Economic Impacts of a California Tsunami

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

Abstract: The economic consequences of a tsunami scenario for Southern California are estimated using computable general equilibrium analysis. The economy is modeled as a set of interconnected supply chains interacting through markets but with explicit constraints stemming from property damage and business downtime. Economic impacts are measured by the reduction of Gross Domestic Product for Southern California, Rest of California, and U.S. economies. For California, total economic impacts represent the general equilibrium (essentially quantity and price multiplier) effects of lost production in industries upstream and downstream in the supply-chain of sectors that are directly impacted by port cargo disruptions at Port of Los Angeles and Port of Long Beach (POLA/POLB), property damage along the coast, and evacuation of potentially inundated areas. These impacts are estimated to be \$2.2 billion from port disruptions, \$0.9 billion from property damages, and \$2.8 billion from evacuations. Various economic-resilience tactics can potentially reduce the direct and total impacts by 80–85%. **DOI: 10.1061/(ASCE)NH.1527-6996.0000212.**

Introduction

Since the 2004 Indonesia tsunami, campaigns to improve public awareness and preparedness of this hazard have increased (e.g., Tsunami Warning and Education Act 2006). The devastating Japanese tsunami of 2011 exemplified the complex interactions from coastal disasters that affect large populations and industrial activity, commercial ports, marinas, and fisheries, as well as nuclear power plants in need of the ocean's water for cooling purposes. Many coastal regions bordering the Pacific, including California, became increasingly concerned about their vulnerability to tsunamis. However, little is understood about tsunamis' economic consequences.

California's major fault lines are in the interior of the state rather than off the coast, which means the state is primarily vulnerable to tsunamis from other places in the Pacific Rim. Tsunamis emanating from earthquakes in Chile (1960 and 2008), and Alaska (1964) caused relatively minor or very localized severe damage (such as that for Crescent City in 1964). The most likely and damaging tsunami source for southern California is offshore of the Alaskan Peninsula (Kirby et al. 2013). The science application for risk reduction (SAFRR) tsunami scenario is a hypothetical tsunami created by a magnitude 9.1 earthquake from this source. The earthquake is assumed to occur at 11:50 a.m. pacific daylight time (PDT) on March 27, 2014, and the first waves hit Southern California around 4:50 p.m. PDT (SAFFR Tsunami Scenario Modeling Working Group 2013). Wave surges and inundation are dangerous for 2 days after the initial tsunami notification (Miller and Long 2013), and ocean current velocities and inundation damage ports, marinas, and coastal property and infrastructure (Porter et al. 2013a). The analysis of economic impacts from the SAFRR tsunami scenario is based on these assessments of the hazard, advisory, and damages. Despite the fact that the scenario is subject to multiple uncertainties that introduce the possibility of both underestimation and overestimation into the analysis, the potential for a tsunami to inundate land along the California coastline is firmly established (Wilson et al. 2013).

Very few studies have estimated the direct economic impacts of tsunamis, and even fewer have measured indirect effects both within and beyond the inundated areas. A rare study of the economic impacts of a Tsunami event—the Tohoku-Oki earthquake and tsunami (Kajitani et al. 2013)—found that quarterly declines in Japan's GDP peaked at −1.63% in the second quarter after the event and remained relatively constant for the rest of the year. The majority of the economic impacts are attributed to the tsunami rather than to the earthquake, before the cascading effects of the Fukushima power plant disaster are considered. For California, Borrero et al. (2005) estimate \$7–\$40 billion economic impacts on the Southern California economy if a locally generated tsunami scenario closes the Ports of Los Angeles and Long Beach (Ports of LA/LB) for up to 1 year. Other studies examine the economic impacts of different threats of port closure. Analyses of an 11-day labor lockout produce a range of estimated national impacts up to \$1.94 billion/day (Park et al. 2008; Martin Associates 2001), and examination of a potential terrorist attack that closes the Ports of LA/LB for 1 month yields a \$29 billion impact on the California economy (Park 2008).

These studies reinforce the importance of recognizing economic resilience, or the ability of the economy to adjust to disruptions in ways that mute potential negative impacts (Rose 2009). Hall (2004) criticizes the upper-end estimate of national economic impacts from the labor lockout based on model shortcomings that neglect short-run substitution behavior and assume constant long-run economic behaviors. Following the Japanese Tsunami, resilience is observed in the forms of rapid recovery of manufacturing sectors, energy conservation, and insurance (Kajitani et al. 2013).

All but the Kajitani et al. (2013) study used regression analysis or input-output models. The data requirements of the former are substantial, while the latter is limited by linearity and lack of

[1]Research Professor, Sol Price School of Public Policy, and Faculty Affiliate, Center for Risk and Economic Analysis of Terrorism Events (CREATE), Univ. of Southern California, 230 RGL, 650 Childs Way, Los Angeles, CA 90089. E-mail: adamzros@price.usc.edu

[2]Associate Professor, Dept. of Earth and Environment, Boston Univ., 675 Commonwealth Ave., Boston, MA 02215. E-mail: isw@bu.edu

[3]Research Assistant Professor, Sol Price School of Public Policy, and Faculty Affiliate, Center for Risk and Economic Analysis of Terrorism Events (CREATE), Univ. of Southern California, 100D University Gateway, Los Angeles, CA 90089 (corresponding author). E-mail: danwei@usc.edu

[4]Operations Research Analyst, Western Geographic Science Center, U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025. E-mail: awein@ugsg.gov

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behavioral content and workings of markets. An approach that is able to overcome these limitations is computable general equilibrium (CGE) analysis. It models the economy as a set of interconnected supply chains interacting through markets and is explicitly able to include constraints stemming from death, injury, and property damage. CGE models have become the state-of-the-art in providing valuable insights into and estimates of economic impacts for a range of disasters (e.g., Sue Wing et al. 2015; Huang and Hosoe 2014). The authors apply the CGE modeling approach and other established techniques to model the economic impacts for the SAFRR tsunami scenario. In addition, given the nature of the tsunami hazard, a framework for analyzing economic impacts from port damages and disruptions is developed that disentangles the complexity of this important aspect of a tsunami scenario. The base analysis of economic impacts to southern, northern, and total California economies from port damages and disruptions and coastal property damages are described in Wein et al. (2013). Herein, these analyses are summarized and the methodologies are extended to provide a more comprehensive estimate of economic impacts. This includes estimates of the ripple effects throughout the rest of the United States and impacts from population evacuations.

This study is the first comprehensive assessment of economic impacts from a distant source tsunami scenario affecting California. Economic impacts are measured by the reduction of gross domestic product (GDP) at scales of the regional, state, and national economies. The analysis of economic impacts on the Southern California, Rest of California, and U.S. economies is accomplished in several steps: (1) estimation of the direct economic impacts (immediate business interruption losses) in individual sectors of the economy due to physical damage to facilities, disruption of the flow of production units (commodities necessary for production), and evacuation; (2) estimation of the total economic impacts including the general equilibrium (essentially quantity and price multiplier) effects of lost production in industries upstream and downstream of affected sectors; and (3) estimation of various economic resilience measures that reduce the direct and total impacts.

The paper is organized as follows. Section "Framework for Estimating Economic Impacts" provides an overview of the framework used to estimate economic impacts from port disruptions resulting from a tsunami disaster. Section "Direct Economic Impacts from Trade Disruption and Coastal Damages" presents the analysis of the direct economic impacts from port trade disruption, as well as property damages at the ports, marinas and coastal regions. These direct impacts are assessed both with and without the consideration of resilience. Section "Total Economic Impacts from Damages and Disruption" models the total economic impacts of disruptions and damages resulting from the tsunami scenario on the California economy, including a discussion of evacuation impacts. Section "National Economic Impacts of the Tsunami Scenario" analyzes national economic impacts of the tsunami scenario, including ripple effects of import/export disruptions and property damages in California on the rest of the United States, and the economic impacts of disruptions to imports and exports that have shipment destinations and production origins outside of California. The "Conclusion" section summarizes major findings and policy implications.

Framework for Estimating Economic Impacts

Port-Related Impacts

Fig. 1 displays the major linkages in tracing port disruptions from closure and damages beginning with direct economic impacts through short-run and longer-run impacts across five analytical stages of a disaster scenario (Rose and Wei 2013).

The analysis begins with the tsunami event, which first translates into a risk of a port shutdown, cargo damage, and isolated terminal downtime for extended periods of time. At the port level, this leads to disruption of imports, exports, and onsite activities and operations. Various resilience measures can be implemented to mute impacts at the outset, including rerouting the traffic to other ports, diverting exports for use as import substitutes, using inventories by port customers, relocating activities within the ports, and rescheduling of activities once the port reopens by working overtime or extra shifts.

At the level of the macroeconomy, impacts stem from increased scarcity of intermediate and final commodities, and reduction in final demand associated with a decline in exports. Because both supply-side and demand-side impacts must be taken into account when evaluating total economic impact. Supply-side impacts affect customers of imported goods down the supply chain, while demand-side impacts affect these customers' suppliers up the supply chain. Intermediate goods imports are subject to both supply and demand impacts. Firms using imports as intermediate inputs to production, as well as successive rounds of downstream customers, are subject to supply shortfalls. In addition, curtailment of production by import-using businesses also reduces the demand for intermediate commodities produced by successive rounds of upstream suppliers within the region or nation. Curtailments of final (finished) imported goods supplies only impact end-users (consumers, government, and purchasers of capital equipment) without generating forward or backward linkage effects, and are simply added to the total macroeconomic impacts.

The shutdown of port operations, thus limiting export shipments, is characterized as an impact on suppliers, since downstream customers are outside the region and thus do not affect California's GDP. Conversely, disruption of export commodities reduces the demand for inputs to the production of these goods. First-round suppliers in turn reduce their demand, triggering a cascading decline in upstream production activities, analogous to that experienced for imports. The sum of all of these impacts is a multiple of the original initiating shock; hence, the term *multiplier effect* (both price and quantity) characterizes that manner in which these reactions yield macroeconomic impacts.

Fig. 1 focuses on trade-related port activities. It does not explicitly depict disruption to marina rentals and commercial fishing, all of which generate their own demand-side effects. The operation of marinas and commercial fishing are analogous to the disruption of port activities at the microeconomic level. Resilience measures applicable there, and at other junctures in Fig. 1.

In aggregating the various types of supply-side and demand-side impacts, a linear model such as input-output analysis treats the various boxes in Fig. 1 additively, and calculates and presents them separately to identify the relative influence of the multiple or offsetting factors. More-complex models, such as the one used in this study, capture important interactions between these various components (such as substitution effects and resource constraints) that cannot be readily decomposed. Potential long-run effects might arise from permanent loss of business for the port due to advantages of newly established logistics networks, or from stigma stemming from the fear of vulnerability to a repetition of the disaster. However, such considerations are beyond the scope of this paper.

Additional economic impacts can emanate from costs that arise from several sources: environmental damage at ports, delayed shipments of commodities to their intended destinations, and opportunity costs of resilience measures (e.g., rerouting shipping to other ports, or substitution of less efficient inputs to production activities down the supply chain). The first two categories are likely to be relatively small except in the case of a large-scale environmental incident such as a major oil spill that extends the duration

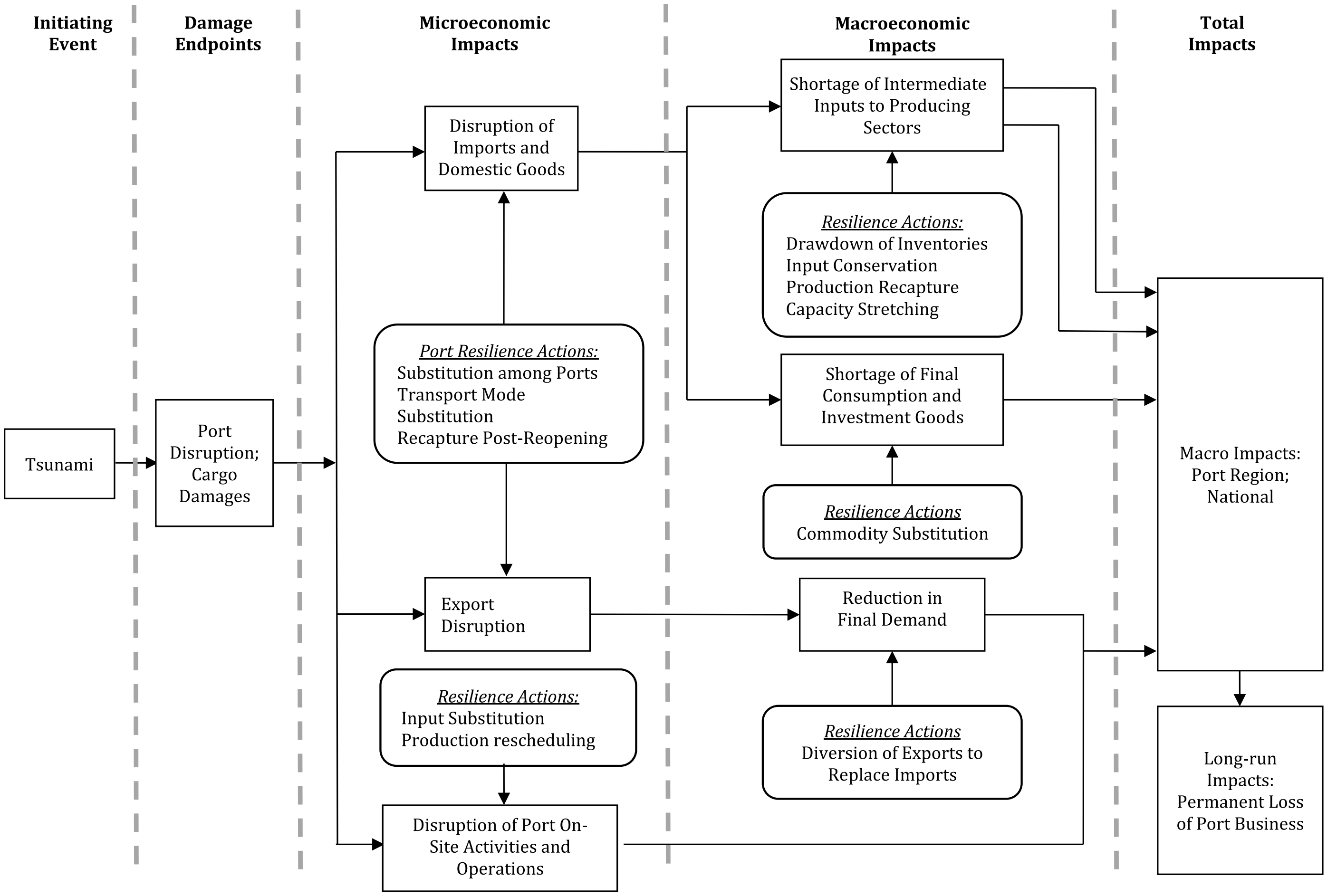

Fig. 1. Estimating total economic impacts of a port disruption, cargo damages, and terminal downtime

of the port closure (Rose and Wei 2013). As shipment delay costs rise, rerouting will be pursued more aggressively. And while some resilience measures can be costly, the corresponding benefit of avoided business interruption is likely to be larger.

Other Impacts

Another dimension of the economic impacts entails precautionary evacuation of the state's maximum tsunami zone in a suite of scenarios. This zone extends beyond the projected scenario inundation zone for reasons of safety, in particular the lack of time necessary to calculate the actual incidence of inundation. The economic impact of evacuation is twofold. The duration of individuals' movement away from their homes and places of work constitutes a reduction in labor supplied to their employers, and results in losses to the sectors within or adjoining the maximum tsunami zone. Symmetrically, accompanying such movements are increases in key categories of household demand over and above normal consumption levels (e.g., additional fuel, vehicle repair, and parking, lodging, and the services of eating establishments). The resilience tactic of production recapture can help reduce the economic losses stemming from evacuation.

Direct Economic Impacts from Trade Disruption and Coastal Damages

Estimation of the direct economic impacts to the California economy from the SAFRR Tsunami Scenario includes impacts derived from damages and trade disruptions at the ports of LA/LB, and damages to marinas and property within the California tsunami inundation zone. The direct impacts are estimated in terms of the most accessible measure of loss available: (1) import and export value affected by port shutdown, facility downtime, and cargo damages; (2) repair and replacement costs of damaged buildings and contents; and (3) gross output (business revenue) losses for marina-related sectors and the fishing industry. These impacts' calculations do not include damage to other ports, agricultural production, transportation infrastructure, lifeline infrastructure, and nonbuilding assets such as vehicles. Such omissions are deemed minor—except for other ports for which damage estimates are not currently available. These considerations suggest that the estimated direct economic impacts represent a lower bound. On the other hand, these impacts are inflated in the absence of resilience considerations, which are addressed later in this section. In addition to the economic impacts relating to trade disruptions and coastal property damages, the economic impacts of a 2-day evacuation of population from the state's maximum tsunami inundation zone are also analyzed, which will be presented in detail in section "Total Economic Impacts from Damages and Disruption."

Estimation of Direct Economic Impacts

The analysis of direct economic impacts utilizes a combination of data provided by the SAFRR tsunami physical damage analysis (Porter et al. 2013a), publicly available sources, and side calculations performed by the authors. For trade disruption, input data on port disruptions were obtained from the SAFRR tsunami physical damage analysis team, which include cargo damages by commodity type, length of the entire port shutdown, and durations of extended shutdown at specific terminal facilities. The building and content loss estimates for the state coastal regions were obtained from the Hazards U.S. Multi-Hazard (HAZUS-MH) (FEMA's expert loss estimation system) modeling employed by Porter (2013). In addition, Porter et al. (2013b) provide damages to marinas along the coast of California, and Brosnan et al. (2014) describe the disruptions to the Port of LA fishing industry.

The data on port disruptions and cargo damages are translated to direct economic impacts in terms of import and export reductions based on the 2010 trade data at the four-digit harmonized tariff schedule (HTS) code level. The building and content losses are translated into percentage reduction of capital stock. The damages to marinas are translated into output reductions in marina-related service sectors based on the total annual revenues of these sectors and the time it takes to repair the damaged slips. Finally, the output losses in the fishing industry are estimated on the basis of the number of fishing-days lost because of the strong currents and the time required to repair the damaged fishing fleet. Details of these calculations are provided in Wein et al. (2013).

The direct impact results of different categories are mapped to the 65-sector CGE model that is used to estimate the total economic impacts of the SAFRR tsunami scenario. The industry aggregation aligns with important categories of traded commodities and occupancy classes in HAZUS. The locations of damages and California import destinations and export origins are used to designate the direct impacts on the Southern California 5-County Region (Ventura, Los Angeles, Orange, San Bernardino, and Riverside counties) and the Rest of California. Finally, direct impacts measured in gross output terms are converted to gross domestic product (GDP) in the course of the analysis.

Results (Without Resilience)

Direct-impact results are produced for the import and export disruptions, marina slip damages, and effects on commercial fishing at the Ports of LA/LB. Beyond the ports' direct impact, results for damages to coastal property and marinas are also presented.

Import Disruptions

Direct import disruptions are measured as the values of imports destined for Southern California and the Rest of California that are affected by the 2-day port shutdown, cargo losses, and terminal downtime (Table 1). The 2-day port shutdown corresponds to the length of the warning and advisory based on tsunami modeling, which predicted that POLA and POLB areas would experience strong currents for at least 2 days.

Two-Day Port Shutdown

Two days of shutdown of the twin ports results in direct disruption to $417.3 million (in 2010 U.S. dollars) of import goods from more than half of the 65 sectors in Southern California. The imported commodities experiencing the largest impacts are Machinery, Other Transportation Equipment, and Apparel Manufacturing products related to container activities. However, expressed as a percentage of gross output, Plastics and Fishing Products suffer the most severe disruptions.

Cargo Losses

Cargo losses are related to inundation of terminals, as well as the character of the cargo (e.g., perishable goods). Cargo losses destined for Southern California total $60.8 million. The major imported cargo losses are Automobiles, which contribute nearly 83% of the total value of cargo damages.

Facility Down-Time

In the tsunami scenario, several port facilities (primarily cargo-handling terminals) would be damaged. For example, several marine oil terminals in Port of LA would only be able to operate at 50% capacity for 1 month due to the damage to the terminal operating systems. A few other terminals are considered unusable during debris clean up. Due to the reduced handling capacity of several terminals, the total estimated import disruption is $197 million. Affected commodities are Iron and Steel, Petroleum Refining, and Chemicals. The latter impact is negligible, while the former two represent approximately 65 and 35% of the total impact on imports, respectively.

The total import disruption for the Southern California Region is over $675 million, or 0.214% of its total annual imports. The total import disruption on the Rest of California Region is about $312 million, or 0.061% of its total annual imports. All three categories of import-related losses are lower for the rest of the state

Table 1. Direct Impacts of the SAFRR Tsunami Scenario (without Resilience) (in Millions of 2010 Dollars and Percentage Changes)

Impacted category	Unit of measurement	Southern California region	Rest of California	Total California
Direct impacts related to ports				
Import disruption	Import value	$675.2 (0.21%)	$312.1 (0.06%)	$987.3 (0.12%)
2-day shutdown	Import value	$417.3 (0.13%)	$208.2 (0.04%)	$625.4 (0.08%)
Cargo losses	Import value	$ 60.8 (0.02%)	$5.8 (0.00%)	$66.6 (0.01%)
Facility downtime	Import value	$197.1 (0.06%)	$98.2 (0.02%)	$295.2 (0.04%)
Export disruption	Export value	$131.8 (0.03%)	$78.2 (0.02%)	$210.0 (0.03%)
2-day shutdown	Export value	$91.7 (0.02%)	$57.5 (0.01%)	$149.2 (0.02%)
Cargo losses	Export value	$2.8 (0.00%)	$1.8 (0.00%)	$4.6 (0.00%)
Facility Downtime	Export value	37.2 (0.01%)	$18.9 (0.00%)	$56.1 (0.01%)
Marina slip damages	Gross output	$0.7 (0.00%)	N/A	$0.7 (0.00%)
Commercial fishing damages	Gross output	$0.7 (0.00%)	N/A	$0.7 (0.00%)
Direct impacts along other parts of the California coast				
Building damages	Capital stock	$52.0 (0.004%)	$246.4 (0.016%)	$298.4 (0.011%)
Content damages	Capital stock	$367.4 (0.047%)	$1,159.5 (0.124%)	$1,526.9 (0.089%)
Marina slip damages	Gross output	$71.4 (0.005%)	$50.8 (0.003%)	$122.2 (0.004%)

Note: Percentages for output, import value, and export value are measured as proportions of annual flows; percentage of capital stock loss is measured with respect to capital stock in place at the time of the tsunami.

because on average a higher proportion of the affected imports in Ports of LA/LB are delivered to users in Southern California. The difference is most pronounced for cargo losses, which are only $5.8 million for the Rest of California versus $60.8 million for the Southern California region alone.

Export Disruptions

Direct export disruptions are measured as the values of exports emanating from Southern California and the Rest of California that are affected by the 2-day port shutdown, cargo losses, and terminal downtime (Table 1). For Southern California, the 2-day shutdown results in a direct export disruption of $91.7 million. Major affected export categories are Chemicals, Machinery, and Food products, each exceeding $10 million. Export disruptions from facility down-time cost $37.2 million, and are concentrated in Petroleum Refining and Chemicals. Associated losses of cargo for export total $2.8 million, with the largest damages in the three sectors identified earlier. The total direct export disruption to the Southern California Region is about $132 million, or 0.034% of its total annual exports.

Direct export disruptions for the Rest of California are also presented in Table 1, and amount to $78.2 million, or 0.017% of the total annual exports from the region. Export disruptions from 2-day port shutdown, facility downtime, and cargo losses are $57.5, $18.9, and $1.8 million, respectively. Overall, the export disruptions are significantly smaller than their import counterparts.

Direct Gross Output Losses Associated with Marina Slip Damages at the Port of LA

Direct losses from damages to Port of LA marinas are measured as gross output (revenue) losses to the marina-activity-related sectors defined by Martin Associates (2007). These sectors are Retail Trade, Scenic and Sightseeing Transportation, Other Amusement and Recreation, and Food Services and Drinking Places. The total estimated gross output loss to the marina-related sectors is $0.72 million (Table 1).

Gross Output Losses to Port of LA Commercial Fishing

Direct losses from damages and disruption to commercial fishing are measured as revenue losses. The effects of the SAFRR tsunami scenario on commercial fishing at the Port of LA are assumed to be 25% of a normal day's fish haul perished on board vessels at sea, 4 lost fishing days, and damage to 5% of the fishing fleet. Based on conversations with fishermen, damaged boats are repaired or replaced after 2 months on average. The direct revenue loss to the fishing industry amounts to $734,425.

Capital Losses of Building and Content Damages

Direct impacts of building and content damages (loss of capital stock) are measured as repair and replacement costs. In the Southern California region, building-related and content-related property losses are $52 million and $367 million, respectively, representing about 0.004 and 0.047% of the total capital stock in this region. The building-related and content-related property losses in the Rest of California are $246.4 million and $1.16 billion, respectively. They represent 0.016 and 0.124% of the total capital stock in the Rest of California (Table 1).

Direct Gross Output Losses Associated with Marina Damages in All California Coastal Counties

The damages to the docks at the marinas along the coast of California are translated into total direct revenue losses of $71.4 in Southern California and $50.8 million in the Rest of California.

Evacuation-Related Direct Losses

Evacuation is assumed to last 2 days, based on the tsunami warning for inundating waves and advisory for strong currents. The percentage of developed land in the evacuation zone with respect to the total developed land area in each affected county is first calculated based on the results of a geographic information system (GIS) analysis of the 2006 National Land Cover Database (Fry et al. 2011). Next, the direct gross output loss for each sector in each county is estimated by multiplying the imputed 2-day sectoral gross output by the countywide evacuated percentage of developed land.

In summary, the direct economic impacts of the USGS SAFRR Tsunami Scenario in Southern California and the Rest of California without resilience are dominated by the disruption to imports, especially from the 2-day shutdown of the twin ports and damages to building content. The direct port-related impacts in Southern California tend to be approximately twice those for Rest of California. The latter shoulders more of the property damages along the coastline.

Direct Economic Impacts (With Resilience)

Various static resilience measures will mute the direct economic impacts from the tsunami by using existing resources more efficiently (Rose 2009). For example, the largest impacts are port-related and can be reduced by using excess capacity at the marine oil terminals and marinas, avoiding ship rerouting for a port shutdown as brief as 2 days, diverting exports of petroleum products to substitute for the same type of disrupted import, conserving production inputs using storage, handling, and maintenance precautions, recycling and repairing materials to cope with the import disruptions, and running down inventories to buffer import disruptions.

Detailed discussions of the data, assumptions, and methodology used in the resilience analysis are presented in Wein et al. (2013). The offsetting effects of resilience are calculated separately and the use of inventories has the greatest potential to reduce losses. However, the savings from individual resilience measures are not additive and jointly reduce the direct economic impacts from import disruption from $675.2 million to $28.9 million or from 0.214 to 0.009% of annual import value for the Southern California region; and from $312.1 million to $1,797, or from 0.061 to 0.000% of annual import value for the Rest of California region. On the export side, the combined effect of resilience reduces the export disruption impact from $131.8 million to $93.9 million, or 0.034 to 0.024% of annual export value for the Southern California region; and from $78.2 million to $59.0 million, or from 0.017 to 0.013% of annual export value for the Rest of California region. Excess slip capacity in the Port of LA marinas reduces the estimate of direct losses from $700,000 to $600,000.

Total Economic Impacts from Damages and Disruption

Total economic impacts stemming from the various direct impacts include positive or negative ripple effects transmitted upstream and downstream along supply chains, as well as changes in spending of wages/salaries and capital-related income, and the further ripple effects these induce throughout the supply chains of the economy as well. These effects are modeled using a computable general equilibrium model. The total economic impacts (or business interruption) from the direct impacts are first evaluated without resilience to expose the economic vulnerabilities. Resilience is revisited after the presentation of results.

Estimation of Total Economic Impacts: Computable General Equilibrium Modeling

The assessment of broader economic consequences makes use of a stylized static CGE model of the California economy over the 6-month period following the tsunami's impact. CGE simulations have been successfully applied to other disaster scenarios. This includes a study of the economic impacts of a Bay Area earthquake closing off the California Aqueduct water supplies to Los Angeles County (Rose et al. 2012) and the USGS scenario about atmospheric river (AR) winter storms in California (called ARkStorm) (Sue Wing et al. 2015).

The authors' purpose-built model divides the state into two economic regions: five Southern California counties where the impacts of a tsunami on the ports of LA/LB and related economic activity are geographically proximate and most likely to be concentrated (Ventura, Los Angeles, Orange, San Bernardino, and Riverside), and an aggregate of the state's remaining counties. The model embodies a detailed representation of production, consumption, and trade—among industries within each region, as well as between regions, the rest of the United States, and the rest of the world. Producers in each region are divided into 65 industry sectors, each of which is modeled as a representative firm with multilevel constant elasticity of substitution (CES) production technology. Each region's consumers are divided into nine income categories, each of which modeled as a representative agent with CES preferences. Regional governments are represented in a simplified fashion: collecting taxes from industries and passing some of the resulting revenue to the households as lump-sum transfers, in addition to purchasing commodities to create a composite government good that is consumed by the households. Two primary factors of production are represented within the model: labor—which has a fixed endowment but its allocation among sectors responds to changes in the wage rate—and capital—which is in similarly fixed total supply but is in addition sector-specific and immobile among industries and regions. The two factors are owned by the representative agents, who rent them to the firms in the agents' region of residence in exchange for factor income. Each region is modeled as an open economy that engages in commodity trade with the other California region, the rest of the United States and the rest of the world. Following the commonly-used Armington (1969) specification, commodities are differentiated according to their place of production (reflecting quality differences and hence imperfect substitution), with each good consumed by sectors and representative agents modeled as a CES composite of imported and domestic varieties. Details of the model's structure and calibration are given in an appendix to that paper.

The 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 6-month period. The boundary conditions of the stylized economy determine the equilibrium price and quantity vector. There are five such conditions: (1) the endowments of the factors of production (labor and capital) owned by the households, (2) the nonfactor productivities of the various producers that modulates each sector's transformation of inputs into output, (3) exogenous household expenditures that are not normally incurred but become necessary during or after the onset of a disaster, (4) United States and rest-of-world demands for exports shipped by the two California regions, and (5) United States and rest-of-world supplies of imports to these regions. Each of these conditions is affected by the various direct damage categories calculated in section "Direct Economic Impacts from Trade Disruption and Coastal Damages." Import and export disruptions listed as Points 4 and 5 in the preceding sentence map to Categories 1 and 2 in the previous section. These constitute exogenous percentage reductions of the benchmark levels of the commodity-specific import supplies faced by industries and households, and the commodity-specific export demands faced by industries, in each region. It is useful to conceptualize direct output losses sustained by different industries (Categories 3, 4, and 6 in the previous section) as a disruption of the ability to transform inputs into output. This type of damage can thus be represented as the analogue of Point 3, percentage reductions in the productivity of all inputs below sectors' baseline levels (so-called neutral productivity shocks). Capital stock losses (Category 5 in the previous section) are equivalent to secular reductions in the capital that households supply to each sector below the benchmark endowment levels in the economic accounts as per Point 1.

Total Economic Impact Results (Without Resilience)

Total economic impacts stem from damages and disruption at the twin ports of LA and LB, coastal marinas, and buildings and contents within the tsunami inundation zone in California. The two-region California CGE model uses as inputs the direct economic impacts from Table 1, and estimates the total economic impacts of the SAFRR tsunami scenario event. The results are presented in Table 2 for the 5-County Southern California Region, the Rest of California, and for California as a whole.

Overall, the impacts on GDP (in 2010 dollars) are $1.7 billion for the 5-County Southern California region, $1.5 billion for the Rest of California, and $3.1 billion for California. These impacts represent only 0.378, 0.276, and 0.323% of annual GDP of the three regions, respectively.

Import disruption impacts are the largest component of the negative economic shocks in all three regions, totaling $1.7 billion. The total economic impacts of import disruptions represent nearly 50% or more of the predicted declines in GDP total in each region. The category that represents the largest share is the shutdown of the ports themselves, and the smallest by far stems from the loss of cargo. The import losses are higher for the Southern California region than for the rest of the state due to the lower direct import disruption impacts and the greater substitution stimulus from the reduced flow of imports for the rest of the state relative to the same for the Southern California region.

Export disruptions are estimated to incur $0.57 billion in GDP losses for California, with the port shutdown by far being responsible for the largest component. Again, cargo losses are the smallest component. Export shutdowns do not stimulate any offsetting effects like the case of imports, because it would not pay to produce more goods for export if they cannot be shipped.

Building and content damage in coastal California due to flooding is predicted to amount to $0.9 billion in GDP losses, with the vast majority being due to content damage. Here the CGE analysis is a straightforward price and quantity multiplier effect extension of the direct impacts, and the total impacts for the two subcategories have similar proportions as the direct impacts. Other impacts of the tsunami stemming from marina damages and fishing losses are very small, totaling only $14 million, or only 0.001% of California's annual GDP.

Reductions in GDP are also estimated on a sectoral basis. Disruption of imports and exports incur the largest output losses

Table 2. Summary of Tsunami Business Interruption, without Resilience and Reconstruction (Million 2010 Dollars of GDP Losses)

Impacted category	Southern California region	Rest of California	Total California
San Pedro import total	$1,117 (0.251%)	$538 (0.102%)	$1,655 (0.170%)
2-day port shutdown	$570 (0.128%)	$338 (0.064%)	$908 (0.093%)
Cargo loss	$39 (0.009%)	$3 (0.001%)	$42 (0.004%)
Facility downtime	$505 (0.114%)	$195 (0.037%)	$700 (0.072%)
San Pedro export total	$257 (0.058%)	$316 (0.060%)	$573 (0.059%)
2-day port shutdown	$194 (0.044%)	$221 (0.042%)	$414 (0.043%)
Cargo loss	$6 (0.001%)	$7 (0.001%)	$13 (0.001%)
Facility downtime	$58 (0.013%)	$88 (0.017%)	$146 (0.015%)
California coast property damage total	$300 (0.068%)	$601 (0.114%)	$901 (0.093%)
Buildings	$18 (0.004%)	$39 (0.007%)	$57 (0.006%)
Contents	$283 (0.064%)	$561 (0.106%)	$844 (0.087%)
Other impacts total	$9 (0.002%)	$5 (0.001%)	$14 (0.001%)
California coast marinas	$8 (0.002%)	$4 (0.001%)	$12 (0.001%)
POLA fishing	$1.0 (0%[a])	$0.3 (0%[a])	$1.3 (0%[a])
Grand total[b]	$1,679 (0.378%)	$1,458 (0.276%)	$3,137 (0.323%)

[a]Less than 0.0005%.
[b]Totals may not add due to rounding.

in manufacturing industries (leather products, primary and fabricated metal products, machinery, and ship building/repair). The pattern of losses is broadly similar for both the 5-County Southern California and Rest of California regions, with the former experiencing larger losses in both absolute and percentage terms. The overall magnitude of the losses affecting hardest-hit manufacturing industries is small in both absolute and percentage terms, over the 6-month assessment period totaling 0.4–2% of annual output, or $151 million in the 5-County region and $55 million in the Rest of California.

Direct damage to capital stocks has its largest impact on a different slate of industries, and the associated output losses are at an order of magnitude smaller in percentage terms than in the imports/exports disruption case. In the Southern California region, the output of service sectors is most affected (healthcare, real estate, retail trade, education, and food service establishments, and other services), while in the Rest of California, adverse impacts are concentrated in accommodation services, transportation and gas distribution, miscellaneous manufacturing industries, and other services. The larger baseline GDP of these sectors in the Rest of California means that the dollar value of losses is larger despite being smaller in percentage terms.

Finally, looking at the combined impact of all conduits of shock, the sectors that are most affected relative to projected GDP are those that face the largest exposure to losses from trade, with the notable exception of fishing, which is both small and hardest hit in Southern California. The fishing sector is impacted by both trade disruption and fishing-vessel damages, but the latter impact dominates the total impacts on this sector. Although fishing damages are not evaluated in the Rest of California, the impact is traceable to demand reductions and price responses in the food manufacturing and service industries.

The results are miniscule compared to the devastation of the Japanese coast in 2011 and the ensuing cascading disasters. The main reason is that the SAFFR tsunami scenario produces smaller waves and less inundation along the California coast than what occurred along the Japanese coast. The estimates in Table 2 are very much lower than those for the two previous U.S. Geological Survey disaster simulations, where GDP losses (in 2010 dollars) are about $70 billon for the ShakeOut (Rose et al. 2011) and $300 billion dollars for ARkStorm (Sue Wing et al. 2015), even before any resilience adjustments are made for the tsunami scenario.

A couple of critical economic impact modeling closure assumptions include the savings-investment balance, labor supply-demand balance, and labor-supply elasticities. The static model implemented in this study cannot address the investment–saving relationship, but, given the small impacts relative to the California economy, the authors would not expect a negligible effect on the savings–investment balance. A sensitivity analysis of the labor market elasticities reveals a significant effect on estimated economic impacts. However, the original formulation of the model is more consistent with empirical evidence on labor elasticities (McClellan and Mok 2013), though this and other studies reviewed do not take into account the effect of a disaster. For a comparatively small disaster such as this, the authors expect it would be more likely that individuals will keep working through the recovery period at slightly lower compensation levels rather than reduce their hours or quit their jobs.

Total Economic Impacts (With Resilience)

The resilience tactic that applies to total economic impacts is production and sales recapture (recouped at a later date). Production recapture refers to the ability of businesses to recapture lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs are available. On the export side, a similar concept is sales recapture. At the ports, recapture applies to the import and export disruptions from the 2-day port shut down because no ships are rerouted; they are delayed for 1–2 days on average over a week or so. Therefore, import and export disruptions are recaptured with the exception of perishable agricultural products. Recapture can also be applied to import and export disruptions from 2-week or 1-month facility downtime. This is because for a short duration (less than 3 months) most customers do not cancel their orders. Production recapture does not apply to lost marina slip fees, but catching up on lost days of fishing could reduce total impacts from fishing damages and disruption by about 75%. Manufacturing sectors have the highest potential (about 98%) to recapture their interrupted production, with the lowest recapture factors being in the service sectors (between 51 and 80%). The potential for recapture would be smaller for longer periods, as customers begin looking elsewhere for their source of supply. Recapture could greatly reduce the total impact from import and export disruptions by 80–85% on top of the potential for resilience tactics to reduce direct impacts.

Sector recapture factors can also be applied to the total economic impacts from the building and content damages. This procedure reduces those total economic impacts by approximately 80% in each of the regional and California economies.

Evacuation Impacts

Sectoral direct business interruption (BI) losses were expressed as a percentage of benchmark gross output, which was then applied as a productivity shock to the CGE model to simulate the total impacts of a 2-day evacuation. The results indicate total GDP impacts of $1.8 billion in the Southern California region, $1.0 billion in the Rest of California, and $2.8 billion in California statewide (Wei and Rose 2014a). The impacts are larger in the more-populated Southern California evacuation area where a greater percentage of developed land in the maximum tsunami inundation zone claims more of the economic activity. The evacuation impacts are similar in magnitude to those from the physical damages and port disruptions. However, evacuation impacts have potential overlaps with others, such as the 2-day port shut-down. The offsetting impacts of increased evacuation expenditures (such as on food, temporary lodging, and transportation) and resilience effects of production recapture are also estimated. Compared with the evacuation BI losses, the spending effect is minimal at about $8 million. However, production recapture is estimated to have the potential to reduce nearly 85% of the evacuation GDP losses.

National Economic Impacts of the Tsunami Scenario

National economic impacts are derived from three aspects: the ripple effects of California trade disruptions and property damages, and the disruption of imports and exports with destinations and origins outside of California. The methodology for each of these aspects is described, followed by GDP impact results, and consideration of resilience.

Methodology

Ripple Effect of California Trade Disruptions

A national input-output (I-O) model is used to examine the ripple effect of California trade disruptions on the Rest of the United States because the impacts are rather straightforward (e.g., price changes are likely to be minimal in the context of the large national economy). The methodology developed by Rose and Wei (2013) and Wei and Rose (2014b) is adapted as follows:

1. Utilize the CGE model sectoral GDP impacts of total trade disruptions in California as input;
2. Compute the total effect of port disruption impacts in California on the United States by applying the U.S. I-O model to the direct sectoral impacts;
3. Compute the ripple impacts on the Rest of the United States as the difference between the national impacts and the California impacts calculated from the CGE model in section "Total Economic Impacts from Damages and Disruption"; and
4. Consider resilience by performing a national impact analysis based on cargo damage estimates alone. Use this case to estimate the lower bound of impacts with optimistic resilience assumptions, i.e., assume that the port can offset the disrupted cargo-handling activities by relocating activities both within the twin port facilities and by rerouting the ships to other ports, and by utilization of the existing oil inventories.

Ripple Effect of California Property Damage

A similar approach to the one presented in the preceding section is used to compute the ripple effect of California property damage impacts on the rest of the United States. Resilience is considered in the form of rescheduling lost production by applying the sectoral recapture factors to the GDP impact results.

National Impacts of Import and Export Disruptions on the Rest of United States

The national impacts of disruptions of imports and exports that are delivered to or produced in the rest of the country are estimated by the following steps:

1. Import Disruption
   a. Identify major sectors utilizing imported commodities from the Impact Analysis for Planning (IMPLAN) (2010) U.S. Industry Import Matrix that tracks the distribution of imported commodities to the producing sectors of the country. The major importing sectors of each type of imported commodity are defined as the sectors that consume at least 10% of the total import of that commodity.
   b. Calculate the input disruption for the identified sectors as $\%\text{Input Disruption} = \%\text{Import Disruption} \times \%\text{Input Imported}$. This equation accounts for sectors that purchase the inputs from both domestic and foreign producers and assumes the quality is comparable from both sources.
   c. Compute supply-side and demand-side gross output (GO) impacts of import disruption by applying the U.S. supply-driven and demand-driven I-O models to the vectors of sectoral value-added changes and sectoral final demand changes of the major import using sectors. Calculate GDP and employment impacts for sectors by multiplying the sectoral gross output impact by GDP and employment coefficients of the corresponding sector.
   d. In the resilience case, use only the cargo damage estimates as a lower and optimistic bound on the national impact analysis.
2. Export Disruption
   a. Convert the export commodity disruption into a vector of final demand decreases to the rest of United States.
   b. Compute the gross output impacts by applying the demand-driven U.S. I-O model to the final demand change vector calculated in Step 2a.
   c. In the resilience case, the cargo damage estimates are again used as a lower and optimistic bound on the national impact analysis.

Results

Table 3 summarizes the impacts for the three impact categories in the three regions of interest. The economic spillover effects of trade disruptions and property damages in California to rest of the United States are about 30 and 20% of the size of the total impacts on California, respectively. The total impacts of Import and Export Disruptions in regions outside California are only computed for the nation as a whole (Table 3). Any spillover effects from rest of United States to California would be relatively small compared with the total national impacts. Overall, the total economic impacts on the U.S. economy are a decline of $10.0 billion in GDP from port disruption and property damages.

Table 4 summarizes results of the three impact categories with resilience. After incorporating resilience, total GDP impacts on the U.S. economy are reduced from $10 billion to about $0.6 billion. Recapture of trade disruptions has the potential to reduce the total impacts by more than 95%. Production recapture due to property damage can reduce the impacts on GDP by about 61%. Adjusting for resilience, the economic spillover effects of trade disruptions (cargo damages only) and property damages in California on rest of the United States are around 19% of the total impacts on California. The ratio of spillover effects to national total effects is smaller in the resilience case than in the non-resilience case.

Table 3. Summary Table of Total National GDP Impacts for the Major Tsunami Shocks (without Resilience) (Million 2010 Dollars of GDP Losses)

Impact category	California	Rest of United States	United States
Impacts of import and export disruptions to California	2,228	699	2,927
Impacts of building damage in California	901	180	1,081
Impacts of import and export disruptions to rest of United States	[a]	[a]	6,054
Total impacts	[b]	[b]	10,061

[a]See text.
[b]Not calculated because the impact results are only available for two out of the three impact categories.

Table 4. Summary Table of Total National GDP Impacts for the Major Tsunami Shocks (with Resilience) (Million 2010 Dollars of GDP Losses)

Impact category	California	Rest of United States	United States
Impacts of import and export disruptions to California	55	10	64
Impacts of building damage in California	351	67	418
Impacts of import and export disruptions to rest of United States	[a]	[a]	149
Total impacts	[b]	[b]	631

[a]See text.
[b]Not calculated since the impact results are only available for two out of the three impact categories.

For the impacts of trade disruption, this is mainly because the sectors accounting for a major part of the GDP losses in California from cargo damages are sectors that have relatively low spillover effects on regions outside of California (GDP losses in Retail Trade, Finance and Insurance, and Health Care account for about 50% of the total GDP losses in California stemming from cargo damages, and each of these three sectors only have 4–8% spillover effects with respect to the impacts occurred in California). Regarding property damages, the sectors that have higher spillover effects, such as manufacturing, have relatively high production recapture factors.

Impacts from cargo damages represent a lower bound on economic impacts with resilience. The results are consistent with the assessment in the tsunami report by Wein et al. (2013), which concludes, for an optimistic scenario, effective implementation of all the applicable resilience tactics have the potential to reduce the *direct* economic impacts of trade disruptions on California by 80–95%.

Further Discussion

This paper has focused on the range of economic impacts of a potential major disaster. The future course of the economies affected will, however, be influenced by the recovery from it. In previous research on another disaster scenario, which related to a severe winter storm, both the disaster and the recovery were analyzed (Sue Wing et al. 2015). It is important to keep these two aspects separate because of unique features of both disaster consequences and economic recovery, and because greater insight can be obtained by separate analyses. The authors refer the reader to the previous study for details of modeling economic recovery in a CGE framework, but do summarize below two aspects that are rarely discussed in this context.

The first deals with the role of the insurance industry in the disaster and its recovery. On one hand, interindustry and final demands for insurance services will decline with the fall in purchases that result from curtailed economic activity and income of downstream firms and households. The CGE model does not consider the insurers as a separate industry, instead incorporating them within the Finance Insurance and Real Estate sector, which experiences a modest negative impact of output losses that are the 15th largest of the 65 modeled industries considering all damage categories.

More consequential are the direct and indirect impacts of insurance payouts on both insurers and insured entities. The challenge for capturing the indirect impacts is the static character of the CGE model. For a combined analysis of disaster impacts and recovery, federal disaster assistance can be modeled simply as exogenous reductions in the quantity of direct capital losses sustained by California industry sectors (due to the use of the assistance for repair and reconstruction), which softens the net blow to the economy. A straightforward method for modeling in-state payouts is to impose a secular reduction in the capital input to the insurance sector, and, symmetrically, distribute the equivalent value of funds to policy-holding firms (as secular increments to these sectors' capital stocks) and households (as increments to income, denominated in units of the final consumption good). But in the present static setting, such transfers merely move real purchasing power from one part of the economy's factor endowment to another, and therefore have a negligible impact on equilibrium prices and quantities. By contrast, staggering of the timing of payouts and receipts does have significant economic effects, particularly if funds for reconstruction must be raised through in-state private borrowing in the immediate aftermath of the disaster, but insurance payouts and/or federal assistance are delayed (Sue Wing et al. 2015).

The bigger challenge is characterizing the direct impacts, in terms of the size and sectoral distribution of the financial transfers that would need to be imposed as shocks within such a model. The payouts that would need to be represented depend on the details of policies and the fraction of damaged assets underwritten by California insurers, which are fundamental unknowns. In all likelihood, local insurers will be responsible for significantly less than the full amount of direct building, content, cargo and output losses calculated in section "Direct Economic Impacts from Trade Disruption and Coastal Damages," as the largest port in the country will likely hold policies with global, or at least national, private insurers, as well as FEMA's National Flood Insurance Program (NFIP). Detailed assessment of the insured losses for physical damages and business interruption was deemed to be outside the scope of this study due to the insurmountable complications of multiple sources and forms of insurance (e.g., Maritime Administration

1998) and the dearth of publicly available information on firms' and households' private insurance coverage. A first line of coverage is expected through NFIP, to which most California coastal communities subscribe. Property owners and renters located within state-designated tsunami hazard zones, but outside FEMA high-risk flood zones are encouraged to obtain NFIP coverage at fairly low rates (California TPWG 2014). However, the salutary experience of Crescent City in the 2004 tsunami aftermath highlights the issue of lengthy delays related to the FEMA reimbursement process (R. Young, personal communication, 2013) highlights the importance of dynamic modeling approaches capable of capturing the associated costs in present value terms (Sue Wing et al. 2015).

The second oft-neglected aspect of recovery deals with what is often referred to as *demand surge*. (e.g., Olsen and Porter 2011). This typically refers to the heightened demand for critical inputs into repair and reconstruction following a disaster. Initially, there is the obvious, though usually only vaguely expressed, concern about the availability of these inputs. But the attention then quickly shifts to the likely sharp rise, or surge, in their prices. There are several implications of these initial price increases, not all of which have been examined. First, while some customers will be willing to pay the higher price, others will withdraw or delay their demand. Second, not only do all remaining customers pay the higher prices directly, but they are magnified, or multiplied, potentially several-fold, through a type of cost-push inflation on all other goods and services. Third, this reduces the purchasing power of consumers, so the demand for all goods and services in the economy is stunted, including some further reduction in demand for inputs into recovery, repair, and reconstruction. Fourth, any stimulus from an inflow of insurance or aid funds aside, this leads to an overall economic contraction in real economic terms, i.e., the total sales price may be higher, but the quantity of goods and services in the market basket is lower.

Rose and Liao (2012) have pointed out that several factors are not fully appreciated in this characterization of the problem that pervades the literature today. First, damage to plant and equipment may have at least as great a direct influence on prices as does the pure demand surge, so the problem might also be referred to as a demand surge-supply shock. Second, the economy-wide spread of cost-push inflation has a dampening aspect that needs to be examined further in terms of iterating price and quantity interactions across markets. The price increases cause a decrease in demand, which in turn offsets the initial price increases and output decreases somewhat. The CGE methodology is able to address both of these concerns if it is applied to recovery, as well as the basic aspects of the demand surge problem discussed in the previous paragraph. This is because the CGE modeling approach is inherently geared to examining price changes in the presence of resource constraints.

Conclusion

In this paper, the economic impacts of the hypothetical USGS SAFRR tsunami scenario created by a magnitude 9.1 earthquake offshore of the Alaskan peninsula are simulated. The analysis is based on extensive prior modeling for the tsunami scenario: wave propagation, damaging coastal current velocities and inundation (SAFRR Tsunami Scenario Working Group 2013), physical damage assessments (Dykstra et al. 2013; Porter 2013; Porter et al. 2013b; Brosnan et al. 2014), and the evacuation of California residents in response to tsunami advisories (Miller and Long 2013). Quantification of the impacts from port damage and trade disruptions, damages to coastal marinas and property, and evacuation of the maximum tsunami-inundation zone indicate the vulnerabilities of regional and California economies to potential tsunami disasters. However, the results emphasize the potential effectiveness of economic resilience when preparing and planning for future tsunami events.

The estimate of total impact on California's GDP of physical damages and port trade disruption without resilience is about \$3.1 billion. By far the largest share of these losses, comprising more than 50% of the total, stems from import disruptions due to a 2-day port shutdown, loss of cargo, and port facility downtime. More than half of these losses occur in Southern California. Without resilience, there is a positive shift in economic activity to the Rest of California via production of import substitutes, but still not enough to offset the negative impact on the latter region. Losses from import and export disruption more than triple when the ripple effects of the California impacts and the import destinations and export origins outside of California are included, a result which highlights the considerable sensitivity of economic impacts to port damages, and points to the importance of investigating the SAFRR tsunami scenario's effects on California's other major ports in Oakland, Richmond, San Diego, and Hueneme.

The national impacts are small relative to the larger national economy. The impacts are even small relative to the California economy, which suggests the impacts tend to manifest themselves more at the local level than regionally.

However, economic resilience measures greatly reduce the total economic impact to the California economy. The port's ability to compensate for a 2-day shutdown by clearing the backlog of ships in the harbor and the awaiting export orders nullifies most of the cost of import and export disruption (except for the perishable goods). The month-long reduced capacity at numerous marine oil terminals might be compensated for by excess capacity at the terminal and inventories at the port, off-site and at major customers. Resilience would have a greater effect on reducing direct impacts on the import side (\$1 billion reduced to \$30 million) than the export side (\$200 million reduced to \$150 million). The most effective adjustment on the import side is for producers to run down inventories, a tactic which is not available in the case of exports. However, inventories have a limited term, such that a longer period of reduced capacity at marine terminals would eventually curtail Southern California's fuel supply. Furthermore, the various resilience measures' technical potential will not necessarily be fully exploited due to implementation obstacles related to regulatory barriers, management limitations, and uncertainties. Hence, the resilience reduction estimates presented in the paper are optimistic.

Some resilience adjustments have not been modeled because of data limitations. For example, the availability of underutilized slips and temporary moorings in marinas along the coast is unknown. After the 2011 Japanese Tsunami, Crescent City boats were redirected to Eureka and some boat owners in Crescent City moored on buoys and rowed out to their boats due to fierce competition for available slips (Brosnan et al. 2014). The full services of a slip (with power and water) may not be provided, but some of the marina-related activities could continue. Although recapture resilience measures are applied to the direct property damage, HAZUS' tsunami module was incomplete with respect to business relocation.

Moreover, given the static character of the CGE model, financial resilience (whole or partial funding of reconstruction by disaster funds and insurance) is not considered in this analysis. This gap leaves open the possibility that losses that are incurred in sectors and locations where nonfinancial resilience options are limited (e.g., marinas and small harbors) may be compensated by gains from reconstruction and related activities, similar to the findings of a dynamic CGE analysis of the ARkStorm scenario (Sue Wing et al. 2015). Such outcomes are consistent with anecdotal evidence gleaned through interviews (Brosnan et al. 2014). For example, the harbormaster of Crescent City reported city businesses profiting after the impacts of the 2004 and 2011 tsunamis. Also, delays in FEMA reimbursements have impeded Crescent City's recovery, and streamlining the process presents an opportunity to increase resilience.

From a methodological standpoint, the analysis of resilience following a disaster in this study is among the most extensive to date (Wein et al. 2013). An overarching conceptual framework has been developed to identify major resilience options, and these measures have been associated with corresponding classes of economic activity in order to quantify their potential effectiveness. The authors' use of CGE modeling for the subsequent macroeconomic consequence analysis represents the state of the art. Interregional interactions between Southern California and the remainder of the state are especially important, as disruption in economic activity in one region induces relocation of production activities and input substitution in neighboring ones. Such market-mediated general equilibrium effects are an important contributor to the cost-saving resilience of systems of production and demand at regional scales by relocation of economic activity, and ignoring them risks substantially overestimating total economic losses. Even so, the approach adopted in this study comes with several caveats, the major one being the assumption of re-equilibration of commodity and factor markets within a 6-month time frame. Although this might be viewed as somewhat unrealistic for large shocks to the economy, given the relatively small magnitude of losses, it was felt to be reasonable in the analysis for this study.

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Supplemental Data

Eqs. (S1)–(S4) and Tables S1–S3 are available online in the ASCE Library (http://www.ascelibrary.org).

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