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ENGINEERING AND ECONOMIC LESSONS OF THE SAFRR TSUNAMI SCENARIO

K. A. Porter[1] and A. M. Wein[2]

ABSTRACT

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Engineering and Economic Lessons of the SAFRR Tsunami Scenario

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ABSTRACT

Disaster scenarios provide insight into society's disaster vulnerability that structural analyses and catastrophe risk models do not (and vice versa). The USGS Science Application for Risk Reduction (SAFRR) program constructed the SAFRR Tsunami Scenario, a hypothetical event resulting from an Mw 9.1 Alaskan earthquake, to help California communities with disaster planning. The tsunami would have far greater impact on California than did 2010 Chile or 2011 Tohoku. Among these are 1800 census blocks with flooded buildings; \$5 to \$10 billion in repair costs and business-interruption losses; 1/3rd of coastal small craft damaged or sunk; damage and several days of downtime for shipping, piers, and cargo; fire at marine oil terminals; and scour damage to important roads and bridges. In collaboration with facility stakeholders (port officials, US Coast Guard, Caltrans engineers, county emergency managers and others), scenario writers identified a variety of options to enhance resiliency, either through strengthening measures, emergency planning activities, or recovery strategies. Among these are: lengthening dock pilings to accommodate tsunami heights; changes to tsunami messaging protocols to increase warning time; and redundant and flexible operating capacity at coastal ports. The scenario produced new techniques and procedures, such as preliminary tsunami fragility functions for small craft, estimating the regional economic impacts from tsunami damages, and disruption and examining the effectiveness of economic resilience strategies. It highlighted some research needs, such as the economic impact from evacuating the maximum tsunami zone, and economic impacts and resilience at the local scale. A social-science assessment of the scenario process revealed that hundreds of scenario consumers such as facility operators and emergency managers found the scenario credible and plan to use it to improve their tsunami risk-management decisions.

Introduction

Disaster scenarios can provide insight into society's disaster vulnerability that structural analyses and catastrophe risk models do not. Whereas scenarios tend to be blind to outcome probability distributions (they provide partial information for risk-based decision-making) and can involve the application of judgment, they can focus deeply on a single event and involve numerous experts who are familiar with the relevant sciences and assets at risk. They capture interaction among systems and people, and depict how recovery unfolds over time. They can illuminate how human behavior affects damage and recovery. They measure societal interests in terms of dollars, deaths, and downtime. They inform decision-making for planning, mitigation, response, and recovery. Scenarios are not constrained by available methods because the process allows time to develop ones. They are not used to develop building codes, so the acceptance threshold is plausibility. Scenarios invite collaboration among experts in different disciplines to recognize and analyze uncharted failure mechanisms, such as the flooding of high-voltage transformers

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with long-duration replacement requirements [1] or the overtopping of floating-dock pilings.

SAFRR, among other projects, constructs large, plausible events worth planning for. These scenarios reflect science and engineering consensus and are intended to inform risk-management decisions by anyone responsible for disaster management. They are crafted in broad collaboration among USGS and other science partners, engineers, and other stakeholders. This work summarizes the SAFRR Tsunami Scenario, focusing on physical damage, economic consequences, and issues related to resilience strategies [2,3,4]. The scenario posits a hypothetical but highly plausible event resulting from an Mw 9.1 earthquake and tsunami originating in Alaska. Studies by subject experts and stakeholder panels, plus elements of HAZUS-MH, are used to estimate physical damage, facility downtime, and repair costs. Economic impacts in terms of business-interruption (BI) losses to the state economy are calculated for the three most major categories of physical damage: marinas and harbors, the Ports of Los Angeles and Long Beach, and property along the California coast. The BI losses are measured by the estimated reduction in the total value of goods and services produced -- California's gross domestic product (GDP). The BI losses incorporate market adjustments of price and input substitution. The potential effectiveness of additional economic resilience in affected sectors and throughout the supply chain is examined.

The Earthquake and Tsunami

The SAFRR Tsunami Scenario is a hypothetical event resulting from an Mw 9.1 Alaskan earthquake, similar to the 2011 Tohoku rupture. Located between 1946 and 1964 sources, it affects the entire California coast and represents the biggest contribution to tsunami hazard in Los Angeles (Fig. 1). Other tsunamis could produce greater local effects. But among all plausible sources, this one produces the largest statewide tsunami amplitudes. Mean recurrence intervals for the wave heights associated with the scenario vary between 100 and 1000 years along the entire coast, based on analysis of thousands of scenario tsunamis from sources around the Pacific, their recurrence rates and probabilities [2].

The hypothetical earthquake occurs at 11:50 AM PDT on Thu 27 Mar 2014, the 50th anniversary of the 1964 Good Friday Alaskan earthquake. The National Oceanic and Atmospheric Administration (NOAA) produced a series of 50 tsunami messages consistent with current practice. We focus on the part of those messages addressing California. The magnitude estimate (initially Mw 8.2) increases over time, reaching Mw 9.0 after 1 hour. A tsunami watch (meaning watch for further information) is issued at 11:53 AM PDT. A tsunami warning (to move inland to higher ground) is issued for California around 2 PM PDT, when NOAA estimates 6 to 21 hours duration of tsunami currents and runups of 2 to 5 feet. Amplitude and duration estimates increase over time as real-time measurements of the earthquake and tsunami become available. The first wave arrives in Crescent City at around 4 PM, so decision-makers there have only 2 hours to receive the message, understand it, consult with people who need to take action, decide what action to take, communicate those decisions, and successfully act. San Francisco has 3 hours of warning time (the first wave arrives around 5 PM); San Pedro, 3.5 hours. These warning times may be very challenging when action is costly and time consuming, such as dispersing ships and evacuating coastal population. The warning is downgraded to an advisory (advising people to stay away from beaches and harbors) around 8 PM on Friday 28 March and cancelled at 12 PM on Saturday 29 March 2014, indicating up to 44 hours of strong currents.

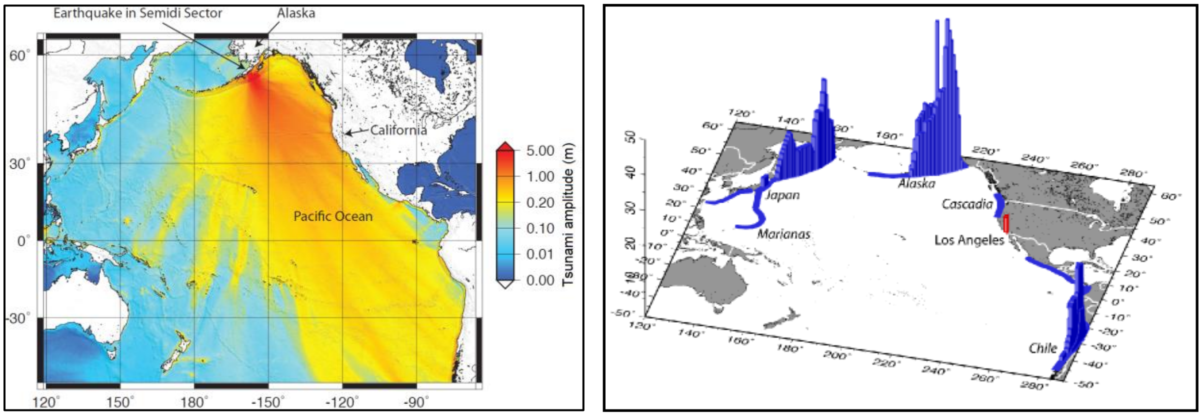

Figure 1. Left: source. Right: tsunami hazard deaggregation. This source contributes most to Los Angeles' hazard. Bars indicate probability contribution to 475-year wave height.

Hydraulic and hydrological modeling of the tsunami was performed by URS Corporation, University of Southern California, NOAA, and the University of Alaska. Where they overlap, the models generally agree. Consensus is important because it minimizes ambiguity aversion and conflict aversion—the tendency of decision-makers not to take action in the face of ambiguous or conflicting information [5]. The tsunami produces waves up to 5 m above mean higher high water (MHHW) at shore. The first wave is generally not the largest. Inundation reaches up to 100s of meters inland in some California communities. See http://bit.ly/15yN9VR for maps, which were requested by many of the 200 planners, operators, and other participants of workshops that were held after the completion of the study.

Marinas and Harbors

Observing the performance of piers and jetties in the 2004 Sumatra earthquake, Rai et al. [6] note unexpected loading conditions such as vessels floating onto piers and tsunami forces shearing connections between piers and decks. Wilson et al. [7] report various effects in California marinas from the 2010 and 2011 tsunamis: damage to small craft, barges, concrete piers, floating docks, and pilings; a fatal drowning; a broken sewer line; and sediment transport.

California has approximately 58 groups of coastal harbors and marinas with 43,000 small craft with replacement costs on the order of \$2 billion, moored to 13 million square feet of floating docks with approximately \$1.3 billion replacement cost. Quantities of harbors, small craft and docks were estimated using Google Earth imagery dated March 2011. Replacement costs were obtained from a survey of 2010–2013 model-year boat listings and the current cost of concrete modular floats. Currents and amplitudes reach 20 nautical miles per hour (kt) and 5 m above mean higher high water (MHHW). While ASCE [8], among others, provides design guidance for small craft harbors, it considers tsunami waves too rare to consider in design. There appear to be no existing probabilistic, phenomenological damage models of these assets. We developed new fragility functions using observations in [7] and derivation methods from [9]. They take the form of lognormal cumulative distribution functions. Median current capacities for boat damage, boat sinking, and dock damage are 13 kt, 20 kt, and 7.0 kt respectively. We assigned a logarithmic standard deviation of 0.4 in each case by judgment. (Better observations are needed to improve these models—a research need.) Where docks overtop pilings, we assume half the boats sink and half are damaged but repairable, while 75% of docks are destroyed and the other 25% can be repaired. These figures come from project participants' judgment, revealing another research need: to replace these judgments with empirical evidence.

Applying the foregoing models, we estimate that 35% of boats are damaged or sink and 60% of dock square footage is damaged or destroyed. Repairs cost $700 million, excluding sediment transport, hazardous material release, fire, and navigation hazards. The damage results in $30 million of BI losses. Interestingly, service sectors, including and relating to marinas (recreation, food services, and retail), indicate possible gains (0.02-1%) from price increases that outweigh losses from quantity decreases. Sectors associated with development (residential construction, water and sewage, and health care) suffer the most from marina damages with BI up to 0.03% of annual revenue. However, these sectors will likely be bolstered by reconstruction. Economic hardships from marina and harbor damage would generally be localized. Past experience indicates that marinas and harbors suffer directly through slip-fee losses and repair costs. Where alternative moorings are used the activity dependent on them may continue, but with a loss of slip fees to harbors. Furthermore, economic recovery of harbors has been impeded by delays in environmental permitting and disaster reimbursement (Richard Young, oral commun., 2013).

One option to increase resiliency is to lengthen pilings, an assertion that was verified by informal communication with harbormasters who agree that piling heights are an important issue. To enhance economic resilience, harbormasters could arrange for excess and temporary slip capacity. The presence of underutilized slips in the Port of Los Angeles could reduce the economic impacts from marina damages by 25%. Decommissioned slips at the Port of San Francisco were available for temporary installation in the Crescent City harbor after the 2011 Tohoku tsunami. Streamlining of environmental permitting and disaster reimbursements would reduce the costs of recovery delays. A local workforce with reconstruction skills will help to maintain employment in the affected community.

Ports and Commercial Fishing

Among California ports, we focused on the Ports of Los Angeles and Long Beach (POLA/LB) in San Pedro Bay because they handle 70% of containerized cargo entering the US from the Pacific Rim and 22% of U.S. total foreign value of cargo. We do not catalog here all quantities exposed in POLA/LB, but based on recent statistics, daily throughput on 27 Mar 2014 would realistically include 44,000 twenty-foot-equivalent container units (TEUs), 25,000 metric tons of dry bulk, 117,000 metric tons of liquid bulk, and 10,000 metric tons of breakbulk cargo.

We considered damage in historical tsunamis from 1922 (Chile) to 2011 (Tohoku), including vessel impact with piers; sediment transport; deformation of wharfs and cranes; flooding and hydrodynamic damage to buildings, equipment, cargo, and vehicles; floating of tanks and damage to liquid bulk terminals; wetting damage and debris deposition on port rail; flooding damage to substations; and fires. For this scenario, the most costly damage is caused by the loss of 2,650 flooded import cars temporarily stored at the port and 1,040 flooded TEUs.

Currents reach 10 kt. Currents of 4 kt have caused large vessels to part their moorings [10]. Another issue is warning time: 3.5 hr. With 30-40 large vessels typically in port and pilots' ability to remove 5-8 per hour, port dispersal by standard procedures is impossible. An 11-page dispersal plan [11] contains no guidance to trigger dispersal in a tsunami and is not exercised, raising another potential issue. It is realistic that a large moored cargo vessel that intrudes into the current would part its moorings (Fig. 2). The crew could lose control of the vessel, which could damage itself, other vessels and wharfs, and possibly cranes. However, among all 39 instances of container vessels becoming grounded or colliding with piers, wharves, or docks from June 2011 through May 2013 (see http://shipwrecklog.com), only 3 were accompanied by leakage of oil or other pollution, and only 2 sank, suggesting that hazardous material release or sinking is possible but unlikely. This scenario posits that the vessel is undamaged or is quickly refloated.

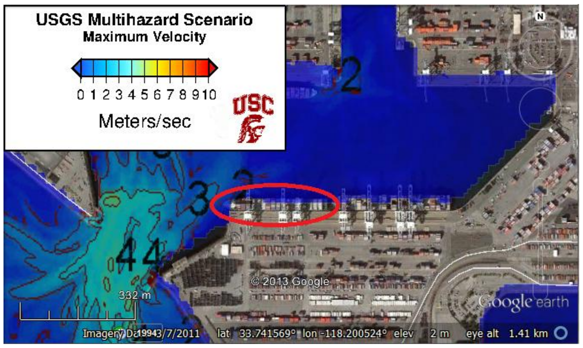

Figure 2. Currents exceed 6 kt (3 m/sec) near a berth where a vessel intrudes into the current.

Physical damage to cargo, moorings, and operating systems could cost \$100M and have an economic impact of \$103M, with two-thirds of the BI occurring in the southern California economy. The California economy is more vulnerable to disrupted trade (imports and exports) during 2 to 3 days of port shutdown and extended downtime at certain terminals. The BI losses amount to \$4.2B, with about 75% pertaining to import disruption. The sectors potentially most affected by trade disruptions are leather, metal, and motor vehicle manufacturing. Operations at the marine oil terminals could be slowed by manual operations while computerized systems are repaired. A slowdown at the marine oil terminals raises concerns about the fuel supply to southern California, particularly transportation fuel supply. Damages to POLA fishing boats and catch and lost fishing days could make fishing the most sensitive sector in terms of reduction in sector output. Ship-building and repair could also be harmed, but these impacts would be offset somewhat by reconstruction, which is not accounted for.

An analysis of economic resilience to port damages and disruption revealed that alternative modes of operation and excess capacity at the ports, inventories on and off site, export conversion to national uses, and conservation of production inputs could reduce the direct trade impacts by 85%. Notable examples are the ability for marine oil terminals to continue to operate manually and the presence of petroleum inventories at the ports, off-site, at refineries and airports. However, there is a limit to the use of inventories and prolonged handling capacity reductions could eventually threaten the fuel supply and demand other measures. It is important to understand how much downtime or slowdown can be tolerated at dedicated terminals. Where production is delayed throughout the economy, production recapture alone (including clearing the backlog of waiting ships at the ports and using overtime to catch up on lost production) could reduce BI losses by 85%. The impacts to the fishing sector would depend on readiness and priorities to protect fishing vessels (e.g., moving them out of the harbor or to more sheltered areas), the speed at which boats are repaired, and whether lost fishing days can be recuperated.

Coastal Buildings

Buildings are damaged by tsunami wetting, hydrodynamic forces, debris impact, foundation scour, floatation, and fire. Using the estimated building-stock inventory extracted from the HAZUS-MH database, we estimate that 103 million sf of coastal buildings with $22B building and content replacement cost (2010 USD) in 15 counties and 1,800 census blocks would be wetted. (The year 2010 is the most recent for which relevant economic data area available.) This is approximately equivalent to 70,000 single-family dwellings. We employed the draft vulnerability model developed for a HAZUS-MH tsunami module by Kircher (written commun., 2012) to produce the damage estimates in Table 1, which may be the first experimental application of these vulnerability functions to US tsunami losses. It is a validation only in the sense that the losses do not appear obviously unreasonable.

Table 1. Building damage in the SAFRR Tsunami Scenario.

County	Wetted building area, million ft^2	Wetted building value, 2010 $M	Content value in wetted buildings, 2010 $M	Building loss, 2010 $M	Content loss, 2010 $M
Alameda	11.8	$2,064	$1,513	$28	$233
Contra Costa	1.4	$217	$181	$2	$27
Del Norte	1.3	$152	$94	$6	$24
Humboldt	5.2	$709	$470	$18	$88
Los Angeles	10.8	$1,837	$1,055	$33	$199
Marin	10.3	$2,166	$1,316	$48	$242
Mendocino	1.0	$137	$87	$1	$13
Monterey	3.1	$510	$324	$17	$74
Orange	18.5	$3,246	$1,836	$37	$293
San Diego	20.0	$3,131	$1,787	$87	$341
San Francisco	11.8	$2,344	$1,778	$78	$365
San Luis Obispo	0.9	$121	$70	$2	$12
San Mateo	5.6	$1,089	$716	$40	$130
Santa Cruz	5.1	$882	$504	$21	$98
Ventura	2.3	$343	$197	$3	$30
Total	110	$19,000	$12,000	$420	$2,200
% of wetted value				**2.2%**	**18%**

Damage to coastal buildings and contents ($2.6 billion in 2010 USD) represents the largest category of property loss in the scenario. Most of the property loss would be uninsured. Remediation opportunities appear to be limited to new flood control measures (primarily levees) and code enhancements to ensure that replacement buildings are situated at higher elevation. We estimate BI of $1.7B from coastal damages. Relying on production recapture to recoup BI losses could reduce the economic impacts from property damages by 80%. It is important to consider continuation and recovery of business operations when the damages are primarily to contents.

We have not yet considered the costs and BI impacts of evacuation (a research need), which potentially could exacerbate the effects on businesses in the inundated area and directly affect economic activity outside of the inundated areas.

Highways and Bridges

Tsunamis scour roadway shoulders and bridge embankments. Where tsunamis reach bridge superstructures they can push them from their piers. They carry debris that can impact bridges. These damage modes were observed for example in the 2011 Tohoku tsunami. We used Google Earth to inventory coastal roads and bridges, emphasizing highway routes. Bridge superstructures are not endangered by wave amplitudes in this event. Lacking phenomenological probabilistic damage models, we created new damageability models for road shoulders and bridge embankments subject to scour. FHWA [12] provides guidance for minimum stone diameter D_{50} in abutment riprap as a function of current speed V at the constriction. We assumed median stone diameter D_{50} = 0.075 m (3 in), riprap specific gravity $S_S = 2.4$, abutment geometry parameter $K = 1.0$ in FHWA's equation, and reorganized to produce Eq. 1.

$$V < \sqrt{\frac{(S_S - 1) \cdot g \cdot D_{50}}{K}} \tag{1}$$

We assume a median capacity to resist scour equal to $\theta = 3\ V$ (i.e., a factor of safety of 3). After canceling flow depth y, reorganizing, and converting units, $\theta = 6$ kt. Given the limited (deterministic) objectives of the scenario, we use 6 kt as a deterministic threshold for scour damage to bridge abutments that intrude into the flow. For scour of the roadway shoulder, we assume soil with $D_{50} = 0.01$m and $S_S = 1.2$, which leads to very small median capacity of the shoulder soil to resist scour. This implies any flow overtopping an elevated roadway (elevated in the sense that vortices can form on the downstream side) can cause scour damage. Caltrans peer reviewed these modeling assumptions, although the many assumptions require further research.

In the scenario, 20 highway lane-miles are damaged at 7 locations on US101 near Eureka and King Salmon, CA-1 near Costa Mesa and Sunset Beach, I-80 (the San Francisco-Oakland Bay Bridge toll plaza) and I-5 near Camp Pendleton. The last two have limited route alternatives, suggesting good targets either for mitigation (e.g., armor shoulders) or special attention for emergency planning. At \$5 million per lane-mile for repair (per Caltrans engineers), repair costs \$100 million. Isolated long stretches of US101 with damage and good route alternates could take 3 months to repair. Other stretches are repaired in 1-3 days, by Caltrans' judgment. Twelve bridge abutments that intrude into flows of at least 6 kt are damaged: US101 near Bucksport and Cardiff, CA-1 at locations from Malibu to Costa Mesa, I-5 at Camp Pendleton, and two bridges on San Francisco surface streets. Caltrans estimates that repair take 3 days and \$3 million.

Tunnels

The Muni Metro tunnel at Embarcadero and Howard Streets in San Francisco is subject to flooding (Fig. 3). It connects to the BART Transbay Tube. The tsunami would partially flood the tube. (Ground slopes are near zero at the inundation line, so flooding could realistically extend farther inland.) One mitigation option is to add floodgates at the entrance that could be closed during the warning period. Another is to review BART's emergency response plan with the intent of improving response, with the objective of at least partially mitigating the effects of tsunami flooding. One detail of such a plan could be to stop BART service through the tube, deenergize electric equipment that might be flooded, then clean and possibly reenergize it afterwards, or replace it if it cannot be reenergized.

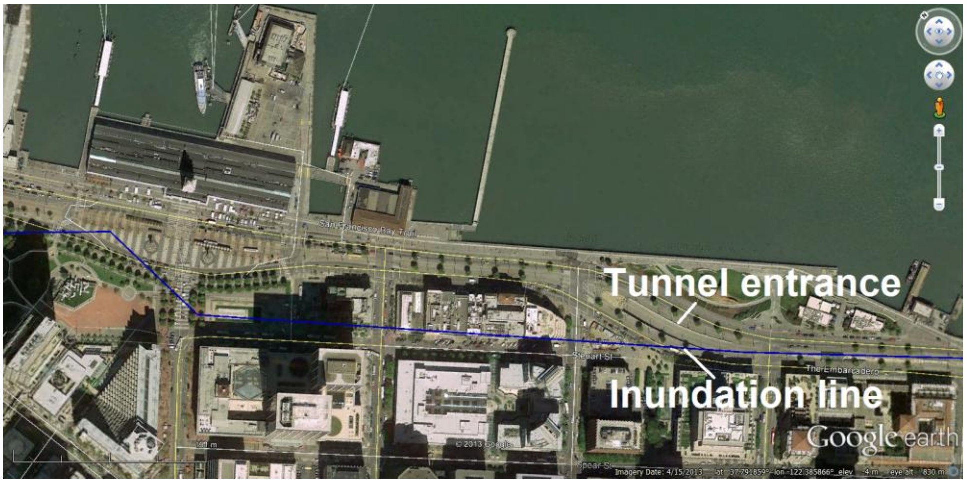

Figure 3. Potential to flood Transbay tube through Embarcadero Muni Metro tunnel entrance.

Other infrastructure

The tsunami could also damage rail and railbed at Port of Richmond, Santa Cruz, Carpinteria, POLA/LB, and San Clemente, and rolling stock at POLA/LB. The Oakland Airport would be largely inundated in the scenario. Two wastewater treatment plants (Santa Cruz and San Francisco International Airport) are also inundated and could suffer damage.

Conclusions

The tsunami scenario would have far greater impact on California than did either the 2010 Chile or 2011 Tohoku tsunamis. Wave amplitudes would reach 5 m and produce currents in excess of 10 kt, with strong currents lasting 2 days. Table 2 summarizes damage and loss, but briefly, a tsunami like this could damage or sink 1 in 3 boats, damage 60% of docks, and cause 2-3 days of downtime at ports. Flooding would affect 1,800 census blocks and 100 million square feet of buildings, comparable to 70,000 single-family dwellings, most of which would be uninsured. Property damage and other repair costs could exceed $4B to $5B. BI losses could range between $1B and $6B. The bottom line depends greatly on actions and preparation. The most significant potential for savings comes from efforts to enhance economic resilience through redundancy, flexibility, and cultural change [13]. Redundancy is present in excess capacity to relocate or continue operating and in inventories, although the strategy can be less economically efficient.

Flexibility is evident in a labor force and in systems that can operate manually or at another time and place. Cultural resilience in organizations is embodied in leadership and distributed decision making and social capital in supplier and customer relations. This type of resilience is difficult to represent within the current economic models.

The scenario was presented to 200 emergency managers and operators in several workshops. A formal evaluation of its effectiveness showed that workshop participants and other stakeholders found the scenario credible and plan to use its knowledge to change their approach to making decisions or offering advice within their organizations about tsunami hazards [14].

Table 2. Summary of California damage, downtime, BI and resilience

Asset	Damages & disruption*	Business interruption (CA GDP)	Economic resilience strategies	% BI reduction from resilience**
Coastal property	$2.6B building and content damage (mostly contents) Repair time	$1.7B	Catch up lost production (production recapture)	80%
San Pedro port trade	$100M damage 2-day port shutdown 2 weeks terminal downtime 1 month terminal slowdown	$4.3B	Ships wait out port shutdown Excess terminal capacity Inventories Export diversion Conservation Production recapture	80-95%
Coastal marinas	$700 M boat &dock damage Repair time	$30M	TBD	
Coastal roads and bridges	$100M damage SF-Oakland Bay Bridge toll plaza flooding Up to 3 month repair	TBD	TBD	
POLA fishing	Boat damage Perished catch Lost fishing days	$2M	Make up for lost fishing days	75%

* Sediment transport, fires, hazardous material, and other damage could add $1B

** Maximum resilience potential; administrative issues may prevent full reduction

Physical damages and downtime estimates were used in a model of the California economy. Economic impacts from evacuation of a larger area than that inundated by a tsunami, from damage to highways and bridges, from disruption to fishing along the coast, and from BI losses outside of California remain to be addressed. Also, focus on the impacts to local coastal economies would add insight to enhancing community resilience when the state economy is otherwise quite resilient to a large tsunami.

Operators from the Port Authority of New York and New Jersey, reflecting on the lessons they learned from 2012's Hurricane Sandy, offered the following advice to their West Coast colleagues: "Stay out of the habit of only reacting to the last event." The next large tsunami affecting California will not occur exactly in the way outlined here, but that is not the point. SAFRR's scenarios, reflecting consensus among hundreds of stakeholders and the best available science from the USGS and its partners, show what could realistically happen in a future tsunami. Consistent with SAFRR's goals and as demonstrated by [14], the SAFRR Tsunami Scenario is an event worth planning for.

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