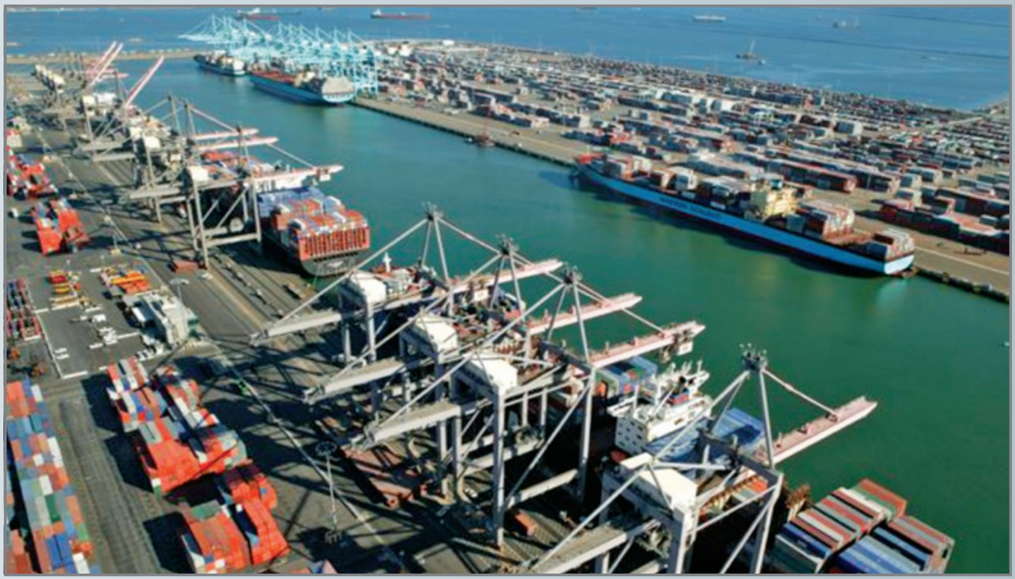
Economic Impacts of the SAFRR Tsunami Scenario in California



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COVER—The California coastal economy depends on activities served by ports, marinas, and, development, all of which are vulnerable to tsunamis. (top) satellite image of Marina del Rey, California, (image: USGS); (bottom) Port of Los Angeles, California (photo: Port of Los Angeles)

The SAFRR (Science Application for Risk Reduction) Tsunami Scenario

Stephanie Ross and Lucile Jones, Editors

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By Anne Wein, Adam Rose, Ian Sue Wing, and Dan Wei

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Economic Impacts of the SAFRR Tsunami Scenario in California

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

Introduction

This study evaluates the hypothetical economic impacts of the SAFRR (Science Application for Risk Reduction) tsunami scenario to the California economy. The SAFRR scenario simulates a tsunami generated by a hypothetical magnitude 9.1 earthquake that occurs offshore of the Alaska Peninsula (Kirby and others, 2013). Economic impacts are measured by the estimated reduction in California's gross domestic product (GDP), the standard economic measure of the total value of goods and services produced. Economic impacts are derived from the physical damages from the tsunami as described by Porter and others (2013). The principal physical damages that result in disruption of the California economy are (1) about $100 million in damages to the twin Ports of Los Angeles (POLA) and Long Beach (POLB), (2) about $700 million in damages to marinas, and (3) about $2.5 billion in damages to buildings and contents (properties) in the tsunami inundation zone on the California coast. The study of economic impacts does not include the impacts from damages to roads, bridges, railroads, and agricultural production or fires in fuel storage facilities because these damages will be minimal with respect to the California economy. The economic impacts of damage to other California ports are not included in this study because detailed evaluation of the physical damage to these ports was not available in time for this report.

The analysis of economic impacts is accomplished in several steps. First, estimates are made for the direct economic impacts that result in immediate business interruption losses in individual sectors of the economy due to physical damage to facilities or to disruption of the flow of production units (commodities necessary for production). Second, the total economic impacts (consisting of both direct and indirect effects) are measured by including the general equilibrium (essentially quantity and price multiplier effects) of lost production in other sectors by ripple effects upstream and downstream along the supply chain. An appropriate measure of the economic impacts on the California economy for the SAFRR tsunami scenario is the reduction in GDP.

The economic impacts are first calculated without resilience, the ability of the economy to adjust to disruptions in ways that mute potential negative impacts. There are many types of resilience, including using existing inventories of materials, using unused capacity, conserving inputs, substituting for disrupted supplies, recapturing production after the disruption is restored, and many others. A method for estimating resilience, identified in the port system and sectors affected by property damages, is applied to indicate potential reductions of direct and total economic impacts. In this SAFRR tsunami scenario analysis of economic impacts to California,

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we implement established techniques used to model the economic impacts for two previous U.S. Geological Survey (USGS) scenarios: the southern California Shakeout earthquake (Rose and others, 2011) and the California ARkStorm severe winter storm (Sue Wing and others, written commun., 2013).

For the SAFRR tsunami scenario, we reviewed the relevant studies that assess economic impacts from previous tsunami events affecting California and elsewhere and estimate the economic impacts of potential tsunami and other threats to POLA and POLB. To our knowledge, assessment of impacts to the California economy from distant source tsunamis does not exist. Previous tsunamis, including those from the 1960 Chile earthquake, the 1964 Alaska earthquake, the 2008 Chile earthquake and the 2011 Japan earthquake, had only relatively minor or very localized severe damage (such as that in Crescent City in 1964), and no studies of the economic impacts were completed. A rare study of the economic impacts of a tsunami event has recently been produced for the Tohoku earthquake and tsunami (Kajitani and others, 2013). Quarterly declines in Japan's GDP are observed to peak at −1.63 percent in the second quarter after the event and stagnate for the rest of the year. The majority of the economic impacts are attributed to the tsunami rather than the earthquake. The hardest hit sectors are identified as agriculture, fisheries, manufacturing, retail, and tourism.

Other relevant studies have focused on the economic impacts of threats that close POLA and POLB. We find one analysis of a potential tsunami scenario affecting the California economy through disruption of port operations. Borrero and others (2005) estimated economic impacts to the southern California economy of $7 to $40 billion from a locally generated tsunami that closes POLA and POLB for as much as 1 year. There have also been several studies of the economic impacts of non-tsunami events affecting POLA and POLB. Analyses of an 11-day labor lockout produced a range of estimated national impacts of as much as $1.94 billion/day (Park and others 2008, Martin Associates 2001). Examination of a potential terrorist attack that closes the San Pedro port for 1 month yielded a $29 billion impact to the California economy (Park, 2008).

These studies have reinforced the importance of recognizing economic resilience in economic impact analyses. Hall (2004) criticized the upper-end estimate of national economic impacts from the labor lockout based on model shortcomings that neglected short-run substitution behavior and fixed the long-run economic behaviors. Following the 2011 Japanese tsunami, resilience was observed in the forms of rapid recovery of manufacturing sectors, energy conservation, and insurance (Kajitani and others, 2013).

Overview of Economic Impacts

The total economic impacts (both direct and indirect) of the tsunami will be transmitted through the damages and disruption of POLA and POLB, including damage to cargo on ships and at the ports. Other economic impacts will result from tsunami damage to buildings and contents as well as marinas along the California coast. These other economic impacts can be estimated in a rather straightforward manner as explained in the following section. The port disruptions are more complex and are explained in detail here. Figure 1 displays the major linkages in tracing a port disruption beginning with direct economic impacts through short-run and long-run impacts at five analytical time stages of a disaster scenario (see also Rose and Wei, 2013).

The scenario 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.
- Disruption of exports.
- Disruption of port onsite activities and operations.

Various resilience tactics would be implemented to mute impacts at the outset. Such responses would include rerouting the traffic to other ports, diversion of exports to be used as import substitutes, use of inventories by port customers, relocating activities within the ports, and rescheduling of activities once the port reopens by working overtime or extra shifts.

The next stage occurs at the macroeconomic level. Impacts stem from three aspects here as well:

- Intermediate goods shortfalls.
- Final goods shortfalls.
- Reduction in final demand associated with reduction in exports.

Both supply-side and demand-side considerations are taken into account in the total economic impact evaluation. The supply-side relates to impacts on customers of the imported goods down the supply chain, and the demand-side captures the impacts on suppliers to these customers up the supply chain. Both supply and demand considerations are needed on the import side to address disruptions of intermediate and final goods. Businesses using the imports as intermediate inputs in their production processes and their successive rounds of downstream customers are subject to supply shortfalls. In addition, the reduction in production of import-using businesses also reduces the demand for the goods produced by successive rounds of upstream suppliers within a region or nation. Because the "final" (finished) goods shortfalls to end-users (consumers, government, and purchasers of capital equipment) do not generate any forward or backward linkage effects, they are simply added to the total macroeconomic effects directly.

The shutdown of port operations preventing the shipments of exports are only estimated in terms of impacts on suppliers up the supply chain, because the downstream customers are out of the region and thus do not affect the region's GDP. Production of exports requires another perspective on the problem. Here, the disruption of port activity through the cessation of exports will reduce the demand for inputs in their production. First-round suppliers will in turn reduce their demand, thereby starting a chain reaction of production activity decreasing upstream, analogous to the case on the import side. The sum total of all of these impacts is a multiple of the original shock; hence, the term "multiplier effect" characterizes these reactions to yield the macroeconomic impacts. Disruption to port on-site operations and related activities, including marina rentals and commercial fishing, generate their own demand-side effects. There are a number of resilience tactics applicable here, and at other junctures shown in figure 1, which will be discussed in detail below.

The total-impact stage represents a summing up of all the various types of supply-side and demand-side impacts. In a linear model, all of these various boxes in figure 1 are additive, and can be calculated and presented separately to identify the relative influence of the various and offsetting factors. In more complex models, such as the one used in this study, there are some important interactions, such as substitution effects, between these various components, that cannot be readily decomposed.

There is also the potential of long-run effects. These could arise from permanent loss of business for the port due to advantages of newly established logistical patterns or from stigma that stems from the fear of vulnerability to a repeated disaster. In addition, economic impacts can stem from:

- Economic costs of environmental damage.
- Costs of shipping delays to the intended port.
- Costs of resilience (including of rerouting shipping to other ports, substitution of less efficient inputs into production activities down the supply chain, and other factors).

The costs of the first two options are likely to be relatively small except in the case of environmental damage such as a major oil spill, for example, which extends the duration of the port closure (see Rose and Wei, 2013). If the cost of delays of shipments to the intended ports (that is, until they or terminals are reopened) becomes extremely high, then rerouting will be pursued more aggressively. Although the costs of some resilience tactics can be significant, the benefits, in terms of avoided business interruption, are likely to more than offset the cost.

Figure 1 focuses on general port and port-related activities. It does not explicitly depict the roles of some areas of the regional economy impacted by the tsunami, such as cargo, marinas and commercial fishing. However, both of these can be readily related to the figure. Cargo enters through the disruption of imports and disruption of export boxes. The operation of marinas and commercial fishing are analogous to the disruption of port activities in terms of their placement at the microeconomic level. Of course, resilience tactics will differ between these objects of disruption, as well as differing from port-level resilience.

Direct Economic Impacts

This section summarizes the estimation and results for the direct economic impacts associated with the SAFRR tsunami scenario, including impacts associated with POLA and POLB, coastal marinas, and buildings and contents within the tsunami inundation zone in California. The direct economic impact calculations omit damage to other ports, agricultural production, transportation infrastructure, lifeline infrastructure, and nonbuilding assets such as vehicles. These omissions were deemed minor except for the case of the other ports, where the scale of damages is largely unavailable at this time. On the other hand, the direct economic impacts are inflated in the absence of resilience. Therefore, the analyzed direct economic impacts represent a lower bound on impacts without resilience to California. The analysis of the direct impacts with resilience is conducted in the resilience section to demonstrate the effectiveness of resilience and potential for further enhancement.

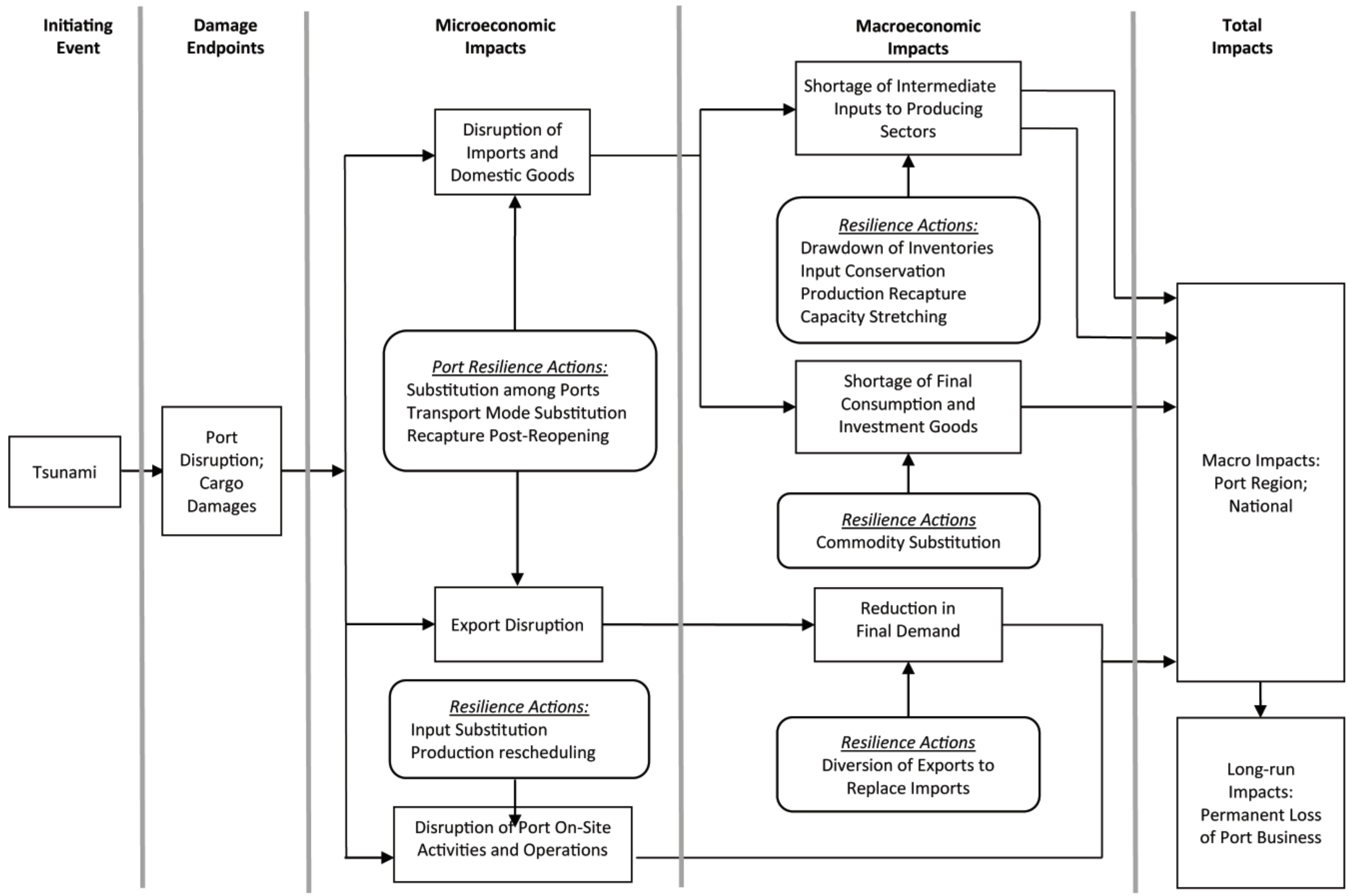

Figure 1. Estimating total economic impacts of a port disruption, cargo damages, and terminal downtime.

Estimation of Direct Economic Impacts

The analysis of direct economic impacts uses a combination of data provided by the Tsunami Research Team members (Porter and others, 2013), outside contacts, and publically available data. Analysis of the physical damages at POLA and POLB (Dykstra and others, 2013) was used extensively except for damages to the Crescent Warehouse and Berth S101 in POLB that were determined to be recently vacated or not in use, respectively. Much of the data were refined by the authors for inclusion in the report (see appendix A for details). Part of the refinement was to make the results compatible with a 65-sector computable general equilibrium (CGE) model that is used to determine the total economic impacts of the SAFRR tsunami scenario, as described below

Appendix B provides details of our calculations of port direct economic impacts. This appendix is in the form of an Excel spreadsheet ("Tsunami_Port_Direct Impacts without and with Resilience" and is available online at *http://pubs.usgs.gov/of/2013/1170/H/*). The "base case" sheet contains four tables of direct impacts of the SAFRR tsunami scenario to the twin ports without any resilience adjustments. The tables are:

- Import disruption.
- Export disruption.
- Direct revenue losses due to marina slip damages.
- Direct revenue losses to commercial fishing.

For both import disruption and export disruption, the impacts are calculated for the following three categories in both dollar values and percentage impacts:

- Impacts of a 2-day port shutdown.
- Impacts of cargo losses.
- Impacts of facility downtime

In addition, the direct import/export disruption impacts are presented for both the southern California five-county region (including Ventura, Los Angeles, Orange, San Bernardino, and Riverside) and for the rest of California. The direct impacts of slip damages at the marinas and loss to the commercial fishing industries in POLA are presented as direct revenue losses to the relevant sectors. They only pertain to the southern California region. Besides the direct impacts resulting from disruptions to the port-related activities, direct impacts also stem from capital damages to buildings and contents in California's coastal counties due to flooding (Porter, 2013). In addition to slip damages in the marinas within the port complex, damages to marinas occur along the coast of California (Porter and others, 2013).

Results (Without Resilience)

In this section we present the direct economic impacts of the tsunami scenario without resilience. Note that the results are presented in terms of the most accessible measure of loss available—values of imports and exports that would be affected by downtime and cargo damages, buildings and contents that would be damaged, and gross output (business revenue) losses for sectors related to marina activities and fishing industry. Consequently, the direct impacts cannot be summed. Please note that these measures differ from GDP, which is the more appropriate measure for total economic impacts economy-wide.

1. Import Disruptions

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. For southern California they are presented in the left-hand partition of table B1 under the three categories of disruption:

2-Day Port Shutdown

Dykstra and others (2013) concluded that the twin ports would be shut down for two days. The resulting direct impacts in southern California are a disruption of $417.3 million (in 2010 dollars) of import goods from more than half of the 65 sectors. The major types of disrupted import commodities are machinery manufacturing, other transportation equipment manufacturing, and apparel-manufacturing products related to container activities. In relative terms, the major disruptions, however, are for plastics and fishing products, each representing slightly more than 0.5 percent of annual imports of these commodities.

Cargo Losses

Cargo losses are related to inundation of terminals, as well as the nature of the cargo (for example, perishable goods). Losses of cargo destined for southern California total $60.8 million. The major imported cargo losses are automobiles, which consist of nearly 83 percent of the total value of cargo damages. These losses also represent 0.64 percent of the annual imports of this commodity in the year 2010.

Facility Downtime

Several port facilities (cargo handling terminals) would be damaged in the tsunami scenario. For example, several marine oil terminals of POLA would only be able to operate at 50 percent 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 include steel, petroleum refineries goods, and chemical products (such as caustic soda), which correspond to iron and steel manufacturing, petroleum refining, and chemical manufacturing sectors, respectively, in our 65-sectoring scheme. The latter represents only a trivial amount, whereas the former two represent approximately 65 percent and 35 percent of the total impacts to imports, respectively, in this category.

The total import disruption to the southern California region is more than $675 million, or 0.214 percent of total annual imports to the region. Direct economic impacts from imports destined for the rest of California are presented in the right-hand partition of table B1 for the same categories of import disruptions as for southern California. All three categories of losses are lower for the rest of the state because on average a higher proportion of the affected imports are delivered to users in the southern California region than to the rest of California. The lower value 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. This result follows from the damages to automobiles that make up the majority of cargo losses. According to the data we obtained from the port expert, more than 90 percent of the imported automobiles are delivered to the southern California region.

The total import disruption to the rest of California region is about $325 million, or 0.061 percent of total annual imports to the region. As explained above, the difference in import disruptions (in dollar values) for different commodities/sectors between the two geographic regions are determined by the proportion of these imports that have destinations within the southern California region or in the rest of California. The percentage impact is also affected by the proportion of each type of import commodities that are imported into the region through the twin ports (versus through other modes of import).

2. Export Disruptions

Direct export disruptions are measured as the values of exports destined for southern California and the rest of California that are affected by the 2-day port shutdown, cargo losses, and terminal downtime. They are presented in table B2. For southern California (left-hand quadrant of table B2), the 2-day shutdown results in a total export disruption of $91.7 million. Major types of affected exports are chemical manufacturing, machinery manufacturing, and food manufacturing products, each exceeding $10 million. Cargo losses on the export side amount to only $2.8 million, with the largest damage to exports of the same three sectors. Facility down time, as related to exports, is $37.2 million, confined primarily to petroleum refining and chemical manufacturing (industrial borate) exports. The total export disruption to the southern California region is about $132 million, or 0.034 percent of total annual exports from the region.

Total export disruptions for the rest of California are presented in the right-hand partition of table B2. The total direct impacts of the 2-day shutdown are $58.0 million. Total facility downtime is $18.9 million. Cargo losses are only $1.8 million. The total impacts are about $78.2 million, or 0.017 percent of the total annual exports from the region. Overall, the export disruptions are significantly smaller than their import counterparts presented in table B1.

3. Direct Gross Output Losses Associated with Marina- Slip Damages at POLA

Direct losses from damages to POLA marinas are measured as gross output (revenue) losses to the marina activity related sectors defined by Martin Associates (2007). The sectors include retail trade, scenic and sightseeing transportation, other amusement and recreation industries, and food services and drinking places related to marina operations. The results are calculated in table B3 according to the following steps:

1. Total revenues of POLA marina-related activities in 2006 were $48.2 million (Martin Associates, 2007). The marina-slip utilization roughly remains the same between 2006 and 2010. Converting $48.2 million to 2010 dollars, we obtain a total revenue of $51.8 million in 2010 dollars.
2. Of the $51.8 million, about $3.6 million is the rental revenue to the ports. For the remaining $48.2 million, we assume that the revenues are distributed evenly among the four marina-related sectors of retail trade, scenic and sightseeing transportation, other amusement and recreation industries, and food services and drinking places.
3. To compute the revenue losses to the affected sectors, we next divide the above revenues by 3 because 1/3 of the POLA marina slips are damaged.
4. In addition, Porter and others (2013) determined that it would take 1 month to repair the damaged slips at a linear rate. Therefore, we further divide the revenues by 12 to account for the loss in 1 month and then divide the result by 2, based on the linear repair rate to obtain the revenue losses for each sector related to marina-slip damages.

The total estimated gross output loss to the marina-related sectors is $0.72 million.

4. Gross Output Losses to POLA Commercial Fishing

Table B4 presents the results for direct revenue losses to POLA commercial fishing. Outcomes of the tsunami scenario would include perished fish on board the vessels at sea and lost fishing days—we assumed 25 percent of a day's fish haul would perish and 4 fishing days would be lost. In addition, 5 percent of the fishing fleet is assumed damaged due to vessels left in the harbor. We note that there is a lack of fragility curves for vessels tied to fixed piers, AlThese estimates should be treated as illustrative. \.) On the basis of conversations with fishermen, we assumed that it would take about 2 months on average to repair or replace the damaged boats. The direct revenue losses to the fishing industry of the above individual components are:

- 25 percent of one day's fish loss: $25,890.
- 5 percent of fishing fleet damage (2-month repair time): $315,000.
- 4 fishing days lost: $393,534.
- Total fishing industry revenue loss: $734,425.

5. Capital Losses of Building and Content Damages

The direct impacts of building and content damages (loss of capital stock) are represented by repair and replacement costs. The first row under section B in table 1 summarizes the building and content damages in coastal counties. In the southern California region, the building and content related property losses are $52 million and $367 million, respectively, representing about 0.004 percent and 0.047 percent of the total capital stock in this region. The building and content related property losses in the rest of California are $246.4 million and $1.16 billion, respectively. They represent 0.016 percent and 0.124 percent of the total capital stock in the rest of California.

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

The damages to docks at marinas are translated into gross output (revenue) losses to three sectors related to marina activities (restaurants, retail stores, and marina-related activities) in two steps: (1) we use the estimate of $13,649 total annual revenues per slip and the assumption that one dock has an average of 50 slips to translate the number of docks that have lost functionality into total revenue losses; (2) we distribute the revenue losses evenly among restaurants, retail trade, and marina-related activities sectors. The total direct revenue losses to the three marina activity related sectors in the southern California region are $71.4 million. The total direct revenue losses are $50.8 million in the rest of California.

Summary of Direct Economic Impacts (Without Resilience)

We provide a summary of the direct economic impacts of the SAFRR tsunami scenario in southern California and the rest of the State without resilience in table 1. In terms of percentage impacts, the impacts are dominated by the disruption to imports, especially from the 2-day shutdown of the twin ports and damages to building content. How the production of each sector would be affected by the import disruption is largely influenced by the dependence on these imports as production inputs, taking into account the sectors' ability to substitute disrupted import goods with other inputs. The total economic impacts stemming from the various direct impacts include the ripple effects transmitted through upstream and downstream supply-chain linkages, as well as the spending of wages/salaries and capital-related income and the ripple effects these induce.

Table 1. Summary of the direct impacts of the SAFRR tsunami scenario (without resilience)(in millions of 2010 dollars and percentage changes[1]).

[%, percent; n.a., not applicable; $, dollars]

Impacted category	Unit of measurement	Southern California region	Rest of California	Total California
A. 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	Gross output	$0.7 (0.00%)	n.a.	$0.7 (0.00%)
B. Direct impacts along other parts of the California coast				
Building damages	Capital stock	$73.8.0 (0.004%)	$349.9.4 (0.016%)	$423.7 (0.011%)
Content damages	Capital stock	$521.7. (0.047%)	$1,646.5 (0.124%)	$2,168.2 (0.089%)
Marina damages	Gross output	$71.4 (0.005%)	$50.8 (0.003%)	$122.2 (0.004%)

[1]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.

Total Economic Impacts

This section summarizes the estimation and results for the total economic impacts (or business interruption) from the SAFRR tsunami scenario. The total economic impacts (consisting of both direct and indirect effects) are the general equilibrium (essentially quantity and price multiplier effects) of lost production in other sectors by ripple effects upstream and downstream along the supply chain. Similar to the direct impacts, total economic impacts are associated with damages and disruption at POLA and POLB, coastal marinas, and buildings and contents within the tsunami inundation zone in California. Likewise, the total economic impacts do not include resilience.

Estimation of Total Economic Impacts—Computable General Equilibrium Modeling

A computable general equilibrium (CGE) model is a stylized computational representation of the circular flow of the economy (see, for example, Sue Wing, 2009, 2011). It solves for the set of commodity and factor (intermediate inputs as well as labor and capital) prices and the set of activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy. The model developed for this study divides California's economy into two regions (the five-county southern California region—Los Angeles, Orange, Riverside, San Bernardino, Ventura—and the remainder of the State), each of which consists of 65 industry sectors and households in nine different income categories.

The industry aggregation is matched with occupancy classes in HAZUS, FEMA's expert loss estimation system, which was employed by another research team member to calculate the building and content losses caused by the tsunami's physical impacts. Each sector is modeled as a representative firm characterized by a constant elasticity of substitution (CES) among combinations of inputs to produce a single good or service. The households in each income class are modeled as a single representative agent with CES preferences and a constant marginal propensity to save and invest out of income. Government is represented in a simplified fashion, its role in the circular flow of the economy being passive—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: (1) labor, whose endowment is fixed but whose allocation among sectors responds to changes in the wage rate, and (2) capital, which is treated as sector-specific and immobile among industries or regions during the short-run period relevant to the tsunami simulations. These factors are owned by the representative agents, who "rent" them out to the firms in the agents' county of residence in exchange for factor income. Each region is modeled as an open economy that engages in trade with the rest of California, the rest of the United States, and the rest of the world according to an assumption in which imports from other counties, States, and the rest of the world are imperfect substitutes for goods produced locally (known as the Armington specification).

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 impacts of a tsunami are modeled as exogenous negative shocks to the productivity of import and export activities, damage to capital stocks in sectors sustaining direct physical damage (with concomitant reductions in endowments of sector-specific capital input), and negative shocks to the productivity of marine-related industries (fishing and marinas). The model is formulated as a mixed complementary programming problem using the Mathematical Programming System for General Equilibrium analysis (MPSGE) subsystem for the General Algebraic Modeling System (GAMS) software (Rutherford, 1999; Brooke and others, 1998) and is solved using the PATH solver (Ferris and others, 2000). A more detailed and technical description of the model is presented in appendix C. The model is calibrated using an IMPLAN (IMpact analysis for PLANning) social accounting matrix for the State of California for the year 2010 (Minnesota IMPLAN Group, Inc., 2012). The key parameters of the model are summarized in appendix C, which also provides the sectoring scheme. The model has been successfully applied to other disaster scenarios. This includes a study of the economic impacts of a San Francisco Bay area earthquake closing off the California Aqueduct water supplies to Los Angeles County (Rose and others, 2012) and the USGS California ARkStorm severe winter storm scenario (Sue Wing and others, 2013).

Total Economic Impact Results (Without Resilience)

The two-region CGE model was applied to the tsunami's direct economic impacts presented in table 1 to estimate the total economic impacts of the event. The direct impacts are entered as a combination of import/export disruptions, capital stock damages, and direct gross output (revenue) losses, depending on the component of the economy affected (see Section III for a discussion of the methodology). The results are presented in table 2 for the five-county southern California region, the rest of California, and for California as a whole. The results are also presented for each conduit of the shock. Overall, the impacts on GDP (in 2010 dollars) are: \$3.2 billion for the five-county southern California region, \$2.8 billion for the rest of California, and \$6.0 billion for California as a whole. These impacts represent only 0.383, 0.244, and 0.303 percent of annual GDP of the three regions, respectively.

Table 2. Summary of business interruption from the SAFRR tsunami scenario, without resilience and reconstruction (in millions of 2010 dollars of Gross Domestic Product losses).

[%, percent; $, dollars; POLA, Port of Los Angeles]

Impacted category	Southern California region	Rest of California	Total California
San Pedro import total	$1,847 (0.222%)	$1,327 (0.116%)	$3,173 (0.161%)
2-day port shutdown	$956 (0.115%)	$780 (0.068%)	$1,736 (0.088%)
Cargo loss	$57 (0.007%)	$21 (0.002%)	$78 (0.004%)
Facility downtime	$828 (0.099%)	$522 (0.046%)	$1,350 (0.068%)
San Pedro export total	$479 (0.058%)	$621 (0.055%)	$1,100 (0.056%)
2-day port shutdown	$357 (0.043%)	$439 (0.039%)	$795 (0.040%)
Cargo loss	$11 (0.001%)	$14 (0.001%)	$25 (0.001%)
Facility downtime	$112 (0.013%)	$169 (0.015%)	$281 (0.014%)
California coast property damage total	$846 (0.102%)	$819 (0.072%)	$1,665 (0.084%)
Buildings	$54 (0.006%)	$51 (0.005%)	$105 (0.005%)
Contents	$792 (0.095%)	$767 (0.067%)	$1,559 (0.079%)
Other Impacts Total	$19 (0.002%)	$14 (0.001%)	$33 (0.002%)
California coast marinas	$17 (0.002%)	$14 (0.001%)	$30 (0.002%)
POLA fishing	$2 (0%[1])	$0[2] (0%[1])	$2 (0%[1])
Grand total[3]	$3,189 (0.383%)	$2,782 (0.244%)	$5,971 (0.303%)

[1]Less than 0.0005%.

[2]Less than $500,000.

[3]Totals may not add due to rounding.

Import disruption impacts are the largest component of the negative economic shocks in all three regions, totaling $3.2 billion. The total economic impacts of import disruptions represent nearly 50 percent or more of the predicted declines in total GDP 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. One interesting feature of import losses, in contrast to export losses to be discussed next, is that the former are higher for the southern California region than for the rest of the State. The reasons for this result are 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 $1.1 billion in GDP losses for California, with port shutdowns by far being responsible for the largest component. Again, cargo losses are by far the smallest component. Export shutdowns do not stimulate any offsetting effects, like the case of imports, because it wouldn't 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 $1.7 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 $33 million, or only 0.002 percent of State annual GDP. By far, the largest share stems from damage to marinas.

Reductions in the value of GDP are shown in table 3 for the five most affected sectors, when losses are expressed as a percentage of annual GDP. Disruption of imports and exports incur the largest output losses 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 five-county 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 to 2 percent of annual output or $302 million in the five-county region and $110 million in the rest of the State. The overall change in gross output due to trade disruption is slight (0.2 percent for the five-county and 0.1 percent for the rest of California), accounting for losses of $2.7 billion in the five-county region and $1.6 billion 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 five-county region the output of service sectors is most affected (healthcare, real estate, retail trade, education, and transportation), whereas in the rest of California adverse impacts are more concentrated in accommodation services, oil seed and grain farming, pipeline transportation and gas distribution, and health care 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. The overall change in GDP due to direct destruction of buildings and contents is slight (0.01 to 0.2 percent), accounting for losses of $710 million in the five-county region and almost $2 billion in the rest of California.

Finally, looking at the combined impact of all conduits of shock, the sectors that are most affected on a percentage basis are dominated by the ones that face the largest exposure to losses from trade, with the notable exception of fishing—which is both small and hardest hit in the five-county region. Although fishing damages were not evaluated in the rest of California, the impact is traceable to demand reductions and price responses in the food-manufacturing and service industries. On the whole, losses for both regions are similarly small, 0.2 percent of output, totaling around $3.5 billion.

The results are miniscule compared to the devastation of the Japanese coast in the 2011 tsunami and 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, even before we make any resilience adjustments, are very much lower than those for the two previous USGS disaster simulations, where GDP losses (in 2010 dollars) were about $70 billon for the ShakeOut (Rose and others, 2011) and a couple of hundred billion dollars for ARkStorm (Sue Wing, 2013).

Note that the results are presented in terms of business interruption relative to projected GDP. Because this assumes the economy of the southern California region and the rest of the State will continue to grow, the impacts are relatively larger than if they were compared to pre-event (static or constant levels of production). However, this distinction is not likely to be great because we are only considering one 6-month forecast period.

Table 3. Sectoral Gross Domestic Product losses from the SAFRR tsunami scenario.

[mfg, manufacturing; $, dollars; POLA, Port of Los Angeles]

Five-county region			Rest of California		
	Mill $	%		Mill $	%
From San Pedro import and export disruption					
Other primary metal mfg	-4.5	-3.6	Leather and allied product mfg	-2.2	-3.4
Fabricated metal product mfg	-29.7	-3.3	Other primary metal mfg	-14.2	-2.8
Leather and allied product mfg	-243.8	-3.2	Automobile and light duty motor vehicle mfg	-26.9	-2.5
Automobile and light duty motor vehicle mfg	-93.2	-2.9	Fabricated metal product mfg	-74.9	-1.9
Iron and steel mills and steel product mfg	-0.8	-2.9	Machinery mfg	-7.7	-1.2
Other sectors	-2,270.2	-0.3	Other sectors	-1,506	-0.2
Total	**-2,642.1**	**-0.3**	**Total**	**-1,632**	**-0.2**
From California building and content damage					
Health care and social assistance	-109.7	-0.2	Accommodation	-12.5	-0.3
Educational services	-211.1	-0.2	Oilseed and Grain Farming	-17.2	-0.2
Retail trade	-58.1	-0.2	Pipeline transportation	-1.5	-0.2
Transit and ground passenger transport	-16.3	-0.2	Natural gas distribution	-0.9	-0.2
Real estate and rental and leasing	-25.5	-0.1	Health Care and Social Assistance	-12.5	-0.2
Other sectors	-132.7	-0.02	Other sectors	-1,066	-0.1
Total	**-553.4**	**-0.07**	**Total**	**-1,111**	**-0.1**
Total including California marina and POLA fishing damages					
Fishing	-1.4	-4.2	Leather and allied product mfg	-2.3	-3.6
Other primary metal mfg	-4.5	-3.6	Other primary metal mfg	-14.1	-2.8
Fabricated metal product mfg	-29.0	-3.3	Automobile and light duty motor vehicle mfg	-27.7	-2.6
Leather and Allied Product Mfg	-241.9	-3.2	Fabricated metal product mfg	-77.7	-2.0
Automobile and light duty motor vehicle mfg	-92.4	-3.0	Machinery mfg	-1.2	-1.3
Other sectors	-2,846.7	-0.3	Other sectors	-2,633	-0.3
Total	**-3,215.9**	**-0.4**	**Total**	**-2,756**	**-0.3**

A couple of critical economic-impact modeling closure assumptions include the savings-investment balance and labor supply elasticities. The static model that we have implemented cannot address the savings-investment relation, but, given the small impacts relative to the California economy, we would not expect a negligible effect on the savings-investment balance. However, a sensitivity analysis of the labor market elasticities reveals a significant effect on estimated economic impacts.

In the original fairly inelastic formulation (0.05), the economy-wide average wage fell by 0.4 percent, and the supply of labor remained essentially constant. In the second ,more elastic formulation (0.5), the wage fell by 0.3 percent and the supply of labor contracted by 0.1 percent. In this analysis, the wage rate varies to clear the market (equilibrate supply and demand). In the Keynesian formulation, with the wage fixed at the baseline level and labor in perfectly elastic supply so as to be able to equilibrate the labor market, labor decreases by 0.3 percent. The consequent reduction in the economy's endowment of productive factors results in an amplification of output and GDP losses. The magnitude of losses rises as the elasticity of labor supply increases. Increasing the labor supply elasticity by an order of magnitude in the original formulation exacerbates losses by 22 to 26 percent, whereas in a full Keynesian closure the losses jump by 61 to 72 percent.

Note that the original formulation is more consistent with empirical evidence on labor elasticities (McClelland and Mok, 2013). However, none of the studies reviewed takes into account the effect of a disaster. Even so, we surmise that the Keynesian estimates are implausible. For a comparatively small disaster such as this, we expect that 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.

Resilience

In this section we analyze the effect of resilience on the economic losses from the SAFRR tsunami, especially the port related disruptions or damages. Resilience refers to various tactics that can mute losses by using existing resources more efficiently (static resilience) and recovering more quickly (dynamic resilience) (Rose, 2009). We analyze only the former category in this report. Detailed notes on the data, assumptions, and methodology used in the resilience analysis are presented in table 4. Results of the application of the resilience tactics on the direct impact estimates are presented in table 5. (See the resilience tactic worksheets in appendix B workbook "Tsunami_Port_Direct Impacts without and with Resilience," available online at *http://pubs.usgs.gov/of/2013/1170/H/*, for details on the port direct economic impacts by sector and by region.) Production and sales recapture (for example, catching up on lost production time) is applied to total economic impacts from port damages and disruption and property damages.

- *Conservation*—We assume a 2-percent level of conservation for businesses to cope with the import disruptions. This resilience tactic have the effect of reducing the direct import disruption impact from $675.2 million to $661.7 million, or from 0.214 to 0.210 percent for the southern California region; and from $312.1 million to $305.9 million, or from 0.061 to 0.059 percent, for the rest of California region.
- *Excess Capacity*—Documented in table 5, this resilience tactic is applicable to facility downtime at the port and for the marina damages at POLA. This resilience tactic has the effect of reducing the direct import-disruption impact from $675.2 million to $581.2 million, or from 0.214 to 0.184 percent for the southern California region; and from $312.1 million to $265.6 million, or from 0.061 to 0.052 percent, for the rest of California region. For marina damages, the availability of excess capacity at the Cabrillo Marina can help reduce the direct revenue losses to the marina-activity related sectors from $719,000 to $561,000, or from 0.00005 to 0.00004 percent on an annual basis.
- *Ship Rerouting*—Based on a consultation with Capt. Dick McKenna (Marine Exchange; oral commun., 2013) we have assumed that ships will not be rerouted for a 2-day port shutdown. As for longer facility downtimes taking place in a few terminals, there is only evidence of possible ship rerouting for the industrial borate export. If rerouting occurs within southern California, ship rerouting can help reduce the total direct export disruption from $131.8 million to $105.4 million, or from 0.034 to 0.027 percent, for the southern California region; and from $78.2 million to $65.0 million, or from 0.017 to 0.014 percent, for the rest of California region. However, if exports are diverted out of other States the impact remains the same for the State of California.

- *Export Diversion (Substitution for Imports)*—Export diversion refers to using goods that were intended for export as substitutions for the lack of availability of imports. Therefore, the application of this resilience tactic relies on export and import disruptions for the same types of commodities in order for exports to substitute for disrupted imports. We assume that during the 2-day port shutdown, import/export shipments will wait until the resumption of the port operation, and no export will be diverted for domestic use. For extended port-facility downtime, there is only limited potential for export diversion of petroleum products, because there are disruptions to these products on both the import and export sides. All the disrupted industrial borate is exported, and all the disrupted steel is imported. Therefore, export diversion is not applicable to either of them. According to table 5, on import side, this resilience tactic has the effect of reducing the direct impact from $675.2 million to $664.3 million, or from 0.214 to 0.211, percent for the southern California region; and from $312.1 million to $306.5 million, or from 0.061 to 0.060 percent, for the rest of California region. On the export side, export diversion can help reduce the export disruption impact from $131.8 million to $120.9 million, or from 0.034 to 0.031 percent, for the southern California region; and from $78.2 million to $72.6 million, or from 0.017 to 0.016 percent, for the rest of California region.
- *Inventory Use*—Use of the available inventories by the producing sector has the greatest potential to reduce the impact from import disruption. As shown in table 4, this resilience tactic has the effect of reducing the direct import disruption impact from $675.2 million to $30 million, or from 0.214 to 0.010 percent for the southern California region; and from $312.1 million to only $1,833, or from 0.061 to 0.000 percent for the rest of California region. More details of inventory utilization are presented in appendix D.
- *Production or Sale Recapture from Port Disruption*—This resilience strategy 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. Recapture applies to total economic impacts. On the export side, a similar concept is sale recapture. At the ports, production or sale recapture applies to the import and export disruptions from the 2-day port shutdown because no ships would be rerouted. Imports and exports would likely be delayed for 1 to 2 days on average for a week or so. We assume that the import and export disruptions would be recaptured with the exception of perishable (agricultural) products. Recapture can also be applied to import and export disruptions from the 2-week to one-month facility downtime. This is because for a short duration of time (less than 3 months) most customers do not cancel their orders. Production recapture would not apply to lost marina slip fees, but catching up on lost days of fishing could reduce total impacts by about 75 percent. Appendix E presents the recapture factors for the other sectors served by the ports. Manufacturing sectors have the highest potential (at about 98 percent) to recapture their interrupted productions. The recapture factor for agriculture, forestry, and fishing industries is at the level of about 75 percent. The recapture factors for the service sectors range between 51 and 80 percent. The potential for recapture would be smaller for longer periods as customers begin looking elsewhere for their source of supply. Recapture can greatly reduce the total impact from import and export disruptions. For the 2-day port shutdown, recapture can reduce the total economic impact to the State from $1,736 million to $314 million for import disruption and from $795 million to $112 million for export disruption, or reductions of potential losses by 82 and 86 percent, respectively. For the facility down time, recapture can help mute the potential total economic losses to the State

from $1,350 million to $196 million for import disruption and from $281 million to $34 million for export disruption.

- *All Resilience Combined for Port Damage and Disruption*—After calculating the effects of the resilience measures separately, we simulate all the above resilience adjustments together. Note, however, that the individual resilience tactics cannot be summed. We apply excess capacity and ship rerouting first, followed by export diversion. The 2-percent conservation is applied after the above three resilience adjustments. Inventories are used to deal with any remaining import disruptions. Applying all these resilience tactics can help reduce the direct import disruption impact from $675.2 million to $28.9 million, or from 0.214 to 0.009 percent, for the southern California region; and from $312.1 million to $1,797 or from 0.061 to 0.000 percent, for the rest of California region. On the export side, the combined resilience has the effect of reducing the export disruption impact from $131.8 million to $93.89 million, or from 0.034 to 0.024 percent, for the southern California region; and from $78.2 million to $59.0 million, or from 0.017 to 0.013 percent, for the rest of California region. Please note production or sale recapture can be applied after all the above resilience tactics. As indicated above, production and sale recaptures have the potential to reduce the total economic impacts by about 80 to 85 percent. 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 to the California economy by 80 percent. See table 6.

Table 4. Methodology for direct resilience for disruptions to port related activities from the SAFRR tsunami scenario.

[Data, green; major assumptions, red; methods, blue. Note that we assume input and import substitution resilience tactics are already incorporated into the computable general equilibrium (CGE) model as inherent resilience; no further adjustment is made to capture adaptive versions of these two tactics. %, percent; n.a., not applicable]

Direct impact type	Conservation	Excess capacity	Ship rerouting	Export diversion for domestic use	Inventories	Production recapture
2-day port shutdown	Assume 2%. Applicable only to the import side. Reduce percent import disruption by 2%.	n.a. Because the entire port is shut down, excess capacity will not be applicable during this time.	n.a. Assume ships will not be rerouted within 2 days.	For a 2-day shutdown, we assume import/export shipments will wait until the port operation resumes, and no export will be diverted for import use.	For marine oil: there is a 50% inventory buffer for a month taking into account the inventories both at the parts and at customers. For other commodities: use Bureau of Economic Analysis manufacturing inventory data. Applicable only to the import side. See appendix D for a summary of method.	Ports recapture nonperishable cargo handling because no ships are rerouted in 2 days. HAZUS recapture factors. Applicable to both import user and exporter sides, and port on-site activities. Recapture factors are not applied directly on the input side of the economic modeling; rather they are applied directly to the economic impact results (no resilience "base case").

Table 4. Methodology for direct resilience for disruptions to port related activities from the SAFRR tsunami scenario.—Continued

[Data, green; major assumptions, red; methods, blue. Note that we assume input and import substitution resilience tactics are already incorporated into the computable general equilibrium (CGE) model as inherent resilience; no further adjustment is made to capture adaptive versions of these two tactics. %, percent; n.a., not applicable]

Direct impact type	Conservation	Excess capacity	Ship rerouting	Export diversion for domestic use	Inventories	Production recapture
Cargo damages	Same as in row 1	n.a.	n.a.	n.a.	Same as in row 1	HAZUS recapture factors Applicable to both import user and exporter sides, and port on-site activities. Recapture factors are not applied directly on the input side of the economic modeling; rather they are applied directly to the economic impact results (no resilience "base case").

Table 4. Methodology for direct resilience for disruptions to port related activities from the SAFRR tsunami scenario.—Continued

[Data, green; major assumptions, red; methods. Note that we assume input and import substitution resilience tactics are already incorporated into the computable general equilibrium (CGE) model as inherent resilience; no further adjustment is made to capture adaptive versions of these two tactics. blue; %, percent; n.a., not applicable]

Direct impact type	Conservation	Excess capacity	Ship rerouting	Export diversion for domestic use	Inventories	Production recapture
Facility downtime	Same as in row 1	Marine oil: Vopak and Valero terminals are short of 40% capacity to handle their throughput even after using excess capacity; other terminals have enough capacity to handle regular throughput after using excess capacity. Steel: various available alternatives at POLA/POLB can help reduce impacts of downtime at steel break bulk terminal by 50%. Industrial borate: no other industrial borate terminal in San Pedro. Use the excess capacity info to adjust import/export disruption; for example, if excess capacity of handling steel import at undamaged terminal is x% of the capacity of damaged steel terminal, reduce steel import disruption by x%.	Assume no ship diversions for imports; assume 100% export rerouting for Borate. Reduce import/export disruption level by percentage of ships that can be rerouted Rerouting cost needs to be reported separately.	Examine the disrupted export and import commodities at the 4-digit Harmonized System code level. Export diversion is applicable if same type of import and export commodities are disrupted.	Same as in row 1	Same as in row 2

Table 4. Methodology for direct resilience for disruptions to port related activities from the SAFRR tsunami scenario.—Continued

[Data, green; major assumptions, red; methods, blue. Note that we assume input and import substitution resilience tactics are already incorporated into the computable general equilibrium (CGE) model as inherent resilience; no further adjustment is made to capture adaptive versions of these two tactics. %, percent; n.a., not applicable]

Direct impact type	Conservation	Excess capacity	Ship rerouting	Export diversion for domestic use	Inventories	Production recapture
Marina slips damaged	n.a.	Cabrillo Marina Phase II: increase the total capacity by 11%, but all currently still vacant; therefore, can be used as excess capacity; when we consider Cabrillo as the excess capacity, we also take into consideration that 1/3 of this marina is damaged (at the average damage rate of marinas at the port). If the excess capacity/alternative locations represent x% of total capacity, we reduce revenue losses to marina related sectors by x%.	n.a.	n.a.	n.a.	Same as in row 1
Impacts to commercial fishing	n.a.	n.a.	n.a.	n.a.	n.a.	Same as in row 1

Table 5. Direct impact estimates for the SAFRR tsunami scenario before and after resilience.

[M 2010$, millions of; %, percent; n.a., not applicable]

Direct Impact Type	Base Case Without Resilience		Conservation		Excess Capacity		Ship Rerouting		Export Diversion		Inventories		Combined Resilience	
	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%
Southern California five-county region														
Import disruption	$675.2	0.214%	$661.7	0.210%	$581.2	0.184%	assume no rerouting for imports		$664.3	0.211%	$30.0	0.0095%	$28.9	0.0092%
Export disruption	$131.8	0.034%	n.a.		$127.4	0.033%	$105.4	0.027%	$120.9	0.031%	n.a.		$93.8	0.024%
Marina slips damaged	$0.7	0.000%	n.a.		$561.2	0.000%	n.a.		n.a.		n.a.		$0.6	0.000%
Impacts to commercial fishing	$0.7	0.000%	n.a.		n.a.		n.a.		n.a.		n.a.		$0.7	0.000%
Rest of California region														
Import disruption	$312.1	0.061%	$305.9	0.059%	$265.6	0.052%	assume no rerouting for imports		$306.5	0.060%	$0.002	0.0000%	$0.002	0.000%
Export disruption	$78.2	0.017%	n.a.		$76.0	0.017%	$65.0	0.014%	$72.6	0.016%	n.a.		$59.0	0.013%

Table 5. Direct impact estimates for the SAFRR tsunami scenario before and after resilience. —Continued

[M 2010$, millions of 2010 dollars; %, percent; n.a., not applicable]

Direct Impact Type	Base Case Without Resilience		Conservation		Excess Capacity		Ship Rerouting		Export Diversion		Inventories		Combined Resilience	
	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%	Value (M 2010$)	%
Total California														
Import disruption	$987.3	0.119%	$967.5	0.117%	$846.8	0.102%	assume no rerouting for imports		$970.8	0.117%	$30.0	0.004%	$28.9	0.003%
Export disruption	$210.0	0.025%	n.a.		$203.4	0.024%	$170.4	0.020%	$193.5	0.023%	n.a.		$152.8	0.018%
Marina slips damaged	$0.7	0.000%	n.a.		$0.6	0.000%	n.a.		n.a.		n.a.		$0.6	0.000%
Impacts to commercial fishing	$0.7	0.000%	n.a.		n.a.		n.a.		n.a.		n.a.		$0.7	0.000%

Table 6. Property damage resilience through recapture for the SAFRR tsunami scenario.
[$M, millions of 2010 dollars; %, percent]

Impacted category		Base case			After recapture		
		Southern California	Rest of California	California Total	Southern California	Rest of California	California Total
Buildings	Value ($M)	54	51	105	12	10	22
	%	0.006	0.005	0.005	0.001	0.001	0.001
Contents	Value ($M)	792	767	1,559	164	139	303
	%	0.095	0.067	0.079	0.020	0.012	0.015

Given the high potential for resilience in the port system and property damages identified above, and the relatively low total economic impacts from the SAFRR tsunami in the first place, we do not deem it necessary to apply the CGE model any further for the case of import disruptions, which would approach zero at the direct level. This is also the case for damages to POLA marinas.

Resilience in the California coast marinas is more challenging to determine at this time. We could assume that lost slip fees cannot be recaptured from destroyed vessels that would not occupy slips until replaced. However, we lack an assessment of excess marina capacity along the coast and an investigation of alternate and temporary mooring options. After the 2011 Japanese tsunami, Crescent City, California, boats were redirected to Eureka, but we have not attempted to identify the potential to relocate boats to remaining slips along the California coast or even along inland water bodies. Also, after the Japanese tsunami, some boat owners in Crescent City moored on buoys and rowed out to their boats as a result of fierce competition for available slips (Brett Fahning, oral commun., 2013). In such a case, the full services of a slip (with power and water) are not provided, but some of the marina-related activities could continue. Resilience of the marina sector, defined as four sectors, will also depend on other coastal recreational pursuits that could be substituted for marina activities to maintain marina-related restaurant and retail activity.

Note, of course, that the full potential resilience of the various resilience tactics will not necessarily be implemented effectively. Hence, the estimates presented above are an optimistic reduction in the SAFRR tsunami scenario direct economic impact estimates for the considered resilience strategies. Moreover, at this stage we have not included any stimulus from reconstruction that will be partially funded by disaster funds and insurance (financial forms of resilience). Therefore, it is possible that the losses in directly impacted sectors that depend on coastal locations and possess more limited resilience options (for example, marinas and small harbors) will be counterbalanced somewhat by the gains from reconstruction and related activities, similar to our simulation results on the economic impacts from the ARkStorm scenario (Sue Wing and others, 2013). Locally, this was the experience of Crescent City harbormaster, who observed other businesses profiting from the damage of the harbor after the 2011 Tohoku-oki tsunami (Richard Young, oral commun., 2013). Also, delays in Federal Emergency Management Agency (FEMA) reimbursements have impeded recovery of Crescent City Harbor, and streamlining the FEMA process presents an opportunity to increase resilience in future disasters.

Given that resilience tactics are potentially very effective at reducing economic impacts for the SAFRR tsunami scenario, goods movement delay costs and impacts from environmental damages may become relatively more important. Also, the likely over evacuation of people from coastal areas that will affect economic activity in areas beyond the inundation area may be of interest.

Conclusion

We have estimated the direct and total economic impacts of the SAFRR tsunami scenario hitting the California coast. The results follow from the selection of the tsunami source (Kirby and others, 2013), the modeling of wave propagation and the damaging current velocities and inundation (SAFFR Tsunami Scenario Modeling Working Group, 2013), the assessment of damages (Porter and others, 2013a); and the economic impact modeling and incorporation of economic resilience. Although uncertainties at each stage propagate throughout the analysis of the scenario in forms of both under and over estimation, the potential for a tsunami to inundate land along the coast of California is firmly established (Wilson and others, written commun., 2013). An integrated analysis culminating with an estimation of economic impacts exposes vulnerabilities of sectors and the California economy. Most importantly, it emphasizes the potential effectiveness of resilience when planning for future tsunami events.

Losses stem from a combination of import and export disruptions at POLA and POLB, property damage to coastal buildings and contents, other losses related to marina damages in coastal counties, and POLA commercial fishing losses. Our estimate of total impact to GDP without resilience for California is just less than $6.0 billion. By far the largest share of these losses, comprising more than 50 percent 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 apply to southern California. Without resilience, there would be some positive shift in economic activity to the rest of California, as production of import substitutes is needed, but still not enough to offset the negative stimulus in that region. National-scale impacts still remain to be investigated, but the results for California indicate that the impacts will be small relative to previously studied port shutdowns of weeks, months, and years.

Without resilience, $4.3 billion of the potential total economic impacts to California stem from the 2-day port shutdown and $100 million of physical damages to terminals and cargo at the POLA and POLB through import and export disruptions. Damages to cargo and facilities are responsible for $1.7 billion of port impacts. Coincidentally, these port damage economic impacts are matched by $1.7 billion of economic impacts from $2.5 billion of coastal property damages. This result highlights a hypersensitivity of economic impacts to port damages, suggesting that it could be worthwhile investigating the effects of the SAFRR tsunami scenario on other California ports, including the Ports of Oakland, Richmond, San Diego, and Hueneme.

However, economic resilience tactics greatly reduce the total economic impact to the California economy. The ports' ability to sustain the 2-day shutdown by clearing the back log of ships in the harbor and the awaiting exports nulls most of the import and export disruption. The month-long reduced capacity at numerous marine oil terminals could be compensated for by excess capacity at a terminal and inventories at a port, off-site, and at major customers. Resilience would have a greater effect on reducing direct impacts on the import side ($1 billion reduced by $30 million) than the export side ($200 million reduced to $150 million). The most effective resilience tactic on the import-disruption side is inventory use, a tactic that is not applicable to the export-disruption side. However, inventories have a limited term, such that a longer period of reduced capacity at the marine oil terminals will eventually result in fuel supply challenges for southern California.

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References Cited

Borrero, J., Cho, S., Moore, J.E., Richardson, H., and Synolakis, C., 2005, "Could It Happen Here?": Civil Engineering, v. 75, no. 4, p. 54–65, 133.

Brooke, A., Kendrick, D., Meeraus, A., and Raman, R., 1998, GAMS—A user's guide: Washington, D.C., GAMS Development Corporation, 302 p.

Bureau of Economic Analysis, 2013, National economic accounts—National data on real inventories and sales data: U.S. Department of Commerce, Bureau of Economic Analysis, Web site, accessed March 14, 2013, at http://www.bea.gov/iTable/iTable.cfm?ReqID=12&step=1#reqid=12&step=1&isuri=1.

Dykstra, D., Lim, A., and Porter, K., 2013, Tsunami scenario engineering impacts of port of Long Beach and port of Los Angeles *in* Porter, K., Byers, W., Dykstra, D., Lim, A., Lynett, P., Ratliff, J., Scawthorn, C., Wein, A., and Wilson, R., 2013, Physical damage in the SAFRR California tsunami scenario**:** U.S. Geological Survey Open-File Report 2013–1170–E, 183 p., http://pubs.usgs.gov/of/2013/1170/e/.

Ferris, M.C., Munson, T.S., and Ralph, D., 2000, A homotopy method for mixed complementarity problems based on the PATH solver, *in* Griffiths, D.F., and Watson, G.A., eds., Numerical analysis 1999: London, Chapman and Hall, p. 143–167.

Hall, P.V., 2004, "We'd have to sink the ships'—Impact studies and the 2002 west coast port lockout": Economic Development Quarterly, v. 18, p. 354.

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

Kirby, S., Scholl, D., Huene, R.V., and Wells, R., 2013, Alaska earthquake source for the SAFRR California tsunami scenario: U.S. Geological Survey Open-File Report 2013–1170–B, 45 p., http://pubs.usgs.gov/of/2013/1170/b/.

Martin Associates, 2001, An assessment of the impact of west coast container operations and the potential impacts of an interruption of port operations—2000: Martin Associates report prepared for the Pacific Maritime Association, Lancaster, Pa.

Martin Associates, 2007, Economic impacts of the Port of Los Angeles: Martin Associates report prepared for Port of Los Angeles, 41 p.

McClelland, R., and Mok, S., 2012, A review of recent research on labor supply elasticities: Congressional Budget Office Working Paper 2012-12, October 2012, 41 p.

Minnesota IMPLAN Group, Inc., 2012, Year 2010 input-output tables for California State and counties: Minnesota IMPLAN Group, Inc.

Park, J.Y., 2008, The economic impacts of dirty bomb attacks on the Los Angeles and Long Beach ports—Applying the supply-driven NIEMO (National Interstate Economic Model): Journal of Homeland Security and Emergency Management 5, v. 1, no. 21, 22 p.

Park, J.Y., Gordon, P., Moore II, J.E., Richardson, H.W., 2008, The state-by-state economic impacts of the 2002 shutdown of the Los Angeles-Long Beach ports: Growth and Change, v. 39, no. 4, p. 548–572.

Porter, K., 2013, Building damage, *in* Porter, K., Byers, W., Dykstra, D., Lim, A., Lynett, P., Ratliff, J., Scawthorn, C., Wein, A., and Wilson, R., 2013, Physical damage in the SAFRR California tsunami scenario: U.S. Geological Survey Open-File Report 2013–1170–E, 183 p., http://pubs.usgs.gov/of/2013/1170/e/.

Porter, K., Byers, W., Dykstra, D., Lim, A., Lynett, P., Ratliff, J., Scawthorn, C., Wein, A., and Wilson, R., 2013a, Physical damage in the SAFRR California tsunami scenario: U.S. Geological Survey Open-File Report 2013–1170–E, 183 p., http://pubs.usgs.gov/of/2013/1170/e/.

Porter, K., Lynett, P., and Wilson, R., 2013b, Damages and restoration of marinas and small craft, *in* Porter, K., Byers, W., Dykstra, D., Lim, A., Lynett, P., Ratliff, J., Scawthorn, C., Wein, A., and Wilson, R., Physical damage in the SAFRR California tsunami scenario: U.S. Geological Survey Open-File Report 2013–1170–E, 183 p., http://pubs.usgs.gov/of/2013/1170/e/.

Rose, A., 2009, Economic resilience to disasters: Community and Regional Resilience Institute Research Report 8, 40 p., accessed August 13, 2013, at http://research.create.usc.edu/published_papers/75.

Rose, A., Sue Wing, I., Wei, D., and Avetisyan, M., 2012, Total regional economic losses from water supply disruptions to the Los Angeles County economy: Final Report to Los Angeles Economic Development Corporation, 66 p.

Rose, A., and Wei, D., 2013, Estimating the economic consequences of a port shutdown—The special role of resilience: Economic Systems Research, v. 25, no. 2, p. 212–232.

Rose, A., Wei, D., and Wein, A., 2011, Economic impacts of the ShakeOut scenario: Earthquake Spectra, v. 27, no. 2, p. 539–557.

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

SAFRR Tsunami Scenario Modeling Working Group, 2013, Modeling for the SAFRR tsunami scenario—Generation, propagation, inundation, and currents in ports and harbors: U.S. Geological Survey Open-File Report 2013–1170–D, 127 p., http://pubs.usgs.gov/of/2013/1170/d/.

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

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

U.S. Census Bureau, 2012, 2010 U.S. export and import data for Port of Los Angeles and Port of Long Beach: U.S. Census Bureau, USA Trade Online website, accessed December, 2012, at https://usatrade.census.gov/.

Appendix A. Methodology and Data

[Data, green; major assumptions, red; methods, blue. POLA, Port of Los Angeles; 2010$, 2010 dollars; CGE, computable general equilibrium; M, million; K, thousand; %, percent]

Direct impact type	Data/major assumptions/estimation method	Direct economic impact	Further conversion	Applicable resilience	Comments
2-day port shutdown	U.S. Census Bureau, 2012; Dykstra and others (2013). Assume essentially no ship diversions. Import and export disruption to all trade commodities for 2 days.	1. Percent import disruption by sector. 2. Percent export disruption by sector.		Inventories; conservation; input substitution; production recapture.	Import disruption means a disruption of import input to the producing sectors. For a 2-day port shutdown, it is reasonable to believe that it is just a delay of shipping the imports to the domestic importers. Therefore, most of the economic losses should be able to make up by use of inventories and production recapture. Export disruption means a disruption or demand reduction to exporters because of the interruption of the port transportation. However, for a 2-day port shutdown, it is just a delay of shipping out of the export commodities. It is unlikely that the foreign buyers will cancel the order within 2 days. The majority of the service disruption can be made up by the port by working overtime (production recapture) after the port reopened.

[Data, green; major assumptions, red; methods, blue. POLA, Port of Los Angeles; 2010$, 2010 dollars; CGE, computable general equilibrium; M, million; K, thousand; %, percent]

Direct impact type	Data/major assumptions/estimation method	Direct economic impact	Further conversion	Applicable resilience	Comments
Cargo damages	Damage data provided by Dykstra and others (2013). 1. Map cargo damage data to CGE sectors. 2. For imports, aggregate the data for POLA and POLB and then calculate percent import input disruption by sector. 3. For exports, aggregate data for POLA and POLB and then calculate export demand reduction by sector.	1. Percent import disruption by sector. 2. Percent export disruption by sector.		Inventories; conservation; input substitution; production recapture.	Cost of cleanup of the damaged cargos is not included in the analysis.
Facility downtime: 1. POLA berths 165–166 (industrial borates). 2. POLA berths 163, 164, 167–169, 187–191 (marine oil and fuels). 3. POLA berths 174–181 (steel)	Downtime data provided by Dykstra and others (2013). 1. Berths 165–166 downtime is translated into export disruption for borate for 2 weeks 2. Berths 163, 164, 167–169, 187–191 downtime is translated into 50% reduction in capacity for 1 month for marine oil and fuels (import and/or export) 3. Berths 174–181 downtime is translated into import disruption for steel for 2 weeks	1. Percent direct export disruption to sector 28 (chemical manufacturing) 2. Percent import disruption or Percent direct export disruption of sector 26 (petroleum refineries). 3. Percent import disruption of sector 31 (iron and steel mills/steel product manufacturing).		Excess capacity; ship rerouting; inventories; conservation; export diversion (only in cases of import and export disruption of same commodity at same time); input substitution; production recapture.	

Appendix A. Methodology and Data—Continued

[Data, green; major assumptions, red; methods, blue. POLA, Port of Los Angeles; 2010$, 2010 dollars; CGE, computable general equilibrium; M, million; K, thousand; %, percent]

Direct impact type	Data/major assumptions/estimation method	Direct economic impact	Applicable resilience
Marina: 1/3 POLA marina slips damaged	According to Martin Associates (2007), direct revenue of marina tenants estimated to be $48.2 M in 2006. Although there has been a capacity increase of about 11% because new capacity is still vacant; Convert $48.2 M to 2010$, we get a total revenue of $51.8M in 2010$. The monthly rental revenue to the port is $300K. Assume marina tenants would lose 1/3 of their business during slip repair time; it will take 1 month to repair the damaged slips at a linear rate. We distribute the total revenue losses (excluding the rental revenue to the port) evenly among restaurant, retail, and marina-related activities sectors.	$300K revenue loss to POLA. As for the remaining direct revenue losses, we distribute them to marina recreation industries, restaurants, and retail trade.	Excess capacity of marina; production recapture.
Impacts to commercial fishing	Economic impacts pertain to perished fish on board of the vessels at sea and lost fishing days: 25% of a day's fish haul will perish. In addition, 5% of fishing fleet will be damaged, and 4 fishing days lost. It will take about 2 months on average to repair or replace the damaged boats, so it will lead to a 5% of 2-month total revenue loss to the fishing industry.	These are converted to direct revenue loss to the fishing sector.	Production recapture.
Miscellaneous: A. Cruise ship	No POLA cruise ships affected during the 2-day time period of the scenario.		

Appendix B. Tsunami Port Direct Impacts Without and With Resilience

[This appendix is provided online only as an Excel spreadsheet (Tsunami_Port_Direct Impacts without and with Resilience) at http://pubs.usgs.gov/of/2013/1170/H/]

Appendix C. CGE Model Description

Introduction

This appendix summarizes the design, construction and application of a static computable general equilibrium (CGE) simulation model of the California economy. The application of the model simulates single semiannual period that begins with the occurrence of a tsunami.

A CGE model is a stylized computational representation of the circular flow of the economy. It solves for the set of commodity and factor prices and activity levels of firms' outputs and households' incomes that equalize supply and demand across all markets in the economy (Sue Wing, 2009, 2011). The present model divides California into two regions, the five counties surrounding Los Angeles (Los Angeles, Orange, Riverside, San Bernardino, Ventura) and an amalgam of the remaining counties in the State. Production in each region is divided into 65 industry sectors (table C1), each of which is modeled as representative firm characterized by a constant elasticity of substitution (CES) technology to produce a single good or service. Households are modeled as a representative agent with CES preferences and a constant marginal propensity to save and invest out of income. Government is also represented in a simplified fashion. Its role in the circular flow of the economy is passive—collecting taxes from industries and passing some of the resulting revenue to the households as a lump-sum transfer, in addition to purchasing commodities to create a composite government good, which is consumed by the households. Three factors of production are represented within the model—(1) labor, (2) intersectorally mobile capital, and (3) sector-specific capital, all of which are owned by the representative agent and rented out to the firms in exchange for factor income. California is modeled as an open economy that engages in trade with the rest of the United States and the rest of the world using the Armington specification (imports from other States and the rest of the world are imperfect substitutes for goods produced in California).

The static component of the model computes the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments. This equilibrium submodel is embedded within a dynamic process, which on a 6-month time-step specifies exogenous improvements in firms' productivity and updates the economy's capital endowments based on investment-driven accumulation of the stocks of capital. The impacts of a tsunami are modeled as exogenous shocks to the productivity of industries, reductions in household consumption and investment, and contemporaneous destruction of capital stock, with concomitant reductions in the economy's endowments of capital input.

Production

The supply side of the model employs a simple hierarchical nested CES production structure. In each region r and sector j, the price and quantity of output are given by $PY_{j,r}$ and $QY_{j,r}$. Output is produced by combining a composite of capital and labor ($QKL_{j,r}$, with price $PKL_{j,r}$) with a composite of intermediate inputs ($QZ_{j,r}$, with price $PZ_{j,r}$). This production relation is represented in dual form by the unit cost function:

$$PY_{j,r} \leq \left(1 - \Phi_{Y,j,r}\right)^{-1} \cdot \left[\alpha_{KL,j,r}^{\sigma_Y} PKL_{j,r}^{1-\sigma_Y} + \alpha_{Z,j,r}^{\sigma_Y} PZ_{j,r}^{1-\sigma_Y}\right]^{1/(1-\sigma_Y)}. \quad \text{(1a)}$$

Here, σ_Y denotes the top-level the elasticity of substitution between intermediate inputs and value-added, and $\Phi_{Y,j,r}$ is a parameter that captures the impact of output losses associated with the tsunami. In turn, the capital-labor composite is produced from sector-specific capital ($QK_{j,r}$, with price $PK_{j,r}$) and labor ($QL_{j,r}$, with average wage PL) according to the unit cost function:

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

in which σ_{KL} is the elasticity of substitution between capital and labor. Finally, the intermediate input composite is modeled as a CES aggregation of intermediate inputs of the i commodities ($q_{i,j,r}$, with "Armington" user prices $PA_{i,r}$) according to the unit cost function:

$$PZ_{j,r} \leq \left[\sum_i \alpha_{i,j,r}^{\sigma_Z} PA_{i,r}^{1-\sigma_Z}\right]^{1/(1-\sigma_Z)}, \quad \text{(1c)}$$

where σ_Z is the elasticity of substitution among intermediate inputs.

Trade and Commodity Supply

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

The calibration dataset does not record bilateral trade among counties or county aggregates. Consequently, the $QXUS_{i,r}$ units of the i^{th} commodity exported by region r to U.S. consumers in other locales is treated as feeding into a national pool at a commodity-specific U.S.-wide price (PUS_i), whereas the $QXF_{i,r}$ units exported to consumers abroad are treated as feeding an international pool at a single price (the generalized price of foreign exchange, PFX). Using $PYT_{i,r} = \left(1 + \tau_{i,r}^Y\right) PY_{i,r}$ to represent the gross-of-tax price of i (where $\tau_{i,r}^Y$ denotes the production tax rate), the transformation of regional output into exports (quantity $QX_{i,r}$) is specified in terms of the dual by:

$$PYT_{i,r} \geq \left(1 - \Phi_{X,j,r}\right) \cdot \left[\beta_{XCA,i}^{\eta_{X,i}} PUS_i^{1-\eta_{X,i}} + \beta_{XF,i}^{\eta_{X,i}} PFX^{1-\eta_{X,i}}\right]^{1/(1-\eta_{X,i})}. \quad \text{(2a)}$$

Here, η_X is the elasticity of transformation among export destinations, whereas $\Phi_{X,j,r}$ is a parameter that is introduced to capture the adverse shock to export productivity caused by the tsunami's impact on port operations.

Symmetrically, r imports $QMUS_{i,r}$ units of i from other U.S. regions and $QMF_{i,r}$ units from abroad. Its aggregate imports of each good (quantity $QM_{i,r}$ with price $PM_{i,r}$) are modeled as a CES composite of these quantities, given in terms of the dual by:

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

in which σ_{MM} is the elasticity of substitution among import origins, and the parameter $\Phi_{M,j,r}$ captures the tsunami's adverse shock to imports. In turn, each region's uses of a commodity are fulfilled by the Armington total supply ($QA_{i,r}$, with price $PA_{i,r}$), which is modeled as a CES composite of domestic and imported varieties given in dual form by

$$PA_{i,r} \leq \left[\beta_{D,i,r}^{\sigma_{DM,i}} PYT_i^{1-\sigma_{DM,i}} + \beta_{M,i,r}^{\sigma_{DM,i}} PM^{1-\sigma_{DM,i}}\right]^{1/(1-\sigma_{DM,i})}, \quad (2c)$$

where σ_{DM} is the elasticity of substitution.

We adopt a simple trade closure for the model. Each region is treated as a small open economy that cannot affect the price of foreign exchange. Following open-economy modeling convention, we designate the variable PFX as the numeraire price by fixing its value at unity. The model only resolves regions within the State of California, and not elsewhere in the United States, so in the general case the trade in a particular good recorded by the benchmark input-output accounts will not balance. California's net export position vis-a-vis the rest of the United States is calculated by applying Shephard's lemma, yielding the supply-demand balance condition:

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

where $QBUS_i$ is introduced as a balancing quantity of net exports of good i. The corresponding expression for trade with foreign countries is:

$$\sum_r QXF_{i,r} \geq \sum_r QMF_{i,r} + QBF_i \Rightarrow \sum_r \frac{\partial PTY_{i,r}}{\partial PFX} QX_{i,r} \geq \sum_r \frac{\partial PM_{i,r}}{\partial PFX} QM_{i,r} + QBF_i, \quad (2e)$$

with balancing quantity QBF_i.

Final Demands and Commodity Market Closures

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

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

where $PU_{h,r}$ is the unit expenditure index and σ_C is the elasticity of substitution among inputs to consumption. There are also g levels of government, each of which consumes commodity inputs ($q_{i,G,g,r}$ at price $PA_{i,r}$) for the purpose of producing a government good ($QG_{g,r}$, at price $PG_{g,r}$) with CES technology. The associated cost function is:

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

and σ_G is the elasticity of substitution among inputs to government. As well, each region produces an investment good (QI_r, at price PI_r) from a CES aggregation of commodities ($q_{i,I,r}$ at price $PA_{i,r}$):

$$PI_r \leq \left[\sum_i \gamma_{i,I,r}^{\sigma_I} PA_{i,r}^{1-\sigma_I}\right]^{1/(1-\sigma_I)}, \quad (3c)$$

and σ_I is the elasticity of substitution among inputs to investment. We assume that each representative agent exhibits a fixed marginal propensity to save (MPS) and invest out of income. Supply-demand balance for households' savings ($QS_{h,r}$) requires:

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

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

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

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

$$QG_{g,r} \leq \left(\xi_{g,r} \sum_j \tau^Y_{j,r} PY_{j,r} QY_{j,r} + PFX \cdot GXFER_{g,r}\right) / PG_{g,r}. \tag{3f}$$

The supply-demand balance for domestic output is given by:

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

where the unconditional demand for domestic uses is given by Shephard's Lemma: $QD_{i,r} = \frac{\partial PA_{i,r}}{\partial PYT_{i,r}} QA_{i,r}$. The supply-demand balance for imports is given by Shephard's Lemma:

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

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

$$QA_{i,r} \geq \sum_j q_{i,j,r} + \sum_h q_{i,C,h,r} + q_{i,I,r} + \sum_g q_{i,G,g,r}\ , \tag{3i}$$

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

$q_{i,j,r} = \frac{\partial PY_{j,r}}{\partial PA_{i,r}} QY_{j,r}$, $q_{i,C,h,r} = \frac{\partial PU_{h,r}}{\partial PA_{i,r}} U_{h,r}$, $q_{i,I,r} = \frac{\partial PI_r}{\partial PA_{i,r}} QI_r$ and $q_{i,G,g,r} = \frac{\partial PG_{g,r}}{\partial PA_{i,r}} QG_{g,r}$.

Intersectoral Factor Mobility and Static Income Closures

Given the short duration of each time step, the assumption of frictionless intersectoral reallocation of capital common in CGE models is unlikely to accurately capture the behavior of factor markets. Although we continue to treat labor as mobile across industries and regions, we model capital as a sectorally and geographically fixed factor at each time-step, with instantaneous supply-demand balance determined by the region-specific aggregate supply of capital input ($\mathcal{E}_{K,j,r}$):

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

The effect of capital stock destruction on the left-hand side of this expression, given by the parameter $\Phi_{K,j,r}$, is another driver of the tsunami's economic impact. Traditional CGE models close the labor market either through the "neoclassical" assumption of full employment (perfectly inelastic supply) or "Keynesian" variable employment (perfectly elastic supply at a fixed wage). Neither of these extremes adequately captures the impact of a large transitory shock, which typically induces simultaneous adjustments in both employment and wages. Accordingly, we model labor as a variable factor whose endowment is price responsive. This is achieved by specifying a short-run labor supply curve with elasticity η_L, which scales each region's labor supply from its benchmark level ($\mathcal{E}_{L,r}$):

$$\sum_r \mathcal{E}_{L,r} \cdot PL^{\eta_L} \geq \sum_j \sum_r \frac{\partial PKL_{j,r}}{\partial PL} QKL_{j,r}. \tag{4b}$$

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

$$\zeta_{K,h,r} \cdot \sum_j PK_{j,r}\mathcal{E}_{K,j,r} + \zeta_{L,h,r}PL^{1-\eta_L}\mathcal{E}_{L,r} + PFX \cdot HXFER_{h,r}$$
$$\geq PU_{h,r}U_{h,r} + PI_r\, QS_{h,r} + \sum_i PCA_i\, SA_{i,h,r}. \tag{4c}$$

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

$$\sum_i (PUS_i \cdot QBUS_i + QBF_i) + \sum_g \sum_r GXFER_{g,r} + \sum_h \sum_r HXFER_{h,r} = 0. \tag{4d}$$

The Impacts of a Tsunami on the Economy

The static equilibrium submodel made up of equations 1–4 is subjected to the shock of economic damage caused by the tsunami event represented by adverse shocks to the efficiency of production in key affected sectors ($\Phi_{Y,j,r}$), shocks to the productivity of exports and imports ($\Phi_{X,j,r}$ and $\Phi_{M,j,r}$), and reductions in sectors' endowments of capital input ($\Phi_{K,j,r}$). In the economy's baseline state these shock parameters are set to zero, whereas in the tsunami scenario they take on values between zero and one, reflecting different components of damage. Import and export losses generally affect all sectors, and primarily encompass losses associated with interrupted operation of POLA and POLB, destruction of cargo, and loss of function of damaged facilities and infrastructure. Direct damage to buildings and their contents also affects all sectors in coastal areas of both regions of California. Direct output losses affect only fishing (sector 7) and marinas (sectors 43, 61, and 63).

Model Calibration, Formulation and Solution

The vectors of technical coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ in equations 1–4 are calibrated using an IMPLAN social accounting matrix for the state of California for the year 2010 (Minnesota IMPLAN Group, Inc., 2012) in conjunction with values of the elasticities of substitution, transformation, and supply in table C2. The model is formulated as a mixed complementarity problem using the MPSGE subsystem for GAMS (Rutherford, 1999; Brooke and others, 1998) and is solved using the PATH solver (Ferris and others, 2000).

Table C1. Computable general equilibrium (CGE) model sectors for the SAFRR tsunami scenario.

[NAICS, North American Industry Classification System; mfg, manufacturing]

	Description	NAICS Code	HAZUS occupancy class[1]
1	Oilseed and grain farming	1111	AGR1
2	Vegetable and melon farming	1112	AGR1
3	Fruit and tree nut farming	1113	AGR1
4	Other crop farming	1114, 1119	AGR1
5	Animal production and aquaculture	112	AGR1
6	Forestry and logging	113	AGR1
7	Fishing	1141	AGR1
8	Hunting and trapping	1142	AGR1
9	Support activities for agriculture and forestry	115	AGR1
10	Oil and gas extraction	211	IND4
11	Other nonmetallic mineral mining and quarrying	21239	IND4
12	Other mining	212 (ex. 21239)	IND4
13	Electric power generation, transmission and distribution	2211	COM4
14	Natural gas distribution	2212	COM4
15	Water and sewage	2213	COM4
16	Nonresidential construction	23	IND6
17	Residential construction	23	IND6
18	Food mfg	311	IND3
19	Beverage and tobacco product mfg	312	IND3
20	Textile and textile product mills	313, 314	IND1
21	Apparel mfg	315	IND2
22	Leather and allied product mfg	316	IND2
23	Wood product mfg	321	IND1
24	Paper mfg	322	IND1
25	Printing and related support activities	323	IND2
26	Petroleum refineries	32411	IND3
27	Other petroleum and coal products mfg	324	IND3
28	Chemical mfg	325	IND3
29	Plastics and rubber products mfg	326	IND2
30	Nonmetallic mineral product mfg	327	IND1
31	Iron and steel mills and steel product mfg	3311 and 3312	IND4
32	Other primary metal mfg	331 (ex. 3311), 3312	IND4
33	Fabricated metal product mfg	332	IND4
34	Machinery mfg	333	IND1
35	Computer and electronic product mfg	334	IND5
36	Electrical equipment, appliance and component mfg	335	IND2
37	Automobile and light duty motor vehicle mfg	33611	IND1

Table C1. Computable general equilibrium (CGE) model sectors for the SAFRR tsunami scenario.—Continued

[NAICS, North American Industry Classification System; mfg, manufacturing]

	Description	NAICS Code	HAZUS occupancy class[1]
38	Ship and boat building and repairing	3366	IND1
39	Other transportation equipment mfg	336 (ex. 33611), 3366	IND1
40	Furniture and related product mfg	337	IND2
41	Miscellaneous mfg	339	IND2
42	Wholesale	42	COM2
43	Retail trade	44-45	COM1
44	Air transportation	481	COM4
45	Rail transportation	482	COM4
46	Water transportation	483	COM4
47	Truck transportation	484	COM4
48	Transit and ground passenger transport	485	COM4
49	Pipeline transportation	486	COM4
50	Scenic and sightseeing transport & support activities	487, 488	COM4
51	Couriers and messengers	492	COM4
52	Warehousing and storage	493	COM2
53	Information	51	COM4
54	Finance and insurance	52	COM4; COM5
55	Real estate and rental and leasing	53	COM4
56	Professional, scientific and technical services	54	COM4
57	Admin support and waste management and remediation	56	COM4
58	Educational services	61	EDU1; EDU2
59	Health care and social assistance	62	COM6; COM7
60	Arts, entertainment and recreation	71 (ex. 71391-3), 71399	COM8
61	Other amusement and recreation, including marinas	71391-3, 71399	COM8
62	Accommodation and food services	721	RES4
63	Food services and drinking places	722	COM8
64	Other services (except public administration)	55, 81	COM3
65	Government and non-NAICS	92	GOV1; GOV2

[1]Key: AGR1 Agriculture; IND1 Heavy Industry; IND2 Light Industry; IND3 Food/Drugs/Chemicals; IND4 Metals/ Minerals Processing; IND5 High Technology Industry; IND6 Construction; COM1 Retail Trade; COM2 Wholesale Trade; COM3 Personal and Repair Services; COM4 Professional/Technical Services; COM5 Banks/Financial Institutions; COM6 Hospitals; COM7 Medical Offices/Clinics; COM8 Entertainment & Recreation; EDU1 Schools; EDU2 Colleges/Universities; RES4 Temporary Lodging for Accommodation; GOV1 General Government Services; GOV2 Emergency Response.

Table C2. Elasticities of substitution, transformation, and supply or the SAFRR tsunami scenario.

Elasticities of substitution		
Between value added and a composite of intermediate inputs in production	σ_Y	0.1
Between capital and labor in production	σ_{KL}	0.25
Among intermediate inputs to production	σ_Z	0.1
Among regions' imports from the rest of the United States and abroad	$\sigma_{YY,i}$	2
Between domestic (California) and imported varieties of each good in regional Armington composite	$\sigma_{DM,i}$	0.5
Among inputs to household consumption	σ_C	0.25
Among inputs to investment	σ_I	0.25
Among inputs to government	σ_G	0.25
Elasticities of transformation		
Between rest of United States and foreign exports	η_X	2
Elasticities of supply		
Labor	η_L	0.3

Appendix D. Calculation of Inventory Availability for Resilience

In disaster impact analysis, inventories of raw materials and finished goods used as inputs or intended for final customers through wholesale and retail markets can cushion the blow of a supply disruption, such as those associated with the port shutdown in this study. We summarize the methods, assumptions, and data sources we use to compute the available inventory in the southern California region that can be used to deal with supply disruptions.

Our major data source of inventories is the real inventories and sales in the national economic accounts released by the U.S. Department of Commerce, Bureau of Economic Analysis (Bureau of Economic Analysis, 2013). The data used here are only for manufacturing sectors. Table D1 presents these data for the United States for the year 2011 for three fabrication stages of inventories—materials and supplies, work-in-process, and finished goods. In the last three columns in table D1, inventory to annual sale ratios are computed.

For each of the three individual stages of fabrication, the data pertain to the total amount of inventories held by each manufacturing sector. There is no reference to the types of input in the first two categories. To disaggregate the inventories of materials and supplies into different types of raw material inputs available for each manufacturing industry, we make use of the regional input-output table. For inventories of finished goods, we create a matrix that shows the amount of own output each sector holds.

Below, we use the five-county southern California region as an example to illustrate the steps in the inventory calculation. In table D2, the first column presents the annual sectoral sales in the southern California region. Applying the national level inventory to sales ratios in the last three columns of table 1 to the annual sales of the southern California region, we estimated the inventories in the fabrication stages in the region for the manufacturing sectors (the last three columns in table D2).

For inventory of materials and supplies, we disaggregated the total value in the second column of table D2 for each sector into various raw material inputs based on the column (input) coefficients in the regional input-output table. Note that we include the following sectoral inputs as raw material inputs: agriculture, fishing, and forestry, mining, utility (except for electricity), and all manufacturing sectors. In other words, we did not count the production inputs from the electric power generation, construction, and service sectors as raw materials. Table D3 presents the calculation results, with each row representing different types of raw material inputs, and each column representing different sectors. Because we only have the inventory data for manufacturing sectors, we have omitted other sectors in the table.

For inventory of work-in-process products, because they are midway between finished commodities and raw material inputs and difficult to disaggregate on a sectoral basis, we do not include this category of inventory in our calculation to obtain the commodity inventory buffers that can help reduce the impacts of import disruptions. Table D4 shows the amount of "own" outputs that are held by each sector as finished goods inventory for the southern California region.

Finally, for each commodity in table D5, we add up the numbers over the corresponding rows in tables D3 and D4 to obtain the total amount of inventories that are available in the southern California region to be used to reduce the impact from import disruptions.

Our calculation of inventory availability is conservative from three perspectives. First, we only count for the inventories that are held by the manufacturing sectors in the region. However, the inventories held by the other sectors are likely to be small compared with those held by the manufacturing sectors. Major inventories of the agriculture sector may include water, gas, pesticide, and feed. The inventories for the transportation sectors may include oil, gas, and water. Most of the service sectors may only possess limited inventories. Second, we did not take into consideration the consumer goods held by the wholesalers and retailers in the region that can help cushion the supply disruption impacts to the end users. And finally, again we did not include the work-in-process inventories in our calculation.

Table D1. Real manufacturing inventories for the United States, by stage of fabrication, seasonally adjusted, end of 2011 (data from Bureau of Economic Analysis, 2013).

[M 2005$, millions of 2005 dollars; %, percent]

Sector	2011 annual sales (M 2005$)	End of 2011 inventories (M 2005$)			Inventory to sale ratio		
		Materials and supplies	Work-in-process	Finished goods	Materials and supplies	Work-in-process	Finished goods
Manufacturing industries	4,283,928	182,015	172,059	194,142	4%	4%	5%
Durable goods manufacturing industries	2,205,444	109,907	134,751	92,847	5%	6%	4%
Wood product manufacturing	70,596	4,025	1,456	3,474	6%	2%	5%
Nonmetallic mineral product manufacturing	79,236	4,263	1,123	5,260	5%	1%	7%
Primary metal manufacturing	213,444	8,835	7,838	7,686	4%	4%	4%
Fabricated metal product manufacturing	251,196	14,113	11,830	12,939	6%	5%	5%
Machinery manufacturing	300,228	18,333	12,806	15,134	6%	4%	5%
Computer and electronic product manufacturing	371,904	22,995	20,365	16,956	6%	5%	5%
Electrical equipment, appliance, and component manufacturing	93,468	5,871	4,938	2,908	6%	5%	3%
Transportation equipment manufacturing	632,496	20,699	69,019	15,138	3%	11%	2%
Motor vehicle and parts manufacturing	451,224	12,179	6,103	8,046	3%	1%	2%
Other transportation equipment manufacturing	183,024	8,534	62,992	7,103	5%	34%	4%
Furniture and related product manufacturing	53,448	3,643	1,307	2,377	7%	2%	4%
Miscellaneous durable goods manufacturing	136,980	7,789	4,451	11,532	6%	3%	8%
Nondurable goods manufacturing industries	2,079,984	72,604	38,329	101,612	3%	2%	5%
Food manufacturing	531,648	10,942	5,653	22,589	2%	1%	4%
Beverage and tobacco product manufacturing	113,916	5,812	2,842	5,321	5%	2%	5%
Textile mills	24,156	1,635	921	1,979	7%	4%	8%
Textile product mills	19,836	1,272	573	1,517	6%	3%	8%
Apparel manufacturing	15,528	1,745	984	3,474	11%	6%	22%
Leather and allied product manufacturing	5,196	426	248	779	8%	5%	15%
Paper manufacturing	134,256	7,873	1,643	6,314	6%	1%	5%
Printing and related support activities	74,640	2,137	827	2,671	3%	1%	4%
Petroleum and coal product manufacturing	433,716	10,523	8,941	15,692	2%	2%	4%
Chemical manufacturing	552,840	21,286	13,223	31,137	4%	2%	6%
Plastics and rubber product manufacturing	163,764	9,056	2,146	9,725	6%	1%	6%

Table D2. Inventories by stage of fabrication for manufacturing industry in southern California region (in millions of 2010 dollars).

[Data in second column from Minnesota IMPLAN Group, Inc. (2012). Numbers in the remaining three columns computed by the authors]

Sector	2010 Annual sales	Materials and supplies	Work-in-process	Finished goods
Oilseed and grain farming	6.81			
Vegetable and melon farming	820.83			
Fruit and tree nut farming	1,491.43			
Other crop farming	1,447.33			
Animal production and aquaculture	895.13			
Forestry and logging	67.38			
Fishing	70.43			
Hunting and trapping	1.68			
Support activities for agriculture and forestry	799.21			
Oil and gas extraction	4,447.24			
Other nonmetallic mineral mining and quarrying	40.22			
Other mining	1,132.62			
Electric power generation, transmission, and distribution	10,436.73			
Natural gas distribution	15,205.43			
Water, sewage and other systems	192.19			
Nonresidential construction	40,214.90			
Residential construction	21,728.61			
Food manufacturing	25,194.47	518.53	267.89	1,070.48
Beverage and tobacco product manufacturing	7,228.67	368.81	180.34	337.65
Textile mills and textile product mills	2,902.35	191.79	98.57	230.65
Apparel manufacturing	8,897.59	999.89	563.83	1,990.61
Leather and allied product manufacturing	335.53	27.51	16.01	50.30
Wood product manufacturing	1,380.90	78.73	28.48	67.95
Paper manufacturing	5,318.06	311.86	65.08	250.11
Printing and related support activities	4,956.64	141.91	54.92	177.37
Petroleum refineries	29,523.18	716.30	608.62	1,068.16
Other petroleum and coal products manufacturing	1,415.89	34.35	29.19	51.23
Chemical manufacturing	41,590.96	1,601.38	994.79	2,342.48
Plastics and rubber products manufacturing	8,850.26	489.41	115.98	525.57

Table D2. Inventories by stage of fabrication for manufacturing industry in southern California region (in millions of 2010 dollars).—Continued

[Data in second column from Minnesota IMPLAN Group, Inc. (2012). Numbers in the remaining three columns computed by the authors]

Sector	2010 Annual sales	Materials and supplies	Work-in-process	Finished goods
Nonmetallic mineral product manufacturing	3,519.98	189.38	49.89	233.67
Iron and steel mills and steel product manufacturing	2,114.57	87.53	77.65	76.14
Other primary metal manufacturing	3,620.23	149.85	132.94	130.36
Fabricated metal product manufacturing	17,220.63	967.51	811.00	887.03
Machinery manufacturing	9,722.29	593.68	414.70	490.08
Computer and electronic product manufacturing	44,222.52	2,734.30	2,421.57	2,016.21
Electrical equipment, appliance, and component manufacturing	5,715.18	358.99	301.94	177.81
Automobile and light duty motor vehicle manufacturing	1,280.57	34.56	17.32	22.83
Ship and boat building and repairing	110.11	5.13	37.90	4.27
Other transportation equipment manufacturing	29,020.87	949.73	3,166.80	694.58
Furniture and related product manufacturing	4,223.61	287.88	103.28	187.84
Miscellaneous manufacturing	13,535.31	769.65	439.81	1,139.50
Wholesale	70,405.20			
Retail trade	67,965.42			
Air transportation	5,447.77			
Rail transportation	1,935.02			
Water transportation	1,691.02			
Truck transportation	10,576.43			
Transit and ground passenger transport	1,528.19			
Pipeline transportation	1,119.28			
Scenic and sightseeing transportation and support activities for transportation	7,164.95			
Couriers and messengers	3,854.49			
Warehousing and storage	3,959.39			
Information	107,126.54			
Finance and insurance	127,450.38			
Real estate and rental and leasing	184,545.94			
Professional, scientific, and technical services	118,419.85			

Table D2. Inventories by stage of fabrication for manufacturing industry in southern California region (in millions of 2010 dollars).—Continued

[Data in second column from Minnesota IMPLAN Group, Inc. (2012). Numbers in the remaining three columns computed by the authors]

Sector	2010 Annual sales	Materials and supplies	Work-in-process	Finished goods
Administrative and support and waste management and remediation services	38,541.13			
Educational services	14,022.91			
Health care and social assistance	85,694.17			
Arts, entertainment, and recreation	25,645.11			
Other amusement and recreation industries including marinas	1,407.32			
Accommodation and food services	6,838.84			
Food services and drinking places	35,200.46			
Other services (except public administration)	40,667.72			
Government and non-NAICS	103,768.70			
Total	271,900.35	12,608.67	10,998.50	14,222.90

Table D3. Availability of raw material inputs computed from materials and supplies inventory for the southern California region (in millions of 2010 dollars).

[Table D3 is provided online only as an Excel spreadsheet at *http://pubs.usgs.gov/of/2013/1170/h/*]

Table D4. Finished goods held by sector for the southern California region (in millions of 2010 dollars).

[Table D4 is provided online only as an Excel spreadsheet at *http://pubs.usgs.gov/of/2013/1170/h/*]

Table D5. Available inventory in the southern California region (in millions of 2010 dollars).

Sector	Value
Oilseed and grain farming	0.41
Vegetable and melon farming	11.46
Fruit and tree nut farming	29.21
Other crop farming	53.21
Animal production and aquaculture	64.90
Forestry and logging	13.23
Fishing	1.03
Hunting and trapping	0.00
Support activities for agriculture and forestry	0.00
Oil and gas extraction	416.10
Other nonmetallic mineral mining and quarrying	3.54
Other mining	71.54
Electric power generation, transmission, and distribution	0.00
Natural gas distribution	455.08
Water, sewage and other systems	1.54
Nonresidential construction	0.00
Residential construction	0.00
Food manufacturing	1,509.86
Beverage and tobacco product manufacturing	393.06
Textile mills and textile product mills	945.02
Apparel manufacturing	2,190.44
Leather and allied product manufacturing	53.80
Wood product manufacturing	186.75
Paper manufacturing	789.98
Printing and related support activities	264.58
Petroleum refineries	1,715.41
Other petroleum and coal products manufacturing	105.17
Chemical manufacturing	4,616.41
Plastics and rubber products manufacturing	1,206.19
Nonmetallic mineral product manufacturing	454.95
Iron and steel mills and steel product manufacturing	566.26
Other primary metal manufacturing	748.73
Fabricated metal product manufacturing	2,279.40
Machinery manufacturing	691.09
Computer and electronic product manufacturing	3,766.17
Electrical equipment, appliance, and component manufacturing	406.03
Automobile and light duty motor vehicle manufacturing	23.07
Ship and boat building and repairing	4.32
Other transportation equipment manufacturing	1,178.37

Table D5. Available inventory in the southern California region (in millions of 2010 dollars).—Continued

Sector	Value
Furniture and related product manufacturing	259.18
Miscellaneous manufacturing	1,356.08
Wholesale	0.00
Retail trade	0.00
Air transportation	0.00
Rail transportation	0.00
Water transportation	0.00
Truck transportation	0.00
Transit and ground passenger transport	0.00
Pipeline transportation	0.00
Scenic and sightseeing transportation and support activities for transportation	0.00
Couriers and messengers	0.00
Warehousing and storage	0.00
Information	0.00
Finance and insurance	0.00
Real estate and rental and leasing	0.00
Professional, scientific, and technical services	0.00
Administrative and support and waste management and remediation services	0.00
Educational services	0.00
Health care and social assistance	0.00
Arts, entertainment, and recreation	0.00
Other amusement and recreation industries including marinas	0.00
Accommodation and food services	0.00
Food services and drinking places	0.00
Other services (except public administration)	0.00
Government and non-NAICS	0.00

Appendix E. Production Recapture Factors

Sector	Description	1–90 days	91–180 days
1	Oilseed and grain farming	0.75	0.56
2	Vegetable and melon farming	0.75	0.56
3	Fruit and tree nut farming	0.75	0.56
4	Other crop farming	0.75	0.56
5	Animal production and aquaculture	0.75	0.56
6	Forestry and logging	0.75	0.56
7	Fishing	0.75	0.56
8	Hunting and trapping	0.75	0.56
9	Support activities for agriculture and forestry	0.75	0.56
10	Oil and gas extraction	0.98	0.74
11	Other nonmetallic mineral mining and quarrying	0.98	0.74
12	Other mining	0.98	0.74
13	Electric power generation, transmission, and distribution	0.90	0.68
14	Natural gas distribution	0.90	0.68
15	Water, sewage and other systems	0.90	0.68
16	Nonresidential construction	0.95	0.71
17	Residential construction	0.95	0.71
18	Food manufacturing	0.98	0.74
19	Beverage and tobacco product manufacturing	0.98	0.74
20	Textile mills and textile product mills	0.98	0.74
21	Apparel manufacturing	0.98	0.74
22	Leather and allied product manufacturing	0.98	0.74
23	Wood product manufacturing	0.98	0.74
24	Paper manufacturing	0.98	0.74
25	Printing and related support activities	0.98	0.74
26	Petroleum refineries	0.98	0.74
27	Other petroleum and coal products manufacturing	0.98	0.74
28	Chemical manufacturing	0.98	0.74
29	Plastics and rubber products manufacturing	0.98	0.74
30	Nonmetallic mineral product manufacturing	0.98	0.74
31	Iron and steel mills and steel product manufacturing	0.98	0.74
32	Other primary metal manufacturing	0.98	0.74
33	Fabricated metal product manufacturing	0.98	0.74

Appendix E. Production Recapture Factors—Continued

Sector	Description	1–90 days	91–180 days
34	Machinery manufacturing	0.98	0.74
35	Computer and electronic product manufacturing	0.98	0.74
36	Electrical equipment, appliance, and component manufacturing	0.98	0.74
37	Automobile and light duty motor vehicle manufacturing	0.98	0.74
38	Ship and boat building and repairing	0.98	0.74
39	Other transportation equipment manufacturing	0.98	0.74
40	Furniture and related product manufacturing	0.98	0.74
41	Miscellaneous manufacturing	0.98	0.74
42	Wholesale	0.87	0.65
43	Retail trade	0.87	0.65
44	Air transportation	0.90	0.68
45	Rail transportation	0.90	0.68
46	Water transportation	0.90	0.68
47	Truck transportation	0.90	0.68
48	Transit and ground passenger transport	0.90	0.68
49	Pipeline transportation	0.90	0.68
50	Scenic and sightseeing transportation and support activities for transportation	0.90	0.68
51	Couriers and messengers	0.90	0.68
52	Warehousing and storage	0.87	0.65
53	Information	0.90	0.68
54	Finance and insurance	0.90	0.68
55	Real estate and rental and leasing	0.90	0.68
56	Professional, scientific, and technical services	0.90	0.68
57	Administrative and support and waste management and remediation services	0.90	0.68
58	Educational services	0.60	0.45
59	Health care and social assistance	0.60	0.45
60	Arts, entertainment, and recreation	0.60	0.45
61	Other amusement and recreation industries including marinas	0.60	0.45
62	Accommodation	0.60	0.45
63	Food services and drinking places	0.60	0.45
64	Other services (except public administration)	0.51	0.38
65	Government and non-NAICS	0.80	0.60