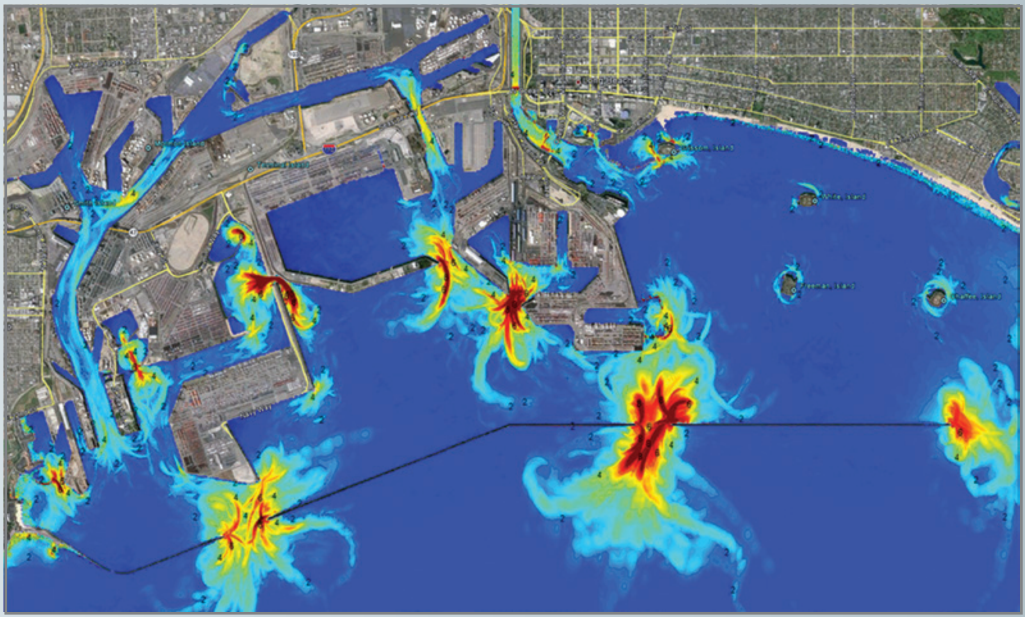
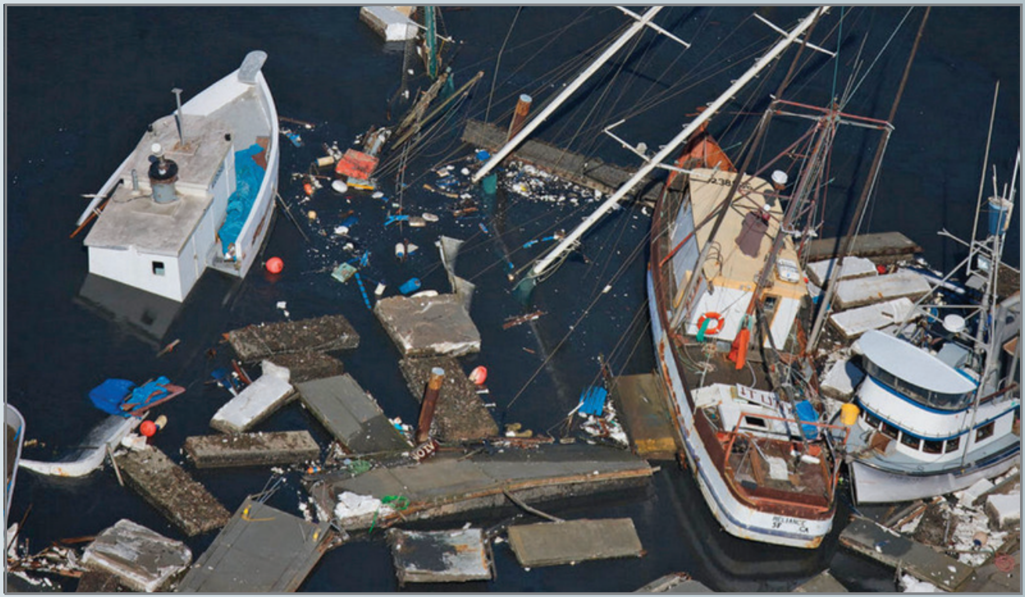
The SAFRR (Science Application for Risk Reduction) Tsunami Scenario—Executive Summary and Introduction





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COVER— Top: maximum current speeds for the Ports of Los Angeles and Long Beach generated during the SAFRR tsunami scenario (in knots). Bottom: damage to boats and docks at Crescent City Harbor, California, due to the tsunami generated by the M9.1 Tohoku earthquake in 2011.

The SAFRR (Science Application for Risk Reduction) Tsunami Scenario—Executive Summary and Introduction

By Stephanie L. Ross, Lucile M. Jones, Kevin Miller, Keith A. Porter, Anne Wein, Rick I. Wilson, Bohyun Bahng, Aggeliki Barberopoulou, Jose C. Borrero, Deborah M. Brosnan, John T. Bwarie, Eric L. Geist, Laurie A. Johnson, Stephen H. Kirby, William R. Knight, Kate Long, Patrick Lynett, Carl E. Mortensen, Dmitry J. Nicolsky, Suzanne C. Perry, Geoffrey S. Plumlee, Charles R. Real, Kenneth Ryan, Elena Suleimani, Hong Kie Thio, Vasily V. Titov, Paul M. Whitmore, and Nathan J. Wood

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Evaluation of the Tsunami Scenario

The USGS engaged a team from the University of Colorado, Boulder, to document the scenario process and provide an external evaluation of its effectiveness in increasing awareness and knowledge of the users in the coastal community. Their report will be completed after the release of the scenario. Apart from the description of the logic model process in the Introduction, they bear no responsibility for the contents of our report. The team included:

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Executive Summary

The Science Application for Risk Reduction (SAFRR) tsunami scenario depicts a hypothetical but plausible tsunami created by an earthquake offshore from the Alaska Peninsula and its impacts on the California coast. The tsunami scenario is a collaboration between the U.S. Geological Survey (USGS), the California Geological Survey, the California Governor's Office of Emergency Services (Cal OES), the National Oceanic and Atmospheric Administration (NOAA), other Federal, State, County, and local agencies, private companies, and academic and other institutions. This document presents evidence for past tsunamis, the scientific basis for the source, likely inundation areas, current velocities in key ports and harbors, physical damage and repair costs, economic consequences, environmental and ecological impacts, social vulnerability, emergency management and evacuation challenges, and policy implications for California associated with this hypothetical tsunami. We also discuss ongoing mitigation efforts by the State of California and new communication products. The intended users are those who need to make mitigation decisions before future tsunamis, and those who will need to make rapid decisions during tsunami events. The results of the tsunami scenario will help managers understand the context and consequences of their decisions and how they may improve preparedness and response. An evaluation component will assess the effectiveness of the scenario process for target stakeholders in a separate report to improve similar efforts in the future.

Scenario Design

Several historical distant-source tsunamis, including those generated by the 1946 magnitude (M) 8.1 Aleutian, 1960 M9.5 Chile, and 1964 M9.2 Alaska earthquakes, caused known inundation along portions of the northern and central California coast. Twenty wetland sites were evaluated for paleotsunami evidence as part of the most comprehensive tsunami-deposit field program ever undertaken in California. Paleotsunami sands, which indicate past tsunami inundation, were found in Half Moon Bay and Crescent City stemming from the 1946 and 1964 Alaskan events, respectively, and showed that evidence for distant-source tsunamis can be found in California's coastal marshes (see fig. 1 for locations). Tsunami sand from the 1700 Cascadia event was also found in Crescent City. Similar sand units at those sites (older than 1946 at Half Moon Bay, and between 1700 and 1964 in Crescent City) are pending further analyses to determine if they were also deposited by tsunami. In southern California, the potential for discovering tsunami deposits is low relative to other parts of the state due to the lower modeled wave heights for many tsunami sources and because most coastal wetlands in southern California have been disturbed by human activity.

The source earthquake for the scenario, defined by the USGS Tsunami Source Working Group, is set in the Semidi subduction sector, between Kodiak Island and the Shumagin Islands off the Pacific coast of the Alaska Peninsula (fig. 1 of the Introduction). The strike of the fault in that area tends to focus the waves towards the California coast and especially towards southern California and the economically critical Ports of Los Angeles and Long Beach (fig. 1). The Semidi sector's geology and tectonic setting are similar to the setting of the 2011 Tohoku event, so the assumed slip distribution is approximately that of the Tohoku earthquake adapted to the fault structure in the Semidi sector. The scenario earthquake has a moment magnitude of 9.1 and a fault length of 360 km.

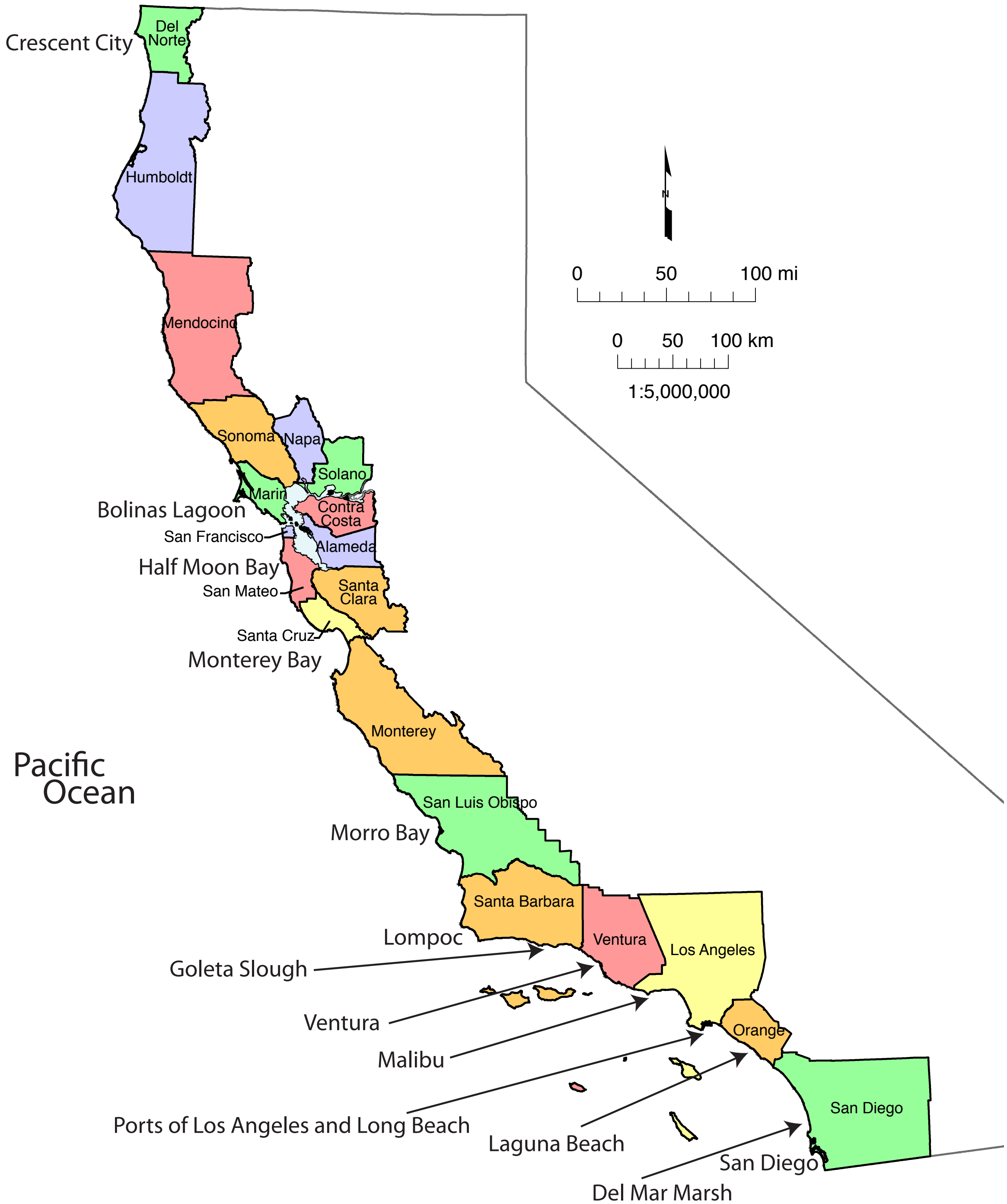

Figure 1. Map showing the 20 coastal counties in California and locations of features mentioned in the text. Digital geographic data from the State of California Spatial Information Library.

For purposes of making the scenario more tangible, we have simulated an earthquake that occurs at 11:57 a.m. PDT on Thursday March 27, 2014, which is the 50th anniversary of the 1964 Alaska earthquake and tsunami. Travel times to California from the occurrence of the earthquake to the arrival of the first tsunami waves range from 4 hours in Crescent City to almost 6 hours in San Diego (fig. 1). Thus, tsunami warnings and wave arrivals would occur during a workday afternoon.

Tsunami Modeling

Six independent teams of scientists were engaged to create computer models of the tsunami source and tsunami wave propagation field. A coarse model of wave height was run for the whole Pacific basin, higher resolution models were run for coastal areas primarily in California, and water-current velocity models were analyzed for a few ports and harbors in southern California. Overlap between the models shows that the results are consistent, stable, and credible. Only one model was chosen to create the inundation maps, but all of the main features highlighted here are shared among the models; they all show similar wave amplitudes, current velocities, and runup.

The modeled tsunami waveforms are quite different in character at different locations along the California coast. The initial waves at each location are among the largest. However, the first wave is the largest one in only a few locations such as Monterey Bay and Morro Bay (fig. 1). In most cases the largest waves arrive several hours—sometimes more than 7 hours—after the initial one. Especially in southern California, the tsunami waves attenuate slowly in time.

The shape of the California coast, bending east near Lompoc (fig. 1), causes the wave height of the tsunami (which approaches from the north) to be significantly reduced in southern California compared to the wave height in central and northern California. The tsunami hazard from this scenario is generally less in southern California than elsewhere along the California coast. However, some areas of southern California may be more vulnerable because of low-lying topography, larger coastal population, and concentration of maritime assets.

Inundation and Evacuation

The time of high tide is significant in determining the amount of inundation. By planning for the scenario earthquake at a time when high tide coincides with larger wave heights, the area inundated increases. Some of the largest Pacific Ocean tsunamis in the twentieth century (for example, waves propagating from the 1960 M9.6 Chile, 1964 M9.2 Alaska, and 2011 M9.1 Tohoku earthquakes) coincided with low tide in southern California, so this scenario is plausibly worse than the historic events. For many sections of the California coast, the inundation area for the scenario simulated in this report is up to several times the areas for those previous events.

The area of inundation is limited where the coastline is steep. More than half of California's coastline is cliff, which prevents inundation beyond the beach in those areas. In other locations, inundation varies from the first few street blocks to completely submerged peninsulas and man-made islands. The State of California has developed a map of estimated maximum inundation considering a wide range of the largest credible tsunami sources. The inundation area in the SAFRR Tsunami Scenario extends farther inland than the State's maximum inundation area in only a few places, due to more detailed modeling and higher-resolution topographic input used for the SAFRR Scenario, not because of a larger source event. The higher resolution modeling of the SAFRR Tsunami Scenario also showed tsunami surges and bores traveling several miles inland up coastal rivers. In addition to the State maps, local jurisdictions have created evacuation maps which take into account not only modeled inundation, but streets and landmarks to guide people to safe, high ground when outside. These evacuation lines are the most conservative, drawn further inland than any modeled inundation lines that exist for California, as they were produced for both life safety and emergency operations.

Over the entire California coastline, less than 40 percent of the State's maximum tsunami inundation zone is flooded in the SAFRR Tsunami Scenario. Fourteen cities have more than 1,000 residents in the scenario inundation area, with the largest affected areas in Long Beach and San Diego (fig. 1). Other highly impacted areas are low-lying portions of southern Los Angeles and northern Orange Counties, along with coastal communities in Northern California including Del Norte, Marin, San Francisco, Alameda, and Santa Cruz Counties. Nearly 92,000 people live inside the SAFRR Tsunami Scenario inundation zone. An additional 175,000 residents would be evacuated if such an order were to be given using the State's maximum tsunami inundation zone. An estimated 81,000 employees would be in the scenario inundation zone with an additional 88,000 within the State's maximum tsunami inundation zone. Additionally, more than 260,000 visitors would be expected on California's beaches and in parks on the day of the scenario event. The visitor numbers would increase to over one million if the same tsunami were to occur during summer months, when beach and coastal use is highest. An estimated 8,500 residents in the SAFRR tsunami scenario inundation zone would likely need shelter because of damage to their homes. Some island and peninsula communities, and low-lying landfill islands within the ports, could provide serious evacuation challenges because of limited exit options and short warning time prior to expected inundation. Evacuations would also be a challenge for dependent-care populations such as patients in hospitals and nursing homes and children in daycare facilities. Education and planning tailored to each of these communities would be required to make tsunami evacuations successful.

Currents in Ports and Maritime Issues

In addition to inundation, the scenario tsunami would generate strong, unpredictable currents in the ocean close to shore, causing significant damage in harbors and bays. An extrapolation of the damage in California from the 2011 Tohoku tsunami predicts that the SAFRR scenario tsunami, which produces larger waves and currents in California than did the 2011 event, will damage or sink one-third of the boats and damage or destroy over one-half of the docks in California coastal marinas. Small craft damages would include commercial fishing boats. In northern California, the scenario timing in March is considered the off-season and many fishermen would be away from their boats, which aggravates the exposure of the fleets to the tsunami. Loose boats would become floating debris or sink, posing navigational hazards to other vessels. Areas in California that survived the 2011 Tohoku tsunami unscathed could easily be damaged in this scenario and other future large tsunamis.

Boats at sea have lower risks during tsunamis, but the hazards increase in shallow, coastal waters. In southern California, March is an active fishing time and fishermen target coastal pelagic fish, which live near the surface of coastal waters, and dive for nearshore benthic invertebrates, which live near the bottom. The currents from the scenario tsunami would make coastal fishing difficult, and dive fishing would be extremely hazardous because of tsunami surge. Persistent strong currents and debris would make it difficult for boats to return to port. It might be many months before vessels could return to work because of damage to harbor infrastructure and fish processing plants. Alerts to take their boats to sea, alerts to remain at sea, and contingency planning for the possibility that they cannot return to port could improve outcomes for the fishing fleets.

Larger vessels that remain in ports might also be vulnerable. For example, given the short time between the tsunami warning being issued and the first wave arrival (3.5 hours at the Ports of Los Angeles and Long Beach), it may be difficult or impossible to fully execute the Merchant Vessel Dispersal Plan for Los Angeles and Long Beach Harbors, and damage to vessels in the ports is possible. Other ports in San Francisco Bay and San Diego Bay are also likely to be damaged in such a scenario.

Fires would likely start at many sites where fuel and petrochemicals are stored in ports and marinas. Many fires during past tsunamis have been caused when flammable liquids were released, spread by water, and ignited by mechanisms such as electrical leakage, short circuits, and sparks created by pieces of debris colliding. It is difficult to quantify the extent of the potential losses because they depend heavily on whether the fires spread.

Impacts to the Environment and Ecosystems

The scenario tsunami has the potential to cause environmental contamination in both inundated areas onshore and the coastal marine and estuarine environments. Potential sources for contamination are many and varied, and include, for example, debris from damaged piers, ships, commercial and industrial facilities, and large numbers of residences; petroleum products released from damaged ships and inundated or damaged marine petroleum terminals, petroleum storage facilities, marinas, power plants, and airports; raw sewage from inundated wastewater treatment plants; household and commercial building contents (lubricants, fuels, paints, pesticides, fertilizers, electronics); smoke, ash, and debris from fires; runoff from inundated agricultural fields containing pesticides, herbicides, and fertilizers; and redistribution of existing contaminated sediments in ports, the near-shore marine environment, and in estuaries, sloughs, and bays.

Based on recent past disasters, the cleanup of debris, damaged buildings, contaminated sediments, and other potentially hazardous materials in ports, harbors and inundation areas could be a long and costly process and add to business interruption. Characterization of debris, tsunami sediment deposits, and sands used to replenish beaches for the presence of asbestos, lead paint, pesticides, and other potentially hazardous materials would be needed to determine appropriate disposal measures (for example, placement in specialized landfills), and the ability to reuse or recycle these materials. Such assessments could add significant time and costs to the post-disaster cleanup and recovery. Environmental damage and restoration costs have not been thoroughly studied for disasters, so it is difficult to provide reasonable estimates for the total environmental costs of the scenario tsunami. This is a topic where future research is needed. Cleanup and recovery of inundated and damaged areas could take days, months, or years depending on the severity of impacts and the available resources for recovery. Improving preparedness, mitigation, and continuity planning for tsunamis can reduce damage and economic impacts and enhance recovery efforts.

Ecosystems have evolved with tsunamis but their resilience to tsunamis depends on their health and abundance. Where heavily impacted by humans, California's natural resources are no longer robust in the face of extreme events. Malibu, Laguna, and other beaches are already suffering chronic erosion problems and it is uncertain whether sand eroded by the surge would return fully or naturally; communities may be faced with expensive and controversial beach nourishment challenges.

The strong currents would pick up material so that sediment scour, sediment deposition, and environmental contamination would be serious issues and would increase downtime and recovery costs in harbors. Coastal pelagic species are unlikely to be significantly impacted but benthic invertebrate species and their habitats would be vulnerable. As with many aspects of this scenario, we cannot fully quantify all the impacts, but preliminary attempts to model the sediment transport in California due to the 2011 Tohoku tsunami show that sediment transport and environmental contamination can become major issues.

As coastal marshes are inundated, they absorb wave energy and slow the speed of tsunami surges, preventing damage to human communities. However, marshes adjacent to urban or industrial areas, including Goleta Slough and Del Mar Marsh (fig. 1) would likely be inundated with urban and or industrial debris and possibly contaminants, both of which have proven difficult to clean up. Restoration sites including coastal wetlands, beaches, shellfish beds, and low-lying islands would be inundated, and several sites would be at risk from surge, sediments, debris and contaminants. Restoration areas at Del Mar and Bolinas Lagoon (fig. 1) would be extensively inundated. This is significant because of the high financial, scientific and community investment made or being made in restoration.

Economic Implications

A significant economic impact of the scenario in California may be disruptions of the Ports of Los Angeles and Long Beach. A tsunami warning would advise evacuation of port personnel. Strong and dangerous currents would last for two days. Therefore, the ports would be shut down for at least that long. There would also be inundation of dry land in the ports resulting in approximately $100 million in damages to container and vehicle cargo and related systems, and additional downtime at some terminals. The direct exposure of port trade value from damages and downtime totals more than $1.2 billion, while associated business interruption losses would be more than triple that value. However, resilience in the forms of using excess cargo handling capacity, using existing inventories of materials, and working extra shifts could reduce these business interruption losses by an order of magnitude.

Coastal fisheries, particularly invertebrate species such as sea cucumber, sea urchin, inshore crab, and spiny lobster are vulnerable to risk from surge, debris or other habitat damage and fishery disruptions. Collectively these fisheries are valued at about $78 million per year. Shellfish farms and restored shellfish beds along the central and northern California coast and San Francisco Bay area are also at risk. Business interruption to commercial fishing at the ports would involve lost fishing days, perished catch, and damages to vessels, but in our estimates an allowance was made for the industry to make up for lost fishing days.

Although there is only a small exposure for the agricultural sector, there would be damage and impacts to soils, crops, and infrastructure that have not been experienced in recent distant-source tsunamis. Repair to agricultural fields and infrastructure could cost $4 million. This estimate does not include soil remediation, which could add substantially to costs.

These and other damages estimated from the scenario are summarized in table 1. Repair and replacement of boats and docks in California marinas are estimated to be much greater than related business interruption. Property damages include about 69,000 single-family-equivalent homes. The business interruption from property damages would be increased by evacuation of an area larger than the inundation zone. Highway repairs include potential damage to the Oakland-San Francisco Bay Bridge Toll Plaza, and railroad repairs include tracks, infrastructure, and rolling stock. Agricultural damages pertain to crop income losses. We have estimated repair and replacement costs of approximately $3.4 billion to California marinas, coastal properties, and the Ports of Los Angeles and Long Beach. Collectively, these damages expose approximately $6 billion of business interruption losses, assuming no resilience in sectors of the California economy. These potential losses could be reduced by 80–90 percent with the implementation of resilience strategies. Impacts will vary across sectors; those industries dependent on trade through the ports (and therefore relatively more affected by business interruption) potentially include leather, metals, and motor vehicle manufacturing. Service industries related to marinas may gain from price increases outstripping quantity reductions. The fishing sector may suffer from business interruption, but fishermen who escape damage to their boats and find places to moor and land their catch may benefit from higher revenue and lower competition while others may suffer significant economic hardship. Similarly, business interruption will vary across communities with local impacts such as those experienced in Crescent City after the 2011 Tohoku tsunami, for example (Wein and others, 2013). However, reconstruction that would be partially funded by disaster funds and insurance (financial forms of resilience) would eventually provide a stimulus to the local and State economies.

Potential economic losses due to physical damage and business interruption in the SAFRR tsunami scenario.

[Figures are in 2010 USD. For 2013 values, add 6 percent]

Assets	Repair cost (in millions)	Business interruption cost (in millions)	
		Without resilience strategies	With resilience strategies *
Ports of Los Angeles and Long Beach	$100	$4,300	$200-900
Fishing in Port of Los Angeles		$2	$0.3
Marinas, docks, and small craft	$700	$30	
Property	$2,600	$1,700	$300
Roads and bridges	$80		
Railroads	$2		
Agriculture	$4		
Total (rounded)	$3,500	$6,000	$500-1200

* The estimates are maximum resilience potential, but may not be implemented at that level because of administrative and managerial issues

Public Policy Issues

Translating the lessons of the SAFRR Tsunami Scenario into action may depend on changes in public policy. The USGS does not make recommendations for specific policy decisions but below we list a number of issues that could be considered by policy makers.

With few modern large tsunami experiences to draw upon, the vast majority of disaster-related policy reflects learning from other perils and it is not as well developed for tsunamis as it is for other hazards and disaster-management policy areas in both California and elsewhere in the United States. The lack of experience, risk awareness, planning, and implementation practices for tsunami mitigation, preparedness, response, and recovery in some communities could amplify impacts and losses, even beyond what has been estimated for this scenario. There is an overarching challenge to reach the general public as well as special-interest sectors such as the maritime community, and to adequately train and prepare the multiple levels and types of governments to mitigate tsunami hazards and manage the impacts and consequences of this scenario and other potential tsunamis that threaten California. Possible courses of action to strengthen tsunami-related policy and to enhance California tsunami resiliency include:

- Continue the National Tsunami Hazard Mitigation Program, TsunamiReady and affiliated state and local programs, and recruit and assist all California coastal communities, ports, and harbors to become TsunamiReady.
- Develop a coordinated and sufficiently robust policy framework for tsunami hazard assessment and mitigation planning for California coastal communities, ports, and harbors. The framework could includes adoption of official state tsunami hazard zones under the State Seismic Hazard Mapping Act, better integration of tsunami hazard zones in state and local planning and development requirements and tsunami-resilient building-design-code provisions, and consistent guidelines statewide for maritime tsunami response and recovery.
- Advance multihazard mitigation planning along California's coast and bays to more holistically address issues of future tsunami risk, sea level rise, coastal flooding and erosion, and earthquake-induced liquefaction.
- Conduct baseline ecological surveys to take account of potential tsunamis and emergency plans that include ecosystems and natural resources; they would help to alleviate damage to valuable resources and communities.
- Encourage responders and government managers at all levels to conduct self-assessments, devise exercises, and utilize tsunami evacuation playbooks and maritime mapping and guidelines under development by the State of California. These activities could test assumptions embedded in warning and evacuation protocols, emergency response and planning, and organizational structures and systems. These approaches would also test the abilities of the emergency management systems to scale up and meet the demands of large tsunami disasters.
- To help facilitate recovery following a major tsunami, promote broader participation in the National Flood Insurance Program, improved regulatory and permitting processes for port dredging and disposal and removal of debris and contaminated soil, and the development of other resources and tools to assist coastal communities, ports and harbors, and the fishing and agriculture sectors.
- Enhance tsunami risk awareness by amending California's natural hazards disclosure law to notify real estate purchasers when a property is located in a tsunami hazard zone.
- Expand California's annual ShakeOut earthquake exercise and outreach effort to include tsunami education and preparedness.
- Strengthen tsunami education and training for key professionals working in engineering as well as land use, hazard mitigation, and response planning along California's coast.
- Develop State and local policies that foster both rapid assessment of potential tsunami-related contamination and rapid decision making for disposal options should hazardous debris or sediment be identified.

Recognizing many of these issues after the 2010 Chile and 2011 Tohoku tsunamis, the State of California has begun to improve planning in the evacuation/response, maritime, land-use, and recovery communities. The SAFRR tsunami scenario provides valuable information that helps stimulate further improvements at the state and local level.

This scenario is intended to support local decisionmakers in understanding potential risks for a possible future tsunami that may require evacuation and cause damage, and to improve coordination, communication, and mitigation before that event. Positive outcomes have already resulted from the SAFRR tsunami scenario. For instance, emergency managers in areas where the scenario inundation exceeds the State's maximum inundation zone have been notified and evacuation plans have been updated appropriately. The State has also worked with NOAA's West Coast and Alaska Tsunami Warning Center to modify future message protocols by moving the location of a preset breakpoint between alert zones that would have impeded effective evacuations in this scenario. The SAFRR tsunami scenario provides the basis for further improvements to the resilience of coastal communities to future large tsunamis. Although our specific results pertain to California, the approach and the lessons learned from our scenario can be applied to other regions.

For more detail on these results, please see the other chapters of this report. They are available at *http://pubs.usgs.gov/of/2013/1170*

Introduction

By Stephanie L. Ross, Lucile M. Jones, Keith A. Porter, Liesel A. Ritchie, and Hong Kie Thio

The U.S. Geological Survey Science Application for Risk Reduction (SAFRR) project, in collaboration with the California Geological Survey (CGS), the California Governor's Office of Emergency Services (Cal OES), the National Oceanic and Atmospheric Administration (NOAA), other Federal, State, County, and local agencies, private companies, and academic and other institutions, have developed the SAFRR tsunami scenario to describe in detail the impacts of a tsunami generated by a hypothetical but realistic moment magnitude (M) 9.1 earthquake offshore of the Alaska Peninsula (fig. 1). Our target audience includes people who need to plan for a potential tsunami such as emergency managers, business continuity planners, maritime managers, land use planners, corporate real estate managers, and elected officials. This scenario attempts to provide these people more information about what they are planning for.

The overarching objective of SAFRR and its predecessor, the Multi-Hazards Demonstration Project (MHDP), is to foster the use of science in decision making in order to help communities reduce losses from natural disasters. As requested by emergency managers and other community partners, our primary approach has been to provide comprehensive, scientifically credible scenarios that start with a model of a meteorological or geologic event and extend it through estimates of damage, casualties, and major social and economic consequences at the societal level. The scenarios are based on plausible events that are likely enough to be worth planning for and may require multijurisdictional or regional planning. No scientist can guarantee that a particular disaster will happen, but a plausible event is one that is consistent with our scientific knowledge. An event worth planning for is one that is plausible and would produce such significant effects that preparation for this event will improve outcomes for a variety of possible occurrences.

The first MHDP product was the ShakeOut scenario (Jones and others, 2008), addressing a hypothetical earthquake on the southern San Andreas Fault. The ShakeOut scenario spawned the successful Great California ShakeOut, now an annual event and the nation's largest emergency preparedness exercise. It has also been adopted in other states and abroad with the same name, making the ShakeOut an international contribution. The ShakeOut scenario was followed by the ARkStorm scenario (Porter and others, 2010), which addresses California winter storms that surpass hurricanes in their destructive potential.

Some of the tsunami scenario's goals included developing advanced models of currents and inundation for the event; spurring research related to Alaskan earthquake sources; engaging port, harbor and Coast Guard decision makers; estimating the physical damages and downtimes, and examining the economic impacts to the California economy with and without resilience; understanding the ecological, environmental, and societal impacts of coastal inundation; creating enhanced communication products for decision-making before, during, and after a tsunami; and evaluating the scenario-development process. The State of California, through CGS and Cal OES, is using the SAFRR tsunami scenario as an opportunity to evaluate policies regarding tsunami impact. The scenario will serve as a long-lasting resource to enhance preparedness and inform decision makers.

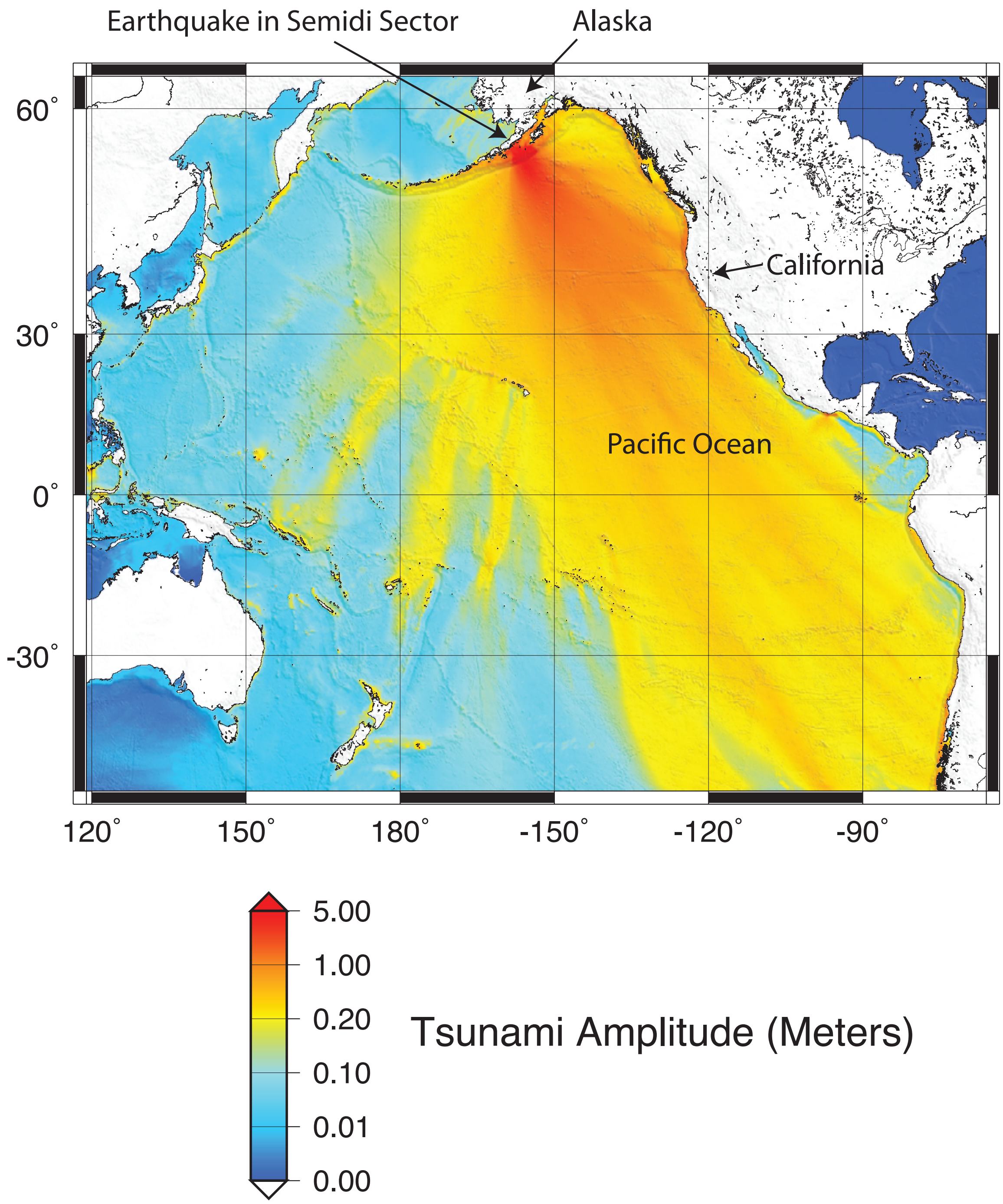

Figure 1. Maximum wave heights of the tsunami simulated in the SAFRR (Science Application for Risk Reduction) tsunami scenario across the Pacific basin.

To accomplish such a broad set of goals, we needed to engage a wide range of disciplines. The SAFRR tsunami scenario was organized by a coordinating committee and several working groups, including Earthquake Source, Paleotsunami/Geology Field Work, Tsunami Modeling and Mapping, Engineering and Physical Impacts, Ecological Impacts, Environmental Impacts, Emergency Management and Education, Social Vulnerability, Economic and Business Impacts, Policy, and Evaluators. The coordinating committee included the working group leads. To ensure that specialists from a wide range of disciplines stayed on the same evolving page, the coordinating committee held biweekly teleconferences. Members of individual working groups were invited to join the calls. The tsunami modelers remained engaged, participating in the teleconferences to make sure their results were understood and appropriately applied.

The tsunami scenario process is being evaluated by researchers from the Natural Hazards Center at the University of Colorado Boulder. This is the first time that a scenario of this scale has been formally and systematically evaluated by an external party. As an early step in the evaluation process, a logic model (fig. 2) was developed in consultation with key stakeholders to illustrate how the scenario is intended to achieve the goal of fostering the use of science in decision making. The logic model demonstrates that resource investment and activities in working groups produce project outputs that are designed to improve community resilience to tsunamis. It helps ensure a common understanding of the way the project is intended to work, how activities are monitored, and how outputs and outcomes are evaluated.

The model presented here is somewhat different from more traditional logic models that present detailed inputs such as staff/personnel time, volunteers, partners, money, materials, equipment, technology, and so forth. On the far left side of the tsunami scenario logic model are the highest level inputs associated with the development of the tsunami scenario—the working groups. There are a total of 10 working groups, with an additional committee facilitating the coordination and integration of all of these groups. In each box is the name of the working group and its fundamental responsibilities. Moving to the center of the model are the outputs expected as a result of the combined efforts of the workings groups. This is the "what" component of the project—what is being done? Included in those boxes are the various activities associated with the tsunami scenario, all of which are conducted in the context of the desired outcomes of the project—the next column to the right. The content of these boxes represents the "so what?" of the project, or the impacts of the efforts of the working groups and the overall scenario. It is the desired project outcomes that frame the working group efforts and the project outputs; they also guide evaluation efforts. On the far right of the model is the ultimate goal of the tsunami scenario—to foster the use of science in decision-making. Finally, the "ongoing evaluation activities" label at the bottom of the graphic represents the notion that reflection and evaluation are continuous throughout the life of the project, from its developmental and formative phases through the rollout of the scenario.

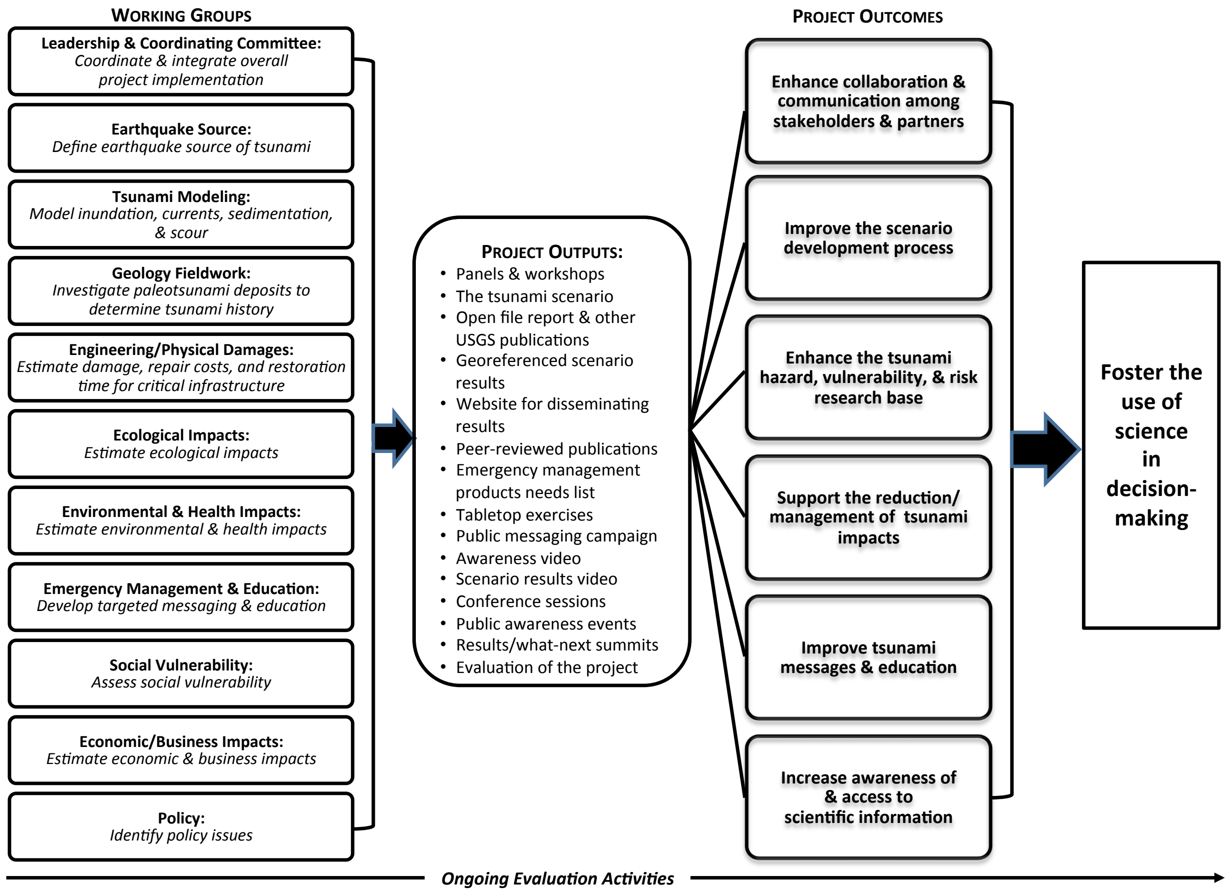

Figure 2. Tsunami scenario project logic model.

Because of the national economic importance of the Ports of Los Angeles and Long Beach, the source earthquake was designed to impact southern California. The scenario earthquake, defined by the USGS Tsunami Source Working Group, is an earthquake similar to the 2011 M9.1 Tohoku event, but set in the Semidi subduction sector (fig. 1) between Kodiak Island and the Shumagin Islands off the Pacific coast of the Alaska Peninsula (Kirby and others, 2013). Comparisons of the geology and tectonic settings between Tohoku and the Semidi sector suggest that this location is appropriate and the earthquake plausible.

Several tsunami-modeling studies were conducted covering a range of methods, geographic locations, and model resolutions (SAFRR Tsunami Modeling Working Group, 2013). Two studies examined how including different models of the physics of earthquake rupture and different characterization of the tsunami generating process affects the tsunami as it strikes southern California. Another two studies used the generation of the tsunami as inputs and then modeled the propagation of the waves across the ocean, into the near shore environment, and onto land.

Tsunami models are computed by representing the ocean at points on a grid. Coarse grids were used to model the tsunami in the open ocean and progressively finer grids were used to model the tsunami near shore and in important locations. Tsunamis increase in height as they approach the shore. In southern California, the tsunami amplitudes would range from 1 to 3 meters near shore. In central California, from Lompoc through Marin County, they would range from 2 to 7 meters in amplitude. And in northern California, the range would be from 3 to 7 meters. Project modelers assumed high tide conditions, increasing the total tsunami height by about a meter.

Where there was geographic overlap, the results from several modelers are remarkably similar even though the modeling methods differ. The similarity between different models suggests a degree of scientific consensus that should provide confidence in the scenario results.

These models were used to draw inundation lines that delimit the area of dry land that is flooded during the tsunami. Those inundation lines were adjusted by examining fine-scale structures such as steep beaches and levees that may not be well represented in the gridded bathymetric and topographic data used in the numerical calculations. These examinations used high-resolution topographic data, aerial photography, and site visits by field teams.

Two other studies modeled the hydrodynamics, including current velocities, in the Ports of Los Angeles and Long Beach, San Diego, and in Ventura Harbor. High current velocities would occur where the scenario tsunami would be forced through channels and these highly localized features could produce jets and whirlpools. Maximum modeled currents in Ventura Harbor would exceed 14 knots and have widespread speeds of 8 knots, which is fast enough to cause significant damage. In contrast, the Ports of Los Angeles, Long Beach, and San Diego would experience widespread currents that are less extreme, reaching 6 to 8 knots in just a few locations. But, in those locations, the modeled currents are fast enough to damage mooring dolphins, potentially break mooring lines, and impede navigation.

We determined how often tsunami waves similar to those in the SAFRR tsunami scenario would impact different spots along the California coast. Using an aggregate of sources from around the Pacific Ocean, waves with the same or larger offshore amplitude as those in the scenario would occur, on average, on the order of hundreds of years (fig. 3).

Earthquakes like the scenario posited here have happened elsewhere under very similar geological conditions. When they have happened, tsunamis resulted. Several historical transoceanic tsunamis, including those produced by the 1946 M8.1 Aleutian, 1960 M9.5 Chile, and 1964 M9.2 Alaska earthquakes, caused known inundation along portions of the northern and central California coast. Earthquakes like these will occur in the future and will generate tsunamis. The physics of wave motion are well understood, and there is very little uncertainty about tsunami travel times. When they impinge on the built environment, even in well constructed areas, tsunamis cause damage; they can injure and kill people, and they can disrupt the economy. California's experience with tsunamis over the last century is probably far from the worst that can happen. A tsunami generated by the scenario source discussed here would be bigger and cause much more damage in California than the 2011 Tohoku tsunami, the Chilean tsunamis of 2010, 1960, and 1922, and the Alaskan-Aleutians tsunamis of 1964 and 1946. Thus, there is strong reason to believe that California faces a tsunami threat that could realistically cause billions of dollars in losses and, although we have not discussed it here, substantial loss of life.

There are uncertainties. The degree of inundation in any particular place, and the resulting losses, are uncertain for many reasons, having to do with imperfect knowledge about the tsunami source, bathymetry and topography, roughness of the sea floor, precise quantities and vulnerability of assets, the resourcefulness of emergency responders and the people and businesses whose property is affected, and financial responses. The uncertainties operate in both

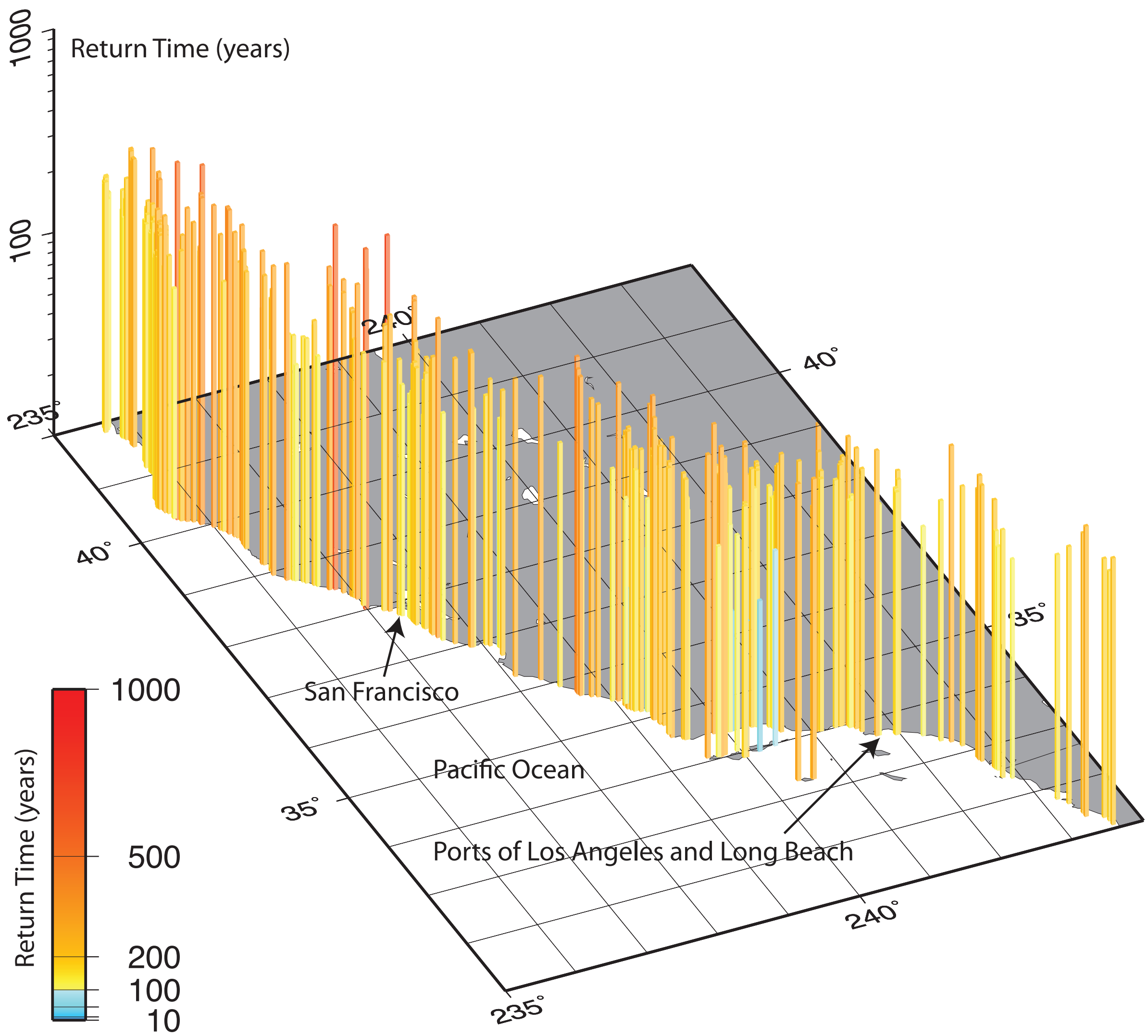

Figure 3. Map of the California coast, where bars at individual locations show equivalent return times of the offshore amplitudes of the tsunami simulated by the SAFRR (Science Application for Risk Reduction) scenario when compared to the Probabilistic Tsunami Hazard Analysis of Thio and others (2010). The probabilistic map is based on a comprehensive analysis of tsunamis from sources around the Pacific, their recurrence rates and probabilities, and is an aggregate of thousands of individual scenario calculations. The return time gives the average time between tsunami waves, at each site, that are as larger or larger than the SAFRR scenario tsunami at that site and is shown by both the height and color of each bar.

directions: the particular earthquake-generated tsunami simulated in this project could produce more severe losses than are depicted here, as well as less severe losses. Earth scientists, engineers and social scientists will continue to study the processes discussed here in an attempt to better understand them and more accurately estimate the outcomes of future tsunamis. When tsunamis occur that affect California, there will probably be surprises, effects, or sequences of events we did not expect—a bigger earthquake than we imagined possible could occur, or our engineered facilities and defense structures may not perform as well as we had planned, or people could make unexpected mistakes in the response that aggravates the damage and loss of life.

There are also caveats. The scenario describes actions taken by ports where all communication and emergency response activities are performed quickly and correctly, largely without serious mistakes. But human error, including unanticipated delays in communication or decision-making, could lead to greater damage, greater economic losses, or more severe environmental outcomes than are posited here. There are also likely unforeseen short- and long-term issues that we may not have considered. And although the scenario was relatively detailed in and around the Ports of Los Angeles and Long Beach, other areas of the California coastline outside the ports were evaluated with less detail. Some of these areas, especially in central and northern California, will experience higher waves than southern California. The evaluation of those regions has not been done to the same level of detail as for the Ports of Los Angeles and Long Beach. Consequently, we might not fully understand the short- and long-term impacts to these other ports and harbors.

The timing of the tsunami can have a considerable impact on potential exposure to damage and risk to life. The scenario is set during March 2014, coinciding with the 50th anniversary of the 1964 Alaska earthquake and tsunami. Although the outcomes of the scenario at that time are significant, greater challenges and impacts might result if the scenario were to occur during a summer weekend when beachgoers and recreational boaters are more numerous along the California coast.

The time of high tide is significant in determining inundation. By planning this earthquake at a time when high tide coincides with larger wave heights, the area inundated increases. Though the highest tides only cover about 4 hours per day, preparing for this possibility ensures that we are well prepared, especially when hazardous tsunami conditions can last for up to one or two days. In the other direction, long-term sea level rise due to climate change will increase the inundation area if an event like the SAFRR tsunami scenario occurs later in this century; we have not included that effect in our analysis.

While our uncertainties and caveats affect the quantities we have estimated, they do not change our finding about the qualitative threat to California that is posed by tsunamis from distant earthquakes. Because our uncertainties operate in both directions, and because an underestimate of loss can be graver than an overestimate, they provide more reason to prepare for a severe California tsunami, rather than to wait for scientists to eliminate all uncertainties.

In a speech to the National Defense Executive Reserve Conference (1957), President Eisenhower said, “Plans are worthless, but planning is everything. There is a very great distinction because when you are planning for an emergency you must start with this one thing: the very definition of "emergency" is that it is unexpected, therefore it is not going to happen the way you are planning.” The SAFRR Tsunami Scenario depicts an event that will not happen exactly as presented. However, it provides a useful opportunity for planning.

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