Economic Consequences of the HayWired Earthquake Scenario

Ian Sue Wing[1]; Dan Wei[2]; Adam Z. Rose[3]; and Anne M. Wein[4]

[1]Dept. of Earth and Environment, Boston Univ. Email: isw@bu.edu
[2]Sol Price School of Public Policy and Center for Risk and Economic Analysis of Terrorism Events, Univ. of Southern California. Email: danwei@usc.edu
[3]Sol Price School of Public Policy and Center for Risk and Economic Analysis of Terrorism Events, Univ. of Southern California. Email: adam.rose@usc.edu
[4]US Geological Survey. Email: awein@usgs.gov

ABSTRACT

This study evaluates the economic impacts of a M_w7.0 Hayward fault scenario earthquake on the greater San Francisco Bay Region's economy and the California economy as a whole using a detailed multiregional, static computable general equilibrium model. Economic impacts in terms of Gross Regional Product (GRP) losses caused by both capital stock (building and content) damages and water and electricity utilities, and telecommunications-service disruptions are estimated. The results indicate that the total losses are primarily caused by capital stock damages. 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 GRP over the period), but this result could be reduced by about 43 percent to $25.3 billion after factoring in microeconomic resilience tactics. The GRP losses associated with lifeline service disruptions are estimated to be $1.4 billion, which can be reduced by over 85 percent when resilience tactics are implemented. The most effective tactics are the ability to make up lost production by people working overtime or extra shifts (production recapture), making greater use of processes that do not need disrupted goods or services (production isolation), and substituting for disrupted supplies and services (input substitution), though their impact varies across the various causal factors influencing GRP losses.

INTRODUCTION

Earthquakes and other natural disasters affect regional and national economies by disrupting inputs to the production of goods and services and thereby affecting supply-chains. These inputs include primary factors of production, such as land that provides natural resources, capital that provides productive capacity, and labor that provides human resources, as well as intermediate inputs such as processed goods and utility services. In addition to simultaneously changing the demand for intermediate goods and services as inputs into production processes, disasters also affect the demand for final goods and services by households and government by way of disruptions to income and spending through death and injury and reductions in tax revenues. A prominent example of the potential for widespread economic losses from disasters is the recently formulated HayWired scenario. It 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 estimates the regional economic impacts of capital stock (building and content) damages and telecommunications network and utility-service disruptions from the HayWired scenario on the San Francisco Bay Region economy using a multiregional computable general equilibrium (CGE) model (Sue Wing et al. 2020). The model consists of industrial sectors and institutions (e.g., households and government sectors) and simulates their interaction through production functions and market linkages through supply chains. This means that the effects of earthquake damages in one sector may be direct (effects of property damages and utility outages) or indirect (effects of disruptions to its suppliers and customers). The latter are sometimes referred to as ripple or, multiplier effects, and, when price changes are included, are referred to as general equilibrium effects.

Economic resilience refers to the ability of the economic agents to use remaining resources efficiently and to recover from and 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 GDP (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 defined below 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 by people working overtime or extra shifts (see Rose, 2009; Wein and Rose 2011).[1]

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 and there are 17 counties in the affected region. The Gross Regional Product (GRP) -- the measure of the total value of final goods and services produced in a region -- for the Bay Region in 2012 was $579 billion (IMPLAN, 2014). This accounted for nearly 30 percent of the California total. In the past 15 years, the economy of the bay region experienced a 37-percent growth in GRP, which was about 14 percent greater than the average growth rate for the U. S. (Kroll et al. 2017). We disaggregated each county in the 9-county Bay Region economy into 46 industry sectors (see Sue Wing et al. 2021) using IMPLAN input-output (I-O) analysis data.

ECONOMIC IMPACT ESTIMATION USING COMPUTABLE GENERAL EQUILIBRIUM MODELING

A computable general equilibrium (CGE) model is a stylized computational representation of the circular flow of the economy (see, e.g., Sue Wing 2009; Sue Wing and Balistreri 2018). It solves for the prices of 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) 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 (each of the 17 counties in the region affected by the HayWired

[1]This paper is a synopsis of some of the major findings of the USGS report (Sue Wing et al., 2020): we summarized all sections in the USGS report, except for some of the sub-sections on Resilience Adjustments, the sections on Dynamic Economic Recovery and Study Limitations, as well as all the appendices.

mainshock and the remainder of the State). For each of the regions, in addition to the 46 industry sectors, linked to the other regions through trade, the model disaggregates households into nine income categories.

The industry classification is matched to the occupancy classes in Hazus (FEMA 2012), which was used by other HayWired team members to calculate the capital stock losses caused by the earthquake's physical impacts (Seligson et al. 2018).

DEFINING ECONOMIC RESILIENCE

There are many definitions of resilience, but researchers have generally found more commonalities than differences (Rose 2007; Cutter 2016). 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 (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. Major resilience tactics of this type include: input substitution, import substitution, conservation, resource isolation, excess capacity, inventories, relocation, technological change, management effectiveness, and production recapture (Rose 2009, 2017). Static economic resilience does not restore damaged capacity and is therefore not likely to lead to complete recovery.

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. We did not explore dynamic resilience.[2]

Another important distinction is between inherent and adaptive resilience. The former is already built into the system before the disaster strikes. It is either intrinsic, such as the ability to substitute ordinary inputs or the existence of excess capacity, or pre-positioned, as in the purchase of a portable electricity generator or lining up alternative input suppliers, both of which would be implemented once the disaster strikes. Adaptive resilience typically involves unanticipated actions and even improvisation, such as relocation or technological change (Rose, 2007, 2009).

[2]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 beyond what the engineering experts on the overall HayWired study team identified. 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 post-disaster regional economic growth. We only conducted a highly stylized partial equilibrium intertemporal simulation discussed in the section on Dynamic Economic Recovery in Sue Wing et al. (2020). See also the dynamic regional economic modeling of the HayWired scenario by Kroll et al. (2020).

INPUTS INTO THE ECONOMIC IMPACT MODEL

There are three types of inputs into the HayWired scenario economic impact model. First, the percentage of capital stock losses incurred in each sector is calculated by county. Second, telecommunications 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. The effects of most of the resilience tactics are incorporated in the analysis by adjusting the inputs to the CGE model, including interregional shifts in production activities. Recapture of production activities and adjustments for telework are applied to the CGE modeling outputs of GRP losses to further ameliorate the negative impacts.

To compare the baseline economy with direct economic impacts of property damages, the sectoral percentages of these capital losses are applied to baseline sector capital inputs in the model to express the direct impacts in terms of sector gross output. These are divided by baseline sectoral gross outputs to produce the percentages of gross output losses in Figure 1 for the mainshock and aftershock shaking and fire[3] within each county of the five most impacted counties. The figure indicates that, direct adverse effects on the Internet Publishing and Broadcasting sector, for example, are modest (losses on the order of 2–3 percent of baseline output). However, related and supporting sectors whose outputs are used intensively as inputs to that industry (telecommunications, electric power, data processing, hosting and related services, computer storage device manufacturing, electronic computer manufacturing, and other information services) are on average among the most directly affected, with average losses of 5 to 10 percent of baseline output.

The earthquake damages on the lifeline infrastructure systems are estimated in Porter (2018) for water distribution, Wein et al. (2021) for telecommunications services, and by using the Federal Emergency Management Agency disaster loss estimation tool Hazus-MH 2.1 for electric power services (Jones et al., 2020, Appendix 3). See Jones et al. (2020) for a compilation of methods and results of lifeline infrastructure system damage and restoration analyses.

The timelines of the base case and resilience case water, power, and data/voice service restorations are as follows:

Electricity service disruptions: By Day 7, all counties are expected to have more than 90 percent of power service back, except for 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.

Water service disruptions: 100 percent restoration of water service will take 90 days in San Mateo County and up to 540 days in Alameda and Contra Costa Counties. For all the other counties, full water services are restored in 30 days. Improvements to water service restoration are estimated for accelerated pipeline replacement and backup fuel plans.

[3]We refer to Scawthorn (2018) for the detailed presentation of the fire impact model. The model factors in ignitions from shaking and spread caused by fire reporting delays, shortage of fire trucks, water outages.

Data/voice service disruptions: data and voice service restoration depends on and lags behind electric power restoration, Furthermore, the increase in demand for information and communication after the earthquake congests the networks and only 7% of demand is met in Alameda county. By Day 7, 25% to 32% of demand is met in Alameda, Contra Costa, and San Mateo counties. By Day 30, more than 95% of the services will be restored in these three counties. Other counties are estimated to have more than 90 percent of data/voice service demands met on Day 7. Resilience from permanent backup power at sites decouples the dependency for the hours or a few days following the earthquake, user behavior management reduces demand, and the deployment of portable equipment and fuel deliveries to sites bolster the restoration over days to weeks.

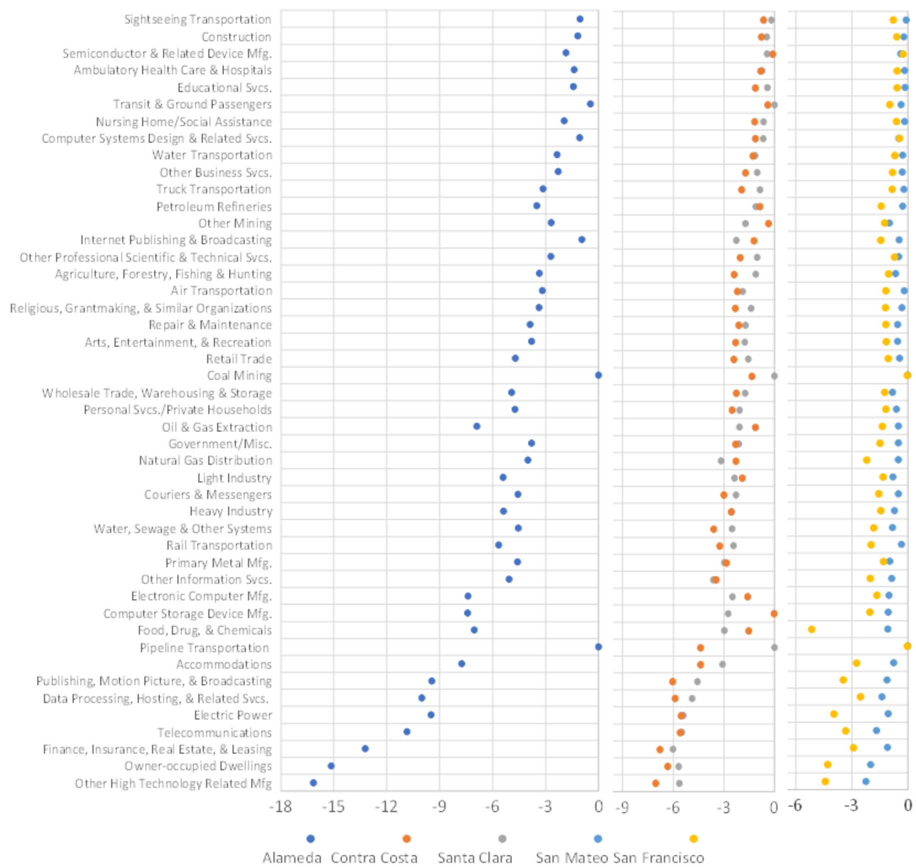

Figure 1. Aggregated direct property damages (percentage of a sector's gross output).

TOTAL ECONOMIC IMPACTS

Total (direct plus indirect) economic impacts are estimated using the CGE model with inputs for the base case and with inputs adjusted for the various resilience cases. The impacts of production recapture and telework are incorporated by adjusting the simulation outputs of the CGE model.

Base Case without Resilience Tactics. Table 1 summarizes the total economic impacts of the HayWired scenario. The base case only includes inherent resilience in the CGE model relating to primary production factors (labor, capital, and land) and locational substitution and price adjustments; it does not include the impacts of any other inherent or adaptive resilience tactics addressed subsequently (see Wei et al., 2020). Note that the Base Case results in Table 1 and the resilience results presented in Table 2 focus on production losses transmitted through market transactions. They do not include inconvenience costs, mainly non-market, for the impacts of water and electricity service disruptions, which are relatively small but significant (the reader is referred to Appendix 4 in Sue Wing et al. 2021 for a more detailed discussion).[4]

Table 1. Gross regional product (GRP) change in the first 6 months following the HayWired mainshock (percent change in parentheses) – Base Case

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

[1]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).

[4]Losses to households from electric and water service disruptions are not included in Table 1 because they are non-market affects. In Appendix 4 of Sue Wing et al. (2020), Keith Porter has estimated these losses as $3.9 billion for electric power and $5.2 billion for water.

By far the greatest BI losses (measured in terms of GRP) 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. The mainshock causes more than three quarters of the statewide economic loss in the 6-month post-earthquake period, which totals $44.2 billion, or 4.2 percent of the State's projected baseline GRP over the period. 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 fire following the earthquake are estimated to be $4.1 billion, or about 9 percent of the total. Secondary business interruption, owing to disruption of utility and telecommunications services, leads to GRP losses of $1.4 billion, which is much lower than the BI losses from property damage. This is mainly because utility-service disruptions are of shorter duration than those from capital stock. Water supply disruption causes a significant amount of the BI, in particular in Alameda County, including some of the fire damage, which is affected by water utility outages. Overall, impact from water service disruption is due to its length, while the impact from power and telecom disruption is from their breadth.

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 GRP in the first 6 months (see the last row of Table 1). 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. Sectors with the largest reductions in gross output statewide include real estate, manufacturing, health services, and professional, scientific, and technical services.

Total Economic Impacts with Resilience. Table 2 shows the total economic impacts of the HayWired earthquake scenario after we consider all the relevant resilience tactics for the various conduits of shock to the economy. Combining all the resilience tactics, total GRP losses in California decrease from $44.2 billion to $25.3 billion, a reduction of about 43 percent. For lifeline service disruptions, the GRP losses from these sources can be reduced by over 85 percent after factoring in the effects of various types of resilience tactics. One finding to note is the effect of telework to reduce BI losses from capital stock damages (by about 6 percent of total losses). Although telework depends on the availability of electricity and telecommunication services and data backups, the assumptions made prior to the pandemic likely underestimated the potential for telework during the first six months after the earthquake.

We compare these impacts with recessions that have affected the U.S. and the State of California since the end of World War II. The formal definition of a recession is a decrease in GRP in two successive calendar quarters. Until the "Great Recession" of 2008–09, these recessions generally resulted in a decrease in U.S. GRP of about 2 percent in at least one of the calendar quarters. On the other hand, the Great Recession resulted in a drop in GRP 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 after factoring in resilience, indicate the largest GRP decrease of 13.8 percent in Alameda County, a decrease of 2 to 6 percent in the other four 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.

Table 2. Total gross regional product (GRP) change in the 6 months following the HayWired mainshock for the base case (percent change in parentheses) – resilience case

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

[a] Resilience tactics considered for BI losses from property damage include telework and production recapture

[b] Resilience tactics considered for water and electricity service disruptions include conservation, production isolation, and production recapture.

[c] Resilience tactics considered for data/voice service disruptions include permanent backup power and portable equipment (cells on wheels or cells on light trucks) used by service providers, user behavior management, and input substitution, production isolation, telework, and production recapture adopted by the customer businesses.

The purpose of a scenario is to collaborate on constructing an integrated story spanning hazards, engineering impacts and societal consequences for disaster planning and preparedness. To understand how uncertainty might propagate in the economic modeling we provide the following insights. First, although the CGE model is non-linear, linear approximations can provide ballpark insights into changes in major variable and parameter inputs. For example, changes in sectoral economic output are linearly related to changes in property damage over a reasonable range of values. Changes in output are approximately linearly related to recovery time (i.e., if recovery time is decreased by 50%, then economic production losses are proximally cut in half as well). Most resilience tactics exhibit linear or near-linear properties (e.g., conservation, inventories, excess capacity, relocation, and production recapture). However, some are likely to be highly non-linear for large variations in their values (e.g., input and import substitution, where the cost penalty is likely to rise exponentially with increased dependence on these resilience tactics as options become scarcer).

CONCLUSION

We estimated total regional economic impacts on GRP by business interruption of the HayWired scenario earthquake on the San Francisco Bay Region economy. 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 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. 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 GRP.

Total GRP 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 isolating production that can continue without these inputs. In the telecommunications industry, backup power and portable equipment also reduce the customer BI losses on the supplier side. The study also indicates that the potential of telework, that depends on the restoration of electricity and telecommunication services and the cloud-backup data availability of the businesses, to reduce BI losses from capital stock losses.

We conclude by acknowledging some of the limitations of this paper. We have not factored in sources of disruption such as transportation, and hence 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 (see, Kroll et al. 2020). Also, we assume that businesses aim to return to business-as-usual conditions, but, in practice, businesses will reposition or redefine themselves and find new efficiencies, as was reported after the Christchurch earthquakes and others, as well as being very likely in the aftermath of the current pandemic. Finally, we have not explored dynamic economic resilience that would accelerate the pace of recovery in relation to a standard recovery path, which could further reduce GRP losses.

ACKNOWLEDGMENTS

We are grateful to Harvey Cutler, Laurie Johnson, Stephen Levy, and Keith Porter for helpful review comments on earlier drafts of the report underlying this paper. This research was funded by the U.S. Geological Survey Land Change Science Program.

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