contents	−0.4	−0.06	−0.1	−0.5	−1.9	−0.1	−0.5	**−3.7**
	(−0.8)	(−0.2)	(−0.2)	(−1.2)	(−1.6)	(−0.1)	(−0.1)	**(−0.3)**
Utility-service disruption	−0.7	−0.05	−0.06	−0.07	−0.2	−0.09	−0.2	**−1.4**
	(−1.4)	(−0.2)	(−0.1)	(−0.2)	(−0.1)	(-0.06)	(−0.04)	**(−0.1)**
Power	−0.02	−0.01	−0.01	−0.01	−0.04	−0.01	−0.03	**−0.1**
	(−0.04)	(-0.03)	(−0.02)	(-0.02)	(−0.03)	(−0.01)	(−0.01)	**(−0.01)**
Water[1]	−0.7	−0.02	−0.002	−0.03	−0.02	−0.05	−0.1	**−0.9**
	(−1.2)	(−0.07)	(−0.005)	(−0.08)	(−0.02)	(−0.04)	(−0.02)	**(−0.09)**
Data and voice[2]	−0.06	−0.02	-0.05	−0.03	−0.09	−0.03	−0.08	**−0.4**
	(−0.1)	(−0.06)	(-0.08)	(−0.07)	(-0.08)	(-0.02)	(-0.01)	**(−0.03)**
Total (mainshock, aftershocks, and utility-service disruption)	**−12.7**	**−3.6**	**−2.5**	**−3.6**	**−13.1**	**−2.1**	**−6.5**	**−44.2**
	(−23.5)	**(−11.4)**	**(−4.0)**	**(−8.4)**	**(−11.2)**	**(−1.3)**	**(−1.0)**	**(−4.2)**

[1]Results shown for the "preplan" scenario.

[2]Disruption of the inputs of digital and other information services to intermediate and final consumers in the various counties (internet publishing, telecommunications, data processing, and other information services).

the percentage of GRP losses are calculated with respect to the benchmark 6-month (as opposed to annual) value of the affected regions. Additional GRP losses caused by postmainshock fires are estimated to be $4.1 billion, or about 9 percent of GSP losses. Secondary business interruption, owing to disruption of utility services, leads to GSP losses of $1.4 billion, which is much lower than the BI losses from property damage. This is mainly because utility-service disruptions are largely confined to the three heavily impacted counties (Alameda, Santa Clara, and Contra Costa), and almost all of the counties restore more than 90 percent of power service within 7 days, with data and voice services following.

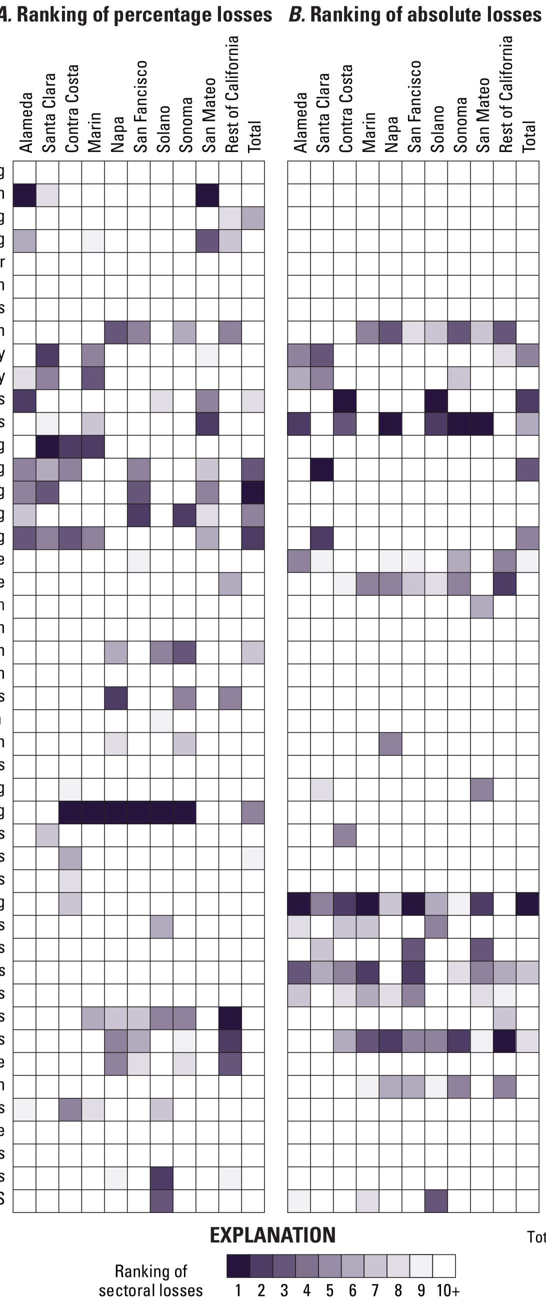
Water service takes the longest time to restore compared to power and data and voice services. Within 30 days, water service is fully restored in most counties. The two most affected counties, Alameda and Contra Costa, have 80 percent of their water service restored within 180 days. Economic losses from water-service disruptions for the HayWired earthquake scenario are much smaller than those found in the previous ShakeOut earthquake scenario. Four factors account for this divergence. First and foremost, the CGE model used in our analysis includes several possibilities to substitute other inputs for piped utility water services in production and consumption, less water-intensive products for those that use relatively more water, and commodity supplies in unaffected counties for production in damaged areas, as the latter become relatively scarce. By contrast, economic analysis of the ShakeOut scenario employed an input-output model whose fixed-coefficient representation of production and consumption activities precludes substitution behavior within activities; the only substitution that occurs is through differential changes in the levels of sectoral production. The additional margins of substitution in our analysis thus confer substantial cost-savings. Second, our analysis considers a broader array of resilience measures (including both additional inherent resilience tactics that are not already embedded in the CGE model and adaptive resilience tactics), all of which substantially lessen the magnitude of shock to water supplies that producers and consumers might actually experience. Similarly, a third factor is that the HayWired scenario water services are restored relatively faster than ShakeOut scenario water disruptions owing to the character of bay region infrastructure and the earthquake damage it sustains. Finally, in the ShakeOut analysis, water accounted for a larger part of the cost of production in industries in Southern California, with concomitantly larger increases in sectoral production costs associated with disruptions of water service.[17]

[17]Examination of the detailed input-output structure of the economies of Los Angeles County and Alameda County (which suffers the most damage in this study) reveals that, out of the 440 sectors in our 2012 IMPLAN database, water intensity (water and sewer utilities' share of total production cost) was higher for 269 industry groups in Los Angeles, compared to only 144 industries in Alameda. Additionally, the difference in the magnitude of economic output of the two sets of water-intensive sectors suggests that a given percentage disruption in water supply will likely incur absolute losses that are far larger in Los Angeles County, as the total gross output of sectors that were relatively more water-intensive in Los Angeles amounted to $553 billion, as compared with only $36 billion for those in Alameda.

Overall losses are concentrated in the five bay region counties that are most directly affected by the earthquake property damage, which together account for 80 percent of the overall reduction in GSP in the first 6 months (see the last row of table 14). Alameda and Santa Clara Counties are most severely impacted by destruction of buildings and their contents as a consequence of both the mainshock and aftershocks, and suffer reductions in economic output of $12.7 billion and $13.1 billion, or more than 23 percent and 11 percent of county-level baseline GRP, respectively. GRP of areas not directly damaged by the earthquake decreases by 1 percent ($6.5 billion). The percent decrease for the rest of the bay region is closer to the rest of California than the five most affected counties.

Figure 2 summarizes the effects of the earthquake at the sectoral level in the bay region and across the State. The "heatmaps" identify the sectors within each county that experience the ten largest reductions in gross output, and rank their losses shown in terms of percentages in figure 2*A*, and absolute dollars in figure 2*B*. The losses themselves are detailed in figure 2*C*. The figure highlights two clusters of activities that are most affected. The first encompasses manufacturing (food/drugs/chemicals, light and heavy industry, petroleum refining, computer/high tech manufacturing), trade (wholesale and retail trade, warehousing), and construction. Across the counties, manufacturing and construction generally show larger absolute and percentage effects, although percentage effects are most notable for device manufacturing, whereas trade sectors feature for absolute impacts. The second encompasses "brick and mortar" services (education, hospitals and nursing homes, arts/entertainment/recreation), information and hi-tech services (publishing/motion pictures/broadcasting, internet publishing, other business and scientific/technical services, computer systems design), as well as finance and real estate (finance/insurance/real estate, dwellings). These sectors feature across counties for absolute effects except for the percentage of effects on information and education. The latter do not show up in the ten largest reductions in Alameda and Santa Clara Counties where effects to the manufacturing sectors dominate.

Regarding the magnitude of sectoral effects, Santa Clara and Alameda Counties are hardest hit, experiencing similar aggregated net losses of gross output (on the order of $20 billion), whereas the effect on Contra Costa County's gross output is less than half as large and San Francisco's is less than a quarter as large. The aggregated reductions in gross output in figure 2*C* are considerably larger than the GRP losses in table 14, in both percentage and absolute terms. This result is unsurprising, however, given that the reductions in output of upstream sectors are a direct consequence of reduced demand owing to curtailment of production by downstream sectors. For this reason, summing gross output losses across the sectors in each region dramatically overstates the true economic effect. In earthquake-affected counties, building-, content-, and fire-related destruction of capital stocks triggers direct curtailment of the production and domestic supply of goods, with concomitant increases in their prices. Because the outputs



C. Sectoral gross output loss (in billions of 2012 dollars [percent change from baseline])

Sector	Alameda	Santa Clara	Contra Costa	Marin	Napa	San Francisco	Solano	Sonoma	San Mateo	Rest of California	Total
Agriculture, forestry, fishing, and hunting											
Oil and gas extraction	–0.02 [–44]	–0.01 [–13]							0.00 [–13]		
Coal mining										0.00 [–2]	0.00 [–10]
Other mining	–0.01 [–37]			0.00 [–5]					0.00 [–12]	–0.05 [–2]	
Electric power											
Natural gas distribution											
Water, sewage, and other systems											
Construction				–0.03 [–5]	–0.01 [–4]	–0.14 [–6]	–0.03 [–3]	–0.03 [–3]	–0.18 [–8]	–0.92 [–2]	
Heavy industry	–1.42 [–31]	–2.40 [–14]		–0.01 [–6]					–0.13 [–10]	–0.37 [–0.6]	–4.62 [–5]
Light industry	–1.28 [–31]	–1.35 [–13]		–0.01 [–8]				–0.01 [–1]			
Petroleum refineries	–0.64 [–42]		–3.67 [–10]				–0.11 [–4]		–0.01 [–12]		–4.99 [–7]
Food, drug, and chemicals	–1.81 [–27]	–0.41 [–12]	–0.46 [–12]	–0.02 [–5]	–0.05 [–2]		–0.10 [–3]	–0.04 [–1]	–1.14 [–13]		–4.60 [–4]
Primary metal manufacturing		–0.04 [–15]	–0.10 [–16]	0.00 [–10]							
Electronic computer manufacturing	–0.62 [–37]	–4.07 [–13]	0.00 [–15]			–0.02 [–6]			–0.07 [–11]		–4.94 [–13]
Computer storage device manufacturing	–0.22 [–37]	–0.15 [–14]				–0.01 [–7]			–0.02 [–11]		–0.42 [–16]
Semiconductor and related device manufacturing	–0.07 [–33]					0.00 [–7]		0.00 [–4]	–0.01 [–10]		–0.20 [–13]
Other high technology related manufacturing	–0.83 [–39]	–3.84 [–14]	–0.01 [–16]	0.00 [–6]					–0.02 [–11]		–4.74 [–13]
Wholesale trade, warehousing, and storage	–1.42 [–26]	–0.76 [–11]			0.00 [–2]	–0.12 [–6]		–0.01 [–1]		–0.50 [–0.8]	–3.38 [–4]
Retail trade			–0.21 [–10]	–0.03 [–4]	–0.01 [–3]	–0.16 [–5]	–0.02 [–3]	–0.02 [–2]		–1.03 [–2]	
Air transportation									–0.23 [–8]		
Rail transportation											
Water transportation					0.00 [–4]		0.00 [–5]	0.00 [–3]			–0.15 [–9]
Truck transportation											
Transit and ground passengers					0.00 [–5]			0.00 [–3]		–0.03 [–2]	
Pipeline transportation							0.00 [–4]				
Sightseeing transportation					–0.01 [–3]			0.00 [–3]			
Couriers and messengers											
Publishing, motion picture, and broadcasting		–0.79 [–12]	–0.05 [–15]						–0.39 [–9]		
Internet publishing and broadcasting			0.00 [–23]	0.00 [–10]	0.00 [–10]	–0.06 [–9]	0.00 [–10]	0.00 [–5]			–0.63 [–11]
Telecommunications		–0.48 [–13]	–0.30 [–14]								
Data processing, hosting, and related services			–0.02 [–15]								–0.37 [–7]
Other Information services			0.00 [–15]								
Finance, insurance, real estate, and leasing	–2.09 [–25]	–1.77 [–12]	–1.26 [–15]	–0.13 [–3]	–0.01 [–0.9]	–0.74 [–3]	–0.03 [–2]	–0.01 [–0.3]	–0.86 [–8]		–7.43 [–3]
Owner–occupied dwellings	–0.95 [–25]		–0.25 [–10]	–0.03 [–4]			–0.04 [–4]				
Computer systems design and related services		–0.83 [–8]				–0.30 [–5]			–0.62 [–7]		
Other professional, scientific, and technical services	–1.45 [–22]	–1.16 [–10]	–0.32 [–12]	–0.05 [–3]		–0.37 [–4]		–0.01 [–1]	–0.35 [–7]	–0.44 [–0.6]	–4.40 [–4]
Other business services	–1.14 [–22]		–0.23 [–12]	–0.03 [–4]	–0.01 [–2]	–0.22 [–4]			–0.17 [–8]	–0.36 [–0.8]	
Educational services				–0.01 [–6]	0.00 [–3]	–0.09 [–6]	–0.01 [–5]	–0.01 [–3]		–0.40 [–2]	
Ambulatory health care and hospitals			–0.26 [–7]	–0.04 [–4]	–0.02 [–4]	–0.22 [–6]	–0.04 [–3]	–0.04 [–2]	–0.16 [–7]	–1.76 [–2]	–4.37 [–4]
Nursing home/social assistance					0.00 [–4]	–0.05 [–6]		–0.01 [–3]		–0.31 [–2]	
Arts, entertainment, and recreation				–0.02 [–3]	–0.01 [–2]	–0.18 [–4]	–0.02 [–3]	–0.02 [–2]		–0.54 [–1]	
Accommodations	–0.07 [–31]		–0.02 [–15]	0.00 [–5]			0.00 [–4]				
Repair and maintenance											
Personal services/private households											
Religious, grantmaking, and similar organizations					0.00 [–3]		–0.01 [–6]			–0.15 [–2]	
Government and non-NAICS	–0.86 [–15]			–0.02 [–3]			–0.10 [–6]				
Total:	–20.5 [–23]	–22.7 [–12]	–8.6 [–11]	–0.5 [–4]	–0.2 [–2]	–3.5 [–4]	–0.6 [–3]	–0.3 [–1]	–5.5 [–8]	–9.5 [–0.8]	–76.8 [–4]

Figure 2. Top ten sectoral total gross output losses in San Francisco Bay region counties and the rest of California. NAICS, North American Industry Classification System (U.S. Census Bureau, 2017).

of producing sectors are used as intermediate inputs to production by other sectors, a crucial secondary effect of the initial damage is to reduce the quantity of intermediate inputs to producing sectors. The result is further reductions in sectoral output beyond those attributable solely to shrinkage in the economy's endowment of capital.

This multiplier effect is moderated by the inherent resilience of the economic system, in the form of substitution along two margins. The first is the producers' ability to substitute mobile factors (in our simulations, labor) for damaged capital and curtailed intermediate commodity inputs. The second margin is producer and consumer substitution of commodities imported from other counties, States, or world regions for domestically produced goods. But movement along the second margin is balanced by the income effects of earthquake damage on final consumers—by shrinking the endowment of, and the value of returns to, capital, the disaster reduces households' real income at the same time as their purchasing power is eroded by spiking goods prices, dampening their ability to increase imports. When the CGE model is simulated with all components of damage, the latter dampening effect outweighs the former propagating effect, resulting in a decrease in aggregate consumption and imports of commodities statewide (see fig. 4).

Within California, the concomitant reduction in the demand for commodity exports from unaffected counties induces a decrease in goods prices, domestic supply, and the returns to non-reproducible factors of production (labor and capital). It is for this reason that sectoral output and GRP decrease in both less affected bay region counties and unaffected counties in the remainder of the State. Even though the latter effect is very slight in intensity (percentage) terms, it is spread over a large swath of economic activity, and thus generates a more substantial aggregate impact.

Differences between parts *A* and *B* of figure 2 suggests that although internet publishing experiences some of the most acute gross output losses in percentage terms, that industry's comparatively small size relative to other industries means that its losses in absolute terms are dwarfed by those of less severely impacted, but economically much larger, sectors. Even so, out of all industries, the absolute losses sustained by the telecommunications and internet publishing sectors are ranked 14th and 15th in San Francisco County and 11th and 12th in Santa Clara County, respectively, and the telecommunications sector suffers the 5th largest output decrease of any sector in Contra Costa County.

Figure 3 suggests that capital stock damage owing to the mainshock and aftershocks is strongly predictive of the decrease in gross output experienced by telecommunications, data processing, other information services, and, for large losses, internet publishing.[18] The last of these sectors highlights the role of trade in the propagation of business interruption across the regional economy in counties such as Marin, Solano and Santa Cruz, that are geographically contiguous to the main disaster zone and export more than 80 percent of their internet publishing output. Internet publishing in these counties suffers slight damage (<5 percent of capital input), but experiences decreases in gross output that are two to three times as large. Because our CGE model's Armington (1969) structure does not explicitly model county-to-county bilateral trade in commodities and services, these decreases cannot be directly traced to the decrease in aggregate absorption by the bay region counties directly affected by the earthquake.[19] Notwithstanding this, figure 4 demonstrates that our simulations nonetheless capture the reduction in aggregate consumption of domestic and imported goods (fig. 4*A*) and aggregate intra-state exports (fig. 4*B*), which are the key drivers for this phenomenon.

[18]General equilibrium effects are the primary reason that some sectors' outputs do not decrease in lock-step with the direct damage to their capital stocks. For example, internet publishing not only suffers direct damage (on the x-axis) but also faces smaller supplies of data processing and telecommunications inputs, whose prices increase significantly.

[19] In the model, commodity exports from individual counties augment a statewide pool, from which individual counties' imports are then drawn. See appendix 3 for algebraic details.

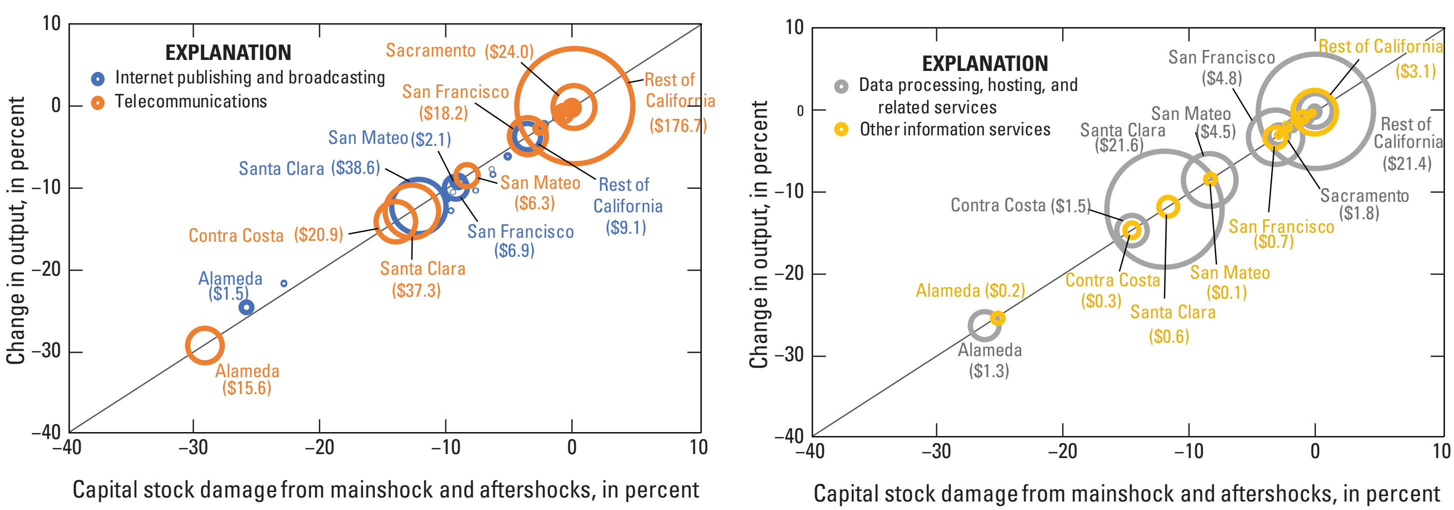


Figure 3. Damage and output impacts on information and communications technology service sectors.

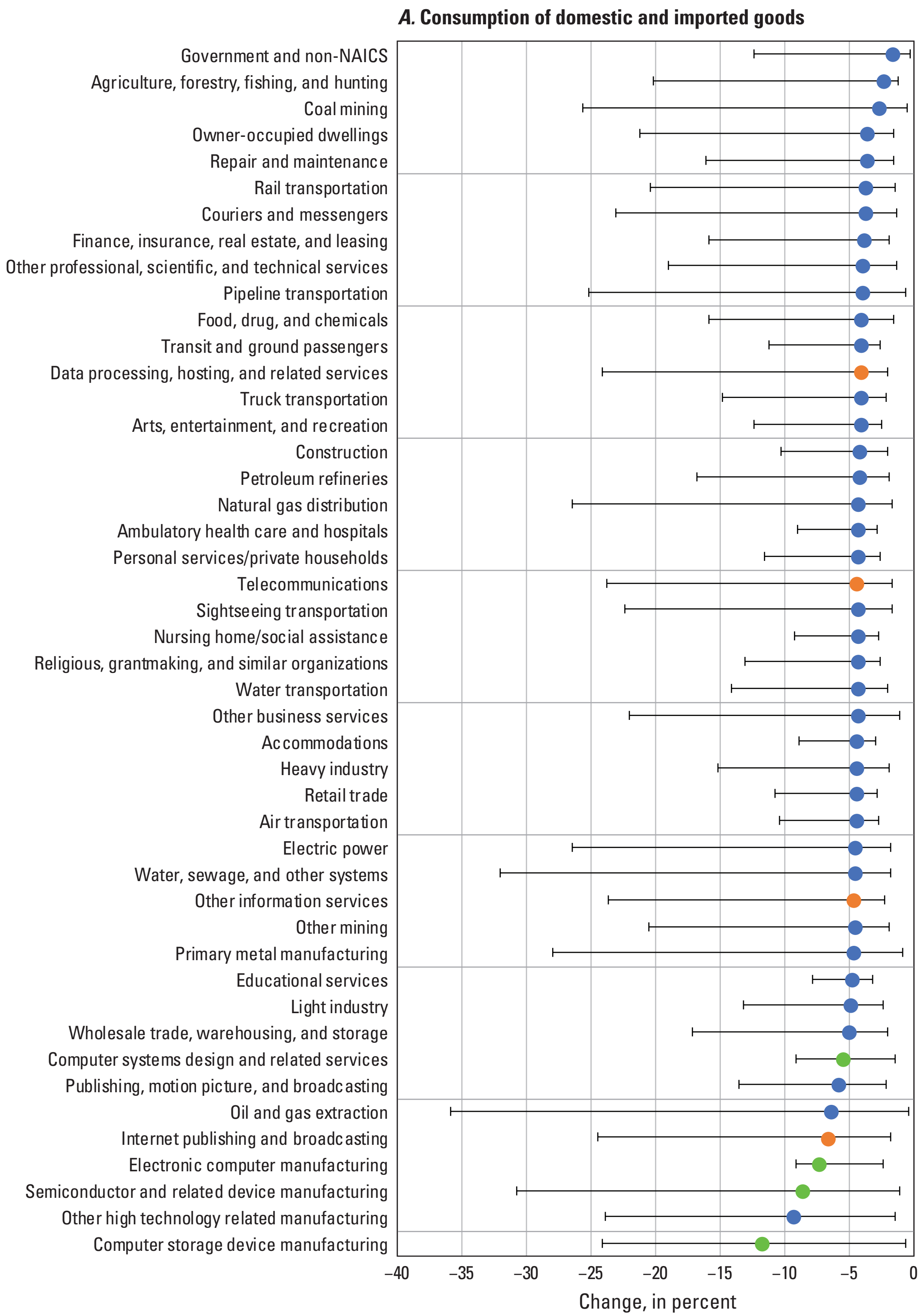


Figure 4 (pages 22–23). Statewide effects on goods and services trade and consumption, by commodity. In part *A*, error-bars show range across model regions of percentage changes in Armington aggregate use. Information and communications technology (ICT) and other information sectors in orange, ICT-supporting hi-tech service and durable goods sectors in green, all other sectors in blue. NAICS, North American Industry Classification System (U.S. Census Bureau, 2017).

B. **Aggregate intrastate exports**

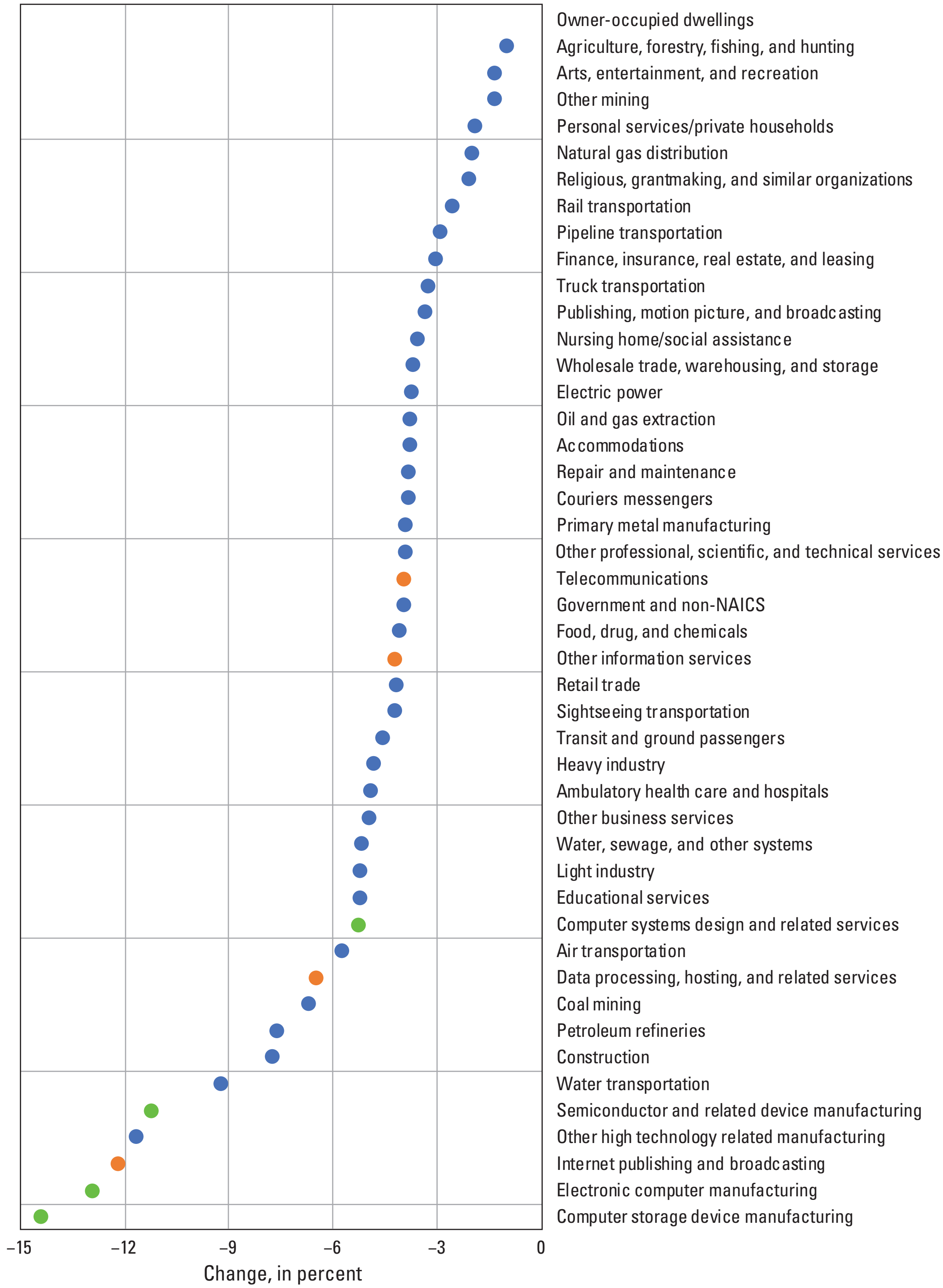


Figure 4 (pages 22–23).—Continued

Total Economic Impacts with Resilience Tactics

In this section, we discuss the total economic effects of various resilience tactics for different loss categories (property damages, water- and power-service disruptions). Next, the aggregate effects after combining all the resilience adjustments are discussed.

Economic Impacts from Property Damage with Resilience Tactics

BI losses from property damage are reduced by telework and production recapture (discussed in subsection on Resilience Adjustments). Table 15 shows GRP losses caused by property damage for the base case and adjusting for telework, production recapture, and combined resilience tactics. Property damages without and with fire are considered. Table 16 shows the potential for these resilience tactics to reduce BI losses stemming from property damage. Loss-reduction potential is calculated by dividing the avoided losses by the total losses for the base case. The results indicate that production recapture has a much higher loss-reduction potential than telework.

Table 16. Gross State product (GSP) loss-reduction potential of individual resilience tactics for property damage for California.

[Combined resilience is telework and production recapture. The combined reduction of GSP losses is not equal to sum of both entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by property damage, in percent
Mainshock (without fire) and aftershocks	
Telework	6.4
Production recapture	38.0
Combined resilience	44.7
Mainshock (with fire) and aftershocks	
Telework	6.3
Production recapture	36.9
Combined resilience	40.9

Table 15. Gross regional product (GRP) change caused by property damage in the first 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP shown in parentheses. Combined resilience is telework and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Mainshock (without fire) and aftershocks								
Base case	−10.0	−3.2	−2.3	−3.4	−11.6	−1.7	−5.5	**−37.6**
	(−18.5)	(−5.7)	(−3.7)	(−7.6)	(−10.0)	(−1.0)	(−0.9)	**(−3.5)**
Telework	−9.4	−2.9	−2.0	−3.1	−11.0	−1.6	−5.2	**−35.2**
	(−17.4)	(−5.4)	(−3.3)	(−6.9)	(−9.5)	(−1.0)	(−0.8)	**(−3.3)**
Production recapture	−6.5	−2.0	−1.4	−2.0	−6.7	−1.1	−3.6	**−23.3**
	(−12.1)	(−3.7)	(−2.2)	(−4.6)	(−5.7)	(−0.7)	(−0.6)	**(−2.2)**
Combined resilience	−6.2	−1.9	−1.2	−1.8	−6.3	−1.0	−2.4	**−20.8**
	(−11.4)	(−3.5)	(−2.0)	(−4.2)	(−5.4)	(−0.6)	(−0.4)	**(−2.0)**
Mainshock (with fire) and aftershocks								
Base case	−11.8	−3.5	−2.4	−3.6	−12.9	−2.1	−6.2	**−42.5**
	(−21.8)	(−6.4)	(−3.9)	(−8.1)	(−11.1)	(−1.3)	(−1.0)	**(−4.0)**
Telework	−11.1	−3.3	−2.1	−3.3	−12.2	−1.9	−5.9	**−39.8**
	(−20.5)	(−6.0)	(−3.5)	(−7.4)	(−10.5)	(−1.2)	(−0.9)	**(−3.7)**
Production recapture	−7.8	−2.3	−1.5	−2.2	−7.6	−1.3	−4.1	**−26.8**
	(−14.5)	(−4.2)	(−2.4)	(−5.0)	(−6.5)	(−0.8)	(−0.7)	**(−2.5)**
Combined resilience	−7.4	−2.1	−1.3	−2.0	−7.2	−1.2	−3.9	**−25.1**
	(−13.6)	(−3.9)	(−2.1)	(−4.5)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**

Economic Impacts of Water-Service Disruptions with Resilience

Table 17 shows GRP losses by region caused by water-service disruptions for both the base case and adjusting for various resilience tactics. The first three rows show the base case (no resilience tactics) for the three water-service-disruption scenarios: preplan (as-is conditions), postplan (fuel management plan), and ideal world (fuel management plan and pre-event mitigation). The next four rows show the results for the conservation, production isolation, production recapture, and combined resilience tactics (combining all three resilience tactics) for the preplan scenario, respectively. The last two rows show the results for the combined resilience tactics for the postplan and ideal-world scenarios.

Table 18 shows a summary of the loss-reduction potentials of each individual water resilience tactic for the preplan water-service-disruption scenario. The most effective resilience tactic is production isolation. The combined effect of all resilience tactics considered reduces the water-service disruption GSP losses for California by 91 percent, 86 percent, and 78 percent for the preplan (base case), postplan, and ideal-world water-service-disruption scenarios, respectively.

Table 18. Gross State product (GSP) loss-reduction potential of individual resilience tactics for water-service disruption for the preplan water disruption scenario for California.

[Combined resilience is conservation, production isolation, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by water disruption, in percent
Conservation	7.4
Production isolation	86.1
Production recapture	34.4
Combined resilience	91.0

Table 17. Gross regional product (GRP) change caused by water-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is production isolation and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case—preplan	−0.654	−0.022	−0.002	−0.030	−0.023	−0.052	−0.127	**−0.911**
	(−1.211)	(−0.071)	(−0.005)	(−0.075)	(−0.023)	(−0.037)	(−0.022)	**(−0.090)**
Base case—postplan	−0.309	−0.017	0.000	−0.022	−0.023	-0.037	−0.075	**−0.508**
	(−0.566)	(−0.052)	(0.000)	(−0.052)	(−0.019)	(−0.022)	(−0.015)	**(−0.045)**
Base case—ideal-world scenario	−0.053	−0.007	0.000	−0.015	−0.009	−0.015	−0.030	**−0.149**
	(−0.097)	(−0.019)	(0.000)	(-0.037)	(−0.009)	(−0.007)	(−0.007)	**(−0.015)**
Preplan and conservation	−0.592	−0.020	−0.002	−0.030	−0.023	−0.052	−0.119	**−0.844**
	(−1.087)	(−0.067)	(−0.005)	(−0.075)	(−0.019)	(−0.030)	(−0.015)	**(−0.082)**
Preplan and production isolation	−0.053	−0.005	0.000	−0.007	−0.009	−0.015	−0.022	**−0.127**
	(−0.088)	(−0.019)	(0.000)	(−0.022)	(−0.009)	(−0.007)	(−0.007)	**(−0.015)**
Preplan and production recapture	−0.433	-0.013	−0.002	−0.022	−0.019	−0.037	−0.082	**−0.597**
	(−0.795)	(−0.046)	(−0.004)	(−0.045)	(−0.014)	(−0.022)	(−0.015)	**(−0.060)**
Combined resilience—preplan	−0.035	−0.003	0.000	−0.007	−0.005	−0.007	−0.015	**−0.082**
	(−0.062)	(−0.012)	(0.000)	(−0.015)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Combined resilience—postplan	−0.027	−0.002	−0.001	0.000	−0.005	−0.015	−0.015	**-0.067**
	(−0.053)	(−0.007)	(−0.001)	(0.000)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Combined resilience—ideal-world	−0.009	−0.002	0.000	0.000	−0.005	0.000	−0.007	**−0.030**
	(−0.018)	(−0.005)	(0.000)	(-0.007)	(−0.005)	(0.000)	(0.000)	**(0.000)**

Economic Impacts of Power Disruptions with Resilience

Table 19 shows GRP losses by region caused by power-service disruptions for both the base case and adjusting for various resilience tactics. The resilience tactics analyzed include conservation, production isolation, and production recapture. The combined effects (after eliminating double counting) of these three resilience tactics are shown in the last row of table 19. The GSP losses in California stemming from power-service disruptions can be reduced from $100 to $50 million after adjusting for these three resilience tactics. Table 20 shows a summary of the loss-reduction potentials of each individual resilience tactic. Production recapture is the most effective resilience tactic for power-service disruption, and alone could reduce GSP losses in California by nearly 40 percent.

Economic Impacts of Data- and Voice-Service Disruption with Resilience

Table 21 shows GRP losses caused by data- and voice-service disruption for both the base case and adjusting for various resilience tactics. Table 22 shows a summary of the loss-reduction potentials of each individual ICT service-related resilience tactic. The loss-reduction potentials are calculated by dividing the avoided losses from each individual resilience tactic by the total losses calculated in the base case (without resilience tactics) for data- and voice-service disruption (see Rose, 2017).

Table 20. Gross State product (GSP) loss-reduction potential of individual resilience tactics for power-service disruption for California.

[Combined resilience is conservation, production isolation, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions.]

Resilience tactic	Potential reduction of base-case GSP losses caused by power disruption, in percent
Conservation	2.3
Production isolation	12.9
Production recapture	40.2
Combined resilience	49.2

Total Economic Impacts with Resilience

Table 23 shows the total economic impacts of the HayWired earthquake scenario after we consider all the resilience tactics we discussed above for the various conduits of shock to the economy. The base-case total GRP change are first shown, followed by the GRP change for various conduits of shock to the economy, property damage, and various types of utility service disruptions, adjusting for the combined resilience tactic cases discussed in the previous sections. The total economic impacts with resilience are shown in the last row of table 23. Combining all the resilience tactics we considered in this study, GSP losses in California decrease from $44.2 billion to $25.3 billion, a reduction of about 43 percent of the total losses.

Table 19. Gross regional product (GRP) change caused by power-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is conservation, production isolation, and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	SanFrancisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars percent change)							
Base case	−0.023	−0.009	−0.014	−0.009	−0.037	−0.011	−0.029	**−0.132**
	(−0.042)	(−0.026)	(−0.023)	(−0.021)	(−0.033)	(−0.007)	(−0.005)	**(−0.012)**
Conservation	−0.023	−0.008	−0.013	−0.009	−0.037	−0.011	−0.029	**−0.129**
	(−0.041)	(−0.026)	(−0.021)	(−0.021)	(−0.031)	(−0.007)	(−0.005)	**(−0.012)**
Production isolation	−0.019	−0.008	−0.011	−0.008	−0.034	−0.009	−0.026	**−0.115**
	(−0.035)	(−0.024)	(−0.019)	(−0.018)	(−0.030)	(−0.005)	(−0.004)	**(−0.011)**
Production recapture	−0.014	−0.005	−0.009	−0.005	−0.022	−0.007	−0.018	**−0.079**
	(−0.025)	(−0.016)	(−0.014)	(−0.013)	(−0.019)	(−0.004)	(−0.003)	**(−0.008)**
Combined resilience	−0.011	−0.004	−0.007	−0.005	−0.019	−0.005	−0.016	**−0.067**
	(−0.020)	(−0.014)	(−0.011)	(−0.011)	(−0.016)	(−0.003)	(−0.003)	**(−0.007)**

Table 21. Gross regional product (GRP) change caused by data- and voice-service disruption in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. Combined resilience is supplier backup power and portable equipment, user behavior management, and customer input substitution, production isolation, telework, and production recapture]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case	−0.064	−0.020	−0.047	−0.030	−0.090	−0.028	−0.075	**−0.354**
	(−0.119)	(−0.063)	(−0.076)	(−0.067)	(−0.078)	(−0.017)	(−0.012)	**(−0.033)**
Supplier backup power	−0.056	−0.017	−0.041	−0.025	−0.076	−0.025	−0.064	**−0.302**
	(−0.103)	(−0.053)	(−0.066)	(−0.056)	(−0.065)	(−0.015)	(−0.010)	**(−0.028)**
Portable equipment	−0.037	−0.009	−0.034	−0.019	−0.044	−0.021	−0.044	**−0.208**
	(−0.069)	(−0.030)	(−0.056)	(−0.042)	(−0.037)	(−0.013)	(−0.007)	**(−0.020)**
User behavior management	−0.059	−0.015	−0.041	−0.026	−0.071	−0.025	−0.064	**−0.302**
	(−0.108)	(−0.049)	(−0.067)	(−0.060)	(−0.061)	(−0.015)	(−0.010)	**(−0.028)**
Customer input substitution	−0.035	−0.010	−0.030	−0.017	−0.049	−0.018	−0.043	**−0.202**
	(−0.065)	(−0.033)	(−0.048)	(−0.039)	(−0.042)	(−0.011)	(−0.007)	**(−0.019)**
Production isolation	−0.026	−0.006	−0.024	−0.013	−0.033	−0.012	−0.031	**−0.145**
	(−0.048)	(−0.020)	(−0.039)	(−0.030)	(−0.029)	(−0.007)	(−0.005)	**(−0.014)**
Telework	−0.063	−0.019	−0.045	−0.028	−0.089	−0.027	−0.073	**−0.345**
	(−0.117)	(−0.061)	(−0.073)	(−0.064)	(−0.076)	(−0.017)	(−0.012)	**(−0.032)**
Production recapture	−0.038	−0.012	−0.027	−0.017	−0.052	−0.017	−0.046	**−0.209**
	(−0.070)	(−0.038)	(−0.044)	(−0.038)	(−0.045)	(−0.011)	(−0.007)	**(−0.020)**
Combined resilience	−0.005	−0.001	−0.006	−0.003	−0.005	−0.010	−0.007	**−0.037**
	(−0.010)	(−0.003)	(−0.009)	(−0.006)	(−0.005)	(−0.006)	(−0.001)	**(−0.003)**

Table 22. Gross State product (GSP) loss-reduction potential of individual resilience tactics for voice and data service-related disruptions for California.

[Combined resilience is supplier backup power and portable equipment, user behavior management, customer input substitution, production isolation, telework, and production recapture. The combined reduction of GSP losses is not equal to sum of all entries owing to overlaps in individual loss reductions]

Resilience tactic	Potential reduction of base-case GSP losses caused by data and voice disruption, in percent
Supplier permanent backup power	14.7
Supplier portable equipment	41.3
User behavior management	14.8
Customer input substitution	43.0
Production isolation	59.0
Telework	2.7
Production recapture	40.9
Combined resilience	89.6

To place our economic impact estimates in perspective, we compare them with recessions that have affected the United States and the State of California since the end of World War II. The formal definition of a recession is a decrease in GDP in two successive calendar quarters. Until the “Great Recession” of 2008–09, these recessions generally resulted in a decrease in U.S. GDP of about 2 percent in at least one of the calendar quarters. On the other hand, the Great Recession resulted in a drop in GDP of about 8.4 percent, in the fourth quarter of 2008 and 4.4 percent in the first quarter of 2009. The annual rates of decrease were 0.1 percent in 2008 and 2.5 percent in 2009 for the Nation. The San Francisco-Oakland-Hayward Metropolitan Statistical Area suffered GRP decreases of 4.9 percent in 2008 and 2.8 percent in 2009. Our estimates of total economic impacts after factoring in resilience (see table 23) indicate the largest GRP decrease of 13.8 percent in Alameda County, a decrease of 2 to 6 percent in the other five most affected bay region counties, a decrease of 0.8 percent in the rest of the bay region, and a decrease of 0.6 percent in the rest of California in 6 months. The predicted economic effects of the HayWired scenario earthquake would result in a type of recession but would not have a multiyear effect like the Great Depression of the 1930s.

Table 23. Total gross regional product (GRP) change in the 6 months following the HayWired mainshock for the base case and adjusting for various resilience tactics in San Francisco Bay region counties and rest of California.

[Percent change with respect to 6-month benchmark GRP in parentheses. BI, business interruption]

Loss-reduction tactic	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of bay region	Rest of California	California total
	GRP change in billions of 2012 dollars (percent change)							
Base case (no resilience)	−12.7	−3.6	−2.5	−3.6	−13.1	−2.1	−6.5	**−44.2**
	(−23.5)	(−11.4)	(−4.0)	(−8.4)	(−11.2)	(−1.3)	(−1.0)	**(−4.2)**
BI from property damage (with resilience)	−7.4	−2.1	−1.3	−2	−7.2	−1.2	−3.9	**−25.1**
	(−13.6)	(−3.9)	(−2.1)	(−4.5)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**
Water-service disruption (with resilience)	−0.035	−0.003	0.000	−0.007	−0.005	−0.007	−0.015	**−0.082**
	(−0.062)	(−0.012)	(0.000)	(−0.015)	(−0.005)	(−0.007)	(0.000)	**(−0.007)**
Power-service disruption (with resilience)	−0.011	−0.004	−0.007	−0.005	−0.019	−0.005	−0.016	**−0.067**
	(−0.020)	(−0.014)	(−0.011)	(−0.011)	(−0.016)	(−0.003)	(−0.003)	**(−0.007)**
Data- and voice-service disruption (with resilience)	−0.005	−0.001	−0.006	−0.003	−0.005	−0.010	−0.007	**−0.037**
	(−0.010)	(−0.003)	(−0.009)	(−0.006)	(−0.005)	(−0.006)	(−0.001)	**(−0.003)**
Total effects (with resilience)	−7.45	−2.11	−1.31	−2.02	−7.23	−1.23	−3.94	**−25.29**
	(−13.8)	(−3.4)	(−2.1)	(−4.6)	(−6.2)	(−0.8)	(−0.6)	**(−2.4)**

Dynamic Economic Recovery

In this section, we seek to understand how the differences in capital stock destruction across California drive reconstruction and thereby affect growth. The CGE model is limited in its suitability to analyze the effect of the earthquake on the dynamic path of California's economies, principally because its static formulation is set up to capture short-run economic effects, as opposed to forward-looking investment decisions that drive recovery. To address this shortcoming we construct a multiregional intertemporal partial equilibrium simulation that does not delve into the sectoral and regional details that underlie many of the results in the section on Direct Economic Impacts in order to place into sharp relief the impacts on, and consequences of, accumulation of capital. We adopt a simplified modeling approach to circumvent the substantial analytical and computational challenges required for the specification and solution of a multisector, multiregion, intertemporal model in which interregional productivity differences can be arbitraged by trade flows. The outcome is a multiregional model of the California economy that simulates aggregate investment, capital accumulation, production, consumption, and commodity trade in eight regional economies within the State over the 17-year (2018–2035) horizon on a semi-annual time-step. (A detailed description of the model is given in appendix 8.)

The main results, shown in figure 5, indicate that, with intertemporally optimizing economic agents, perfect markets, and an absence of frictions, California's economy will substantially recover over a period as short as a decade. Figure 5*A* shows that damage from shaking and fire reduce the size of the initial aggregate capital stock by nearly 30 percent in Alameda County, 14 percent in Santa Clara and Contra Costa Counties, and 10 percent in San Mateo County, whereas the remaining bay region counties sustain damage to their capital stocks of less than 5 percent. Interestingly, in the 6-month period immediately following this economic shock, capital stocks in the largely unaffected remainder of the bay region and the State also decrease relative to the baseline (business as usual). The reason is reallocation of investment toward the most severely damaged counties, shown in figure 5*B*. Statewide, the earthquake reduces initial capital by 4 percent. This in turn induces an increase in investment that initially covers the capital loss and then reverts slowly to the long-run baseline level over the course of the simulation horizon. This behavior arises from the fact that the quantity of investment is smaller than the capital stock, so that damage to the latter can only be offset by a sustained increase in the rate of accumulation of the former. Relative to baseline levels of investment, increases of 160 percent in Alameda County and 80 percent in Santa Clara and Contra Costa Counties drive rapid accumulation of capital, with stocks approaching 95 percent of their baseline levels less than 5 years after the earthquake, and 99 percent a decade postearthquake in these three counties. In the less-affected and unscathed areas of the State, investment and capital stocks—which are larger in magnitude—recover more slowly, attaining 98 percent and 99 percent of their baseline levels after 5 years and a decade, respectively.

In response to the departure of regional capital stocks from their baseline trajectories, gross output, value added, intermediate commodity uses, and final consumption all exhibit qualitatively similar dynamics (fig. 5*C*–*F*). The regions' initial declines and subsequent patterns of recovery mirror those of their respective capital stocks in figure 5*A*. This congruence is unsurprising given the small values of the elasticities of substitution, which limits the ability of regional

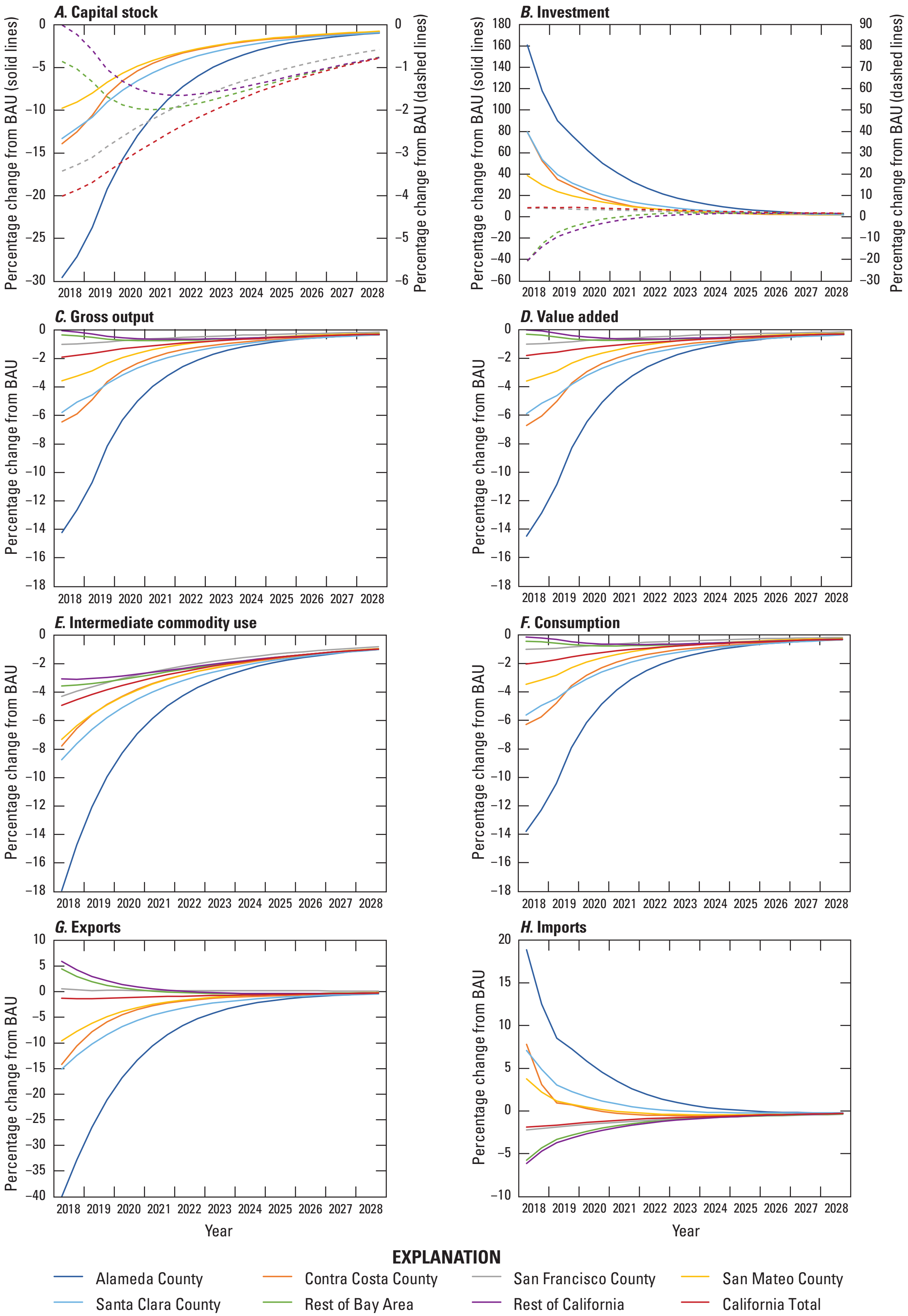


Figure 5. Plots showing percentage change from business as usual by semi-annual time steps following the HayWired mainshock for several economic factors, illustrating the dynamics of postearthquake recovery. BAU, business as usual.

producers to compensate for the impact of capital damage on production by increasing the quantity of intermediate commodity inputs. The consequent near-complementarity between capital and intermediate goods means that inputs of the latter decrease, albeit by a smaller amount than the shock to capital. The upshot is that the economy experiences a slightly larger reduction in value added than gross output, and both quantities decrease by a much smaller amount than capital. California's aggregate gross output and value added experience decrease by about 2 percent initially, after which they slowly increase to their long-run levels over the simulation horizon. The decrease in consumption is even smaller, as households attempt to preserve their level of utility, consistent with the model's objective function to maximize social welfare.[20] The magnitude of value-added losses is one-half to two-thirds as large as those computed by the CGE model. This result can be traced to the growth model's homogeneous representation of regional production, which implicitly assumes perfect substitutability among the outputs of, and the intermediate inputs to, different sectors, whereas the CGE model assumes far less elastic substitution among intermediate inputs to each sector, and among the contributions of the various sectors to regional consumption, investment, and exports.

Especially in the most affected counties, the need to allocate larger quantities of final goods to increased investment causes precipitous decreases in exports, coupled with increases in imports (fig. 5*G* and *H*). The result is a reorganization of commodity trade and a shift in counties' trade balances. Along the baseline dynamic trajectory, San Francisco County is a net exporter, Alameda County and the rest of the bay region are net importers, Contra Costa and San Mateo Counties and the rest of California are initially net importers that subsequently transition to net exporters, and Santa Clara County is initially a net exporter that becomes a net importer. Overall, the shock induces severely impacted counties to increase imports, accentuating baseline patterns of trade—in the counterfactual solution to the model, Alameda, Contra Costa, Santa Clara, and San Mateo Counties all remain net importers throughout the simulation horizon, and increase their consumption of goods and services exported by San Francisco County, other bay region counties, and the remainder of the State.

The results have several important implications for the interregional nature of recovery from a major shock such as the HayWired earthquake scenario. They indicate that, as in the case of the direct and indirect consequences themselves, the pattern of recovery reveals further departures from simple direct assessments of investment in repair and reconstruction, after considering various types of dynamic interregional general equilibrium effects. Those counties implementing the higher levels of repair and reconstruction investment benefit the most, but these effects spill over onto neighboring counties as well. The spillover effect is greater than in ordinary circumstances because the less-affected counties have greater productive capacity relative to directly affected counties than in the base case, and they are relied upon as the sources of supplies of direct and indirect inputs into recovery. Thus, the lightly damaged counties gain from picking up the slack of lost capacity in the core of the damaged region and also provide valuable inputs to all affected counties during the recovery process.

[20]Counties in figure 5 experience sizeable negative shocks to both their capital stocks and domestic output. The representative agent within each county reallocates the disposition of this smaller quantity of output preferentially to investment, as a way of quickly rebuilding lost capital, while simultaneously cutting back on other components of domestic expenditure (as consumption, exports, and intermediate commodity uses) and increasing imports. Rather than being allocated to producers, the larger quantity of imports is consumed. This, combined with reduced exports of domestic product, serves to sustain the level of consumption.

Study Limitations

There are limitations to both the CGE analysis of economic consequences during the first 6 months and the simple dynamic recovery model over 17 years.

CGE Model Limitations

In the CGE model analysis we have excluded sources of disruption such as transportation. We do not consider the effects from damages to roads, bridges, or railroads, although we expect that the delays to goods and people movement during repairs and reconstruction will be costly. The Regional Economic Models, Inc. (REMI) model analysis conducted by Kroll and others (this volume) estimates that close to half of the region's output losses come from transportation network and commuting disruptions, rather than directly from building damage.

Several key assumptions about resilience tactics are based on the best data we could obtain at the time of this work. For example, the percentage production isolation factors in the voice- and data-service resilience analysis are calculated by scaling down the telephone production isolation factors in order to factor in the large use of internet (not just telephone) by sector. The telework potentials by sector and by county are calculated based on the BLS (2017) data on telework potential by job type, and factoring the considerations of readiness of employees to go back to work after the major disaster, internet access, and the availability of backup data. Future studies can benefit from better sectoral and region-specific data on these resilience tactic assumptions.

Another limitation of the CGE model analysis of economic impact and resilience is the assumption that businesses aim to return to business-as-usual conditions. In practice, businesses will reposition or redefine themselves and find new efficiencies, as was reported after the Christchurch earthquakes (Chang and others, 2014; Stevenson and others, 2014; Brown and others, 2015). The recovery of an economy affected by a major disaster is inherently a transitory disequilibrium phenomenon that is influenced by a multitude of non-economic forces. However, the non-economic factors often tend to be subject to large uncertainties, making them very challenging to characterize and to model in a tractable way. Our analytical approach sidesteps some of these difficulties by taking as given many of the details of the recovery trajectory, in order to focus squarely on the equilibrium to which the economy converges during the (Keynesian) “short-period.” over which prices are determined and bring supply and demand into balance. The benefit of such analytical clarity can only be obtained at the expense of realism and detail, not the least of which are potential differences in the behavioral responses of economic factors to the main earthquake as opposed to decreasingly punctuated and less intense aftershocks. The 6-month horizon selected for our analysis thus represents a compromise between capturing the effects of most aftershocks and having the increasingly long intervening periods of normal economic functioning dampen their apparent effects. More detailed elaboration of the effects of these and other fine temporal-scale forces can be accomplished using modeling approaches other than CGE, but these are beyond the scope of our study.

We have also not explored dynamic economic resilience that would accelerate the pace of recovery (to jumpstart and [or] reduce the duration of recovery) in relation to a standard recovery path. Accelerating the recovery path is based on numerous decisions by government officials, businesses, and households for which we did not have data, and hence were not able to provide any reasonable estimates. For an analysis of longer term impacts of the HayWired scenario the gold standard is an intertemporal CGE model that simulates the dynamic impacts of the foregoing decisions on postdisaster regional economic growth. Given the dearth of relevant input data, our contingency was a highly stylized partial equilibrium intertemporal simulation discussed in the section on Dynamic Economic Recovery and appendix 8. The reader is also referred to the regional economic modeling in the accompanying report by Kroll and others (this volume).[21] For CGE modeling of dynamic resilience, the reader is referred to papers such as Xie and others (2018).

We offer the following additional caveats about population effects. First, we emphasize that it would be wrong to think of substitution of labor for destroyed capital as resulting from an increase in the labor supply. On the contrary, depending on the scenario being simulated, labor endowments in all counties, and statewide, decrease by 2–7 percent in 6 months.[22] Crucially, however, in the most severely affected counties earthquake damage reduces the amount of capital by a larger amount. The result is a relative increase in labor intensity that reflects substitution, whereby the resulting smaller pool of labor moves among producing sectors, and is used in place of lost capital to different degrees, until the equilibrium condition of the marginal productivity of labor being equalized across production activities is satisfied. Such reallocation of labor to its highest marginal-value use is a key mechanism of inherent resilience (Rose and Liao, 2005; Rose, 2017).

Given this, the main limitation of our analysis is insufficient detail in modeling the earthquake’s effects on the supply side of the labor market. Destruction of capital in the private dwellings, real estate, and accommodation sectors is likely to render a nontrivial fraction of the bay region housing stock uninhabitable, and in turn trigger large-scale short-term displacement of local populations. A key question that we leave unanswered is the degree to which initial population displacement persists over the long term, which is a particular concern given the preexisting shortage of housing in the region. To address this issue it is necessary to undertake additional dedicated modeling of the microeconomic forces that determine, initially, the likely geographic dispersal of evacuees based on intercounty differences in postdisaster housing market conditions, and, subsequently, population return based on the pace of State and Federal provision of temporary housing, and local governments’ proclivity to intervene in housing markets to enable alternative shelter arrangements.

The experience of New Orleans, Louisiana’s, labor supply in the aftermath of Hurricane Katrina points to the importance of such modeling. Figure 6*A* illustrates that the key unknown is whether evacuees return. Although half of the housing units in Orleans Parish were destroyed, displaced populations were able to secure temporary or permanent shelter in neighboring, less-affected counties and States relatively quickly. A Gompertz recovery curve fit to FEMA data (Department of Homeland Security Office of Inspector General, 2008) suggests that the number of households in hotels and motels decreased to half its peak after 4.5 months, and after 6 months would have fallen to the initial level of prestorm evacuation.[23] But many of the workers in these households did not return, causing the New Orleans metro area to lose 23 percent of its labor supply—a shock from which New Orleans has not yet fully recovered after more than a decade.

Even so, several features of the HayWired scenario raise the possibility that the pattern of recovery might be very different in the bay region. The first is simply the character of the hazard: in the HayWired scenario, affected areas do not experience the prolonged inundation that was responsible for further capital stock destruction as well as delaying the return of displaced households by more than 1.5 months. Second, the magnitude of capital stock losses is less severe; figure 6*B* shows that building damage owing to the mainshock, fires following the mainshock, and aftershocks amounts to 20 percent of the capital stock in the accommodation sector, 17 percent of the capital stock in the private dwellings sector in Alameda, and less than 11 percent in the accommodation sector and 6 percent in the private dwellings sector for the next three most impacted counties. The result is that there

[21]Kroll and others (this volume) indicate that the majority of economic losses (including output losses caused by building damages, transportation network and commuting flow disruptions, and amenity loss of the region) of the HayWired scenario will take place in the first year after the mainshock. If the stimulus effects of government response and recovery investment are taken into consideration, the net output effects in the bay region are projected to turn positive starting from year 2 (assuming 3/4 of the government aid is exogenous Federal spending, and thus is additive to the regional economy).

[22]We emphasize that the CGE model neither represents nor measures labor in terms of employment (that is, jobs or workers), but rather the aggregate quantity of hours supplied by all households.

[23]The function is *Displacement Population* $(t) = ae^{-b(t-t_0)}e^{-ce^{-b(t-t_0)}}(1+c(1-e^{-b(t-t_0)}))$, in which t is time, t_0=8/25/2005 is the date of Katrina landfall, a = 120,000, b = 0.175 and c = 2.3 are parameters selected to match estimates of displaced individuals taken from Department of Homeland Security Office of Inspector General (2008).

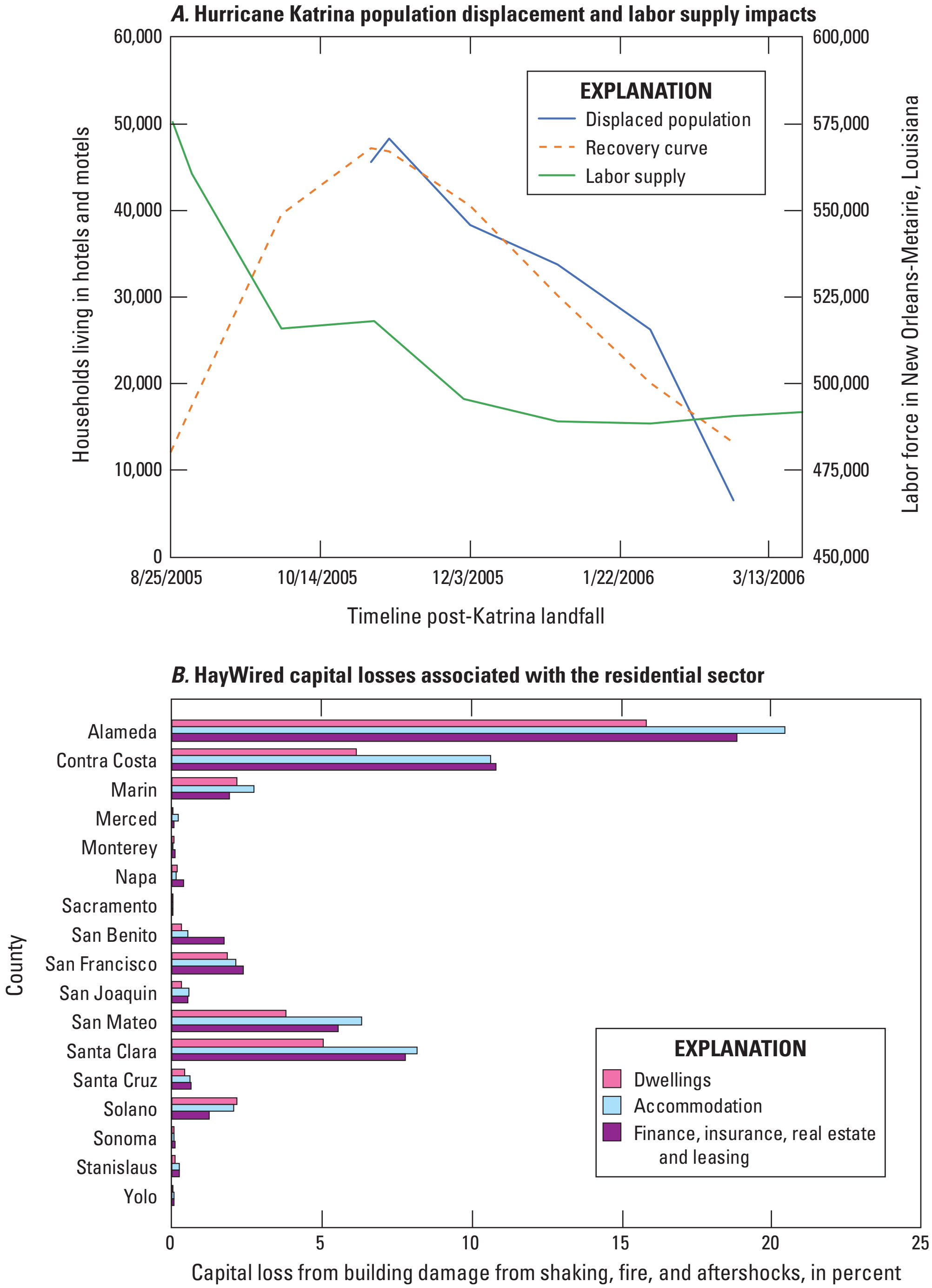


Figure 6. Charts showing postdisaster evacuation and return, illustrating implications for bay region labor supply. *A*, Plot showing Federal Emergency Management Agency estimates (Department of Homeland Security Office of Inspector General, 2008), and our own simulation, of the number of households displaced by Hurricane Katrina across the Gulf Coast and living in hotels and motels and evolution of the labor force in the New Orleans-Metaire, Louisiana, area over time following Hurricane Katrina's landfall. *B*, Percentage of capital loss by housing-related sector owing to building damage from the HayWired mainshock, fire following the mainshock, and aftershocks, in the San Francisco Bay region counties, California.

will likely be a much higher percentage of structures that are sufficiently undamaged compared to the case in New Orleans in the aftermath of Hurricane Katrina, and that they can provide temporary housing, further hastening individuals' ability to return and resume work over a 6-month horizon.[24] Third, the restoration of telecommunications within a few weeks, and the concomitant facilitation of telework, suggests the need to carefully distinguish between population return and recovery of the labor supply, especially in information sectors. Finally, the dynamics of population return may be much more consequential for "brick and mortar" industries that rely on low-wage occupations and require workers to be physically present to supply labor (for example, service sectors such as wholesale, retail, accommodation, repair, health, and education). However, under prevailing baseline economic conditions there is concern that workers in these occupations are being priced out of bay region housing markets and reside increasingly far away from the region's major employment centers. The crucial question is whether existing drivers of households' geographic dispersal already push such workers out of the zone of maximum earthquake damage. If this is indeed the case, the magnitude of worker displacement is likely to be much smaller, and the reduction in labor supply will primarily be a function of the extent of commuting disruption and the pace of restoration of transport links.

Johnson and others (this volume) examine population displacement. For the purposes of this report, and in the face of the substantial uncertainties we opt to generate loss estimates using the standard Keynsian labor market closure rule of a fixed wage and flexible labor supply. Elaboration of additional supply-side dynamics and their potential implications for labor-market equilibrium over the recovery period is beyond the scope of this report and is left to future research.

Simple Dynamic Recovery Model Limitations

Our stylized analysis of dynamic recovery is subject to several caveats. The dynamic model is notable for its lack of frictions, particularly capital adjustment costs that have the potential to introduce divergence between the resources allocated to investment and the consequent formation of new capital. In severely affected counties, such as Alameda, the massive rebuilding efforts across a broad range of sectors would require substantial coordination and involve temporary inefficiencies in investment. The extent to which this might increase the contemporaneous costs of investment is an open question and beyond the scope of this study. Future analysis of this issue would have to determine the extent to which investment in repair and reconstruction would displace investment in ordinary plant and equipment, and it would also determine how much of an injection there would be externally from government assistance, philanthropy, and insurance payments (see Xie and others, 2018). This would also require consideration of factors such as "demand surge." which refers to the likely increase in the cost of construction activity and materials in the aftermath of a disaster (see Olsen and Porter, 2011; Kroll and others, this volume).[25]

As with the CGE impact analysis, a key influence on the dynamics of recovery that remains unmodeled is population displacement and return, and their impacts on regional production, consumption, and capital accumulation in the 1–3 year postdisaster period. Workers emigrating from the most affected counties would further reduce production, consumption, and utility there, but would increase all three variables in the rest of the bay region and other parts of California that would likely receive migrants. Fundamental empirical analysis of spatial and temporal patterns of population displacement and return was outside the scope of the project—we eschew such analysis as being too speculative at this time, and instead leave the definition of the consequent shocks to labor supply and the simulation of their impacts as topics for future research.

More realistic modeling of the recovery of California's regional economies would require differentiating production into multiple sectors, trade into multiple commodities, and investment into a vector of sector-specific investment goods that would be allocated to bring the marginal products of capital across different production activities into equilibrium. In addition to this there would likely be layered non-market policies that direct investment to specific sectors (for example, attempts by State and local governments to restore infrastructure or other public components of the capital stock), which would have additional effects on the relative rates of sectoral capital accumulation, and, ultimately, structural change. Such a model is at the forefront of economic modeling research and is unfortunately outside the scope of our analysis.

We offer some suggestions for future research that emanate from the discussion above. First is a county by county elaboration of the effects on long-run trajectories of economic growth. This would be most effective if it included

[24]However, at the same time, we do note two factors that may delay the process of population return in the HayWired scenario: (1) some of the areas that are severely damaged by fire are likely to be more difficult than flood inundated areas to get repaired and reconstructed; (2) there is a virtually zero vacancy rate for housing in the bay region. The already very high costs of housing will become even higher with the shortage of housing supply after the disaster, which may prohibit the immediate return of the evacuated population.

[25]The dynamic translation of capital investment in one sector at time t into units of new capital stock in another sector in the subsequent time period $t+1$ involves conceptual and empirical modeling difficulties. The Bureau of Economic Analysis (BEA) records data on capital flow according to industry demand (irregularly and at the national level, which, thus, may not reflect the particular structure of California's economy). Most consequentially, a key unknown is whether, in the aftermath of a disaster, the coefficients of such a matrix of sectoral shares of the mix of investment goods will remain constant, especially on the brief 6-month timestep necessary to capture the short-run consequences of an earthquake. In the initial chaotic postdisaster period, it is plausible that localized shortages, and (or) firm resilience tactics, such as bartering intermediate inputs or cooperating to share salvaged plants, equipment, or structures, might lead to localized deviations from the investment shares that would otherwise prevail under normal conditions. However, in the absence of well-founded representations of the microeconomic details of these processes, predicting the deviations in capital flow that might arise would be highly speculative.

the dynamics of county- and sector-level capital-labor substitution that accompany population return, reconstruction, and economic recovery over the long run of one or more decades postdisaster. However, the ability to address this question is complicated by the need to develop a model of short-run evacuation and long-run population repatriation (or decline), ideally endogenously linked to the employment demand shock triggered by firms' loss of productive capacity owing to capital stock destruction. Another area of future research would be to validate the IMPLAN capital stock data that we have used. For example, Cutler and others (2017) have used county assessor data that describes the use of each parcel of land, including data on the size of the parcel, value of the land, and value of the structure on the land (building value or other capital stock), and also distinguishes these data by sector.

Conclusion

In this study, we estimated total regional economic effects (in terms of gross regional product [GRP] losses caused by business interruption) of the HayWired scenario earthquake on the San Francisco Bay region economy. The study follows from the analysis of the physical damages of the earthquake, including property damage caused by mainshock shaking, liquefaction and landslides, fire following earthquake, and aftershocks. Business interruption losses flow from the direct property damage to producing sectors, and are also caused by disruption of water, power, and data and voice services. A multiregional computable general equilibrium model was used to analyze the total regional economic effects of the HayWired earthquake scenario. The basic simulations indicate how the economy is affected, including how it adjusts to damages and disruptions transmitted through price changes, which spur the reallocation of resource use, primarily through substitutions of inputs and geographical redistributions. The capability to undertake such substitutions is an important measure of the inherent resilience of the macroeconomy. The study also evaluates the potential effectiveness of various additional inherent and adaptive microeconomic resilience tactics that can greatly reduce the business interruption losses from the disaster.

The dominant cause of economic losses in the bay region and California is found to be business interruption (BI) from property damage. Without additional resilience tactics, total potential BI losses for California, measured in gross State product (GSP) reduction in the 6-month period after the HayWired mainshock, are estimated to be $44.2 billion (or 4.2 percent of the State's projected baseline GSP during the period). About $42.5 billion in GSP reduction is BI losses caused by property damage (among which $32 billion is caused by the mainshock [including fire] and $10.5 billion is caused by aftershocks). Overall, losses are concentrated in the five bay region counties that are most directly affected by earthquake property damage in absolute terms (Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco), which together account for 80 percent of the overall reduction in GSP. Alameda and Santa Clara Counties are the most affected counties, which suffer reductions in economic output of about $12.7 and $13.1 billion, or more than 23 percent and 11 percent, respectively, of the counties' baseline GRPs. Contra Costa County also suffers an 11 percent reduction in economic output, followed by an 8 percent reduction in San Mateo County and a 4 percent reduction in San Francisco County.

In terms of the sectoral distribution of the total effects, sectors with the largest reductions in gross output statewide include finance, insurance, real estate (FIRE) and owner-occupied dwellings, manufacturing (petroleum refining, light and heavy industry, food, drug, and chemical manufacturing), ambulatory healthcare and hospitals, and professional, scientific, and technical services. The greatest reductions in output are in high-tech device manufacturing and internet publishing and broadcasting. These sectors suffer relatively more intensive property damage (building and content losses) than other sectors, and thus experience greater reductions in the endowments of sector-specific capital.

Information and communications technology (ICT) sectors that are central to the digital economy include internet publishing and broadcasting; telecommunications; data processing, hosting, and related services; and other information services. Both telecommunications and internet publishing and broadcasting are their own top suppliers and customers. Telecommunications and data processing, hosting, and related services purchase from professional services and FIRE sectors. Industry, manufacturing, and mining sectors are top purchasers of the internet publishing and broadcasting sectors. GRP losses in the ICT sectors show a strong correspondence with capital stock (property) losses, although internet publishing and broadcasting show a consistent pattern of percentage of GRP losses exceeding capital losses in counties less directly impacted by the earthquake (San Mateo and San Francisco) and the rest of California. Internet publishing not only suffers direct economic damage but also suffers from smaller supplies of data-processing and telecommunications inputs, whose prices increase significantly.

Our results illustrate how interregional trade in goods and services performs the dual role of a mechanism for broader transmission of the economic consequences and a margin of economic adjustment to the disaster-related business interruption. Firms in directly affected counties can substitute intermediate inputs imported from undamaged counties for curtailed supplies of such inputs that might have been produced locally. This helps moderate the reduction in the former producers' outputs—production still decreases, but by a smaller fraction than would be predicted by the shock to the economy from capital stock destruction and curtailment of utility-service supplies. However, at the same time, counties that are geographically contiguous with the main disaster zone and export a large fraction of their output to firms and households that sustain direct damage incur losses that are far greater than their direct damage would predict. The latter arises because over the short period of our analysis, the disaster has the effect of causing a reduction in the demand for their output. In this way, import and export markets throughout the bay region are responsible for the earthquake's direct effects rippling through the broader California economy.

Economic resilience tactics can potentially greatly reduce the total economic effect on the California economy. The GSP losses could be reduced from $43.5 billion to $25.2 billion (a reduction of 42 percent) if various microeconomic resilience tactics are taken into account. Based on assumptions about the effectiveness of resilience tactics over time, the tactic that has the greatest potential effect on reducing BI losses from property damages is production recapture in which businesses make up for their lost production through employees working overtime or extra shifts after their necessary facilities and equipment have been repaired or replaced and critical inputs become accessible. Production recapture is an effective resilience tactic in the short run (for example, within 3 months)—it is unlikely that most customers will cancel their orders within this timeframe. However, the effectiveness of production recapture decreases over time as customers grow impatient when their orders are not filled and, therefore, seek other suppliers. In this study, we found that, even in the counties that are most directly affected by the earthquake, a large percentage of damaged buildings in commercial and industrial sectors take less than 3 months to repair or recover. Therefore, production recapture has great potential in reducing BI losses stemming from property damage.

The most effective resilience tactic for utility-service disruptions differs across service types. For water-service disruption, production isolation (referring to those parts of a production process that can continue without using water inputs) emerged as the most effective tactic. For power-service disruption, production recapture has the greatest effect on reducing the BI losses. For data- and voice-service disruptions, production isolation is the single most effective tactic, followed by input substitution and production recapture, in accordance with our assumptions. The supplier implemented equipment strategies of back-up power (permanent batteries and generators) and portable equipment (for example, generator on a truck, cell on wheels), implemented in recent disasters, collectively reduce the percentage of BI losses from data and voice service disruption by 90 percent.

In summary, GRP losses are concentrated in the five bay region counties that are most directly affected by earthquake property damage in absolute terms (Alameda, Contra Costa, Santa Clara, San Mateo, and San Francisco), which together account for 80 percent of the overall reduction in GSP. Sectors with the greatest reductions in gross output statewide include real estate (finance, insurance, real estate, and owner-occupied dwellings), manufacturing (petroleum refining, light and heavy industry, food, drug, and chemical manufacturing), ambulatory healthcare and hospitals, and professional, scientific, and technical services. Microeconomic resilience tactics could potentially greatly reduce the total economic effect on the California economy. The GSP losses could be reduced from $44.2 billion to $25.3 billion (a reduction of 43 percent) if various resilience tactics are implemented. The tactic that has the greatest potential effect on reducing BI losses from property damages and power-service disruption is rescheduling production to catch up; the most effective resilience tactic for water-service disruption and data- and voice-service disruptions is production that can continue without these inputs.

A special focus in this HayWired scenario analysis was a study of the core of the digital economy made up of the telecommunications, data hosting and processing, internet publishing and broadcasting, and other services sectors. These sectors are subjected to infrastructure damage, power outages, and business interruption, which are aggravated by their dependence on each other. Their importance in recovery is illustrated by assumptions about telework in sectors that reduce economic impacts (most recently seen during the 2020 COVID-19 pandemic); telework reduces estimated GSP losses from property damage by a few billion dollars (6 percent of baseline GSP). Every resilience tactic, or business continuity practice, implemented by businesses, sector alliances, and governments—including utility and digital economy sectors—preserves economic activity for their organizations, as well as that of others, through sectoral and geographic economic linkages, after this potentially devastating scenario earthquake strikes.

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References Cited

Acemoglu, D., 2009, Introduction to Modern Economic Growth: Princeton, N.J., Princeton University Press, 1,008 p.

Applied Technology Council, 1991, Seismic vulnerability and impacts of disruption of lifelines in the coterminous United States: Redwood City, Calif., Applied Technology Council report ATC-25, 440 p.

Armington, P.S., 1969, A theory of demand for products distinguished by place of production: International Monetary Fund, Staff Papers, v. 16, no. 1, p. 159–178.

Aubuchon, C.P., and Morley, K. M., 2013, The economic value of water—Providing confidence and context to FEMA's methodology: Journal of Homeland Security and Emergency Management, v. 10, no. 1, p. 245–265, accessed September 23, 2020, at https://www.degruyter.com/view/journals/jhsem/10/1/article-p245.xml.

Barker, K., and Santos, J., 2009, Measuring the efficacy of inventory with a dynamic input–output model: International Journal of Production Economics, v. 126, no. 1, p. 130–134.

Brooke, A., Kendrick, D., and Meeraus, A., 1988, GAMS—A user’s guide: Washington, D.C.: GAMS Corp., 281 p.

Brown, C., Stevenson, J.R., Giovinazzi, S., Seville, E., and Vargo, J., 2015, Factors influencing impacts on and recovery trends of organizations—Evidence from the 2010/2011 Canterbury earthquakes: International Journal of Disaster Risk Reduction, v. 14, no. 1, p. 56–72.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O’Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., and von Winterfeldt, D., 2003, A framework to quantitatively assess and enhance seismic resilience of communities: Earthquake Spectra, v. 19, no. 4, p. 733–752.

Bureau of Labor Statistics [BLS], 2017, 24 percent of employed people did some or all of their work at home in 2015: Bureau of Labor Statistics web page, accessed October 23, 2020, at https://www.bls.gov/opub/ted/2016/24-percent-of-employed-people-did-some-or-all-of-their-work-at-home-in-2015.htm.

California Department of Finance, 2017, Total population by county (1-year increments): California Department of Finance web page, accessed June 1, 2017, at http://www.dof.ca.gov/forecasting/demographics/projections/.

California Energy Commission [CEC], 2020, California energy consumption database: California Energy Commission, accessed October 20, 2020, at http://www.ecdms.energy.ca.gov/.

Chang, S.E., Taylor, J.E., Elwood, K.,J., Seville, E., Brunsdon, D., and Gartner, M., 2014, Urban disaster recovery in Christchurch—The central business district cordon and other critical decisions: Earthquake Spectra, v. 30, no. 1, p. 513–532.

Cutler, H., Shields, M., and Davies, S., 2017, Can state tax policy increase economic activity and reduce inequality?: Growth and Change, v. 49, no. 1, p. 142–164, https://doi.org/10.1111/grow.12216.

Cutler, H., Shields, M., Tavani, D., and Zahran, S., 2016, Integrating engineering outputs from natural disaster models into a dynamic spatial computable general equilibrium model of Centerville: Sustainable and Resilient Infrastructure, v. 1, no. 3–4, p. 169–187.

Cutter, S., 2016, The landscape of disaster resilience indicators in the USA: Natural Hazards, v. 80, p. 741–758.

Department of Homeland Security Office of the Inspector General, 2008, FEMA’s sheltering and transitional housing activities after Hurricane Katrina: Department of Homeland Security Office of the Inspector General, Report No. OIG-08-93, 54 p.

Donnelly, N., and Proctor-Thomson, S., 2013, Working from home—lessons from the Christchurch experience: Wellington, New Zealand, Industrial Relations Centre, Victoria University of Wellington, 52 p., accessed October 23, 2020, at https://www.victoria.ac.nz/som/research/research-reports/IRPSA-Working-From-Home-Report-FINAL.pdf.

Drud, S.A., 1994, CONOPT—A large-scale GRG code: ORSA Journal on Computing, v. 6, p. 207–216.

Ellingwood, B., van de Lindt, J., and McAllister, T., 2016, Developing measurement science for community resilience assessment: Sustainable and Resilient Infrastructure, v. 1, no. 3–4, p. 93–94.

East Bay Municipal Utility District, 2015, 2015 audited comprehensive annual financial report: East Bay Municipal Utility District, accessed October 23, 2020, at https://www.ebmud.com/about-us/investors/financial-reports/.

Federal Emergency Management Agency [FEMA], [undated], Key data fields in the utilities screen: Federal Emergency Management Agency Emergency Management Institute web page, accessed October 11, 2020, at https://emilms.fema.gov/IS0277A/groups/657.html.

Federal Emergency Management Agency, 2009, Final BCA Reference Guide: Washington, D.C., Federal Emergency Management Agency, 108 p.

Federal Emergency Management Agency, 2010, Hazard mitigation assistance unified guidance—Hazard mitigation grant program, pre-disaster mitigation program, and flood mitigation assistance program: Federal Emergency Management Agency guidance, accessed September 23, 2020, at https://www.fema.gov/media-library-data/20130726-1737-25045-4275/final_june_1_2010_hma_unified_guidance_09252012a_508.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 June 20, 2019, at https://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf.

Ferris, M., and Munson, T., 2000, Complementarity Problems in GAMS and the PATH Solver: Journal of Economic Dynamics and Control, v. 24, p. 165–188.

GAMS, 2018, GAMS User’s Guide: GAMS web page, accessed October 23, 2020, at https://www.gams.com/latest/docs/UG_MAIN.html.

Heflin, C., Jensen, J., and Miller, K., 2014, Understanding the economic impacts of disruptions in water service: Evaluation and Program Planning, v. 46, p. 80–86, accessed September 23, 2020, at https://doi.org/10.1016/j.evalprogplan.2014.05.003.

Helm, D.R., 2008, Market period, *in* Vernengo, M., Caldentey, E.P., and Rosser, B.J., Jr., eds., The New Palgrave Dictionary of Economics: London, Palgrave Macmillan, accessed October 23, 2002 at https://doi.org/10.1057/978-1-349-95121-5_911-2.

Holling, C., 1973, Resilience and stability of ecological systems: Annual Review of Ecology and Systematics, v. 4, p. 1–23.

IMPLAN, 2014, Impact Analysis for Planning (IMPLAN) System: Huntersville, N.C., IMPLAN.

Independent Sector, 2020, Value of volunteer time: Washington, D.C., Independent Sector web page, accessed September 22, 2020, at https://independentsector.org/value-of-volunteer-time-2020/.

Jones, L.M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J., and Wein, A., 2008, The ShakeOut scenario: U.S. Geological Survey Open-File Report 2008–1150 and California Geological Survey Preliminary Report 25, 312 p. and appendixes, accessed September 13, 2017, at https://pubs.usgs.gov/of/2008/1150/.

Kajitani, Y., Chang, S., and Tatano, H., 2013, Economic impacts of the 2011 Tohoku-Oki earthquake and tsunami: Earthquake Spectra, v. 29, no. S1, p. S457-S478.

Kajitani, Y., and Tatano, H., 2009, Estimation of lifeline resilience factors based on empirical surveys of Japanese industries: Earthquake Spectra, v. 25, no. 4, p. 755–76.

Kerrest, F., 2016, 10 Industries that have embraced the Cloud: Cloud Computing, May 6, 2016, accessed October 23, 2020, at https://www.inc.com/frederic-kerrest/how-do-industries-stack-up-in-the-cloud.html.

Kolowe, P., 2014, The determinants of urban land and property values—The case of Rwanda: San Francisco, Calif., University of San Francisco, Master’s thesis, 34 p., accessed October 11, 2020, at https://repository.usfca.edu/thes/87.

Kroll, C., Jaramillo, J., Lu, S., Olsen, A., Bello, O., Tan, A., Yin, W., Germeraad, M., and Jacoby, R., 2017, San Francisco Bay area comprehensive economic development strategy: San Francisco, Calif., Association of Bay Area Governments, 57 p., accessed October 13, 2020, at https://abag.ca.gov/sites/default/files/complete_ceds_with_all_appendices.pdf.

MacKenzie, C.A., Santos, J.R., and Barker, K., 2012, Measuring changes in international production from a disruption—Case study of the Japanese earthquake and tsunami: International Journal of Production Economics, v. 138, no. 2, p. 293–302, https://doi.org/10.1016/j.ijpe.2012.03.032.

Mushroom Networks, 2017, Is your business internet dependent? 15 businesses that need reliable internet: Mushroom Networks web page, accessed October 22, 2020, at https://www.mushroomnetworks.com/blog/is-your-business-internet-dependent-15-businesses-that-need-reliable-internet/.

National Research Council, 2011, National earthquake resilience—Research, implementation, and outreach: Washington, D.C., The National Academies Press, 278 p., available online at https://doi.org/10.17226/13092.

National Research Council, 2012, Disaster resilience—A national imperative: Washington, D.C., National Academies Press, 260 p.

National Research Council, 2017, Enhancing the resilience of the Nation’s electricity system: Washington, D.C., National Academies Press, 170 p.

North, J.H., and Griffin, C.C., 1993, Water source as a housing characteristic—Hedonic property valuation and willingness to pay for water: Water Resources Research, v. 29, no. 7, p. 1923–1929.

O’Connell, J., 2017, How much it costs to stock the average family refrigerator: Chicago Tribune, July 28, 2017, accessed September 23, 2020, at https://www.chicagotribune.com/business/success/ct-cost-family-refrigerator-20170728-story.html.

Okuyama, Y., 2014, Disaster and economic structural change—Case study on the 1995 Kobe earthquake: Economic Systems Research, v. 26, no. 1, p. 98–117.

Olsen, A. H., and Porter, K. A., 2011, What we know about demand surge—Brief summary: Natural Hazards Review, v. 12, no. 2, p. 62–71.

Parker, M., and Steenkamp, D., 2012, The economic impact of the Canterbury earthquakes: Reserve Bank of New Zealand Bulletin, v. 75, no. 3, p. 13–25.

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.

Pimm, S.L., 1984, The complexity and stability of ecosystems: Nature, v. 307, p. 321–326.

Rose, A., 2004a, Defining and measuring economic resilience to disasters: Disaster Prevention and Management, v. 13, no. 4, p. 307–314.

Rose, A., 2004b, Economic principles, issues, and research priorities of natural hazard loss estimation, *in* Okuyama, Y. and Chang, S., eds., Modeling of Spatial Economic Impacts of Natural Hazards: Heidelberg, Germany, Springer, p. 13–36.

Rose, A., 2009, Economic resilience to disasters: Oak Ridge, Tenn., Oak Ridge National Laboratory, Community and Regional Resilience Institute, Report No. 8, 58 p.

Rose, A., 2015, Macroeconomic consequences of terrorist attacks—Estimation for the analysis of policies and rules, *in* Mansfield, C., and Smith, V.K., eds., Benefit transfer for the analysis of DHS policies and rules: Cheltenham, U.K., Edward Elgar Publishing, p. 172–200.

Rose, A., 2017, Benefit-Cost Analysis of Economic Resilience, *in* Cutter, S., ed., Oxford research encyclopedia of natural hazard science: New York, Oxford University Press.

Rose, A., and Liao, S., 2005, Modeling regional economic resiliency to earthquakes—A computable general equilibrium analysis of water service disruptions: Journal of Regional Science, v. 45, p. 75–112.

Rose, A., Liao, S., and Bonneau, A., 2011, Regional economic impacts of a Verdugo scenario earthquake disruption of Los Angeles water supplies—a computable general equilibrium analysis: Earthquake Spectra, v. 27, no. 3, p. 881–906.

Rose, A., and Lim, D., 2002, Business interruption losses from natural hazards—Conceptual and methodological issues in the case of the Northridge earthquake: Global Environmental Change, Part B; Environmental Hazards, v. 4, no. 1, p. 1–14.

Rose, A., and Miller, N., 2017, Measurement of cyber resilience from an economic perspective, *in* Chatterjee, S., Brigantic, R., and Waterworth, A., eds., Applied risk analysis for guiding Homeland Security policy and decision: Heidelberg, Springer, p. 193–209.

Rose, A., Oladosu, G., and Liao, S., 2007a, Business interruption impacts of a terrorist attack on the water system of Los Angeles—A computable general disequilibrium analysis, *in* Richardson, H., Gordon, P., and Moore, J., eds., Economic costs and consequences of terrorist attacks: Cheltenham, U.K., Edward Elgar Publishing.

Rose, A., Oladosu, G., and Liao, S., 2007b, Business interruption impacts of a terrorist attack on the electric power system of Los Angeles—Customer resilience to a total blackout: Risk Analysis, v. 27, p. 13–31.

Rose, A., Oladosu, G., Lee, B. and Beeler Asay, G., 2009, The economic impacts of the 2001 terrorist attacks on the World Trade Center—A computable general equilibrium analysis: Peace Economics, Peace Science, and Public Policy, v. 15, no. 2, p. 1–31.

Rose, A., Sue Wing, I., Wei, D., and Wein, A., 2016, Economic impacts of a California tsunami: Natural Hazards Review, v. 17, no. 2, p. 1–12.

Rose, A., and Wei, D., 2013, Estimating the economic consequences of a port shutdown—The special role of resilience: Economic Systems Research, v. 25, no. 2, p. 212–32.

Rutherford, T., 1999, Applied general equilibrium modeling with MPSGE as a GAMS subsystem—An overview of the modeling framework and syntax: Computational Economics v. 14, p. 1–46.

San Francisco Public Utilities Commission [SFPUC], 2013, Comprehensive annual financial report for the fiscal year ending June 30, 2013: San Francisco Public Utilities Commission report, accessed October 22, 2020, at https://sfwater.org/modules/showdocument.aspx?documentid=4728.

Santa Clara Valley Water District [SCVWD], 2013, Comprehensive annual financial report for fiscal year ended June 30, 2013: Santa Clara Valley Water District report, accessed October 22, 2020, at https://www.valleywater.org/sites/default/files/2018-01/CAFR_2013.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.

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

Stevenson, J.R., Chang-Richards, Y., Conradson, D., Wilkinson, S., Vargo, J., Seville, E., and Brunsdon, D., 2014, Organizational networks and recovery following the Canterbury earthquakes: Earthquake Spectra, v. 30, no. 1, p. 555–575.

Sue Wing, I., 2009, Computable general equilibrium models for the analysis of energy and climate policies, *in* Evans J., and Hunt, L.C., eds., International handbook on the economics of energy: Cheltenham, U.K., Edward Elgar Publishing, p. 332–366.

Sue Wing, I., 2011, Computable general equilibrium models for the analysis of economy-environment interactions, *in* Batabyal, A., and Nijkamp, P., eds., Research tools in natural resource and environmental economics: Hackensack, N.J., World Scientific, p. 255–305.

Sue Wing, I., and Balistreri, E.J., 2018, Computable general equilibrium models for economic policy evaluation and economic consequence analysis, *in* Chen, S.-H., Kaboudan, M., and Du, Y.-R., eds., The Oxford Handbook of Computational Economics and Finance: New York, N.Y., Oxford University Press, p. 139–203.

Sue Wing, I., Rose, A., and Wein, A., 2016, Economic consequence analysis of the ARkStorm scenario: Natural Hazards Review, Special ARkStorm Issue, v. 17, no. 4, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000173.

Tierney, K., 2007, Businesses and disasters—Vulnerability, impacts, and recovery, *in* Rodríguez H., Quarantelli, E.L., and Dynes, R.R., eds., Handbook of disaster research: Heidelberg, Germany, Springer, p. 275–296.

Tierney, K.J., 1997, Business impacts of the Northridge earthquake: Journal of Contingencies and Crisis Management, v. 5, no. 2, p. 87–97.

Twerefou, D., Tutu, K., Botchway, E., and Darkwah, S., 2015, Willingness-to-pay for potable water in the Accra-Tema metropolitan area of Ghana: Modern Economy, v. 6, no. 12, p. 1285–1296.

U.S. Census Bureau, 2017, 2015 E-commerce multi-sector data tables: U.S. Census Bureau dataset, accessed October 23, 2020, at https://www.census.gov/data/tables/2015/econ/e-stats/2015-e-stats.html.

U.S. Census Bureau, 2017, North American Industry Classification System: U.S. Census Bureau web page, accessed October 23, 2020, at https://www.census.gov/eos/www/naics/.

U.S. Energy Information Administration, 2020, Electricity data browser: U.S. Energy Information Administration database, accessed October 22, 2020, at https://www.eia.gov/electricity/data/browser/.

Varian, H., 1992, Microeconomic Analysis: New York, Norton, 506 p.

Wein, A., and Rose, A., 2011, Economic resilience lessons from the ShakeOut earthquake scenario: Earthquake Spectra, v. 27, no. 2, p. 559–573.

Xie, W., Rose, A., Li, S., He., J., Li, N., Ali, T., and Wei, W., 2018, Dynamic economic resilience and economic recovery from disasters—A quantitative assessment: Risk Analysis, v. 38, no. 6, p. 1306–1318.

Appendixes 1–8

Appendix 1. Sectoring Scheme

This appendix summarizes how we determine the sectoring scheme used in the economic impact modeling of the USGS HayWired Scenario. We follow the seven steps below when we consider the sectoring scheme to be used:

1. Start with the 3-digit NAICS sectoring scheme, which divides the whole regional economy into 86 sectors.

2. Disaggregate the utility sector into water and sewage system, natural gas distribution, and electricity generation and distribution.

3. Based on the 440-sector IMPLAN (short for impact analysis for planning) data, identify the top five sectors in terms of gross output in the 9-county study region, and include them as separate sectors. We also examined the top five sectors in terms of gross output for the three most heavily affected counties (Alameda, Santa Clara, and Contra Costa). The data indicate that the top five sectors in terms of gross output are identical in the 9-county region and in the three most affected counties.

4. Retain two major telecommunication and internet-related sectors at the most disaggregated level in IMPLAN. These include (1) IMPLAN 350, internet publishing and broadcasting (NAICS 519130); (2) IMPLAN 351, telecommunications (NAICS 517); and (3) IMPLAN 352, data processing, hosting, and related services (NAICS 518).

5. Examine the IMPLAN input-output matrix and import matrix, identify major customer sectors of the telecommunication and internet-related sectors, and retain key sectors at the most disaggregated level in IMPLAN.

6. Examine the top upstream supplying sectors to electricity generation, computer manufacturing, and telecommunication and internet services, and retain key sectors at the most disaggregated level in IMPLAN.

7. Aggregate other sectors to arrive at a reasonable total number of sectors to be used in the CGE model. The aggregation of the sectors should also align with Hazus occupancy classes. A major aggregation pertains to the manufacturing sectors. Except for the key sectors we keep disaggregated as noted above, we combine the other manufacturing sectors in line with the Hazus occupancy classes for industrial sectors (IND 1 for heavy industries, IND 2 for light industries, IND 3 for food, drugs, chemicals, and so on)

The final sectoring scheme and its correspondence to IMPLAN sectors, NAICS codes, and Hazus occupancy classes are shown in table 1.1.

Table 1.1. Sectoring scheme for computable general equilibrium (CGE) modeling.

[IMPLAN, impact analysis for planning; NAICS, North American Industry Classification System. No., CGE sector number]

No.	Sector description	IMPLAN sector	NAICS code[1]	Hazus occupancy class
1	Agriculture, forestry, fishing, and hunting	1–19	11	AGR1
2	Oil and gas extraction	20	211	IND4
3	Coal mining	21	2121	IND4
4	Other mining	22–30	212-213 except for 2121	IND4
5	Electric power generation, transmission, and distribution	31, 428, 431	2211	COM4
6	Natural gas distribution	32	2212	COM4
7	Water, sewage, and other systems	33	2213	COM4
8	Construction	34–40	23	IND6
9	Heavy industry	75–81, 95–112, 153–169, 181–233, 276–294	313, 321, 322, 327, 332, 333, 336	IND1
10	Light industry	82–94, 113–114, 142–152, 236–240, 244–275, 295–318	314, 315, 316, 323, 326, part of 334 (except for 334111, 334112, 334411, 334412, 334413), 335, 337, 339, 511, 516	IND2
11	Petroleum refineries	115	32411	IND3

Table 1.1.—Continued

No.	Sector description	IMPLAN sector	NAICS code[1]	Hazus occupancy class
12	Food, drug, and chemicals	41–74, 116–141	311, 312, 324 except for 32411, 325	IND3
13	Primary metal manufacturing	170–180	331	IND4
14	Electronic computer manufacturing	234	334111	IND5
15	Computer storage device manufacturing	235	334112	IND5
16	Semiconductor and related device manufacturing	243	334413	IND5
17	Other high technology related manufacturing	241, 242	334411, 334412	IND5
18	Wholesale trade, warehousing, and storage	319, 340	42	COM2
19	Retail trade	320–331	44-45	COM1
20	Air transportation	332	481	COM4
21	Rail transportation	333	482	COM4
22	Water transportation	334	483	COM4
23	Truck transportation	335	484	COM2
24	Transit and ground passengers	336	485	COM4
25	Pipeline transportation	337	486	COM4
26	Sightseeing transportation	338	487 and 488	COM4
27	Couriers and messengers	339	492	COM4
28	Publishing, motion picture, and broadcasting	341–349	511, 512, 515	IND2, COM4
29	Internet publishing and broadcasting	350	51913	COM4
30	Telecommunications	351	517	COM8
31	Data processing, hosting, and related services	352	518	COM4
32	Other information services	353	51911-2	COM4
33	Finance, insurance, real estate, and leasing	354–360, 362–366	52, 53	COM4, COM5
34	Imputed rental value for owner-occupied dwellings	361	n.a.	RES1-RES3
35	Computer systems design and related services	371–373	5415	COM4
36	Other professional, scientific, and technical services	367–370, 374–380	54 except for 5415	COM4
37	Other business services	381–390	55, 56	COM4
38	Educational services	391–393	6111, 6112-3, 6114-7	EDU1, EDU2
39	Ambulatory health care and hospitals	394–397	621, 622	COM6, COM7
40	Nursing home/social assistance	398–401	623, 624	RES6, COM3
41	Arts, entertainment, and recreation	402–410, 413	711-713, 722	COM8
42	Accommodations	411–412	721	RES4
43	Repair and maintenance	414–418	811	COM3
44	Personal services/private households	419–422, 426	812, 814	COM3
45	Religious, grantmaking, and similar organizations	423–425	813	REL1
46	Government and non-NAICS	427, 429–430, 432–440	n.a.	GOV1, GOV2

[1]See the website of North American Industry Classification System (NAICS) (https://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2017) for example establishments for the various NAICS sectors.

Appendix 2. Technical Description of the CGE Model

Introduction

This appendix summarizes the design, construction, and application of a static computable general-equilibrium (CGE) simulation model of the California economy. The application is over a time horizon of a single 6-month period from the onset of an earthquake.

The CGE model is a stylized computational representation of the circular flow of the economy. It solves for the set of commodity and factor prices and activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy (Sue Wing, 2009, 2011; Sue Wing and Balistreri, 2018). Our model divides California's economy into 18 regions, the 17-county earthquake impacted region (Alameda, Contra Costa, Marin, Merced, Monterey, Napa, Sacramento, San Benito, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Stanislaus, and Yolo) and an aggregate of the rest of the State, and 46 industry sectors (appendix 1, table 1.1), each of which is modeled as a representative firm characterized by a constant elasticity of substitution (CES) technology to produce a single good or service. Households are modeled by a representative agent with CES preferences and a constant marginal propensity to save and invest out of income. The government is also represented in a simplified fashion. Its role in the circular flow of the economy is passive: collecting taxes from industries and passing some of the resulting revenue to the households as a lump-sum transfer, in addition to purchasing commodities to create a composite government good which is consumed by the households. Three factors of production are represented within the model: labor, intersectorally mobile capital, and sector-specific capital, all of which are owned by the representative agent and rented out to the firms in exchange for factor income. California is modeled as an open economy which engages in trade with the rest of the United States and the rest of the world using the Armington (1969) specification (imports from other States and the rest of the world are imperfect substitutes for goods produced in the State).

The model computes the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments. The impacts of an earthquake are modeled as exogenous shocks to the productivity of industries, reductions in house-hold consumption and investment, and contemporaneous destruction of capital stock, with concomitant reductions in the economy's endowments of capital input.

Production

The supply side of the model employs a hierarchical nested CES production structure. In each region r and sector j (see table 2.1), the quantity and price of output are given by $QY_{j,r}$ and $PY_{j,r}$. At the top level of the hierarchy, output is produced by combining a bundle of capital, labor, and lifeline inputs ($QKLV_{j,r}$, with price $PKLV_{j,r}$) with a bundle of intermediate inputs ($QZ_{j,r}$, with price $PZ_{j,r}$). This production relationship is represented in dual form by the unit cost function:

$$PY_{j,r} \leq [\alpha_{KLV,j,r}^{\sigma_Y} PKLV_{j,r}^{1-\sigma_Y} + \alpha_{Z,j,r}^{\sigma_Y} PZ_{j,r}^{1-\sigma_Y}]^{1/(1-\sigma_Y)}. \quad (1a)$$

Here, σ_Y denotes the top-level the elasticity of substitution between intermediate inputs and the value-added-lifelines composite, and α_{KLV} and α_z are the CES distribution parameters, or technical coefficients.

Table 2.1. Values of the elasticities of substitution and transformation in the computable general equilibrium (CGE) model.

Elasticities	Symbol	Values
Elasticities of substitution		
Between a value-added lifelines composite and intermediate input composite in production	σ_Y	0.1
Between a value-added composite and lifeline input composite in production	σ_{KLV}	0.1
Between capital and labor in production	σ_{KL}	0.25
Among lifeline intermediate inputs to production	σ_V	0.1
Among intermediate inputs to production	σ_Z	0.1
Among counties' outputs of a particular good in aggregate commodity supply	$\sigma_{YY,i}$	[1]4.0
Between domestic (California) and imported (rest of world) varieties of each good in county Armington composite	$\sigma_{DM,i}$	[1]2.0
Among inputs to household consumption	σ_C	0.25
Among inputs to investment	σ_I	0.25
Among inputs to government	σ_G	0.25
Elasticities of transformation		
Between California aggregate supply and rest of world exports in California-wide sectoral supply composite	η_X	[1]2.0

[1]0.1 in utility lifeline sectors (electric power, water and wastewater, telecommunications).

At the second level of the hierarchy, the bundle *QKLV* is produced from a value-added composite of labor and capital ($QKL_{j,r}$, with price $PKL_{j,r}$) and a bundle of intermediate lifeline commodity inputs ($QV_{j,r}$, with price $PV_{j,r}$) according to the unit cost function:

$$PKLV_{j,r} \leq [\alpha_{KL,j,r}^{\sigma_{KLV}} PKL_{j,r}^{1-\sigma_{KLV}} + \alpha_{v,j,r}^{\sigma_{KLV}} PV_{j,r}^{1-\sigma_{KLV}}]^{1/(1-\sigma_{KLV})}, \quad (1b)$$

in which σ_{KLV} is the elasticity of substitution between lifelines and value-added, α_{KL} and α_V are technical coefficients.

At the third level, the value-added composite is produced from sector-specific capital ($QK_{j,r}$, with price $PK_{j,r}$) and intersectorally mobile labor ($QL_{j,r}$, with average wage *PL*) according to the unit cost function:

$$PKL_{j,r} \leq [\alpha_{K,j,r}^{\sigma_{KL}} PK_{j,r}^{1-\sigma_{KL}} + \alpha_{L,j,r}^{\sigma_{KL}} PL^{1-\sigma_{KL}}]^{1/(1-\sigma_{KL})}, \quad (1c)$$

where σ_{KL}, α_K, and α_L denote the capital-labor elasticity of substitution and associated technical coefficients. The composite of lifeline inputs is modeled by a CES aggregation of intermediate inputs of a subset of the *i* distinct commodities (of which sector *j* consumes a vector of quantities, $q_{i,j,r}$, with "Armington" user prices $PA_{i,r}$) according to the unit cost function

$$PV_{j,r} \leq [\Sigma_{i \in Lifelines} \alpha_{i,j,r}^{\sigma_V} PA_{i,r}^{1-\sigma_V}]^{1/(1-\sigma_V)}, \quad (1d)$$

with elasticity of substitution, σ_V, and associated technical coefficients α_i. The bundle of intermediate inputs (*QZ*) at the second level of the production hierarchy is modeled in a similar way:

$$PZ_{j,r} \leq [\Sigma_{i' \in Lifelines} \alpha_{i',j,r}^{\sigma_Z} PA_{i',r}^{1-\sigma_Z}]^{1/(1-\sigma_Z)}. \quad (1e)$$

with elasticity of substitution, σ_Z, and associated technical coefficients, $\alpha_{i'}$.

Trade and Commodity Supply

Trade is modeled according to an Armington (1969) formulation, in which the output of a sector in a particular region is allocated between consumption of locally produced goods and exports. In turn, exports are divided between goods destined for other regions within the United States and goods that satisfy foreign demand. Symmetrically, on the demand side, each consumed commodity is a composite of domestic and imported varieties, where the latter is an amalgam of imports from other U.S. regions and from abroad.

The calibration dataset does not record bilateral trade among counties or county aggregates. We use $QXUS_{i,r}$ to denote units of the i^{th} commodity exported by region *r* to U.S. consumers in other locales, and model these quantities as feeding into an aggregate national pool at a commodity-specific nationwide price (PUS_i). Similarly, we use $QXF_{i,r}$ to denote units of commodity *i* exported to consumers abroad. These quantities are treated as feeding an international pool at a single price (the generalized price of foreign exchange, *PFX*). Using $PYT_{i,r} = (1+\tau_{i,r}^Y)PY_{i,r}$ to represent the gross-of-tax price of commodity *i* in region *r* (where $\tau_{i,r}^Y$ denotes the production tax rate), the transformation of regional output into exports (quantity $QX_{i,r}$) is specified in terms of the dual by the following constant elasticity of transformation (CET) equation:

$$PYT_{i,r} \geq [\beta_{XCA,i}^{\eta_{X,i}} PUS_i^{1+\eta_{X,i}} + \beta_{XF,i}^{\eta_{X,i}} PFX^{1+\eta_{X,i}}]^{1/(1+\eta_{X,i})}, \quad (2a)$$

where (suppressing the commodity subscript for the sake of brevity) η_x is the commodity-specific elasticity of transformation between domestic and international export destinations, and β_{XCA} and β_{XF} are commodity-specific technical coefficients. Symmetrically, region *r* imports $QMUS_{i,r}$ units of *i* from other U.S. regions and $QMF_{i,r}$ units from abroad. Its aggregate imports of each commodity (quantity $QM_{i,r}$ with price $PM_{i,r}$) are modeled as a CES composite of these quantities, given in terms of the dual by

$$PM_{i,r} \leq [\beta_{MUS,i,r}^{\sigma_{MM,i}} PUS_i^{1-\sigma_{MM,i}} + \beta_{MF,i,r}^{\sigma_{MM,i}} PFX^{1-\sigma_{MM,i}}]^{1/(1-\sigma_{MM,i})}, \quad (2b)$$

in which (suppressing the commodity subscript) σ_{DM} is the elasticity of substitution among import origins, and β_{MUS} and β_{MF} are commodity-specific technical coefficients. In turn, within each region, sectors' intermediate demands and households' final demands for a particular commodity are satisfied by the Armington total supply of that good ($QA_{i,r}$, with price $PA_{i,r}$). Armington total supply is modeled as a CES composite of domestic and imported varieties of the good, given in dual form by

$$PA_{i,r} \leq (1-\Phi_{A,i,r})^{-1} \cdot [\beta_{D,i,r}^{\sigma_{DM,i}} PY_i^{1-\sigma_{DM,i}} + \beta_{M,i,r}^{\sigma_{DM,i}} PM^{1-\sigma_{DM,i}}]^{1/(1-\sigma_{DM,i})}, \quad (2c)$$

where (suppressing the commodity subscript) σ_{DM} is the commodity-specific elasticity of substitution, β_D and β_M are commodity-specific technical coefficients, and the parameter $\Phi_{A,i,r}$ captures the disaster's adverse shock to the aggregate supply of each commodity.

A simple trade closure is adopted for the model. Each county is treated as a small open economy which cannot affect the price of foreign exchange. Following open-economy modeling convention, foreign exchange is treated as the unit of account; accordingly, the price of foreign exchange (*PFX*) is designated as the numeraire price by fixing its value at unity. The model only resolves regions within the state of California, and not elsewhere in the United States, so in general trade flows of a particular good recorded by the benchmark input-output accounts will not balance. California's net export position vis-a-vis the rest of the United States is calculated by applying Shephard's lemma (for example, Varian, 1992), yielding the supply-demand balance condition:

$$\begin{aligned} &\Sigma_r QXUS_{i,r} \geq \Sigma_r QMUS_{i,r} + QBUS_i \Rightarrow \\ &\Sigma_r \frac{\partial PYT_{i,r}}{\partial PUS_i} QX_{i,r} \geq \Sigma_r \frac{\partial PM_{i,r}}{\partial PUS_i} QM_{i,r} + QBUS_i \end{aligned} \quad (2d)$$

where $QBUS_i$ is introduced as an exogenous balancing quantity of net exports of good *i*. The corresponding expression for trade supply-demand balance with foreign countries is

$$\Sigma_r QXF_{i,r} \geq \Sigma_r QMF_{i,r} + QBF_i \Rightarrow \tag{2e}$$
$$\Sigma_r \frac{\partial PYT_{i,r}}{\partial PFX} QX_{i,r} \geq \Sigma_r \frac{\partial PM_{i,r}}{\partial PFX} QM_{i,r} + QBF_i$$

with exogenous balancing quantity QBF_i.

Final Demands and Commodity Market Closures

In each county there are h household archetypes, each of which is modeled as a representative agent who with CES preferences overconsumption of commodities ($q_{i,C,h,r}$, at price $PA_{i,r}$). The associated dual expenditure functions are given by

$$PU_{h,r} \leq [\Sigma_i \gamma_{i,C,h,r}^{\sigma_C} PA_{i,r}^{1-\sigma_C}]^{1/(1-\sigma_C)}, \tag{3a}$$

where $PU_{h,r}$ is the households' unit expenditure index, and, suppressing subscripts for brevity, σ_C denotes households' consumption elasticity of substitution, and $\gamma_{i,C}$ are technical coefficients. There are also g levels of government, each of which consumes commodity inputs ($q_{i,G,g,r}$ at price $PA_{i,r}$) for the purpose of producing a government good (quantity $QG_{g,r}$, at price $PG_{g,r}$) with CES technology. The associated cost functions are

$$PG_{g,r} \leq [\Sigma_i \gamma_{i,G,g,r}^{\sigma_G} PA_{i,r}^{1-\sigma_G}]^{1/(1-\sigma_G)}, \tag{3b}$$

in which σ_G denotes the elasticity of substitution, and (suppressing subscripts) $\gamma_{i,G}$ are technical coefficients. As well, each region produces an investment good (QI_r, at price PI_r) from a CES aggregation of commodities ($q_{i,I,r,}$ at price $PA_{i,r}$), given in dual form by

$$PI_r \leq [\Sigma_i \gamma_{i,I,r}^{\sigma_I} PA_{i,r}^{1-\sigma_I}]^{1/(1-\sigma_I)}, \tag{3c}$$

where σ_I denotes the elasticity of substitution, and (suppressing subscripts) $\gamma_{i,I}$ are technical coefficients. It is assumed that each representative agent exhibits a fixed marginal propensity to save (MPS) and invests out of income. Supply-demand balance for households' savings ($QS_{h,r}$) requires

$$QI_r \leq \Sigma_h QS_{h,r}, \tag{3d}$$

while a fixed MPS implies a constant of proportionality, $\mu_{h,r}$, which allows savings to scale with changes in activity (consumption) levels:

$$QS_{h,r} = \mu_{h,r} U_{h,r}. \tag{3e}$$

Government consumption is financed out of tax revenue and transfers. Government g is modeled as claiming a fraction $\xi_{g,r}$ of the total tax revenue raised within region r, as well as receiving a net transfer, $GXFER_{g,r}$ (which for convenience is denominated in units of the numeraire). The activity level of public provision is then given by:

$$QG_{g,r} \leq (\xi_{g,r} \Sigma_j \tau_{j,r}^{Y} PY_{j,r} QY_{j,r} + PFX \cdot GXFER_{g,r}) / PG_{g,r}. \tag{3f}$$

The supply-demand balance for domestic output is given by

$$QY_{i,r} \geq QD_{i,r} + QX_{i,r} \tag{3g}$$

where the unconditional demand for domestic uses is given by Shephard's lemma: $QD_{i,r} = \frac{\partial PA_{i,r}}{\partial PY_{i,r}} QA_{i,r}$.

The supply-demand balance for imports is given by Shephard's lemma:

$$QM_{i,r} \geq \frac{\partial PA_{i,r}}{\partial PM_{i,r}} QA_{i,r}. \tag{3h}$$

Finally, the supply-demand balance for Armington commodities is closed via the condition

$$QA_{i,r} \geq \Sigma_j q_{i,j,r} + \Sigma_h q_{i,C,h,r} + q_{i,I,r} + \Sigma_g q_{i,G,g,r} \tag{3i}$$

in which the unconditional demands on the right-hand side are given by

$$q_{i,j,r} = \frac{\partial PY_{j,r}}{\partial PA_{i,r}} QY_{j,r},\ q_{i,C,h,r} = \frac{\partial PU_{h,r}}{\partial PA_{i,r}} U_{h,r},\ q_{i,I,r} = \frac{\partial PI_r}{\partial PA_{i,r}},$$

and $q_{i,G,g,r} = \frac{\partial PG_{g,r}}{\partial PA_{i,r}} QG_{g,r}$.

Inter-Sectoral Factor Mobility and Static Income Closures

Given the brief duration of the period over which the equilibrium represented by the model is established, the assumption of frictionless inter-sectoral reallocation of capital commonly made by CGE models is unlikely to accurately capture the behavior of factor markets. Although the authors continue to treat labor as mobile across industries and counties, capital is modeled as a sectorally and geographically fixed factor at each timestep, with instantaneous supply-demand balance determined by the county- and sector-specific supply of capital input ($\varepsilon_{K,j,r}$):

$$(1-\Phi_{K,j,r}) \cdot \varepsilon_{K,j,r} \geq \frac{\partial PKL_{j,r}}{\partial PK_{j,r}} QKL_{j,r}. \tag{4a}$$

Disaster-related capital-stock destruction on the left-hand side of this expression is the primary driver of economic impact. Traditional CGE models close the labor market either through the "neoclassical" assumption of full employment (perfectly inelastic supply) or "Keynesian" variable employment (perfectly elastic supply at a fixed wage). Although neither of these extremes adequately captures the effect of a large transitory shock (which typically induces simultaneous adjustments in both employment and wages), for the sake of simplicity and computational tractability we employ the latter, Keynesian closure. This is achieved by scaling counties labor endowments relative to their benchmark levels ($\varepsilon_{L,r,}$), with the supply-demand balance condition:

$$\Upsilon_L \cdot \Sigma_r \varepsilon_{L,r} \geq \Sigma_j \Sigma_r \frac{\partial PKL_{j,r}}{\partial PL} QKL_{j,r} \tag{4b}$$

in which the value of the scaling factor, Υ_L, is endogenously chosen to hold the wage constant

$$PL = 1. \tag{4c}$$

County-level household, investment, and government activities are bound together by an income-expenditure balance condition that constrains the value of expenditure and saving to equal the value of factor returns plus net household transfers ($HXFER_{h,r}$, also denominated in units of the numeraire). Thus, using $\zeta_{K,h,r}$ and $\zeta_{L,h,r}$ to denote the shares of labor and capital remuneration going to the various household income groups within each county, income balance is given by

$$\begin{aligned}&\zeta_{k,h,r} \cdot \Sigma_j PK_{j,r} \cdot \varepsilon_{k,j,r} + \zeta_{L,h,r} \Upsilon_L \cdot PL \cdot \varepsilon_{L,r} + PFX \cdot HXFER_{h,r} \\ &\geq PU_{h,r} U_{h,r} + PI_r QS_{h,r} + \Sigma_i PCA_i SA_{i,h,r}.\end{aligned} \tag{4d}$$

The final closure rule is the statewide balance of payments constraint, which balances the net supply of foreign exchange against the demands for transfer payments that make up the idiosyncratic components of household and government income:

$$\begin{aligned}&\Sigma_i PUS_i \left(QBUS_i + \Sigma_r PUS_i \left(QXUS_{i,r} - QMUS_{i,r} \right) \right) + \\ &\Sigma_i PFX \left(QBF_i + \Sigma_r \left(QXF_{i,r} - QMF_{i,r} \right) \right) + \\ &\Sigma_g \Sigma_r GXFER_{g,r} + \Sigma_h \Sigma_r HXFER_{h,r} = 0.\end{aligned} \tag{4e}$$

California's exports to, and counties' imports from, international (U.S.) markets are both valued at the numeraire foreign exchange price (U.S. average commodity-specific domestic prices), with quantities given by the application of Shepard's lemma to equations 2a and 2b:

$$QXUS_{i,r} = \frac{\partial PYT_{i,r}}{\partial PUS_i},\ QMUS_{i,r} = \frac{\partial PM_{i,r}}{\partial PUS_i}, \text{ and}$$

$$QXF_{i,r} = \frac{\partial PYT_{i,r}}{\partial PFX},\ QMF_{i,r} = \frac{\partial PM_{i,r}}{\partial PFX}.$$

Modeling the Impacts of an Earthquake

The static equilibrium model made up of equations 1 through 4 is subjected to the shock of economic damage caused by the earthquake event. Damage to sectoral capital stocks are modeled as secular reductions in sectors' endowments of capital input, $\Phi_{K,j,r} \in (0,1)$, whereas lifeline outages are modeled as secular reductions in the productivity of delivery of Armington lifeline commodities to their intermediate and final uses, $\Phi_{A,i,r} \in (0,1)$ for $i \in Lifelines$. In the economy's baseline state, these shock parameters are set to zero, whereas in the various loss scenarios they take on values between zero and one, reflecting different components of damage.

Model Calibration, Formulation, Solution, and Application

The vectors of technical coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ in equations 1 through 4 are calibrated using an IMPLAN social accounting matrix for the State of California for the year 2012 (IMPLAN, 2014) in conjunction with values of the elasticities of substitution, transformation, and supply in appendix 3, table 3.2. The model is formulated as a mixed complementarity problem using the MPSGE subsystem for GAMS (Rutherford, 1999; Brooke and others, 1988) and is solved using the PATH solver (Ferris and Munson, 2000).

Appendix 3. Sector Property Damages

Table 3.1. Percentage of buildings damaged by HayWired mainshock shaking, liquefaction, and landslide, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	16.69	9.45	1.37	0.09	0.18	0.11	0.05	0.55	2.60	0.32	2.39	3.45	0.60	0.42	0.12	0.19	0.06
Oil and gas extraction	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Coal mining	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Other mining	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Electric power generation, transmission, and distribution	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Natural gas distribution	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Water, sewage, and other systems	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Construction	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Heavy industry	14.25	8.45	1.93	0.06	0.27	0.55	0.04	1.33	3.02	0.72	3.77	4.56	0.54	0.85	0.14	0.35	0.09
Light industry	18.70	9.07	1.92	0.07	0.14	0.75	0.06	1.52	3.15	0.73	3.89	4.92	0.55	0.80	0.18	0.40	0.12
Petroleum refineries	19.11	6.65	2.20	0.11	0.20	0.26	0.03	1.41	2.84	0.57	3.48	4.38	0.67	0.74	0.13	0.53	0.12
Food, drug, and chemicals	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Primary metal manufacturing	31.79	8.13	2.76	0.04	0.09	0.40	0.02	1.92	2.24	0.72	4.67	4.83	0.58	1.10	0.22	0.44	0.08
Electronic computer manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Computer storage device manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Semiconductor and related device manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Other high-tech manufacturing	21.90	10.31	1.69	0.14	0.16	0.33	0.03	0.98	3.21	0.60	3.47	4.29	0.59	0.82	0.14	0.32	0.10
Wholesale trade, warehousing, and storage	19.80	9.00	1.85	0.09	0.17	0.48	0.02	0.91	3.28	0.59	3.50	4.52	0.52	0.77	0.15	0.27	0.06
Retail trade	20.49	11.56	1.42	0.09	0.11	0.28	0.02	0.83	2.31	0.52	3.02	3.68	0.41	0.82	0.10	0.25	0.06
Air transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07

Table 3.1.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Rail transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Water transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Truck transportation	19.80	9.00	1.85	0.09	0.17	0.48	0.02	0.91	3.28	0.59	3.50	4.52	0.52	0.77	0.15	0.27	0.06
Transit and ground passengers	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Pipeline transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Sightseeing transportation	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Couriers and messengers	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Publishing, motion picture, and broadcasting	16.96	9.84	1.44	0.08	0.10	0.38	0.02	1.67	2.35	0.57	3.28	3.97	0.42	0.78	0.11	0.26	0.08
Internet publishing and broadcasting	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Telecommunications	18.83	9.35	1.42	0.14	0.08	0.25	0.03	0.86	2.32	0.55	3.15	3.76	0.45	0.86	0.11	0.27	0.09
Data processing, hosting, and related services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other information services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Finance, insurance, real estate, and leasing	16.69	10.03	1.39	0.08	0.10	0.31	0.02	1.71	2.26	0.53	3.21	3.77	0.41	0.77	0.10	0.24	0.07
Imputed rental value for owner-occupied dwellings	10.09	4.51	0.98	0.04	0.05	0.15	0.01	0.32	1.58	0.33	2.17	2.22	0.27	0.45	0.05	0.12	0.03
Computer systems design and related services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other professional, scientific, and technical services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Other business services	16.62	9.89	1.40	0.08	0.10	0.32	0.02	1.69	2.29	0.54	3.20	3.78	0.40	0.78	0.10	0.24	0.07
Educational services	16.33	13.24	1.15	0.07	0.11	0.23	0.02	0.51	1.96	0.47	2.48	3.21	0.36	0.80	0.07	0.21	0.06

Table 3.1.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Ambulatory health care and hospitals	15.69	8.96	1.37	0.05	0.12	0.30	0.02	0.75	1.92	0.57	2.64	3.27	0.37	0.72	0.10	0.21	0.08
Nursing home/ social assistance	19.64	10.38	1.52	0.09	0.11	0.40	0.02	1.05	2.39	0.55	3.07	3.70	0.45	0.90	0.10	0.26	0.08
Arts, entertainment, and recreation	18.83	9.35	1.42	0.14	0.08	0.25	0.03	0.86	2.32	0.55	3.15	3.76	0.45	0.86	0.11	0.27	0.09
Accommodations	15.31	9.38	1.12	0.21	0.03	0.12	0.04	0.51	2.01	0.55	3.70	3.39	0.35	0.66	0.06	0.24	0.08
Repair and maintenance	19.73	10.53	1.52	0.09	0.12	0.40	0.02	1.07	2.40	0.56	3.09	3.74	0.45	0.93	0.10	0.27	0.08
Personal services/ private households	19.73	10.53	1.52	0.09	0.12	0.40	0.02	1.07	2.40	0.56	3.09	3.74	0.45	0.93	0.10	0.27	0.08
Religious, grantmaking, and similar organizations	17.91	10.20	1.29	0.10	0.09	0.25	0.02	0.77	2.02	0.47	3.08	3.31	0.46	1.04	0.09	0.20	0.06
Government and non-NAICS	14.91	9.05	2.12	0.16	0.06	0.37	0.02	2.07	2.26	0.67	2.95	4.53	0.43	0.86	0.09	0.31	0.07

Table 3.2. Percentage of contents damaged by HayWired mainshock shaking, liquefaction, and landslide, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Agriculture, forestry, fishing, and hunting	6.79	3.82	0.66	0.06	0.11	0.07	0.03	0.34	1.17	0.19	1.15	1.63	0.33	0.24	0.07	0.12	0.05
Oil and gas extraction	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Coal mining	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Other mining	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Electric power generation, transmission, and distribution	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Natural gas distribution	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Water, sewage, and other systems	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Construction	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Heavy industry	6.17	3.40	0.84	0.03	0.14	0.26	0.02	0.64	1.31	0.34	1.61	2.56	0.25	0.40	0.07	0.17	0.05
Light industry	7.52	3.55	0.82	0.03	0.06	0.34	0.03	0.73	1.32	0.32	1.64	2.64	0.26	0.36	0.08	0.18	0.06
Petroleum refineries	7.39	2.63	0.97	0.05	0.09	0.12	0.02	0.56	1.20	0.26	1.49	2.09	0.30	0.34	0.06	0.24	0.06
Food, drug, and chemi-cals	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Primary metal manufacturing	12.15	3.07	1.07	0.02	0.04	0.18	0.01	0.83	0.85	0.32	1.81	2.45	0.25	0.51	0.09	0.20	0.04
Electronic computer manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Computer storage de-vice manufacturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Semiconductor and related device manu-facturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Other high-tech manu-facturing	8.41	3.96	0.67	0.07	0.07	0.15	0.02	0.46	1.30	0.27	1.45	2.10	0.27	0.37	0.06	0.15	0.05
Wholesale trade, warehousing, and storage	7.46	3.46	0.88	0.06	0.11	0.29	0.02	0.54	1.39	0.34	1.53	2.55	0.30	0.43	0.08	0.17	0.05
Retail trade	7.18	4.27	0.67	0.06	0.07	0.17	0.01	0.45	1.00	0.30	1.40	1.78	0.25	0.45	0.06	0.15	0.05
Air transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Rail transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Water transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Truck transportation	7.46	3.46	0.88	0.06	0.11	0.29	0.02	0.54	1.39	0.34	1.53	2.55	0.30	0.43	0.08	0.17	0.05
Transit and ground passengers	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Pipeline transportation	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Sightseeing transporta-tion	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Couriers and messengers	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Publishing, motion picture, and broadcasting	6.19	3.71	0.67	0.04	0.05	0.22	0.01	0.63	0.87	0.30	1.51	2.12	0.24	0.41	0.06	0.15	0.05
Internet publishing and broadcasting	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Telecommunications	5.90	3.51	0.64	0.08	0.04	0.13	0.02	0.42	1.02	0.28	1.45	1.91	0.24	0.44	0.06	0.15	0.05
Data processing, hosting, and related services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other information services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Finance, insurance, real estate, and leasing	5.82	3.77	0.65	0.05	0.05	0.18	0.01	0.60	0.80	0.29	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Imputed rental value for owner-occupied dwellings	4.93	2.64	0.48	0.03	0.04	0.10	0.01	0.25	0.88	0.21	1.26	1.43	0.18	0.28	0.03	0.08	0.03
Computer systems design and related services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other professional, scientific, and technical services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Other business services	5.80	3.72	0.65	0.05	0.05	0.18	0.01	0.60	0.83	0.30	1.48	1.96	0.23	0.42	0.05	0.14	0.05
Educational services	5.12	5.11	0.61	0.06	0.08	0.15	0.02	0.38	0.91	0.29	1.26	1.63	0.24	0.49	0.05	0.16	0.05
Ambulatory health care and hospitals	5.42	3.41	0.59	0.02	0.06	0.17	0.01	0.40	0.83	0.29	1.25	1.51	0.22	0.40	0.05	0.12	0.05
Nursing home/social assistance	6.96	4.03	0.70	0.05	0.07	0.23	0.01	0.56	1.08	0.31	1.46	1.94	0.26	0.49	0.06	0.15	0.05
Arts, entertainment, and recreation	5.90	3.51	0.64	0.08	0.04	0.13	0.02	0.42	1.02	0.28	1.45	1.91	0.24	0.44	0.06	0.15	0.05
Accommodations	5.49	3.74	0.53	0.14	0.02	0.07	0.03	0.32	0.63	0.28	1.76	1.72	0.22	0.36	0.03	0.14	0.05
Repair and maintenance	6.97	4.05	0.70	0.06	0.07	0.23	0.01	0.56	1.08	0.31	1.47	1.94	0.26	0.50	0.06	0.16	0.05

Table 3.2.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Personal services/ private households	6.97	4.05	0.70	0.06	0.07	0.23	0.01	0.56	1.08	0.31	1.47	1.94	0.26	0.50	0.06	0.16	0.05
Religious, grantmaking, and similar organizations	6.43	4.06	0.61	0.07	0.05	0.16	0.02	0.49	0.97	0.28	1.50	1.78	0.28	0.58	0.05	0.12	0.04
Government and non-NAICS	4.60	3.27	1.02	0.10	0.03	0.20	0.01	0.79	0.87	0.36	1.45	1.95	0.24	0.44	0.05	0.15	0.04

Table 3.3. Percentage of buildings and contents damaged by fire following the HayWired mainshock, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Agriculture, forestry, fishing, and hunting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oil and gas extraction	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Coal mining	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Other mining	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Electric power generation, transmission, and distribution	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Natural gas distribution	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Water, sewage, and other systems	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Construction	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Heavy industry	2.37	0.80	2.23	0.00	0.00	0.01	0.00	0.00	0.13	0.00	0.48	0.78	0.00	1.04	0.01	0.00	0.00
Light industry	3.93	1.38	3.84	0.00	0.00	0.03	0.00	0.00	0.04	0.00	0.74	1.34	0.00	0.80	0.03	0.00	0.00
Petroleum refineries	4.48	1.23	4.88	0.00	0.00	0.01	0.00	0.00	0.21	0.00	0.80	1.49	0.00	0.01	0.01	0.00	0.00
Food, drug, and chemicals	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00
Primary metal manufacturing	3.07	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.41	1.32	0.00	1.25	0.00	0.00	0.00

Table 3.3.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Electronic computer manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Computer storage device manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Semiconductor and related device manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Other high-tech manufacturing	5.92	1.59	3.45	0.00	0.00	0.02	0.00	0.00	0.21	0.00	1.40	1.97	0.00	1.98	0.04	0.00	0.00
Wholesale trade, warehousing, and storage	1.55	0.45	0.85	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.23	0.40	0.00	0.30	0.00	0.00	0.00
Retail trade	2.87	1.18	0.70	0.00	0.00	0.02	0.00	0.00	0.06	0.00	0.43	0.68	0.00	1.01	0.02	0.00	0.00
Air transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Rail transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Water transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Truck transportation	1.55	0.45	0.85	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.23	0.40	0.00	0.30	0.00	0.00	0.00
Transit and ground passengers	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Pipeline transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Sightseeing transportation	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Couriers and messengers	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Publishing, motion picture, and broadcasting	2.47	1.26	1.31	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.42	0.82	0.00	0.70	0.02	0.00	0.00
Internet publishing and broadcasting	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Telecommunications	2.50	0.99	0.65	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.43	0.78	0.00	1.20	0.02	0.00	0.00
Data processing, hosting, and related services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other information services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00

Table 3.3.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Finance, insurance, real estate, and leasing	2.03	1.27	0.95	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.36	0.65	0.00	0.68	0.01	0.00	0.00
Imputed rental value for owner-occupied dwellings	10.18	3.08	2.32	0.00	0.00	0.03	0.00	0.00	0.37	0.00	1.11	1.78	0.00	3.36	0.04	0.00	0.00
Computer systems design and related services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other professional, scientific, and technical services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Other business services	1.99	1.25	0.96	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.35	0.64	0.00	0.66	0.01	0.00	0.00
Educational services	23.28	8.00	8.01	0.00	0.00	0.05	0.00	0.00	0.77	0.00	3.17	4.87	0.00	14.13	0.10	0.00	0.00
Ambulatory health care and hospitals	3.37	1.06	0.75	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.46	0.53	0.00	0.64	0.03	0.00	0.00
Nursing home/social assistance	2.75	0.87	0.81	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.69	0.00	1.97	0.02	0.00	0.00
Arts, entertainment, and recreation	2.50	0.99	0.65	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.43	0.78	0.00	1.20	0.02	0.00	0.00
Accommodations	8.77	2.20	3.20	0.00	0.00	0.00	0.00	0.00	0.12	0.00	1.33	2.47	0.00	2.37	0.02	0.00	0.00
Repair and maintenance	2.63	0.82	0.76	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.67	0.00	2.00	0.01	0.00	0.00
Personal services/private households	2.63	0.82	0.76	0.00	0.00	0.01	0.00	0.00	0.05	0.00	0.42	0.67	0.00	2.00	0.01	0.00	0.00
Religious, grantmaking, and similar organizations	6.11	1.93	2.78	0.00	0.00	0.01	0.00	0.00	0.12	0.00	0.89	1.42	0.00	9.91	0.04	0.00	0.00
Government and non-NAICS	7.18	2.55	2.35	0.00	0.00	0.01	0.00	0.00	0.02	0.00	1.16	2.00	0.00	8.67	0.01	0.00	0.00

Table 3.4. Percentage of buildings and contents damaged by the HayWired mainshock and fire following the mainshock, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Agriculture, forestry, fishing, and hunting	23.48	13.27	2.02	0.15	0.30	0.18	0.08	0.88	3.76	0.51	3.54	5.08	0.94	0.67	0.19	0.31	0.11
Oil and gas extraction	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Coal mining	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Other mining	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Electric power generation, transmission, and distribution	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Natural gas distribution	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Water, sewage, and other systems	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Construction	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Heavy industry	22.78	12.65	5.00	0.09	0.41	0.83	0.05	1.97	4.46	1.06	5.86	7.91	0.79	2.30	0.22	0.52	0.14
Light industry	30.14	14.01	6.58	0.10	0.20	1.12	0.08	2.26	4.51	1.06	6.28	8.91	0.81	1.97	0.29	0.58	0.18
Petroleum refineries	30.98	10.51	8.05	0.16	0.29	0.38	0.05	1.97	4.25	0.82	5.77	7.97	0.96	1.09	0.20	0.77	0.18
Food, drug, and chemicals	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Primary metal manufacturing	47.01	11.79	4.76	0.05	0.13	0.58	0.03	2.75	3.13	1.04	6.88	8.59	0.83	2.85	0.31	0.64	0.12
Electronic computer manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Computer storage device manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Semiconductor and related device manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Other high-tech manufacturing	36.22	15.85	5.80	0.20	0.23	0.50	0.05	1.43	4.72	0.87	6.33	8.37	0.85	3.16	0.24	0.47	0.15
Wholesale trade, warehousing, and storage	28.82	12.90	3.58	0.14	0.28	0.78	0.04	1.45	4.70	0.93	5.26	7.47	0.82	1.50	0.24	0.44	0.11
Retail trade	30.54	17.01	2.79	0.14	0.17	0.47	0.04	1.28	3.37	0.82	4.85	6.14	0.66	2.28	0.17	0.40	0.11
Air transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12

Table 3.4.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Rail transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Water transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Truck transportation	28.82	12.90	3.58	0.14	0.28	0.78	0.04	1.45	4.70	0.93	5.26	7.47	0.82	1.50	0.24	0.44	0.11
Transit and ground passengers	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Pipeline transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Sightseeing transportation	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Couriers and messengers	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Publishing, motion picture, and broadcasting	25.62	14.81	3.42	0.12	0.15	0.61	0.04	2.29	3.24	0.87	5.22	6.91	0.66	1.89	0.19	0.41	0.12
Internet publishing and broadcasting	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Telecommunications	27.22	13.84	2.71	0.21	0.12	0.39	0.04	1.28	3.37	0.83	5.03	6.46	0.69	2.50	0.19	0.42	0.14
Data processing, hosting, and related services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other information services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Finance, insurance, real estate, and leasing	24.54	15.07	2.99	0.13	0.15	0.49	0.03	2.31	3.08	0.82	5.05	6.37	0.64	1.86	0.16	0.38	0.12
Imputed rental value for owner-occupied dwellings	25.21	10.23	3.78	0.08	0.09	0.28	0.02	0.58	2.83	0.54	4.54	5.43	0.45	4.09	0.12	0.20	0.06
Computer systems design and related services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other professional, scientific, and technical services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Other business services	24.41	14.86	3.01	0.13	0.15	0.50	0.03	2.29	3.14	0.83	5.04	6.38	0.63	1.86	0.16	0.38	0.12
Educational services	44.73	26.35	9.77	0.13	0.19	0.43	0.04	0.90	3.64	0.77	6.90	9.70	0.60	15.42	0.22	0.37	0.12

Table 3.4.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Ambulatory health care and hospitals	24.48	13.42	2.71	0.07	0.18	0.47	0.03	1.16	2.82	0.86	4.35	5.31	0.59	1.76	0.18	0.33	0.13
Nursing home/social assistance	29.36	15.28	3.03	0.14	0.18	0.64	0.04	1.61	3.52	0.86	4.95	6.33	0.71	3.36	0.18	0.42	0.13
Arts, entertainment, and recreation	27.22	13.84	2.71	0.21	0.12	0.39	0.04	1.28	3.37	0.83	5.03	6.46	0.69	2.50	0.19	0.42	0.14
Accommodations	29.57	15.31	4.85	0.36	0.04	0.19	0.07	0.83	2.76	0.83	6.80	7.58	0.57	3.39	0.11	0.37	0.13
Repair and mainte-nance	29.32	15.40	2.97	0.15	0.18	0.65	0.04	1.64	3.53	0.86	4.97	6.35	0.72	3.43	0.18	0.42	0.14
Personal services/private households	29.32	15.40	2.97	0.15	0.18	0.65	0.04	1.64	3.53	0.86	4.97	6.35	0.72	3.43	0.18	0.42	0.14
Religious, grantmak-ing, and similar organizations	30.46	16.20	4.68	0.17	0.14	0.41	0.04	1.27	3.11	0.75	5.47	6.51	0.74	11.53	0.18	0.33	0.11
Government and non-NAICS	26.68	14.88	5.48	0.25	0.09	0.58	0.03	2.86	3.15	1.03	5.56	8.48	0.67	9.97	0.14	0.46	0.11

Table 3.5. Percentage of buildings and contents damaged by HayWired aftershocks, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Agriculture, forestry, fishing, and hunting	2.19	0.29	0.08	0.01	0.04	0.05	0.01	0.02	0.34	0.02	3.71	4.41	0.22	0.17	0.01	0.01	0.02
Oil and gas extraction	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Coal mining	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Other mining	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Electric power genera-tion, transmission, and distribution	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Natural gas distribu-tion	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Water, sewage, and other systems	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Construction	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Heavy industry	6.16	0.60	0.14	0.02	0.06	0.18	0.02	0.04	0.75	0.04	7.12	5.76	0.50	0.25	0.01	0.02	0.04

Table 3.5.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Monterey	Napa	Sacramento	San Benito	San Francisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stanislaus	Yolo
Light industry	4.67	0.58	0.14	0.01	0.04	0.21	0.02	0.04	0.60	0.04	5.39	7.53	0.60	0.47	0.01	0.02	0.03
Petroleum refineries	4.45	0.44	0.15	0.01	0.06	0.09	0.01	0.05	0.57	0.03	3.99	7.25	0.40	0.34	0.03	0.02	0.04
Food, drug, and chemicals	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Primary metal manufacturing	4.24	0.54	0.15	0.02	0.05	0.16	0.02	0.04	0.42	0.05	11.13	5.81	0.25	0.24	0.01	0.02	0.04
Electronic computer manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Computer storage device manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Semiconductor and related device manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Other high-tech manufacturing	3.24	0.43	0.13	0.02	0.05	0.13	0.02	0.04	0.77	0.03	4.63	5.77	0.58	0.33	0.01	0.02	0.03
Wholesale trade, warehousing, and storage	3.62	0.36	0.11	0.01	0.05	0.13	0.01	0.03	0.50	0.03	2.60	5.24	0.35	0.29	0.02	0.02	0.02
Retail trade	2.16	0.43	0.09	0.01	0.03	0.10	0.01	0.03	0.32	0.02	3.19	5.38	0.43	0.16	0.01	0.02	0.02
Air transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Rail transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Water transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Truck transportation	3.62	0.36	0.11	0.01	0.05	0.13	0.01	0.03	0.50	0.03	2.60	5.24	0.35	0.29	0.02	0.02	0.02
Transit and ground passengers	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Pipeline transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Sightseeing transportation	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Couriers and messengers	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Publishing, motion picture, and broadcasting	2.39	0.31	0.09	0.01	0.03	0.12	0.01	0.03	0.25	0.02	3.88	6.11	0.44	0.26	0.01	0.02	0.02
Internet publishing and broadcasting	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Telecommunications	2.12	0.32	0.10	0.01	0.03	0.09	0.02	0.03	0.36	0.03	3.59	6.53	0.51	0.17	0.01	0.02	0.03

Table 3.5.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Data processing, hosting, and related services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other information services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Finance, insurance, real estate, and leasing	1.99	0.30	0.08	0.01	0.02	0.10	0.01	0.03	0.20	0.02	3.61	5.80	0.42	0.22	0.01	0.02	0.02
Imputed rental value for owner-occupied dwellings	1.26	0.24	0.03	0.00	0.01	0.04	0.00	0.01	0.19	0.01	2.08	3.41	0.27	0.08	0.00	0.01	0.01
Computer systems design and related services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other professional, scientific, and technical services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Other business services	2.01	0.29	0.08	0.01	0.02	0.10	0.01	0.03	0.21	0.02	3.64	5.82	0.42	0.22	0.01	0.02	0.02
Educational services	1.46	0.55	0.07	0.01	0.03	0.08	0.01	0.02	0.28	0.02	2.41	5.49	0.38	0.21	0.01	0.02	0.02
Ambulatory health care and hospitals	1.53	0.31	0.08	0.01	0.03	0.11	0.01	0.03	0.34	0.03	3.59	6.35	0.41	0.16	0.01	0.02	0.02
Nursing home/social assistance	2.20	0.43	0.09	0.01	0.03	0.12	0.01	0.03	0.34	0.03	3.50	5.92	0.46	0.18	0.01	0.02	0.02
Arts, entertainment, and recreation	2.12	0.32	0.10	0.01	0.03	0.09	0.02	0.03	0.36	0.03	3.59	6.53	0.51	0.17	0.01	0.02	0.03
Accommodations	1.34	0.31	0.06	0.01	0.01	0.05	0.01	0.02	0.13	0.02	3.25	5.27	0.46	0.37	0.01	0.01	0.02
Repair and mainte-nance	2.21	0.44	0.09	0.01	0.03	0.12	0.01	0.03	0.35	0.03	3.48	5.95	0.46	0.18	0.01	0.02	0.02
Personal services/private households	2.21	0.44	0.09	0.01	0.03	0.12	0.01	0.03	0.35	0.03	3.48	5.95	0.46	0.18	0.01	0.02	0.02
Religious, grantmaking, and similar organizations	1.76	0.45	0.07	0.01	0.03	0.08	0.01	0.03	0.29	0.02	3.80	5.35	0.46	0.16	0.01	0.02	0.02
Government and non-NAICS	1.41	0.28	0.12	0.01	0.02	0.13	0.01	0.03	0.22	0.03	4.38	5.41	0.47	0.20	0.01	0.02	0.02

Table 3.6. Percentage of buildings and contents damaged by the HayWired mainshock, fire following the mainshock, and aftershocks, by sector and by county, San Francisco Bay region, California, estimated using Hazus.

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Agriculture, forestry, fishing, and hunting	25.67	13.56	2.10	0.16	0.34	0.22	0.09	0.91	4.10	0.53	7.25	9.48	1.15	0.84	0.20	0.32	0.13
Oil and gas extraction	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Coal mining	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Other mining	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Electric power generation, transmission, and distribution	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Natural gas distribution	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Water, sewage, and other systems	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Construction	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Heavy industry	28.94	13.25	5.15	0.10	0.47	1.01	0.07	2.01	5.20	1.10	12.98	13.66	1.29	2.55	0.23	0.54	0.17
Light industry	34.81	14.59	6.72	0.11	0.24	1.33	0.11	2.30	5.11	1.10	11.67	16.44	1.40	2.44	0.31	0.61	0.22
Petroleum refineries	35.43	10.95	8.21	0.18	0.35	0.47	0.06	2.01	4.81	0.86	9.76	15.22	1.36	1.43	0.23	0.79	0.21
Food, drug, and chemicals	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Primary metal manufacturing	51.26	12.33	4.91	0.07	0.18	0.74	0.05	2.79	3.55	1.09	18.01	14.41	1.09	3.09	0.33	0.66	0.16
Electronic computer manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Computer storage device manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Semiconductor and related device manufacturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Other high-tech manu-facturing	39.46	16.28	5.94	0.22	0.28	0.63	0.07	1.47	5.49	0.90	10.96	14.14	1.43	3.49	0.26	0.49	0.19
Wholesale trade, warehousing, and storage	32.44	13.26	3.69	0.16	0.33	0.91	0.05	1.48	5.20	0.96	7.86	12.71	1.16	1.79	0.25	0.45	0.13

Table 3.6.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Retail trade	32.70	17.44	2.88	0.15	0.20	0.57	0.05	1.31	3.69	0.85	8.04	11.52	1.09	2.44	0.18	0.42	0.13
Air transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Rail transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Water transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Truck transportation	32.44	13.26	3.69	0.16	0.33	0.91	0.05	1.48	5.20	0.96	7.86	12.71	1.16	1.79	0.25	0.45	0.13
Transit and ground passengers	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Pipeline transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Sightseeing transportation	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Couriers and messengers	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Publishing, motion picture, and broadcasting	28.01	15.12	3.51	0.13	0.18	0.73	0.05	2.33	3.50	0.89	9.10	13.02	1.10	2.15	0.20	0.43	0.15
Internet publishing and broadcasting	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Telecommunications	29.34	14.17	2.81	0.23	0.14	0.48	0.06	1.31	3.73	0.86	8.62	12.99	1.20	2.68	0.20	0.44	0.16
Data processing, hosting, and related services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Other information services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Finance, insurance, real estate, and leasing	26.53	15.37	3.07	0.14	0.17	0.60	0.04	2.34	3.28	0.84	8.66	12.18	1.06	2.08	0.17	0.40	0.14
Imputed rental value for owner-occupied dwellings	26.47	10.47	3.81	0.08	0.10	0.32	0.02	0.59	3.02	0.55	6.63	8.84	0.72	4.17	0.12	0.21	0.07
Computer systems design and related services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Other professional, scientific, and technical services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14

Table 3.6.—Continued

Sector	Alameda	Contra Costa	Marin	Merced	Mon-terey	Napa	Sacra-mento	San Benito	San Fran-cisco	San Joaquin	San Mateo	Santa Clara	Santa Cruz	Solano	Sonoma	Stan-islaus	Yolo
Other business services	26.41	15.15	3.09	0.14	0.17	0.60	0.04	2.32	3.35	0.85	8.68	12.20	1.05	2.08	0.17	0.40	0.14
Educational services	46.19	26.89	9.84	0.14	0.22	0.50	0.05	0.92	3.92	0.79	9.32	15.19	0.98	15.63	0.22	0.39	0.14
Ambulatory health care and hospitals	26.02	13.73	2.78	0.08	0.21	0.59	0.04	1.18	3.16	0.89	7.94	11.66	1.00	1.92	0.18	0.35	0.15
Nursing home/social assistance	31.56	15.70	3.12	0.15	0.21	0.76	0.05	1.65	3.87	0.88	8.45	12.25	1.16	3.55	0.18	0.43	0.16
Arts, entertainment, and recreation	29.34	14.17	2.81	0.23	0.14	0.48	0.06	1.31	3.73	0.86	8.62	12.99	1.20	2.68	0.20	0.44	0.16
Accommodations	30.92	15.62	4.91	0.37	0.05	0.24	0.08	0.85	2.89	0.85	10.05	12.84	1.03	3.75	0.12	0.38	0.15
Repair and maintenance	31.53	15.83	3.06	0.16	0.22	0.77	0.05	1.67	3.88	0.89	8.45	12.29	1.18	3.61	0.18	0.44	0.16
Personal services/ private households	31.53	15.83	3.06	0.16	0.22	0.77	0.05	1.67	3.88	0.89	8.45	12.29	1.18	3.61	0.18	0.44	0.16
Religious, grantmak-ing, and similar organizations	32.22	16.65	4.74	0.18	0.17	0.49	0.05	1.30	3.40	0.77	9.26	11.86	1.19	11.69	0.19	0.34	0.13
Government and non-NAICS	28.10	15.16	5.60	0.27	0.11	0.71	0.04	2.89	3.37	1.06	9.94	13.89	1.15	10.17	0.15	0.48	0.14

Appendix 4. Household Inconvenience Costs of Electricity and Water Service Disruptions

By Keith Porter[1]

Inconvenience Cost for Loss of Water

Loss of Water Service

Porter (2018, table 30) presented estimates of the fraction of customers receiving water service at several points in time after the HayWired mainshock. The data in the table can be charted as restoration curves: time on the horizontal axis and fraction of customers receiving water on the vertical axis. The area above the curves and below 100 percent represents the average number of days a customer in each county is without water service, referred to here as the average service-days lost per household. Bruneau and others (2003) refer to that area as the loss of resilience; many other authors refer to it as the loss triangle, though it need not have a triangular shape (National Research Council, 2011). One can use the trapezoidal rule to estimate the average service-days lost per household in each county:

$$L = \sum_{i=1}^{n}(t_i - t_{i-1}) \cdot (1 - \frac{y_i + y_{i-1}}{2}). \quad (1)$$

[1]University of Colorado Boulder.

One can then estimate the total service-days lost, that is, the product of service connections and days without service, as

$$S = L \cdot C \quad (2)$$

where

- L average service-days lost per household, in days
- i an index to count the number of time increments (for example, 0 to 1 day, 1 to 3 days, and so on)
- n number of time increments shown in the table ($n = 6$)
- t_i time at the end of increment i, for example, $t_1 = 1$ day after the mainshock
- y_i fraction of customers receiving water at time t_i
- S total service-days lost and
- C number of service connections, taken here as 1.0 times the number of households.

Table 4.1 shows the results of the foregoing calculation. In the table households and total service days lost are displayed only to two significant figures to reduce the appearance of excessive accuracy.

Table 4.1. Loss of water service by county, San Francisco Bay region, California.

County	Households without service[1]	Average service-days lost per household, days	Total service-days lost
Alameda	520,000	54	**28,000,000**
Contra Costa	340,000	54	**18,000,000**
Marin	100,000	1	**100,000**
Merced	64,000	0	**24,000**
Monterey	120,000	0	--
Napa	45,000	0	--
Sacramento	450,000	0	--
San Benito	16,000	0	**1,600**
San Francisco	330,000	7	**2,300,000**
San Joaquin	180,000	0	--
San Mateo	250,000	20	**5,200,000**
Santa Clara	570,000	5	**3,000,000**
Santa Cruz	91,000	0	--
Solano	130,000	0	**27,000**
Sonoma	170,000	0	--
Stanislaus	150,000	0	--
Yolo	59,000	0	--
Total	**3,600,000**	**16**	**57,000,000**

[1]Data from Porter (2018), table 30.

Loss of water service to homes does not affect economic production but it does have a real cost, especially if it exceeds people's emergency supplies, requires a change in habits that people would prefer not to make, or requires purchases that they would otherwise avoid.

Many Californians do stockpile water at the advice of the Red Cross, Earthquake Country Alliance, and others. Emergency managers have been asking Californians to keep 3 to 7 days of water in their homes. It seems likely that people's actual supplies are at the lower end and only provide enough water for drinking, not other household uses such as toilets and showers.

Loss of water service throughout much of the study area lasts far longer than the time people can reasonably go without toilets and showers. The average East Bay Municipal Utility District customer loses water for 6 weeks, which is a long time to have to find substitutes for showers, drinking water, toilets, and so on. What will the loss of water service cost households?

Literature on the Inconvenience Cost of Lost Residential Potable Water

The Federal Emergency Management Agency's (FEMA's) [undated] benefit-cost analysis tool offers a default value of potable water service of $103.00 per person, per day, "calculated based on residential and regional economic impact from national statistics." Elsewhere, FEMA (2009, p. A-5) states, without reference to a source, that its standard values for loss of potable water service is $88 per person per day, which in 2018 would equate with $104 per person per day and $260 per household per day for a household size of 2.5.

Heflin and others (2013) conducted three focus-group studies and collected 162 in-person surveys of people affected by loss of water service. The elicited costs of extra bottled water, boiling or bleaching, replacing water filters, extra costs associated with cooking and eating, effects on work and school schedules, and travel costs, produced an average added expense of $102 per household per day in 2018 dollars.

Aubuchon and Morley (2013) estimate the economic value associated with loss of water service between $67 and $457 per person per day and suggest an average value of $208 per person per day (2011 dollars), approximately equivalent to $231 per person per day (2018 dollars) or $580 per household per day.

Several authors have estimated the hedonic value of potable water in the developing world (for example, in Ghana: Twerefou and others, 2015; in the Philippines: North and Griffin, 1993; in Rwanda: Kolowe, 2014). The present author could find no analogous studies for the United States.

The range suggested by the three U.S. sources is large: $102 to $580 per household per day in 2018 dollars. Let us revisit the question in the context of the HayWired scenario.

A New Estimate of the Daily Household Value of Potable Water

Bottled water will realistically be provided for free on street corners to residences and businesses, as it was in New Orleans after Katrina, but not at zero cost. Bulk bottled water seems to cost about $0.50 per gallon at the wholesaler, implying something like $0.75 per gallon delivered to street corners all over the east bay. At 1 gallon per person per day, and average household size of around 2.5, the cost to provide drinking water is about $2 per household per day.

Portable toilets will also be necessary. The national average rental and service cost is $260 per month and is up to 50 percent higher in San Francisco. (There may not be enough portable toilets in the entire national market to meet the need.) Assuming availability, at $260 per month, and assuming one portable toilet per household, portable toilet rental adds $9 per household per day.

The $11 direct cost seems small compared with the hedonic value of living like that for several weeks—how much people would pay not to have to use a portable toilet. There is no obvious market to use to assess the value of having to rely on the bottled water and to substitute portable toilets for internal plumbing. Short of a survey, we are forced to estimate a realistic number. The author estimates that a typical middle-class household would value the convenience of tap water and toilets at least $10–20 per household per day.

For showers, there is no market-based value of the effort of traveling to a Red Cross shelter. One can at least price the time, using the value that Independent Sector (2020) places on volunteer labor: about $25 per hour. Supposing a shower at the Red Cross shelter adds about an hour of effort per person in terms of travel, lines, and so on, at 2.5 occupants per household, showers add another $65 per household per day (in round numbers).

The foregoing items total $80 to $100 per household per day. That figure is exceeded by the cost of staying in short-term temporary accommodations (hotel and motel) and exceeds the cost of an apartment. It seems reasonable to assume, however, that there are insufficient temporary accommodations of either kind available because of people displaced by shaking damage to their homes. We use the median of the foregoing range to value the inconvenience of lost water service: $90 per household per day. This estimate is consistent with those in the literature on the subject (see, for example, Federal Emergency Management Agency, 2010; Heflin and others, 2013; and Aubuchon and others, 2014).

The total inconvenience cost of lost water service to residences can therefore be conservatively estimated to be $90 per household per day times 57.3 million service-days, totalling $5.2 billion. Using the values suggested by Heflin and others (2013), FEMA (2009), and Aubuchon and Morley (2013), the loss can be estimated as high as $5.8 billion, $14.9 billion, or $33 billion (2018 dollars), respectively.

Total Water Inconvenience Cost

It is conservatively estimated here that the inconvenience cost of the loss of water service to residential water customers is $5.2 billion.

Inconvenience Cost for Loss of Electricity

Loss of Electricity Service

The economic analysis relied on Hazus-MH estimates of the number of households without electric service across the study region (out of 3.6 million households) at days 1, 3, 7, 30, and 90, as shown in table 4.2.

Table 4.2. Number of households without electric service in days after the HayWired mainshock in the San Francisco Bay region, California, estimated using Hazus.

Day	Number of households without service
1	1,373,301
3	606,834
7	195,422
30	46,067
90	3,597

Let Q denote the total number of households (3.60 million) and let H_i denote the number of households without service on day t_i, from table 4.2. A large San Francisco Bay region earthquake would almost certainly cause temporary loss of electricity service to the entire region to protect equipment. Power would then be restored to locations where it was safe to do so, leaving 1.4 million households without electricity 24 hours later, as shown in table 4.2. For purposes of completing the numerical integration then, one can take $t_0 = 0$, $H_0 = 3.60$ million, and assume electricity is restored to the last customer by $t_6 = 180$ days (that is, $H_6 = 0$). Then one can estimate the average service-days lost per household L with equation 1, where

$$y_i = \frac{Q - H_i}{Q}. \quad (3)$$

Evaluating equation 1, $L = 2.9$ days, that is, the average customer is without electricity for about three days. (The average service-days lost per household remains the same to two significant figures whether one takes t_6 to be 91 days, 180 days, or 365 days.)

Literature on the Inconvenience Cost of Lost Residential Electric Service

FEMA [undated] offers a standard value of electric service of $131 per person per day. FEMA (2009, p. A-5) states without reference to the source that its standard values for loss of electric service is $126 per person per day, which in 2018 would equate with $150 per person per day and $375 per household per day for a household size of 2.5, or a total value lost of $3.9 billion. Again, let us revisit the question in the context of the HayWired scenario.

A New Estimate of the Daily Household Value of Residential Electric Services

Obvious sources of inconvenience costs include the following:

- *Food spoilage.*—After about 24–48 hours, one's freezer and refrigerator warm up and one must replace all the food. The Chicago Tribune recently estimated the average family refrigerator costs $250 to stock from scratch (O'Connell, 2017). It takes about 3 hours to replace all the food, with an associated inconvenience cost of $25 per hour, or $75 per household. The total labor and material cost sums to $325 per household that loses electricity for more than 1 day.

- *Inability to cook.*—One generally cannot dine outside of the house because restaurants would also be without power. Californians would therefore use emergency supplies, barbeque, or eat cold meals in the home. No obvious method presents itself to estimate the value of this inconvenience.

- *Inability to charge devices.*—And although some businesses will provide places to charge devices, presumably most people would charge a few devices in their automobile at negligible cost.

Only the inconvenience cost of food spoilage is estimated here, and thus represents a lower bound. Per table 4.2, 1.4 million households in the study area must replace their food at a cost of $325 per household, for a total cost of $450 million. However, using the FEMA (2009) figure, the total value lost could be estimated as high as $3.9 billion.

Appendix 5. Resource Isolation Resilience Factors

Table 5.1. Utility service importance factors by sector.

[Data from Applied Technology Council (1991). No., CGE sector number]

No.	Sector description	Water	Electricity	Telephone	Data and voice
		Importance factor			
1	Agriculture, forestry, fishing, and hunting	53	50	20	24
2	Oil and gas extraction	15	90	10	12
3	Coal mining	15	90	10	12
4	Other mining	15	90	10	12
5	Electric power generation/transmission/distribution	40	80	30	36
6	Natural gas distribution	40	80	30	36
7	Water, sewage, and other systems	40	80	30	36
8	Construction	50	40	10	12
9	Heavy industry	64	98	13	14
10	Light industry	64	99	17	16
11	Petroleum refineries	50	100	10	11
12	Food, drug, and chemicals	75	90	15	18
13	Primary metal manufacturing	90	90	15	19
14	Electronic computer manufacturing	90	100	15	18
15	Computer storage device manufacturing	90	100	15	17
16	Semiconductor and related device manufacturing	90	100	15	18
17	Other high-tech manufacturing	90	100	15	18
18	Wholesale trade, warehousing, and storage	20	90	50	60
19	Retail trade	20	90	50	60
20	Air transportation	20	30	30	36
21	Rail transportation	20	30	30	36
22	Water transportation	20	30	30	36
23	Truck transportation	20	30	30	36
24	Transit and ground passengers	20	30	30	36
25	Pipeline transportation	20	30	30	36
26	Sightseeing transportation	20	30	30	36
27	Couriers and messengers	20	30	30	36
28	Publishing, motion picture, and broadcasting	20	90	40	60
29	Internet publishing and broadcasting	20	90	40	60
30	Telecommunications	20	90	40	60
31	Data processing, hosting, and related services	20	90	40	60
32	Other information services	20	90	40	60
33	Finance, insurance, real estate, and leasing	20	90	60	80
34	Imputed rental value for owner-occupied dwellings	20	90	60	72
35	Computer systems design and related services	20	90	40	60
36	Other professional, scientific, and technical services	20	90	40	60
37	Other business services	20	90	40	60
38	Educational services	40	80	15	18

Table 5.1.—Continued

No.	Sector description	Water	Electricity	Telephone	Data and voice
		Importance factor			
39	Ambulatory health care and hospitals	40	80	15	23
40	Nursing home/social assistance	40	80	15	23
41	Arts, entertainment, and recreation	80	80	40	48
42	Accommodations	80	80	40	48
43	Repair and maintenance	20	90	40	48
44	Personal services/private households	20	90	40	48
45	Religious, grantmaking, and similar organizations	20	90	40	48
46	Government and non-NAICS	25	60	20	24

Table 5.2. Production recapture factors by sector.

[Data from FEMA (2012). Recapture is zero after 1 year. No., CGE sector number]

No.	Sector description	Days 1–90	Days 91–180	Days 181–270	Days 271–360
		Production recapture factor			
1	Agriculture, forestry, fishing, and hunting	0.38	0.28	0.19	0.09
2	Oil and gas extraction	0.49	0.37	0.25	0.12
3	Coal mining	0.49	0.37	0.25	0.12
4	Other mining	0.49	0.37	0.25	0.12
5	Electric power generation/transmission/distribution	0.45	0.34	0.23	0.11
6	Natural gas distribution	0.45	0.34	0.23	0.11
7	Water, sewage, and other systems	0.45	0.34	0.23	0.11
8	Construction	0.48	0.36	0.24	0.12
9	Heavy industry	0.49	0.37	0.25	0.12
10	Light industry	0.49	0.37	0.25	0.12
11	Petroleum refineries	0.49	0.37	0.25	0.12
12	Food, drug, and chemicals	0.49	0.37	0.25	0.12
13	Primary metal manufacturing	0.49	0.37	0.25	0.12
14	Electronic computer manufacturing	0.49	0.37	0.25	0.12
15	Computer storage device manufacturing	0.49	0.37	0.25	0.12
16	Semiconductor and related device manufacturing	0.49	0.37	0.25	0.12
17	Other high-tech manufacturing	0.49	0.37	0.25	0.12
18	Wholesale trade, warehousing, and storage	0.44	0.33	0.22	0.11
19	Retail trade	0.44	0.33	0.22	0.11
20	Air transportation	0.45	0.34	0.23	0.11
21	Rail transportation	0.45	0.34	0.23	0.11
22	Water transportation	0.45	0.34	0.23	0.11
23	Truck transportation	0.45	0.34	0.23	0.11
24	Transit and ground passengers	0.45	0.34	0.23	0.11
25	Pipeline transportation	0.45	0.34	0.23	0.11

Table 5.2.—Continued

No.	Sector description	Days 1–90	Days 91–180	Days 181–270	Days 271–360
		Production recapture factor			
26	Sightseeing transportation	0.45	0.34	0.23	0.11
27	Couriers and messengers	0.45	0.34	0.23	0.11
28	Publishing, motion picture, and broadcasting	0.45	0.34	0.23	0.11
29	Internet publishing and broadcasting	0.45	0.34	0.23	0.11
30	Telecommunications	0.30	0.23	0.15	0.08
31	Data processing, hosting, and related services	0.45	0.34	0.23	0.11
32	Other information services	0.45	0.34	0.23	0.11
33	Finance, insurance, real estate, and leasing	0.45	0.34	0.23	0.11
34	Imputed rental value for owner-occupied dwellings	0.30	0.23	0.15	0.08
35	Computer systems design and related services	0.45	0.34	0.23	0.11
36	Other professional, scientific, and technical services	0.45	0.34	0.23	0.11
37	Other business services	0.45	0.34	0.23	0.11
38	Educational services	0.30	0.23	0.15	0.08
39	Ambulatory health care and hospitals	0.30	0.23	0.15	0.08
40	Nursing home/social assistance	0.30	0.23	0.15	0.08
41	Arts, entertainment, and recreation	0.30	0.23	0.15	0.08
42	Accommodations	0.30	0.23	0.15	0.08
43	Repair and maintenance	0.26	0.19	0.13	0.06
44	Personal services/private households	0.26	0.19	0.13	0.06
45	Religious, grantmaking, and similar organizations	0.30	0.23	0.15	0.08
46	Government and non-NAICS	0.40	0.30	0.20	0.10

Appendix 6. Data- and Voice-Service Tables for Resilience Adjustment Cases

Data- and Voice-Services for the Base Case and Three Resilience Cases

Data and voice service restoration is modeled in Wein, Witkowski, and others, this volume. There are results for the percentage of customer demand met for a base case and three resilience cases: (1) use of permanent backup batteries and generators on telecommunications equipment; (2) use of portable equipment (such as cells on light trucks [COLTS] and cells on wheels [COWS]); and (3) implementation of user behavior management. Tables 6.1 to 6.4 show the percentage of customer demand for data and voice services met by county and by day for the base case and after each of the above three resilience tactics are applied. Table 6.5 shows the percentage of customer demand for data and voice services met by county and by day for the input substitution resilience case.

Table 6.1 Percentage of customer demand for data and voice service met by county and by day in the base case, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.5	8.5	16.8	30.8	41.4	53.4	63.3	73.9	79.8	96.0	100.0
Contra Costa	1.2	18.3	31.6	45.8	56.0	65.2	75.0	85.5	87.4	98.0	100.0
Marin	5.4	50.6	64.1	75.8	82.4	87.7	93.2	98.7	99.1	100.0	100.0
Merced	14.0	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Monterey	17.0	94.0	96.5	99.0	99.3	99.5	99.8	100.0	100.0	100.0	100.0
Napa	13.6	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Sacramento	19.0	98.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.0	63.0	76.0	89.0	91.3	93.5	95.8	98.0	98.0	100.0	100.0
San Francisco	2.2	33.2	51.0	66.6	75.6	82.2	89.0	96.1	97.2	100.0	100.0
San Joaquin	8.0	78.0	87.0	96.0	97.0	98.0	99.0	99.0	100.0	100.0	100.0
San Mateo	2.3	30.5	46.9	62.7	71.8	78.9	86.3	94.1	95.3	99.0	100.0
Santa Clara	0.8	16.0	29.0	43.5	53.8	63.6	74.2	85.5	87.4	98.0	100.0
Santa Cruz	12.0	83.0	90.0	97.0	97.8	98.5	99.3	100.0	100.0	100.0	100.0
Solano	7.9	58.4	68.6	78.9	84.0	88.9	93.9	99.0	99.1	100.0	100.0
Sonoma	13.0	71.8	77.5	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.2. Percentage of customer demand for data and voice service met by county and by day after adjustment for use of supplier batteries and generators, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	4.8	16.5	24.2	31.2	42.9	56.5	67.6	77.8	83.4	97.0	100.0
Contra Costa	7.0	28.1	32.6	48.7	60.8	70.1	79.1	88.5	90.1	98.7	100.0
Marin	11.4	57.9	64.7	76.9	83.9	89.0	94.0	99.1	99.4	100.0	100.0
Merced	19.4	94.0	93.9	98.9	99.2	99.5	99.7	100.0	100.0	100.0	100.0
Monterey	19.7	96.7	98.1	99.5	99.6	99.7	99.9	100.0	100.0	100.0	100.0
Napa	18.8	93.8	96.3	98.9	99.2	99.4	99.7	100.0	100.0	100.0	100.0
Sacramento	19.9	98.9	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	13.9	59.7	68.7	78.3	83.3	88.4	93.6	98.9	98.8	100.0	100.0
San Francisco	10.2	44.9	52.0	68.8	78.8	85.1	91.0	97.1	98.1	100.0	100.0
San Joaquin	18.8	87.9	92.9	97.8	98.3	98.9	99.4	100.0	100.0	100.0	100.0

Table 6.2.—Continued

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
San Mateo	10.5	44.1	48.1	65.7	76.3	83.0	89.3	95.8	96.9	99.3	100.0
Santa Clara	7.4	27.5	30.2	47.1	59.6	69.3	78.7	88.6	90.3	98.7	100.0
Santa Cruz	19.2	90.6	94.5	98.3	98.8	99.2	99.6	100.0	100.0	100.0	100.0
Solano	13.7	65.2	69.1	79.8	85.3	90.1	94.7	99.4	99.5	100.0	100.0
Sonoma	14.3	73.1	77.6	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.3. Percentage of customer demand for data and voice service met by county and by day after adjustment for use of portable equipment, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.5	8.5	16.8	32.8	48.8	67.0	83.6	92.9	93.9	99.6	100.0
Contra Costa	1.7	27.4	47.5	69.8	83.3	90.0	94.5	99.0	99.2	99.8	100.0
Marin	5.4	50.6	65.8	79.2	86.4	91.3	95.6	99.9	99.9	100.0	100.0
Merced	14.0	89.0	96.4	99.8	99.9	99.9	100.0	100.0	100.0	100.0	100.0
Monterey	17.0	94.0	98.1	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0
Napa	13.6	89.0	96.4	99.8	99.9	99.9	100.0	100.0	100.0	100.0	100.0
Sacramento	19.0	98.0	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.0	63.0	86.8	98.9	99.1	99.4	99.6	99.8	99.8	100.0	100.0
San Francisco	2.2	33.2	54.2	74.1	85.0	90.7	95.2	99.6	99.7	100.0	100.0
San Joaquin	8.0	78.0	92.9	99.6	99.7	99.8	99.9	100.0	100.0	100.0	100.0
San Mateo	2.3	30.5	50.5	72.0	84.2	90.4	94.9	99.4	99.5	99.9	100.0
Santa Clara	1.2	23.9	44.3	68.2	82.7	89.8	94.4	99.0	99.2	99.8	100.0
Santa Cruz	12.0	83.0	94.5	99.7	99.8	99.9	99.9	100.0	100.0	100.0	100.0
Solano	7.9	58.4	69.8	80.9	86.7	91.4	95.6	99.9	99.9	100.0	100.0
Sonoma	13.0	71.8	77.7	83.3	87.5	91.7	95.8	100.0	100.0	100.0	100.0

Table 6.4. Percentage of customer demand for data and voice service met by county and by day after adjustment for customer behavior management, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.6	9.3	18.5	33.8	45.5	58.8	69.6	77.8	83.6	96.0	100.0
Contra Costa	1.9	30.1	47.8	64.5	74.4	81.5	85.8	90.0	91.5	98.0	100.0
Marin	5.9	55.6	70.5	83.4	90.7	95.7	97.2	98.7	99.1	100.0	100.0
Merced	15.4	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Monterey	18.7	94.0	96.5	99.0	99.3	99.5	99.8	100.0	100.0	100.0	100.0
Napa	14.9	89.0	93.5	98.0	98.5	99.0	99.5	100.0	100.0	100.0	100.0
Sacramento	20.9	98.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	6.6	63.0	76.0	89.0	91.3	93.5	95.8	98.0	98.0	100.0	100.0
San Francisco	2.4	36.5	56.1	73.3	83.2	89.6	92.9	96.1	97.2	100.0	100.0
San Joaquin	8.8	78.0	87.0	96.0	97.0	98.0	99.0	100.0	100.0	100.0	100.0
San Mateo	2.5	33.5	51.6	68.9	79.0	86.1	90.1	94.1	95.3	99.0	100.0
Santa Clara	1.3	26.3	43.9	61.3	71.5	79.5	84.8	90.0	91.6	98.0	100.0
Santa Cruz	13.2	83.0	90.0	97.0	97.8	98.5	99.3	100.0	100.0	100.0	100.0

Table 6.4.—Continued

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Solano	8.7	64.3	75.5	86.8	92.4	97.0	98.0	99.0	99.1	100.0	100.0
Sonoma	14.3	79.0	85.3	91.6	96.3	100.0	100.0	100.0	100.0	100.0	100.0

Table 6.5. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for input substitution, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	0.6	10.1	20.2	36.9	49.6	64.1	75.9	88.7	95.7	100.0	100.0
Contra Costa	1.4	21.9	37.9	54.9	67.2	78.3	90.1	100.0	100.0	100.0	100.0
Marin	6.5	60.7	77.0	91.0	98.9	100.0	100.0	100.0	100.0	100.0	100.0
Merced	16.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Monterey	20.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Napa	16.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sacramento	22.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	7.2	75.6	91.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Francisco	2.7	39.9	61.2	79.9	90.7	98.6	100.0	100.0	100.0	100.0	100.0
San Joaquin	9.6	93.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Mateo	2.7	36.6	56.3	75.2	86.2	94.7	100.0	100.0	100.0	100.0	100.0
Santa Clara	1.0	19.2	34.8	52.2	64.6	76.3	89.0	100.0	100.0	100.0	100.0
Santa Cruz	14.4	99.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Solano	9.5	70.1	82.3	94.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sonoma	15.6	86.2	93.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Resilience Adjustment of Production Isolation

Production isolation refers to the portion of business operation that can continue without data and voice services. The “importance factors” of telephone service (Applied Technology Council, 1991) are shown in appendix 5, table 5.1, column 5. Based on the review of businesses that are mostly dependent on internet (Mushroom Networks, 2017), we scale the importance factors up by 50 percent for the following sectors (but cap the importance factors at 80 percent) to account for the large use of internet (not just telephone) for these sectors: publishing, motion picture, and broadcasting; internet publishing and broadcasting; telecommunications; data processing, hosting, and related services; other information services; finance, insurance, real estate, and leasing; computer systems design and related services; other professional, scientific, and technical services; other business services; ambulatory health care and hospitals; nursing home/social assistance. For the remaining sectors, we scale up the importance factors by 20 percent for all non-manufacturing sectors in appendix 5, table 5.1 to account for the important role of internet in every aspect of economic activities.

For manufacturing sectors, we adjust the scale-up factor of 20 percent up or down based on the U.S. Census Bureau’s e-commerce data for individual manufacturing sectors relative to the manufacturing average dependence on e-commerce (U.S. Census Bureau, 2017).[1] For example, the average percentage of total shipments through e-commerce for the aggregated manufacturing sector was 63 percent in 2015. The percentage for fabricated metal product manufacturing is 50 percent. Therefore, we adjust the 20 percent scale-up factor downwards to 15.8 percent (20 percent × 50/63). Note that the e-commerce data are also available for wholesale trade, retail trade, and selected service sectors. However, we do not use these data to further adjust the data and voice importance factors for these sectors for two reasons. First, the e-commerce data for these sectors are significantly lower than those that are indicated by the telephone importance factors. The primary reason is that the e-commerce data pertain to the proportion of sale of goods and services that are achieved through online systems, rather than the proportion of business operations and production process (other than sale) that rely on information

[1]The Census e-commerce data report the percentage of sales of goods or services for which the orders are placed (or the price or terms of the sale are negotiated) through any online systems, including internet, mobile device, extranet, email, and so on (U.S. Census Bureau, 2017).

and communications technology (ICT) services. Second, we have already scaled up the telephone importance factors by 50 percent for the top service sectors that depend on ICT services, and 20 percent for all the other trade and service sectors as described above. We consider these adjustments have reasonably incorporated the information on the relative importance of ICT services on business operation across sectors. The production isolation percentages of data and voice service are calculated as 100 minus the importance factors shown appendix 5, table 5.1, column 6.

Based on the gross output by sector for each county, we calculated the weighted average production isolation factor for each county (see table 6.6). The smaller isolation factor value for a county reflects a profile of industries in the county that include more of the industries that have higher dependence on ICT services. For example, finance, insurance, and real estate (FIRE) are disproportionately more present in San Francisco.

Equivalent voice and data service = Base case availability + (100 − Base case availability) × Production Isolation Factor.

Table 6.7 shows the percentage of availability of data and voice service by county and by day for the production isolation resilience case.

Table 6.6. Weighted average production-isolation factor of telecommunication by county, San Francisco Bay region, California.

County	Weighted average telecommunication isolation factor
Alameda	58.3
Contra Costa	69.0
Marin	44.8
Merced	66.7
Monterey	57.9
Napa	63.2
Sacramento	54.2
San Benito	68.3
San Francisco	44.6
San Joaquin	58.6
San Mateo	51.3
Santa Clara	63.0
Santa Cruz	56.6
Solano	67.3
Sonoma	57.5

Table 6.7. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for production isolation of telecommunication, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	58.5	61.8	65.3	71.1	75.6	80.6	84.7	89.1	91.6	98.3	100.0
Contra Costa	69.3	74.6	78.8	83.2	86.4	89.2	92.3	95.5	96.1	99.4	100.0
Marin	47.8	72.7	80.2	86.7	90.3	93.2	96.2	99.3	99.5	100.0	100.0
Merced	71.4	96.3	97.8	99.3	99.5	99.7	99.8	100.0	100.0	100.0	100.0
Monterey	65.1	97.5	98.5	99.6	99.7	99.8	99.9	100.0	100.0	100.0	100.0
Napa	68.2	96.0	97.6	99.3	99.4	99.6	99.8	100.0	100.0	100.0	100.0
Sacramento	62.9	99.1	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	70.2	88.3	92.4	96.5	97.2	97.9	98.7	99.4	99.4	100.0	100.0
San Francisco	45.8	63.0	72.8	81.5	86.5	90.1	93.9	97.9	98.5	100.0	100.0
San Joaquin	62.0	90.9	94.6	98.3	98.8	99.2	99.6	99.6	100.0	100.0	100.0
San Mateo	52.4	66.1	74.1	81.8	86.3	89.7	93.3	97.1	97.7	99.5	100.0
Santa Clara	63.3	68.9	73.7	79.1	82.9	86.5	90.4	94.6	95.3	99.3	100.0
Santa Cruz	61.8	92.6	95.7	98.7	99.0	99.3	99.7	100.0	100.0	100.0	100.0
Solano	69.9	86.4	89.7	93.1	94.8	96.4	98.0	99.7	99.7	100.0	100.0
Sonoma	63.0	88.0	90.5	92.9	94.7	96.5	98.2	100.0	100.0	100.0	100.0

Table 6.8. Equivalent percentage of customer demand for data and voice service met by county and by day after adjustment for use of batteries/generators, use of cell sites on wheels or light trucks (COWs/COLTs), user behavior management tactics, input substitution, and production isolation, San Francisco Bay region, California.

County	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
	Percentage of customer demand met										
Alameda	60.9	67.4	71.6	76.6	85.8	96.0	100.0	100.0	100.0	100.0	100.0
Contra Costa	73.3	86.2	88.9	98.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Marin	53.1	87.0	93.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Merced	75.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Monterey	68.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Napa	72.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sacramento	66.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Benito	74.1	93.3	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Francisco	52.0	77.4	84.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Joaquin	68.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
San Mateo	58.0	79.6	84.5	98.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Santa Clara	68.4	83.1	85.4	97.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Santa Cruz	67.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Solano	73.2	95.5	97.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sonoma	65.5	98.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 6.8 shows the percentage availability of data and voice service by county and by day for all the above resilience cases combined.

Resilience Adjustment of Telework

Table 6.9 shows the percent of workers doing some or all of their work at home by major occupations in the United States in 2015. On average 24.1 percent of the workers across different economic sectors worked at least one day a week from home. We assume that this translates to 12 percent of full-time equivalent work from home (half of the 24.1 percent) because some workers worked less than 5 days a week from home. After the earthquake, we assume that the workers that ordinarily work less than full-time from home could have the capability of doing so from home or at an alternative location (such as hotel) when data and voice services become available. Based on the sectoral employment data by county and the Bureau of Labor Statistics telework data as shown in table 6.9, we computed the employment-weighted average telework percentage for each county in the first numerical column in table 6.11. Based on the assumption above, we assume that only half of these levels represent an incremental amount of telework potential after the earthquake.

Telework capacity will be affected as people deal with the physical and emotional effects of the earthquake. Therefore, we next adjust the incremental telework potential by the percentage of readiness of employees to go back to work, though remotely. A survey study following the Christchurch earthquake indicated that 35 percent of workers were ready to work within the first week. This percentage increased to 82 percent within 30 days and 96 percent within 12 weeks (Donnelly and Proctor-Thomson, 2013). We also adjusted the Christchurch worker-readiness percentages up and down depending on how hard the counties are hit by the earthquake. Specifically, we assume 50 percent lower readiness for the hardest hit counties (Alameda, Contra Costa, and Santa Clara); use the Christchurch percentages for San Francisco, San Mateo, and San Benito; and assume 50 percent higher readiness for all the other counties. This telework potential in the third column of table 6.11 can, in general, be applied to reduce the gross regional product (GRP) losses from property damages.

Two additional factors that affect the feasibility of telework when data and voice services are necessary are analyzed next. First, we assume that telework is only possible when people have internet access. Second, telework may depend on the availability of backup data if the local data are destroyed by the earthquake. For the first factor, we adjust incremental telework percentages by the percentage of data and voice service demand met for the base case. For the second factor, we

- Assume the percentage of loss of local data equals the percentage of content damages by sector and by county.
- Use data on the level of adoption of cloud technologies by major industries (see table 16). For other industries, we assume the level of adoption is half of the lowest average adoption percentage of the top 10 industries (that is, 25 percent).
- Calculate the further decreases in telework potential as: Percentage content damage × (1 – Percentage adoption of cloud technologies).

Columns 4 to 9 in table 6.10 show the increased telework potential after the adjustment for worker readiness, data and voice service restoration, and cloud backup data. These percentages are used to lower the GRP loss estimates from the base case computable general equilibrium (CGE) simulation results.

Table 6.9. Percentage of workers doing some or all of their work on their main job at home in 2015.

[Data from Bureau of Labor Statistics (2017)]

Management, business, and financial operations occupations	Professional and related occupations	Service occupations	Sales and related occupations	Office and administrative support occupations	Construction and extraction occupations	Installation, maintenance, and repair occupations	Production occupations	Transportation and material moving occupations	Total
37.8	34.6	10.5	22.1	11.2	16.2	9.6	5.5	7.7	**24.1**

Table 6.10. Percentage of top industries adopting cloud technologies.

[Data from Kerrest (2016)]

Industry	Cloud document storage	Cloud mail	Cloud developer tools	Average
	Percentage of industry			
Internet and software		90	60	75
Marketing and advertising	70	80	70	73
Biotechnology and pharmaceuticals	60	81		71
Real estate	60	80	27	56
Not-for-profit		90	30	60
Retail	30	70		50
Construction	64	64	18	49
Hospitals and healthcare		72	41	57
Education	40	87	24	50
Finance	70		32	51

Table 6.11. Estimated percentage increase of employee telework, by day and by county, San Francisco Bay region, California.

County	Weighted-average telework potential (percent)	Incremental telework potential (percent)	Increased telework after adjusting for worker readiness, data- and voice-service restoration, and cloud data backup adoption (percent)										
			Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 9	Day 30	Day 90
Alameda	19.7	9.8	0.0	0.1	0.3	0.5	0.7	0.9	1.0	1.2	1.5	3.7	4.5
Contra Costa	21.3	10.7	0.0	0.3	0.6	0.8	1.0	1.2	1.4	1.6	1.8	4.2	5.0
Marin	22.7	11.3	0.3	3.0	3.8	4.5	4.9	5.2	5.5	5.8	6.3	11.3	11.3
Merced	14.0	7.0	0.5	3.3	3.4	3.6	3.6	3.6	3.7	3.7	4.0	7.0	7.0
Monterey	15.3	7.6	0.7	3.8	3.9	4.0	4.0	4.0	4.0	4.0	4.3	7.6	7.6
Napa	16.7	8.4	0.6	3.9	4.1	4.3	4.3	4.3	4.4	4.4	4.7	8.4	8.4
Sacramento	19.3	9.7	1.0	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.5	9.7	9.7
San Benito	15.1	7.6	0.2	1.7	2.0	2.3	2.4	2.5	2.5	2.6	2.9	6.2	7.2
San Francisco	22.6	11.3	0.1	1.3	2.0	2.6	3.0	3.2	3.5	3.8	4.3	9.2	10.8
San Joaquin	17.4	8.7	0.4	3.6	4.0	4.4	4.4	4.5	4.5	4.5	4.9	8.7	8.7
San Mateo	22.2	11.1	0.1	1.2	1.8	2.4	2.8	3.0	3.3	3.6	4.1	8.9	10.6
Santa Clara	20.5	10.3	0.0	0.3	0.5	0.8	1.0	1.1	1.3	1.5	1.7	4.1	4.8
Santa Cruz	18.3	9.2	0.6	4.0	4.3	4.7	4.7	4.7	4.8	4.8	5.2	9.1	9.1
Solano	17.0	8.5	0.3	2.6	3.0	3.5	3.7	3.9	4.2	4.4	4.7	8.4	8.4
Sonoma	18.8	9.4	0.6	3.5	3.8	4.1	4.3	4.5	4.7	4.9	5.3	9.4	9.4

Appendix 7. Adjustments on the Economic Impacts for Electricity and Water Service Disruptions

By Adam Z. Rose and Dan Wei

The input-output table and social accounting matrix of IMPLAN (short for impact analysis for planning) are the most widely used sources of data for constructing computable general equilibrium (CGE) models in the United States today. However, they do have some limitations. One of them is a lack of disaggregation of the State and local government enterprises sector of the final demand quadrant. A major example pertains to government provision of water services, which is not separately identified. IMPLAN databases do, however, include this sector explicitly in the transactions table (intermediate goods and services production) quadrant for local private sector water service providers. The second issue is that, even where public sector utilities are separated out, the data are considered sub-standard, because they are downscaled from national and State economic production structures that do not accurately reflect local conditions. This is especially problematic for the case of electric utilities, where the national structure is dominated by large-scale operations. Hence, we did not choose to use the disaggregated State and local government electricity sector in our analysis.

To compensate for the inadequacy of data on public utilities in IMPLAN, analysts have two choices. One is to undertake some disaggregation or refinement of the State and local government enterprises sector to identify each of these sectors individually by use of supplementary data and data transfer methods or some combination of the two. This requires adding more sectors to the CGE model and can be a cumbersome process. The other is to adjust the results by some ratios of aggregate economic activity between private sector and public sector versions of each type of utility.[1] We have chosen this second, more straightforward, approach.

Tables 7.1 and 7.2 present the adjustment factors on government provision of water and electricity in the four main counties affected by the HayWired scenario earthquake (Alameda, Contra Costa, San Francisco, and Santa Clara) and their effect on gross regional product (GRP) in those counties, the rest of the bay region, and the rest of the State. This appendix also presents the method and data sources we used to calculate the adjustment factors. These factors for the four main counties in the bay region are calculated separately based on the data on private and public provisions of water and power services in each county. We then applied a weighted average of the adjustment factors of the four counties to the other regions. For the rest of the bay region, this weighted average adjustment factor is intended to factor in the public and private sector adjustment for this region, as well as for the adjustment in the interregional multiplier effects of the four main counties on other counties in the bay region. For the rest of California, the factor is applied to take into consideration the adjustment in the interregional multiplier effects of the earthquake in directly affected counties on other counties in the State.

Alameda County has a very high adjustment factor because the majority of the water supply in this county comes from public providers. The IMPLAN private water sector only has an output of $35.5 million. Additional calculations indicate that Alameda County customers received $202.2 million worth of water from the East Bay Municipal Utility District (EBMUD) and another $76.1 million from the San Francisco Public Utility (SFPU).

Essentially, for California as a whole, there is only a 32.1 percent increase in the gross State product (GSP) losses from electricity disruptions, but the increase in GSP losses from water disruptions is nearly 650 percent. The reason for this very large difference in adjustments is due to the very large difference in State and local provision of electricity and water services, which were not separately identified in the underlying IMPLAN data. Only a relatively small proportion of electricity in the affected areas is provided by State and local government electricity generators, whereas a major proportion of water services are provided by the East Bay Municipal Utility District.[2]

We have applied the same adjustment factors presented in column 3 of tables 7.1 and 7.2 to the GRP change results of water and electricity service disruptions for the various resilience cases by region to obtain the final results presented in tables 17 and 19.

[1]Note that there are no government-provided data or voice services, so the adjustment need only be made for electricity and water.

[2]Our adjustment methodology is applicable to all States in which there is a significant proportion of either or both electricity or water services provided by Sstate and local government sources. Note also that this adjustment method will become less necessary as more electricity becomes generated by distributed sources in private hands (such as rooftop solar and smaller windfarms), both because the services are not part of the State and local government sector and also because they are less vulnerable to network outages.

Table 7.1. Gross regional product (GRP) change caused by electricity-service disruptions in the 6 months following the HayWired mainshock by county, in the San Francisco Bay region, California.

Area	GRP change before adjustment (in billions of 2012 dollars)	Adjustment factor	Difference in GRP change from applying adjustment factors (in billions of 2012 dollars)	GRP change after adjustment (in billions of 2012 dollars)
Alameda	−0.020	1.1371	−0.0027	−0.0227
San Francisco	−0.010	1.4273	−0.0043	−0.0143
Contra Costa	−0.008	1.0947	−0.0008	−0.0088
Santa Clara	−0.025	1.4981	−0.0125	−0.0375
4-county total	−0.063	1.3210	−0.0202	−0.0832
Rest of bay region	−0.015	1.3210	−0.0048	−0.0198
Bay region total	−0.078	1.3210	−0.0250	−0.1030
Rest of California	−0.022	1.3210	−0.0071	−0.0291
California total	**−0.100**	**1.3210**	**−0.0321**	**−0.1321**

Table 7.2. Gross regional product (GRP) change caused by water-service disruptions in the 6 months following the HayWired mainshock by county, in the San Francisco Bay region, California.

Area	GRP change before adjustment (in billions of 2012 dollars)	Adjustment factor	Difference in GRP change from applying adjustment factors (in billions of 2012 dollars)	GRP change after adjustment (in billions of 2012 dollars)
Alameda	−0.074	8.8386	−0.5801	−0.6541
San Francisco	−0.002	1.2407	−0.0005	−0.0025
Contra Costa	−0.013	1.6864	−0.0089	−0.0219
Santa Clara	−0.005	4.6711	−0.0184	−0.0234
4-county total	−0.094	7.4661	−0.6078	−0.7018
Rest of bay region	−0.011	7.4661	−0.0711	−0.0821
Bay region total	−0.105	7.4661	−0.6789	−0.7839
Rest of California	−0.017	7.4661	−0.1099	−0.1269
California total	**−0.122**	**7.4661**	**−0.7889**	**−0.9109**

Method and Data Sources for Calculating the Adjustment Factors of Public Versus Private Power and Water Provisions

Electricity

We took the following steps to separate total electricity demand in Alameda, Contra Costa, San Francisco, and Santa Clara Counties between services provided by Pacific Gas and Electric (PG&E) and municipal providers using the data in table 7.3:

1. Obtain data on total electricity consumption for the residential and nonresidential sector for each county in 2012 from the California Energy Commission (CEC) consumption database (CEC, 2020).
2. Obtain 2012 data on electricity generation at the state level for all major power producing entities, including municipal utilities.
3. For each county, subtract the amount of electricity produced by utilities other than PG&E and that was self-generated, from total electricity consumption reported by the CEC to arrive at the total amount produced by PG&E. For example, for San Francisco County, we subtracted electricity produced by the Power Enterprise of the San Francisco Public Utilities Commission and self-generation from the total annual electricity consumption of San Francisco County.
4. Differentiate between production from PG&E versus self-generated by calculating the share of self-generation within the entire area in which PG&E operates as reported by CEC; since the data is not available for specific counties, we assumed that the proportion is the same for all four counties.

5. Use the above calculations as an input for estimating annual sales of electricity. We multiply the amount estimated by utility providers in each county by the average annual electricity price in California in 2012 as reported by the U.S. Energy Information Administration (2020). Our method implicitly assumes that the price of electricity in different counties and produced by different utilities is the same across the State, which is a simplification. For each utility, however, we calculated a different price for nonresidential electricity based on a weighted average of electricity prices for commercial and industrial use and that utility's supply to those sectors as reported by the CEC for 2012. Industrial clients, for example, make up a larger share of total electricity sold for PG&E than for the Power Enterprise of the San Francisco Public Utilities Commission, which sells primarily to commercial clients. Therefore, its average electricity price for the nonresidential sector is more heavily weighted toward average prices for industrial supply.

6. In PG&E service area, calculate that 92.6 percent of self-generation is by nonresidential sectors.

7. For each county, calculate the ratio of total electricity (private plus public) to private electricity provision by dividing total electricity supply by the supply from PG&E in each county. These ratios are used as the adjustment factors to the GRP changes in the original HayWired report.

Table 7.3. Estimation of electricity supply by power producing entities in 2012 in Alameda, Contra Costa, San Francisco, and Santa Clara Counties, California.

[Data from 2012. kWh, kilowatthour]

Utility	County	Residential usage (in millions of kWh)[1]	Nonresidential usage (in millions of kWh)[1]	Residential price (in cents per kWh)[2]	Nonresidential price (in cents per kWh)[2]	Residential annual sales (dollars)	Nonresidential annual sales (dollars)	Total sales (dollars)
Alameda Municipal Power	Alameda	140	234	15.34	13.14	21,424,611	30,762,068	**52,186,679**
Hercules Municipal Utility	Contra Costa	4	12	15.34	12.39	595,652	1,505,228	**2,100,880**
Port of Oakland	Alameda	0	47	15.34	13.10	0	6,192,615	**6,192,615**
Power Enterprise, San Francisco Public Utilities Commission	San Francisco	22	966	15.34	13.34	3,375,268	128,922,280	**132,297,548**
Silicon Valley Power	Santa Clara	244	2,659	15.34	12.15	37,460,280	323,077,587	**360,537,867**
Palo Alto Utilities Department	Santa Clara	158	778	15.34	12.74	24,222,627	99,084,901	**123,307,528**
Self-generation	Alameda	46	749	15.34	11.10	7,121,249	83,150,149	**90,271,398**
Self-generation	San Francisco	24	348	15.34	11.10	3,709,060	38,583,498	**42,292,558**
Self-generation	Contra Costa	45	646	15.34	11.10	6,884,937	71,694,184	**78,579,122**
Self-generation	Santa Clara	57	940	15.34	11.10	8,680,578	104,288,598	**112,969,177**
Pacific Gas and Electric	Alameda	2,815	6,571	15.34	12.63	431,787,854	830,198,119	**1,261,985,974**
Pacific Gas and Electric	San Francisco	1,466	3,049	15.34	12.63	224,894,130	385,230,187	**610,124,317**
Pacific Gas and Electric	Contra Costa	2,721	5,666	15.34	12.63	417,459,383	715,818,046	**1,133,277,429**
Pacific Gas and Electric	Santa Clara	3,431	8,242	15.34	12.63	526,335,782	1,041,251,272	**1,567,587,054**

[1]Data from California Energy Commission (2020).

[2]Data from U.S. Energy Information Administration (2020).

Water

Water sales from three major public water suppliers to Alameda, Contra Costa, San Francisco, and Santa Clara are calculated below.

East Bay Municipal Utility District (EBMUD)

The total revenues of EBMUD from water sales in 2012 was $306.2 million (EBMUD, 2015). EBMUD's service area encompasses cities in northern Alameda County and western and central Contra Costa County. In order to calculate the proportions of EBMUD's water that is sold to customers in Alameda and Contra Costa, we looked up the largest cities that are fully served by the EBMUD. These cities make up 77 percent of the overall population served by EBMUD. We then calculate that 66 percent of the population is in Alameda and 34 percent is in Contra Costa. These percentages are used to split the water sales of EBMUD between Alameda and Contra Costa.

San Francisco Public Utilities Commission (SFPUC)

The total revenues of SFPUC from charges of water services in 2012 was $356.6 million (SFPUC, 2013). One third of SFPUC's delivered water goes to San Francisco, another two-thirds delivered to customers in Alameda, Santa Clara, and San Mateo counties. Table 7.4 presents SFPUC water sales to wholesale water districts outside of San Francisco. We use the percentage estimates in table 7.4 to calculate the water sales from SFPUC to San Francisco, Alameda, and Santa Clara.

Santa Clara Valley Water District (SCVWD)

In 2012, water sales from SCVWD to Santa Clara County was $62.1 million (SCVWD, 2013).

In table 7.5 we summarize the water sales from private and public providers for the four counties.

Table 7.4. San Francisco Public Utilities Commission water sales in 2012, San Francisco Bay region and rest of California.

[Data from San Francisco Public Utilities Commission (2013). n/a, not applicable]

Customer	County	Sales (hundred cubic feet)	Percentage of total water sales
California Water Service	n/a	16,081,887	15.54
Hayward Municipal Water	Alameda	7,610,980	7.36
City of Palo Alto	Santa Clara	5,561,559	5.38
City of Sunnyvale	Santa Clara	4,406,804	4.26
City of Redwood City	San Mateo	4,420,594	4.27
City of Mountain View	Santa Clara	4,273,100	4.13
Alameda County Water District	Alameda	3,953,054	3.82
City of Milpitas	Santa Clara	3,027,111	2.93
City of Daly City	San Mateo	1,766,549	1.71
Estero Municipal Improvement District	San Mateo	1,982,291	1.92
All other wholesale customers	n/a	17,549,128	16.96
Wholesale water sales	n/a	70,633,057	68.27
Total water sales	n/a	**103,455,390**	**100.00**

Table 7.5. Water sales from private and public providers and adjustment factors for Alameda, San Francisco, Contra Costa, and Santa Clara Counties, California.

County	Water sales from private sector[1] (in millions of 2012 dollars)	Water sales from public sector (in millions of 2012 dollars)	Total water sales (in millions of 2012 dollars)	Adjustment factor (ratio of total to private water sales)
Alameda	35.5	[2,4]278.3	313.8	8.839
San Francisco	493.8	[4]118.9	612.7	1.241
Contra Costa	151.5	[2]104.0	255.5	1.686
Santa Clara	47.9	[3,4]175.7	223.6	4.671

[1]Data from IMPLAN (2014).

[2]Data from East Bay Municipal Utility District (2015).

[3]Data from Santa Clara Valley Water District (2013).

[4]Data from San Francisco Public Utilities Commission (2013).

Appendix 8. Technical Description of the Dynamic Economic Model

Introduction

We specify a multiregional dynamic model of the California economy that simulates the effect of the earthquake on capital accumulation and growth in affected and unaffected regions of the State over the 17-year (2018–2035) horizon on a semi-annual timestep.

Algebraic Structure

Table 8.1 outlines the model's variables and their parameterization. The model follows the standard multiregional Ramsey growth model formulation (Acemoglu, 2009), in which a social planner allocates consumption, investment, exports, and imports to maximize social welfare (W) defined as the weighted sum of regional consumers' present discounted value of utility. We assume that consumers in each region have a logarithmic utility function denominated over per-capita consumption, which permits specification of the objective function as:

$$\max_{\widetilde{QC}_{r,t},\widetilde{QI}_{r,t},\widetilde{QX}_{r,t},\widetilde{QM}_{r,t},\widetilde{QZ}_{r,t}} W = \Sigma_r \omega_r \Sigma_{t=0}^{T} \vartheta_t \widetilde{QL}_{r,t} \log\left(\widetilde{QC}_{r,t} / \widetilde{QL}_{r,t}\right). \quad (5a)$$

In this expression r and t={0, ... ,T} index counties and time periods, ω_r is a vector of welfare weights, ϑ_t is a discount factor, and $\widetilde{QC}_{r,t}$ and $\widetilde{QL}_{r,t}$ denote the quantities of consumption and labor supply. For simplicity, employment is assumed to be synonymous with the working population and is treated as exogenous. Throughout, the variables used in this model are aggregate analogues of the corresponding primal quantity variables defined in appendix 2, which we identify using a tilde (~).

The objective in equation 5a is maximized subject to several constraints. The first is the primal definition of production analogous to equations 1a through 1e, in which firms in each county produce a homogeneous final good from a constant elasticity of substitution (CES) composite of capital and labor that substitutes for an aggregate of intermediate inputs. We specify this nested production function in "calibrated share" form:

$$\widetilde{QY}_{r,t} = \overline{QY}_r \left(\tilde{\alpha}_{KL,r} \left(\widetilde{QKL}_{r,t} / \overline{QKL}_r \right)^{(\tilde{\sigma}_Y - 1)/\tilde{\sigma}_Y} + \tilde{\alpha}_{Z,r} \left(\widetilde{QZ}_{r,t} / \overline{QZ}_r \right)^{(\tilde{\sigma}_Y - 1)/\tilde{\sigma}_Y} \right)^{\tilde{\sigma}_Y/(\tilde{\sigma}_Y - 1)} \text{ and,} \quad (5b)$$

$$\widetilde{QKL}_{r,t} = \overline{QKL}_r \left(\tilde{\alpha}_{K,r} \left(K_{r,t} / \overline{K}_r \right)^{(\tilde{\sigma}_{KL} - 1)/\tilde{\sigma}_{KL}} + \tilde{\alpha}_{L,r} \left(\widetilde{QL}_{r,t} / \overline{QL}_r \right)^{(\tilde{\sigma}_{KL} - 1)/\tilde{\sigma}_{KL}} \right)^{\tilde{\sigma}_{KL}/(\tilde{\sigma}_{KL} - 1)}, \quad (5c)$$

where $\overline{QY}_r$, $\overline{QKL}_r$, $\overline{QZ}_r$, and $\overline{QL}_r$ are parameters that denote sectoral aggregations of benchmark quantities from the IMPLAN social accounting matrix that are consistent with the computable general equilibrium (CGE) model's baseline equilibrium, the CES distribution parameters, $\tilde{\alpha}_{KL,r}$, $\tilde{\alpha}_{Z,r}$, $\tilde{\alpha}_{K,r}$, and $\tilde{\alpha}_{L,r}$ are the aggregate analogues of the sectoral input coefficients, and the elasticities of substitution, $\tilde{\sigma}_Y$ and $\tilde{\sigma}_{KL}$, quantify the degree of fungibility between factor inputs and intermediate use of commodities by producers, and between capital and labor, respectively. Compared to the detailed representation of production in the CGE model, the present two-level formulation is simplified and aggregated for the purpose of computational tractability in capturing the economy's dynamics. It does not resolve differences among sectors' production or the supply and use of their intermediate inputs. Note that $K_{r,t}$ and $\overline{K}_r$ indicate the county-specific capital stock as opposed to the value of capital input (that is, the services that flow from the stock). Second, analogous to equation 3g, production of the final good satisfies county-specific demands for domestic uses and exports, where for simplicity the latter aggregate together goods that are destined for other counties, the rest of the United States, and foreign countries:

$$\widetilde{QY}_{r,t} \geq \widetilde{QD}_{r,t} + \widetilde{QX}_{r,t}. \quad (5d)$$

Third, we develop an aggregate approximation to the CGE model's Armington (1969) formulation of intermediate goods trade. As in equations 2a through 2e, counties' exports are treated as imperfect substitutes that feed into an aggregate supply pool, which in turn satisfies all counties' import demands. The former is modeled as a CES aggregation technology, specified according to the calibrated share form, that yields the supply-demand balance condition:

$$\overline{X} \left(\Sigma_r \tilde{\beta}_{X,r} \left(\widetilde{QX}_{r,t} / \overline{QX}_r \right)^{(\tilde{\sigma}_X - 1)/\tilde{\sigma}_X} \right)^{\tilde{\sigma}_X/(\tilde{\sigma}_X - 1)} \geq \Sigma_r \widetilde{QM}_{r,t}, \quad (5e)$$

in which $\tilde{\sigma}_X$ is the elasticity of substitution among exporters, the CES distribution parameters, $\tilde{\beta}_{X,r}$ are region-specific technical coefficients, and $\overline{X} = \Sigma_r \overline{QX}_r$ denotes the aggregate quantity of exports from all California regions. In turn, each county's total supply of the final good is an Armington composite of domestic and imported varieties:

$$\widetilde{QA}_{r,t} = \overline{QA}_r \left(\beta_{D,r} \left(\widetilde{QD}_{r,t} / \overline{QD}_r \right)^{(\tilde{\sigma}_A - 1)/\tilde{\sigma}_A} + \beta_{M,r} \left(\widetilde{QM}_{r,t} / \overline{QM}_r \right)^{(\tilde{\sigma}_A - 1)/\tilde{\sigma}_A} \right)^{\tilde{\sigma}_A/(\tilde{\sigma}_A - 1)} \quad (5f)$$

where $\tilde{\sigma}_A$ is the Armington domestic-import elasticity of substitution, and $\tilde{\beta}_{D,r}$ and $\tilde{\beta}_{M,r}$ are CES distribution parameters.

Fourth, as in equation 3i, each county's Armington composite satisfies domestic demands for consumption, investment and intermediate commodity uses:

$$\widetilde{QA}_{r,t} \geq \widetilde{QC}_{r,t} + \widetilde{QI}_{r,t} + \widetilde{QZ}_{r,t}. \tag{5g}$$

Fifth, the dynamics of the economy are determined by two forces. Growth is fundamentally determined by the exogenous increase in each county's aggregate supply of labor with population expansion (given by growth rates, $\tilde{g}_r$):

$$\widetilde{QL}_{r,t} = \widetilde{QL}_{r,0}\left(1+\tilde{g}_r\right)^t \tag{5h}$$

and endogenous accumulation of capital that follows the perpetual inventory equation:

$$\tilde{K}_{r,t+1} = \kappa_0 \widetilde{QI}_{r,t} + \kappa_1 \widetilde{QI}_{r,t-1} + \kappa_2 \widetilde{QI}_{r,t-2} + \left(1-\delta\right)\tilde{K}_{r,t}, \tag{5i}$$

where δ denotes the rate of depreciation. Time-to-build lags in new capital formation have a significant economic impact at the fine temporal resolution of our analysis, with the duration of construction exceeding 12 months for multi-unit residential buildings. Accordingly, we model investment as maturing into new capital over three periods, controlled by the parameters κ_0, κ_1, and κ_2, whose values are all set to 1/3. Initial capital stocks ($\tilde{K}_{r,0}$) are fixed and are subjected to exogenous perturbations that represent aggregate capital stock destruction from shaking and fires. Finally, we close the model by mandating consistency between investment in the terminal period and balanced growth over the postterminal infinite horizon

$$\widetilde{QI}_{r,T} \geq \left(\tilde{g}_r + \delta\right)\tilde{K}_{r,T}. \tag{5j}$$

Model Calibration, Formulation, Solution, and Application

For computational tractability, and to facilitate detailed understanding of the long-run impacts on the hardest hit counties, we collapse the geographic dimension of the economy into the seven aggregate regions in table 23 (Alameda, Contra Costa, San Francisco, San Mateo, Santa Clara, rest of the San Francisco Bay region, and rest of California). The parameter vectors $\tilde{\boldsymbol{\alpha}}$ and $\tilde{\boldsymbol{\beta}}$ are calibrated using the benchmark quantities in the IMPLAN social accounts, which are also used to initialize the growth model, as shown in table 8.1. We use a depreciation rate of 5 percent, an interest rate of 2.65 percent (equivalent to the average yield on 10-year treasury bonds), and average rates of growth of the labor supply based on California Department of Finance (2017) population projections,[1] consistent with our 6-month timestep (δ=0.025, ρ=0.0133, $\tilde{g}_r$=0.7–1.1 percent). Each county's welfare weight is approximated by its fraction of statewide initial period utility, $\omega_r = \log\left(\widetilde{QC}_{r,0} / \widetilde{QL}_{r,0}\right) / \Sigma_{r'} \log\left(\widetilde{QC}_{r',0} / \widetilde{QL}_{r',0}\right)$. The elasticities of substitution were unchanged from their CGE model counterparts ($\tilde{\sigma}_Y$=0.1, $\tilde{\sigma}_{KL}$=0.25, $\tilde{\sigma}_A$=0.5, $\tilde{\sigma}_X$=2). The model is formulated as a nonlinear program in GAMS and solved using the CONOPT solver (Drud, 1994; GAMS, 2018).

[1]Total estimated and projected population for California and counties: July 1, 2010, to July 1, 2060, in 1-year increments.

Table 8.1. Parameterization of the dynamic economic model.

A. Set indexes

Index	Explanation
i	Commodity
j	Sector
r	County
t	Time period
h	Household income class
g	Level of government

B. Key parameters and benchmark quantities from the IMPLAN social accounting matrix

Quantity	Explanation
ρ	Interest rate
$\bar{q}_{i,C,h,r}$	Private consumption by commodity, county, and household income class
$\bar{q}_{i,I,r}$	Private investment by commodity and county
$\overline{QXUS}_{i,r}$	Exports to U.S. markets by commodity and county
$\overline{QMUS}_{i,r}$	Imports from U.S. markets by commodity and county
$\overline{QD}_r$	Aggregate domestic use by county
$\overline{QL}_{j,r}$	Labor input by sector and county
$\overline{QY}_{j,r}$	Output by sector and county
δ	Depreciation rate
$\bar{q}_{i,G,g,r}$	Government consumption by commodity, county, and level of government
$\bar{q}_{i,j,r}$	Intermediate use by commodity, using sector and county
$\overline{QXF}_{i,r}$	Exports to foreign markets by commodity and county
$\overline{QXM}_{i,r}$	Imports from foreign markets by commodity and county
$\overline{QA}_r$	Aggregate Armington commodity use by county
$\overline{QK}_{i,r}$	Capital input by sector and county

C. Dynamic model variables and their initialization

Variable	Initialization	Explanation
$\widetilde{QC}_{r,t}$	$\widetilde{QC}_{r,0} = \overline{QC}_r = \Sigma_i \Sigma_h \bar{q}_{i,C,h,r} + \Sigma_i \Sigma_g \bar{q}_{i,G,g,r}$	Quantity of aggregate consumption (private and government)
$\widetilde{QI}_{r,t}$	$\widetilde{QI}_{r,0} = \overline{QI}_r = \Sigma_i \bar{q}_{i,I,r}$	Quantity of aggregate investment
$\widetilde{QZ}_{r,t}$	$\widetilde{QZ}_{r,0} = \overline{QZ}_r = \Sigma_j \bar{q}_{i,j,r}$	Quantity of intermediate commodity use
$\widetilde{QX}_{r,t}$	$\widetilde{QX}_{r,0} = \overline{QX}_r = \Sigma_i \left(\overline{QXUS}_{i,r} + \overline{QXF}_{i,r} \right)$	Quantity of aggregate exports
$\widetilde{QM}_{r,t}$	$\widetilde{QM}_{r,0} = \overline{QM}_r = \Sigma_i \left(\overline{QMUS}_{i,r} + \overline{QMF}_{i,r} \right)$	Quantity of aggregate imports
$\widetilde{QD}_{r,t}$	$\widetilde{QD}_{r,0} = \overline{QD}_r = \Sigma_j \overline{QY}_{j,r} - \overline{QX}_r$	Quantity of aggregate domestic use
$\widetilde{QA}_{r,t}$	$\widetilde{QA}_{r,0} = \overline{QA}_r = \overline{QD}_r + \overline{QM}_r$	Quantity of Armington aggregate commodity use
$\widetilde{QL}_{r,t}$	$\widetilde{QL}_{r,0} = \overline{QL}_r = \Sigma_j \overline{QL}_{j,r}$	Labor supply
$\tilde{K}_{r,t}$	$\tilde{K}_{r,0} = \bar{K}_r = \Sigma_j \overline{QK}_{j,r} / \left(\rho + \delta \right)$	Capital stock