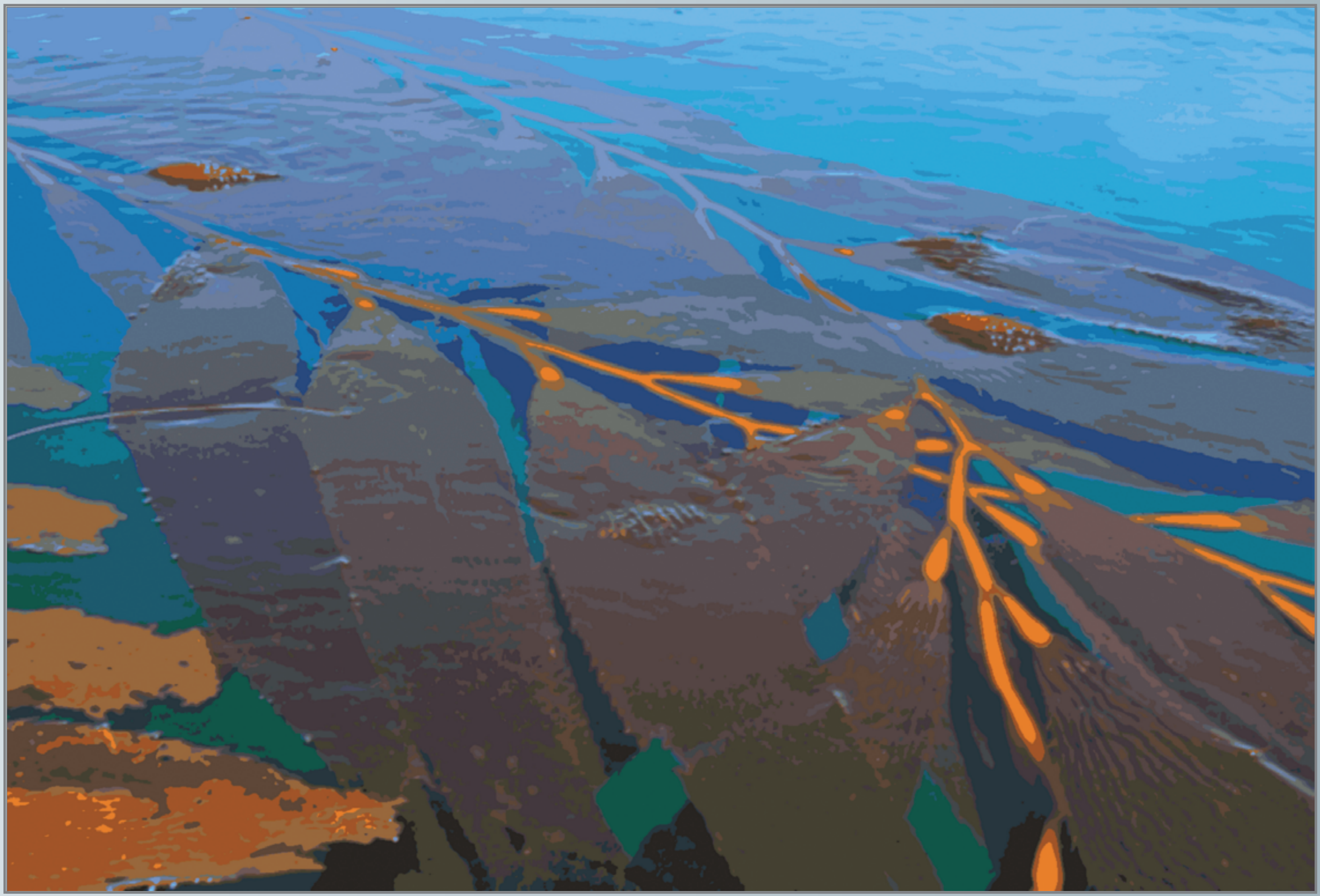
SAFRR Tsunami Scenario—Impacts on California Ecosystems, Species, Marine Natural Resources, and Fisheries



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Cover: Photograph of California's vulnerable nearshore kelp forests. Image courtesy of Deborah Brosnan,

The SAFRR (Science Application for Risk Reduction) Tsunami Scenario

Stephanie Ross and Lucile Jones, Editors

SAFRR Tsunami Scenario—Impacts on California Ecosystems, Species, Marine Natural Resources, and Fisheries

By Deborah Brosnan, Anne Wein, and Rick Wilson

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SAFRR Tsunami Scenario—Impacts on California Ecosystems, Species, Marine Natural Resources, and Fisheries

Section 1. California's Coastal and Marine Ecosystems, Natural Resources, and Endangered Species in the SAFRR Tsunami Scenario: Ecological Factors Overview

By Deborah M. Brosnan

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The Science Application for Risk Reduction (SAFRR) Tsunami Scenario envisions a magnitude 9.1 earthquake occurring off the Alaskan coast on March 27, 2014, at 11.57 a.m. PDT, and generating a tsunami that strikes the California coast between 4 and 6 hours later. The tsunami is not a single wave but an extended series of tsunami surges accompanied by strong and erratic currents that last for several hours to days. Scientific analysis indicates that this is a plausible event (SAFRR Tsunami Modeling Working Group, 2013).

This chapter evaluates the effects of the SAFRR Tsunami Scenario on California's critical ecosystems, natural resources, and species. Our evaluation indicates that all of California's low-lying coastal habitats, including beaches, marshes and sloughs, rivers and waterways connected to the sea, will be inundated and that nearshore submarine habitats will be affected. Beach erosion and complex or high volumes of debris will be major post-tsunami challenges. Several endangered species and protected areas are at risk. Commercial fisheries and fishing fleets will be affected. There is evidence that in some areas intact ecosystems, notably sand dunes, will act as natural defenses against the tsunami waves. However, ecosystems do not provide blanket protection against tsunami surge. The consequences of ecological and natural resource damage are estimated in the millions of dollars. These costs are driven partly by the loss of ecosystem services, including use of beaches, marine habitats, parks, damage to commercially important natural resources, water table and soil contamination, as well as cumulative and follow-on impacts where, for example, increased erosion during the tsunami can in turn lead to subsequent damage and loss to coastal properties. Recovery is likely to be lengthy and expensive. The inability to access favorite natural habitats post-tsunami for recreation or solace can exacerbate human suffering and economic losses.

This report provides an introduction to the role of ecosystems and natural resources in tsunamis and a brief discussion of mitigation and preparedness approaches that can be useful in SAFRR Tsunami Scenario planning. A separate section focuses on specific impacts of the SAFRR Tsunami Scenario on California's ecosystems and endangered species (Section 2). A section on commercial fisheries and the fishing fleet (Section 3) documents the plausible effects on California's commercial fishery resources, fishing fleets, and communities. Sections 2 and 3 each include practical preparedness options for communities and suggestions on information needs or research. Although forming part of a larger ecological chapter, Sections 2 and 3 are each designed as a stand-alone in order to accommodate different audiences.

Coastal and nearshore marine ecosystems are adapted to periodic natural hazards and have an evolved resilience (Holling, 1973; Gunderson and Pritchard, 2002; Folke and others, 2004; Hughes and others, 2005; Brosnan, 2012). Ecological resilience is not, however, equivalent to resistance and the systems are not immune to being damaged by hazards (Holling, 1973; Gunderson and Pritchard, 2002; Hughes and others, 2005; Ramachandran and others, 2005). Resilience implies that the species and ecosystems are damaged by the event, but that they are able to recover naturally over time, although recovery may take decades or longer. Ecological resilience depends on many factors including the robustness and spatial abundance of the ecosystem, history of previous disturbances, and severity of the hazard (Nystrom and Folke, 2001; Gunderson and Pritchard, 2002; Hughes and others, 2005). There is a threshold beyond which any ecosystem loses resilience and is unable to recover (for example, Holling 1973; Folke and others, 2004; Hughes and others, 2005; Brosnan, 2012). California's coastal and marine ecosystems have been severely altered, reduced or degraded by human activities. Many ecosystems do not have the same resilience against extreme events that they once had (Gunderson, and others, 2002; Folke, 2003; Hughes and others, 2005). Sea-level rise, ocean acidification, introduced species, and more severe storms add to the stresses on these coastal habitats, and can diminish their resilience to extreme natural hazards (Nicholls and others, 1999; Barbier and others, 2008; National Research Council of the National Academies (NRC), 2010; Shepard and others, 2012; Arkema and others, 2013).

SAFRR Tsunami Scenario damage to coastal and nearshore ecosystems will result from tidal amplitude, strong currents, and mass-inundation that extends inland to more than 10 km in some places (Wilson, 2013). Debris and pollution created by human structures poses a major threat in many areas. Species and ecosystems do not possess evolved resilience to these debris hazards and can be greatly affected by them. The debris may include residential property debris, ships, military ordnance, industrial compounds, such as crude oil, petroleum products, carcinogenic compounds, and other human-made products (Plumlee and others, 2013). These can seriously affect coastal and marine life including fishes, sea turtles, and marine mammals, as well as posing a threat to human health. In the SAFRR Tsunami Scenario, natural habitats located in proximity to urban, ports, or industrial areas are at risk from such complex debris that will be deposited on beaches, nearshore seabed, and trapped in marshes and sloughs. Flooding is not predicted for the San Onofre nuclear generating station (now inoperative), but any other nuclear materials including for example ordnance exposed to the tsunami impacts may potentially affect the coastal and marine life.

It is now well established that coastal ecosystems can shield natural resources, people, and property against extreme storms and sea-level rise, and that loss of these system exacerbates damage and costs (for example, Nicholls and others, 1999; Day and others, 2007; Barbier and others, 2008; Costanza and others, 2008; National Research Council of the National Academies (NRC), 2010; Shepard and others, 2012; Arkema and others, 2013). However, tsunamis differ from extreme storms or sea-level rise and the ways in which coastal ecosystems can protect humans during tsunamis has not been fully studied.

Analyses from previous tsunamis showed mixed results (Chang and others, 2006; Chatenoux and Peduzzi, 2007; Cochard and others, 2008; Meadows and Brosnan, 2008; Gedan and others, 2011; Renaud and others, 2013). Some indicated that under certain conditions reefs, sand dunes, marshes, trees, and other coastal vegetation protected property and human communities (Fernando and others, 2007a, 2007b; Chang and others, 2006; Danielson and others, 2005, 2006; Olwig and others, 2007; Gedan and others, 2011). In other instances, they failed to do so (Kathiresan and Rahendran, 2005; Chatenoux and Peduzzi, 2007; Kerr and others, 2006, 2007; Cochard and others, 2008; Gedan and others, 2011; Renaud and others, 2013). Proximity to the source event, tidal amplitude and severity of the currents, ecosystem robustness, and severity of existing habitat damage have been shown to be determining factors (Renaud and others, 2013). However, there is as yet little clarity on this issue. There is a great need for research to identify the range of meaningful conditions and threshold levels to inform more effective disaster risk reduction. Strengthening coastal ecosystems to protect communities against storms and sea-level rise will not automatically protect against tsunamis. But, failing to strengthen these systems will, in certain situations, result in greater damage during a tsunami.

Communities will need to be prepared to tackle complex regulatory questions as part of planning and response preparation. Other studies have indicated that complex regulations and policies in addition to challenges to existing regulations have all added to the recovery time and cost (Wilson and others, 2012; Brosnan and others, Section 3, below). Many agencies are unlikely to be prepared for the type of inter-agency coordination and decision-making required, much of which will be unprecedented. Identifying and coordinating with responsible agencies in order to anticipate and plan for a significant tsunami such as the SAFRR Tsunami Scenario may be a valuable planning investment.

This evaluation sends an important educational message to communities and regulators on the value of incorporating ecological and natural resource impacts into emergency management, and provides potential opportunities for doing so.

The scenario focuses on a large, but distinctly plausible tsunami event. Most communities and habitats face multiple hazards each with varying levels of risk and vulnerability. Mitigation that, as far as possible, addresses multiple hazards is usually more cost-effective, efficient and useful to managers and communities. For instance, many of southern California's beaches are already battling erosion, and the same inherent principles of protecting beaches, vulnerable communities, and property apply to storms and tsunamis, even though the two events are oceanographically dissimilar. Transformative ecological and engineering solutions may be necessary and could be considered under a multi-hazard umbrella.

Another important way to look at multi-hazards is from the perspective of interconnectedness or "interaction-terms." For example, tsunami impacts on commercial fish species and the fishing industry is determined by linkages among several factors, many of which are outside of the control of the fishing industry or fishery regulators (Section 3). Identifying the key linkages or interactions and mitigating for these can strengthen emergency management and disaster risk reduction.

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Section 2. Impacts of SAFRR Tsunami Scenario on California's Coastal and Marine Habitats, Resources and Endangered Species

By Deborah M. Brosnan

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The Science Application for Risk Reduction (SAFRR) Tsunami Scenario will significantly affect California's coastal and marine ecosystems, resources and endangered and protected species. All low-lying coastal habitats, such as beaches and marshes, will be inundated. Strong currents, massive water flows, and tsunami debris are likely to cause severe ecological harm in many places. This in turn will affect human communities. Ecological damage will result in measurable economic costs and may reduce revenues and quality of life in locations where people cannot access beaches and reserves for work, recreation, or solace. Contaminated wells and water tables, sewage line breaks or spills exacerbate the challenges. Recovery times may be lengthy, involving one to many years, especially where beaches have been eroded and there are high volumes of debris and/or contaminants present. California's natural resource based communities, many of whom have been affected by recent tsunamis (Wilson and others, 2012), will be adversely affected in this scenario (Brosnan and others, Section 3, below). Commercial fisheries will be affected from damage to fishing ports, infrastructure, and fishing grounds.

Marine and coastal ecosystems mitigate the effects of storms and sea-level changes (Arkema and others, 2013). However, tsunami inundation differs from wind waves and storm surges and is frequently more severe. Overtopping by long waves of high amplitude is accompanied by fast-moving, massive ocean inundation and flooding. Wave heights, mass flow of water and water depth are often greater than those recorded for extreme storms (Hettiarachchi and others, 2013). Tsunamis also contribute to changes in sea-bed bathymetry of nearshore regions leading to long-term changes in coastal erosion patterns.

Strengthening coastal and nearshore habitats against climate change and extreme storms will not provide blanket protection against a major tsunami like the SAFRR Tsunami Scenario. In some situations, reefs, dunes, marshes, trees and other vegetation have mitigated tsunami surge and benefited vulnerable human populations, but in other events they have failed to do so (Kathiresan and Rahendran, 2005; Chang and others, 2006; Danielson and others, 2005, 2006; Kerr and others, 2006; Braatz and others, 2007; Chatenoux and Peduzzi, 2007; Fernando and others, 2007a, 2007b; Kerr and Baird, 2007; Olwig and others, 2007; Cochard and others, 2008; Japan Wildlife Research Center, 2008; Meadows and Brosnan, 2008; Gedan and others, 2011; Hettiarachchi and others, 2013; Renaud and others, 2013). There is a need to better identify those conditions under which ecosystems are effective at reducing the impact of medium to large tsunamis in order to inform preparedness. However, failure to strengthen coastal ecosystems against storms and sea-level rise will almost certainly exacerbate tsunami damage to natural habitats and vulnerable human populations.

This section describes plausible impacts on California's ecosystems and habitats, and concludes with guidelines for decision-makers and researchers. An introductory section (Section 1) provides a broader overview of the interaction between tsunamis and ecological systems. Section 3 of this chapter addresses the commercial fishery and fishing fleets. The focus is the SAFRR Tsunami Scenario but the chapter is designed to provide a meaningful framework and approach applicable to a broad range of natural hazards and extreme coastal events.

The SAFRR Tsunami Scenario

The SAFRR Tsunami Scenario depicts a hypothetical but plausible tsunami created by an earthquake of magnitude 9.1 along a fault length of 360 km in the Semidi subduction sector off the coast of Alaska. The event is modeled for 11:57 a.m. PDT on Thursday, March 27, 2014 (SAFRR Tsunami Modeling Working Group, 2013).

Tsunami Scenario Development

Six different scientific teams developed the hypothetical earthquake and tsunami wave propagation models (SAFRR Tsunami Modeling Working Group, 2013). A coarse model of wave height was run for the entire Pacific basin, higher resolution models were run for coastal areas in California, and current velocity models were analyzed for a few selected ports and harbors. Close overlap among all model results show the robustness of the science underlying the scenario event (Ross and others, 2013). One model was used to create inundation maps, but all models demonstrate general consensus in wave amplitudes, current velocities and run-up. In 2009, a maximum "worst case scenario" statewide inundation map based on several source events was developed by the California Geological Survey. Comparison with the higher resolution modeling and higher LIDAR DEM (for topographic input) used in SAFRR demonstrated that the two efforts had almost identical results with some exceptions. Higher resolution and LIDAR DEM available for SAFRR showed that the tsunami would travel farther inland and have greater amplification (0.5–1.0 m higher) in the small inlets and harbors of San Diego and San Francisco Bays (Wilson, 2013).

To evaluate ecological and natural resource impacts, we used GIS inundation, velocity and amplitude maps, and tsunami flow animations that were derived in the SAFRR models (SAFRR Tsunami Modeling Working Group, 2013; Wilson, 2013). We analyzed tsunami severity along different sections of the coast, and evaluated the potential for ecological damage based on ecosystem type, status, and any existing threats. We considered sensitive or endangered species, human use of the ecosystem (for example, fisheries or recreation), and characterized the adjacent environment, natural, residential, and/or industrial.

These results describe plausible impacts from the SAFRR tsunami on California's marine and coastal ecosystems, natural resources, and sensitive species. There are inherent limits to the evaluation arising from sources such as model uncertainties, spatial resolutions and lack of detailed quantitative ecological and impact data; thus, our results are more qualitative in many locations.

Table S2-1 provides a general statewide evaluation of the tsunami's plausible impacts on the critical ecosystems/habitats, protected areas, sensitive and endangered species, and natural resources along California's coast and nearshore waters. These are more fully described in the text using specific locations as examples. The approach of using example sites is to make the results more accessible and meaningful to a wider audience including decision-makers and the community. Inclusion or exclusion of sites does not indicate that they are more or less likely to be affected by the tsunami than other areas.

SAFRR Tsunami Characteristics

The SAFRR Tsunami is expected to reach northern California 4 hours after the earthquake and southern California between 4 and 6 hours after the earthquake. It is a prolonged surge event lasting 15 hours or more in some areas and with strong tsunami currents persisting for 1–2 days. In most cases, the largest waves arrive several hours, often as many as 7–8 hours, after the initial wave. The shape of the California coast as well as the bathymetry affects wave amplitude and speed. For example, the easterly bending coast near Lompoc causes wave height to be significantly reduced in southern California compared to the central and northern California coast. However, the currents in southern California are severe, and take longer to attenuate after the tsunami (SAFRR Tsunami Modeling Working Group, 2013).

The low-lying topography of southern California, where shoaling increases wave amplitude and inundation, combines with high population density, coastal assets, and natural resources to make this area one of the more vulnerable locations in the SAFRR Tsunami Scenario.

Other coastal and geological features affect the tsunami's severity. Confined entrances to channels, estuaries, ports, and inlets etc., act as funnels that amplify the tsunami. In areas associated with these features, the tsunami wave travels more than 10 km (more than 6 mi) upriver (Wilson, 2013). Offshore features also can dampen or amplify the effect of the tsunami. For instance, the Cobb-Eickelberg seamount chain near Crescent City, and the Mendocino fracture zone farther south act as wave guides to increase onshore wave amplitudes, making the tsunami more severe in these respective areas (SAFRR Tsunami Modeling Working Group, 2013).

Impacts on California's Ecological Resources

Habitats

California's coastal and marine habitats will be significantly affected by the SAFRR Tsunami Scenario. The intensity of impact will vary from place to place, but will be severe in numerous locations. Natural systems that shield the coast against storms can perform the same benefits in a tsunami but under more restricted conditions. The degree of benefit is affected by proximity to the event, wave amplitude and water velocity, as well as ecosystem resilience. In about one-half of California's coastal counties, the total property value per county, for which coastal habitats reduce exposure to storms and sea-level rise, is estimated at up to $9 million per county. In most of the remaining counties, the value ranges from $9 million to $900 million per county, and in the areas around San Francisco, the value is $900 million to $12 billion (Arkema and others, 2013). There is no guarantee that these ecosystems will be as effective against a major tsunami but they will certainly play a significant overall role.

Beach Ecosystems

Under the SAFRR Tsunami Scenario, California's beaches will experience several hours of inundation from multiple wave surges accompanied by strong currents, capable of eroding sand and sediments. Many beaches are likely to experience sand loss.

Beaches are key ecological and recreational sites. They are critical nesting, feeding, and stop-over sites for resident and migratory birds including the endangered snowy plover (*Charadrius nivosus*). Grunion (*Leuresthes tenuis*) need sandy shorelines to breed, and beaches are haul-out locations for marine mammals. More than 140,452,280 people visit California's beaches annually for recreation, and some 261,508 visitors are predicted to be on city, state, or federal beaches on March 27, 2014 (Wood and others, 2013). Beachfront property is desirable and highly priced.

SAFRR Tsunami Scenario models indicate highest tsunami waves amplitudes at 2–4 m. Wave amplitude generally is lower along more open coastlines but currents remain strong. Currents average 2–3 m/s in several channels and ports, but can be higher at the point of shoreline. For instance, at shallow flow depths where the tsunami comes onto the beach, models predict that current velocities may reach 5–8 m/s in some locations (SAFRR Tsunami Modeling Working Group, 2013). Inundation is significant at many beaches and towns especially those adjacent to inlets and harbors.

The sandy shores at Coronado, Huntington Beach, Newport Beach, and Seal Beach are all heavily inundated and sections of these towns are flooded. Figure S2-1 shows sections of Ocean Beach, near San Diego, indicating a tsunami beach run-up extending150–400 m along a 1 km length. Several blocks of the town also are flooded. Close to 9 km of beach length at Hollywood Beach near Oxnard will be inundated with tsunami run-up of 50–140 m.

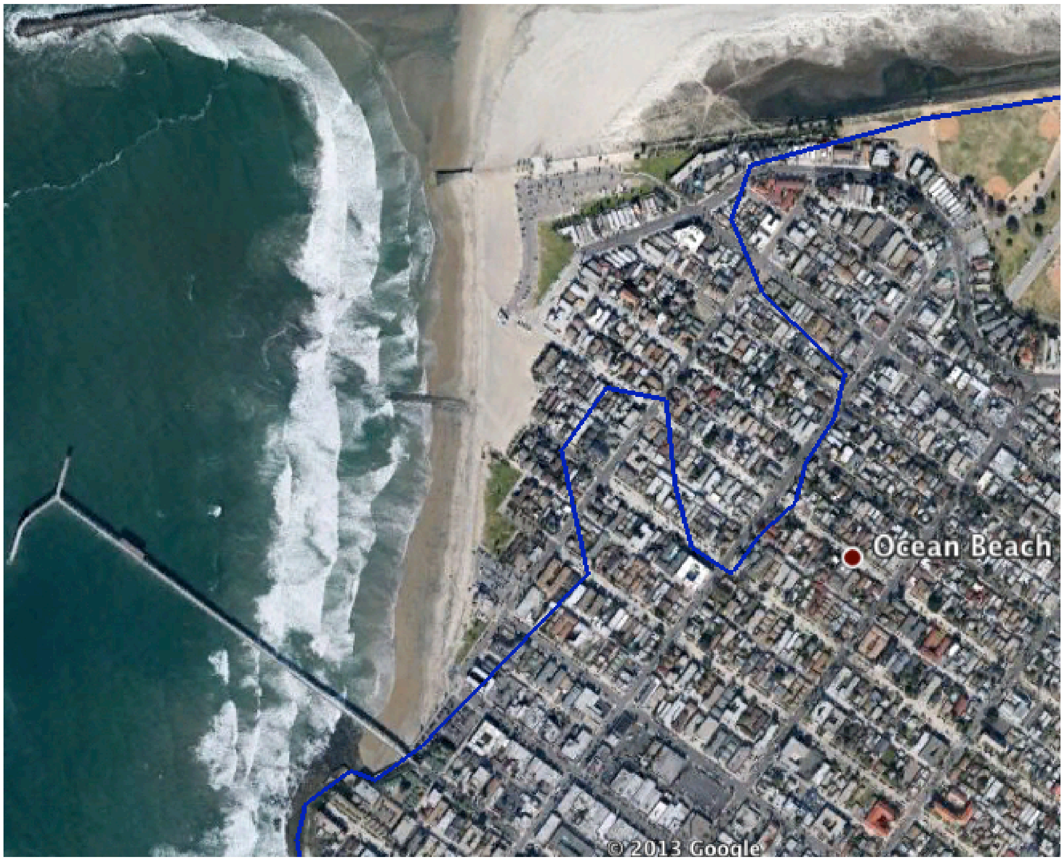

Figure S2-1. SAFRR Tsunami Scenario inundation line at Ocean Beach. In this and other chapter figures, the dark solid line is the inundation limit and represents how far the tsunami surge is forecast to intrude over the beach and parts of the town. (Image courtesy of Wilson, California Geological Survey, 2013.)

Many of California's beaches are already experiencing chronic erosion. The trend in beach loss is expected to continue even without a tsunami event (California Department of Boating and Waterways and State Coastal Conservancy, 2002; Hapke and others, 2006; Coastal Sediment Management Workgroup, 2010; University of California San Diego, Coastal Change Group, 2013). In response to current erosion problems, every year some millions of cubic meters of sand are placed on shorelines to renourish and maintain beaches and shoreline protection is the subject of considerable debate. Renourishment is expensive and the practice is controversial in some communities. Obtaining sand also is becoming more difficult and expensive because of contamination issues, transport expense, and effects on source ecosystems. The SAFRR tsunami scenario demonstrates that many of the currently eroding beaches will have severe tsunami impacts and are at risk of beach loss. Malibu Beach will experience tsunami amplitudes of up to 2.5 m. Current velocities will average 2–3 m/s with some shoreline velocities of 5–8 m/s. The results show that much of the beach will be repeatedly inundated, as will several beach-front properties, including many high value homes. Similar tsunami amplitudes are forecast on other important ecological and recreational beaches with erosion challenges, including at Laguna Beach where beach inundation is forecast to reach up to some 90 m inland.

The likelihood of sand eroded and transported by the tsunami, returning naturally onto damaged beaches is unknown. Many communities probably will be faced with controversial and expensive decisions regarding beach recovery and may find themselves in regulatory quagmires. Environmental policies and regulations become unwieldy and more complex in disaster scenarios (Wilson and others, 2012). Decisions to enforce or relax existing regulations are often made swiftly in response to a disaster and can have un-anticipated negative consequences (Wilson and others, 2012). For those California communities already embroiled in debates and litigation over their beaches, the tsunami will add additional stresses on communities and decision-makers, and in a time of greater community crisis.

Tsunami debris from residential and industrial areas as well as nearby ports is likely to litter beach habitats. In some locations, industrial contaminants and other pollutants, potentially sewage, crude oil, various fuel types, lead paint, legacy pesticides, asbestos (Plumlee and others, 2013), will affect the beach and nearshore waters. Beaches that are covered in large amounts of complex debris or where contamination is a concern may need to be closed until clean up has been completed and/or water quality has returned to safe standards. If the beach remains severely eroded, residents and visitors may have to wait until sand returns naturally or through human intervention before it is usable.

Beach wildlife will be harmed. The tsunami is modeled to strike during grunion and endangered plover breeding seasons, and sand loss will significantly impact these species. In addition, marine mammal haul- out sites and populations are likely to be affected (see Section 2, “Sensitive and Endangered Species”).

Sand Dunes

California has several notable dunes along its coastline, and many are home to rare and ecologically valuable plant and animal species (California Department of Fish and Wildlife, 2013a-d). Sand dunes act as a barrier to waves and flooding and as a reservoir and supplier of sand to beaches. Vegetated dunes are more stable against ocean surges.

The SAFRR Tsunami Scenario forecasts some over-topping and inundation of the sand dunes at Coronado and Pismo Beach. Dunes at Pismo Beach are heavily used recreational sites and also serve a conservation function in that several of the dunes are protected during snowy plover nesting.

Elsewhere, sand dunes appear to function as a natural defense against the tsunami surge. Figure S2-2 shows the inundation line near Fort Bragg in the area known as the Inglenook Fen-Ten Mile Dune Preserve. The coastline is home to California’s only remaining coastal fen and the sand dunes are largely pristine. Most dunes are under 15 m (50 ft) tall and less than 1.6 km (1 mi) in width, and possess abundant and diverse vegetation cover. The predicted SAFRR Tsunami Scenario inundation line closely follows the edge of the sand dunes, suggesting that the dunes will provide some level of natural defense for the coastline. A similar pattern is observed along the coast by Seaside and Sand City north of Monterey, and near the entrance to Morro Bay, where the tsunami line appears to hug the edges of the sand dunes. However, the inundation line does not fully account for conditions where there will be significant long-shore sediment transport. This happens when waves do not strike the coast perpendicularly. Long-shore currents accompanying the tsunami could erode the dune and move the sand elsewhere. In topographies where the tsunami is funneled behind the dune (fig. S2-2) there is potential for the tsunami surge to inundate behind the dunes and seriously undermine them.

Over-topped dunes, especially if well vegetated, can recover quickly from tsunamis and storm surges. But if large amounts of sand are washed away and dunes lose their shape and vegetation, or are undercut, they become destabilized, and can continue to erode indefinitely. If this occurs during the tsunami, then damaged dunes will require human intervention and restoration to stabilize them and the beach that they maintain.

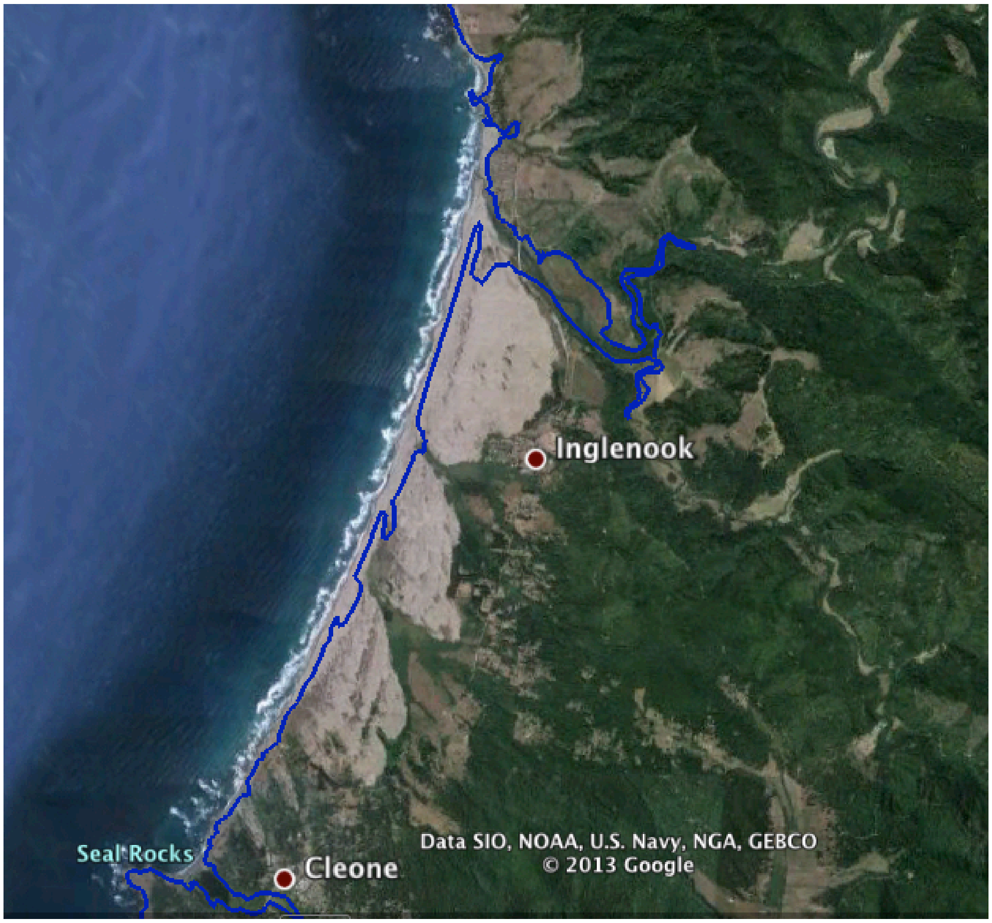

Figure S2-2. SAFRR Tsunami Scenario inundation line along the sand dune coastline near the Inglenook Fen-Ten Mile Dune Preserve area close to Fort Bragg California. The line representing inundation intrusion generally follows the contour of the dunes and the tsunami does not overtop them. Where there are no significant dunes and river channels, the tsunami is shown to travel farther inland. In this figure, North of Inglenook, the tsunami surges up the Ten Mile River inland and the flooding could potentially cause damage to the low-lying habitats located behind the dunes as well as to the back dunes. Any long shore tsunami currents also may erode sand from the seaward side of the dune. (Image courtesy of Wilson, 2013.)

More generally, on a statewide level and under the SAFRR Tsunami Scenario, dunes in a few locations may provide some level of natural defense, but their ability to do so also will depend on the direction of the waves and adjacent topography, in addition to dune height and health. Clean up may be necessary along the dune edges in areas where currents deposit debris onshore and along sandy beaches (fig. S2-3).

Figure S2-3. Boats and debris may be scattered on local beaches. Image shows aftermath of Tohoku tsunami near Crescent City, northern California. (Image courtesy of R. Wilson, California Geological Survey, 2011.)

Coastal Marshlands, Sloughs, and Estuaries

In the SAFRR Tsunami Scenario, almost all of California's coastal marshes and sloughs will be fully inundated and in some places the surge will extend 10 km inland. The impacts on these habitats will depend on the tsunami's local severity (for example, wave amplitude, velocity, duration), ecosystem health and proximity to human activities. Marshes are effective in ameliorating ocean surge and protecting inland habitats and towns (Danielson and others, 2005, 2006; Gedan and others, 2011; Renaud and others, 2013) and many are likely to continue providing some level of protection in the tsunami.

Ecologically, periodic but less severe oceanic influxes can be beneficial, particularly to estuarine marshes, through the exchange of water, nutrients, sediments, larvae etc. However, prolonged exposure to high-salinity water during tsunamis often kills large swaths of vegetation (Hettiarachchi and others, 2013; Renaud and others, 2013). One of the greatest threats to these habitats in a tsunami is from debris, salt, and contaminants that are swept into the habitat and trapped there (fig. S2-4). Depending on the timing of the tsunami, species may be severely affected by damage to nursery and breeding grounds. Clean up will be challenging because of practical, safety, and regulatory complexities.

Figure S2-4. Tsunami and storm surges sweep debris and contaminants into coastal marshes where they remain after the waters have receded. (Image courtesy of D. Brosnan, University of California Davis, 2005.)

Under the SAFRR Scenario, although all coastal marshes and estuaries will experience inundation, damage will vary among them. Below we illustrate some plausible scenarios. These examples are for illustration and are not meant as an exhaustive or definitive coastal description.

Southern California.—Strong tsunami currents are expected to drive inundation into all of southern California's marshes and sloughs. Inundation periods may be prolonged due to the extended duration of the tsunami and the long post-tsunami wave attenuation times for southern California (SAFRR Tsunami Modeling Working Group, 2013). Affected habitats include, for example, San Elijo Lagoon; the extensive Bolsa Chica Ecological Preserve and State Park; and Carpinteria Salt Marsh Reserve and Nature Park—an important bird habitat is inundated along with adjacent urban areas, thus increasing risks from debris.

Goleta Slough State Park, Santa Barbara.—At Goleta Slough State Park near Santa Barbara, coastal wave amplitudes of 2 m are forecast and tsunami inundation extends 1.7 km into the slough (S2-5). However, there is little to no inundation into the immediately adjacent community (although nearby communities in Carpinteria are flooded). Whether as a result of the marsh habitat slowing the incoming waters, and/or a combination of other factors, the inundation line stops short of the airport runway that abuts the marsh. There is little indication from the models that the surge would transport large volumes of sand or debris into the marsh.

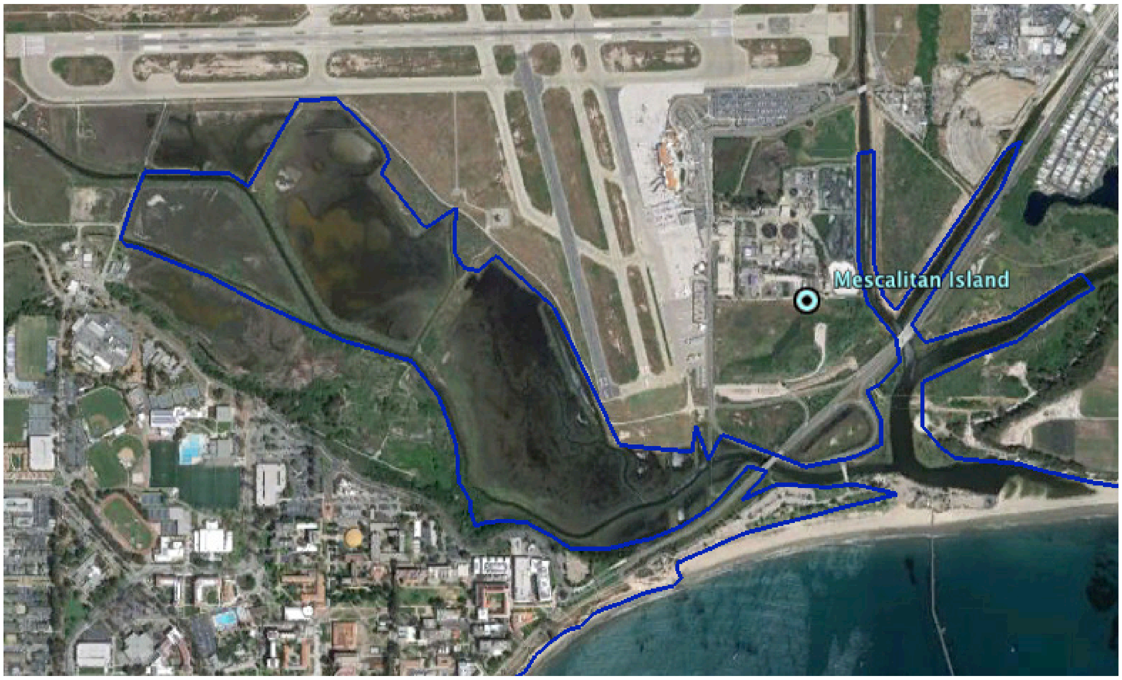

Figure S2-5. SAFRR Tsunami Scenario Inundation line at Goleta Slough (natural habitat area in image) and parts of the town of Santa Barbara. The tsunami surge is predicted to intrude into and cover most of Goleta Slough stopping close to the airport runway. The surge overtops the beach and follows the line of the slough to inundate the marshland. (Image courtesy of R. Wilson, California Geological Survey, 2013.)

Del Mar and San Dieguito Wetlands.—The coast at Del Mar provides a different perspective (fig. S2-6). The tsunami models predict that on open coast sites from Del Mar and extending to La Jolla, the maximum tsunami wave height is on the order of 1.25 m. There is little inland inundation along this line of open coastline beyond beach inundation. However, coastal inundation is evident at the entrance to the Del Mar lagoon (SAFRR Tsunami Modeling Working Group, 2013). There is significant flooding over several blocks of the town at the southern side of the entrance, the fairground is flooded, and the tsunami surge extends fully into the marshland.

Current speeds of 250 cm/s are recorded in the open waters, but hotspots of significantly higher currents in the channel and shoreline are evident from modeling results (SAFRR Tsunami Modeling Working Group, 2013). Inundation into marshlands may be locally significant from a biological and social perspective in several locations. For example, Del Mar Lagoon, site of the San Dieguito Wetlands Restoration Project since the late 1990s has been an environmental focal point. Years of scientific investigations, community debates and regulatory hearings ultimately resulted in an agreement to proceed with a science-based restoration process. The SAFRR tsunami models demonstrate the vulnerability of the project to tsunami surge and the potential for debris accumulation that would be swept into the lagoon from the adjacent built-up area (fig. S2-6).

Figure S2-6. SAFFR Tsunami Scenario inundation line at Del Mar Lagoon and San Dieguto Wetland Restoration area. The tsunami surge extends over the restoration area and the marshland and lagoons. Models predict damage to the adjacent town and infrastructure that may exacerbate damage from debris and contaminants. Restoration habitats are fragile and warrant special consideration in planning and mitigation. (Image courtesy of R. Wilson, California Geological Survey, 2013.)

Central and Northern Coast.—Marsh and lagoon habitats in the central and northern parts of California also are vulnerable in the SAFRR Tsunami Scenario including for example, Humboldt Bay, Elkhorn Slough, Bolinas Lagoon, and others. Tsunami wave amplitudes will be higher in the central and northern coast but attenuation times are shorter (SAFRR Tsunami Modeling Working Group, 2013). Marshes and farmland in Humboldt Bay will be inundated, but current velocities are lower (<2–3 m/s; fig. S2-7). Minimum flow depths that average between 8 and 12 m in the main channel are quickly ameliorated to between 0 and 4 m as the surge encounters and spreads over the mudflats and marshes. As a result, damage may be less severe. Around Monterey Bay, the tsunami surge will travel some 10 km into Elkhorn Slough and there will be some flooding of agriculture lands adjacent to the Slough and around Moss Landing.

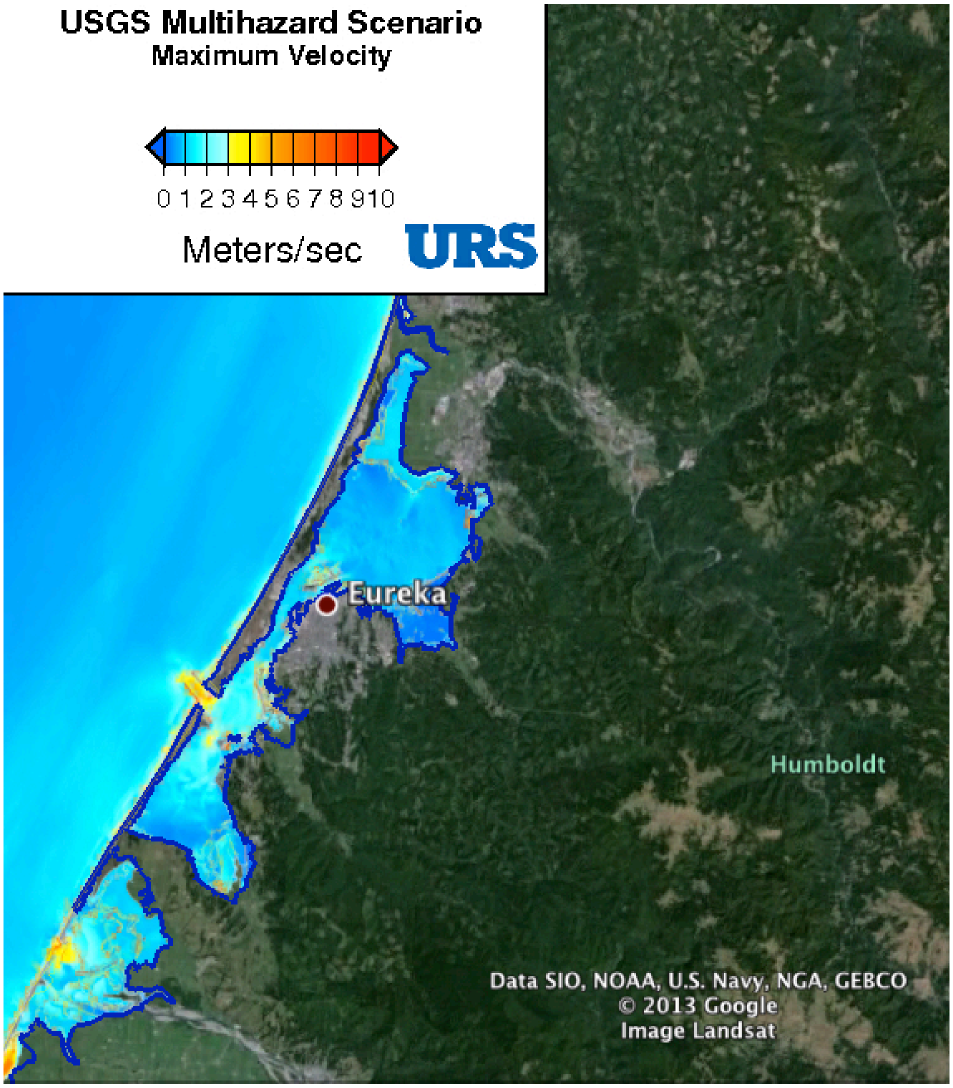

Figure S2-7. SAFRR Tsunami Scenario inundation line and tsunami current velocity at Humboldt Bay, California. (Image courtesy of R. Wilson, California Geological Survey, 2013.)

Bolinas Lagoon.—The habitat of Bolinas Lagoon will be completely inundated and the coastline from Stinson Beach to Bolinas is at high risk (fig. S2-8). The higher wave amplitude will result in overtopping of the spit where most of the town of Stinson is built. Large volumes of infrastructural debris are likely to be swept into and trapped in Bolinas Lagoon, currently ranked among the more pristine lagoon and marsh ecosystems in the State. The SAFRR tsunami models predict that Kent Island located in the lagoon and recently designated for a major habitat restoration will not be overtopped. However, there will be some flooding around the perimeter, and debris accumulation is likely, raising concerns for species such as nesting threatened snowy plover. Debris is likely to include residential and industrial materials including some contaminants, and could be harmful (Plumlee and others, 2013).

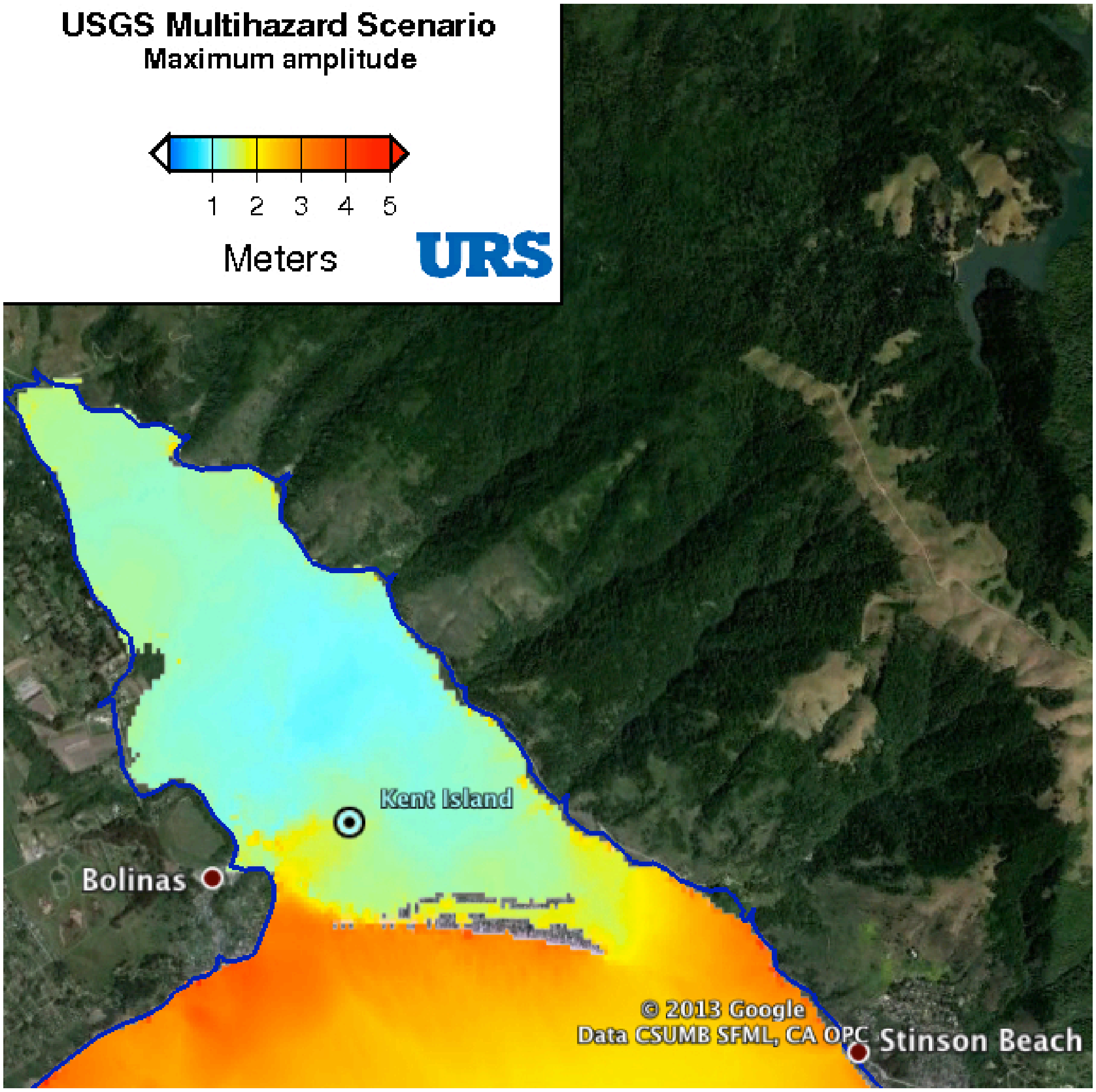

Figure S2-8. SAFRR Tsunami Scenario inundation line from Stinson Beach to Bolinas and into Bolinas Lagoon. The tsunami is forecast to overtop the spit, and fully inundate the lagoon extending to the edge of the solid inundation line. Large amounts of debris are likely to be swept into and deposited inside the lagoon. (Image courtesy of R. Wilson, California Geological Survey, 2013.)

With the exception of the areas primarily around the Golden Gate Bridge and West San Francisco, where currents and amplitude will be strong, tsunami conditions inside San Francisco Bay ameliorate quickly, and models do not indicate much flooding of natural marsh habitats.

Rocky Shores and Tidepools

About one-half of California's coast is comprised of rocky shore and elevated headlands or cliffs that provide a natural barrier, protecting inland areas from tsunami surge (Wilson, 2013).

Species living on rocky shores and tidepools are adapted to withstand strong wave action, but in extreme events like a tsunami, intertidal seaweed beds and small invertebrates can be dislodged or buried (fig. S2-9). Exposed rocky shore biological communities are subject to disturbances from strong seasonal storms. However, although not immune to human impacts, these habitats have been less affected by humans than other coastal ecosystems and seem to have retained more of their natural resilience (Thompson and others, 2002). Ecosystem recovery follows a successional pathway that takes several years (Sousa, 1984; Thompson and others, 2002). The scale of the tsunami, affecting the entire coastline, could alter the ability of tide-pool ecosystems to recover if for instance there is an inadequate supply of larvae to replenish the habitats.

Figure S2-9. California's exposed rocky shore species (for example, *Postelsia palmiformis*, shown here) communities are adapted to disturbances. But the scale and strength of the tsunami along with novel stresses, such as debris and contaminants, may affect their resilience and recovery. (Image courtesy of D. Brosnan, University of California Davis, 2011.)

A significant source of damage to rocky shore ecosystems is likely to come from debris carried by currents and surge that may be tossed onto tidepools and rocky headlands forming local "debris hotspots." In more exposed areas, the debris may continue to affect the intertidal ecosystem long after the tsunami has subsided. This is likely to occur when species are repeatedly battered and scoured by debris that is driven onto the shore by waves and winter storms (Paine and Levin, 1981; Thompson and others, 2002). Longshore currents may transport sediments onto rocky shore habitats, burying the ecosystem in sand.

The amount and type of debris and its accessibility will affect what, if any, action is taken to remove debris from these habitats. Affected tidepools that are popular and accessible (for instance, Point Loma tidepools, which are forecast to be inundated) are more likely to be cleaned up, however, it may not be possible to reach more exposed sites. In addition, marine life in tide pools can quickly be killed by contaminants and may be difficult or impossible to clean up.

Shallow Water Reefs and Nearshore Ecosystems

California's nearshore waters are home to diverse habitats and species. Nearshore reefs, kelp forests, and sandy seabeds contribute to the State's high biodiversity and productivity and support nearshore commercial invertebrate fisheries which in 2011 yielded a catch of 57,424,812 lbs valued at $78,286,360 (California Department of Fish and Game, 2012).

SAFRR Tsunami Scenario models have not been analyzed to fully evaluate the effect of nearshore and shallow reefs on amplitudes and currents, but we hope to make further information available in the near future. However, results from other tsunamis are useful for comparison. Nearshore submerged reefs have been shown in certain tsunami circumstances to act as natural breakwaters that dissipate wave energy—factors such as the distance from the event, length and slope of the reef, water depth above the reef habitat, and reef geometry affect energy dissipation (Chatenoux and Peduzzi, 2007; Hettiarachchi and others, 2013; Renaud and others, 2013). During the Southeast Asia tsunami, the importance of submerged reefs in ameliorating the tsunami was reported as significant along the Kenyan coast (Geological Survey of Denmark and Greenland Bulletin, 2007) and Sri Lanka (Fernando and others, 2007a, 2007b).

In California, nearshore marine plants, animals including commercially important invertebrates, and kelp beds are vulnerable to tsunami damage (fig. S2-10). Under less severe conditions, kelp can ameliorate wave action, but in strong storms and tsunamis, kelp beds are more often ripped from the seabed. The loss of kelp beds can be significant. Each kelp bed is a mini-ecosystem, and supports a diverse biological community that includes commercial marine species. Species, such as sea otters and birds, rely on the kelp forest for food and a place to rest. Loss of kelp will likely have significant effects on the nearshore dynamics. Impacts on keystone species can result in a regime shift to an alternative stable state.

Debris will damage some nearshore habitats. This includes land-based materials, contaminants, and derelict fishing gear, as well as sand/sediments transported offshore by the waves and currents. Contaminant materials may pollute reef and sandy habitats and pose a risk to marine life (Plumlee and others, 2013). Many of these nearshore habitats are important fishing grounds, and the fishery and resources are likely to be affected (fig. S2-11) (Section 3).

Figure S2-10. California's kelp beds provide habitat for several important marine species. Kelp is vulnerable to being ripped out during significant tsunami surges. (Image courtesy of D. Brosnan, University of California Davis, 2013.)

Figure S2-11. In previous tsunamis, fishing nets have been dragged onto rocky and coral reefs damaging the habitat and marine species. The image above is of a net dragged by the Southeast Asia tsunami onto coral and rocky reef. The net stretched for 0.25 km across the seabed. (Image courtesy of D. Brosnan, University of California Davis, 2005).

Parks, Reserves, and Marine Sanctuaries

California has scores of State and Federal marine parks and reserves that conserve marine life, sustain fisheries, and provide for recreational use. They range from small local parks and reserves up to extensive National Marine Sanctuaries, such as those off Monterey, and the Channel Islands Marine Reserve. Combined, California's parks and reserves include every type of coastal and marine habitat in the state—all of them are vulnerable to tsunami impacts, some being more at risk than others.

Ninety-five of the coastal State and Federal parks are estimated to be in the tsunami inundation zone (Wood and others, 2013). These parks attract 60,707,359 people annually and an estimated 166,322 day-use visitors are expected to be present on the day of the tsunami (Wood and others, 2013). The SAFRR tsunami scenario identifies concerns for protecting the investment in natural systems along with human safety during the event (Wood and others, 2013) and opportunities for post-tsunami recreational needs.

Sensitive and Endangered Species

California is home to several coastal and marine endangered and protected species as well as to creatures like grunion that, while not endangered, are culturally and ecologically important. Threatened and Endangered Species are protected under the Federal Endangered Species Act [ESA] (U.S. Fish and Wildlife Service, 2013) and/or the State of California Endangered Species Act [CESA] (California Department of Fish and Wildlife, 2013a). California has listed 289 plant and animal species as threatened or endangered (California Department of Fish and Wildlife, 2013d). Marine mammals are afforded protection under the Marine Mammal Protection Act (National Oceanic and Atmospheric Administration, 2013).

In the aftermath of a significant tsunami, implementing ESA protection and recovery actions, as well as addressing debris, sediment, and contaminant clean up in the habitats used by threatened and protected species, may be challenging. Attempts to balance ESA regulations with pollution statutes and the need for clean up and rebuilding may contribute to the regulatory quagmires (Wilson and others, 2012; Brosnan and others, Section 3, below).

Several threatened, endangered or protected species are at significant risk during the SAFRR Tsunami Scenario. Among them are:

Western Snowy Plover (*Charadrius nivosus nivosus*).—Threatened Snowy Plovers nest on beaches from March to September (U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, 2013a). The SAFRR tsunami is modeled to strike on March 27, early in the nesting season. The SAFRR Tsunami Scenario inundation lines indicate that most nests existing at the time of the tsunami will be destroyed. Birds that escape by flying out of harm's way may not be able to breed again if their beach has been eroded, food source affected (likely as they feed on infaunal and epifaunal species), and/or if they are not energetically capable of producing another brood. Most of California's Western Snowy Plover population, already threatened with extinction, could lose a year of reproduction and suffer stress that may cause mortality or reduced future reproductive success.

Endangered Abalone: Black Abalone (*Haliotis cracherodii*) and White Abalone (*Haliotis sorenseni*).—The black abalone is an endangered species that is particularly vulnerable to tsunami damage because it lives in intertidal and shallow subtidal zones. The species extends from Point Arena, California, to Bahia Tortugas and Isla Guadalupe, Mexico. South of Point Conception, the species has gone locally extinct from several areas (National Oceanic and Atmospheric Administration, Office of Protected Resources, 2013a). Once abundant from Point Conception, California, to Punta Abreojos, Mexico, the white abalone is now critically endangered in California (National Oceanic and Atmospheric

Administration, Office of Protected Resources, 2013d, 2013e). White abalone are found in open low and high relief rock or boulder habitat that is interspersed with sand channels and live deeper than black abalone. Surveys show a 99 percent decrease in white abalone density since the 1970s. Previous densities of 1 per square meter are down to on average 1 per 10,000 square meters in the Channel Islands. Due to low numbers and densities, successful reproduction is likely to be rare for black and white abalone (Allee effect).

The Pinto Abalone (*Haliotis kamtschatkana*) is not a listed species but is mentioned because it was recently petitioned for listing under the Federal ESA. It lives on exposed and protected rocky shores and kelp beds from Alaska to California with a separate subspecies found in southern California.

There is evidence that abalone are vulnerable to tsunamis (Brosnan and others, Section 3, below). Surveys showed that the Tohoku tsunami significantly reduced abalone density, by up to 50 percent in some places, and that younger and smaller individuals were particularly affected. Loss of any individuals in the SAFRR Tsunami Scenario will be highly significant for such a small size population.

California Clapper Rail (*Rallus longerostris obsoletus*).—The California Clapper Rail is an endangered subspecies. Birds live in salt and brackish water marshes and use tidal sloughs for foraging and to escape from predators. They construct nests within 10 m of tidal sloughs from March to July (U.S. Environmental Protection Agency, 2010). Populations now live almost exclusively in the marshes of the San Francisco estuary (San Mateo, Santa Clara, Alameda, Contra Costa, Solano, Napa, Sonoma, and Marin Counties) with smaller populations elsewhere including Monterey and Morro Bay. SAFRR Tsunami Scenario model results indicate that most of its habitat in the San Francisco estuary will not be inundated, but nests and individuals in other counties may be affected by inundation.

Salmon (*Oncorhyncus* spp.).—There are many salmon species and populations protected in California. The threatened Evolutionary Significant Unit (ESU) Spring-Run Chinook Salmon (*Oncorhyncus tshawytscha*) enter the Sacramento River from late March through September (California Department of Fish and Wildlife, 2013c). Winter steelhead runs also peak in March. However, there is no information to suggest what, if any, impacts the tsunami may have on these ESUs. There are few data available to reliably predict any potential lingering effects of the tsunami on other salmon runs, and many of which occur later in the year, for example, winter steelhead runs.

Green Sturgeon (*Acipenser medirostris)* (listed as a threatened southern Distinct Population Segment (DPS) and species of concern over the rest of it range).—Green sturgeon range from Alaska to Mexico and spend the majority of their lives in nearshore oceanic waters, bays, and estuaries. Spawning is believed to occur every 2–5 years. Adults typically migrate into freshwater beginning in late February, and spawning occurs from March to July. One of the main threats to the southern DPS is the loss of habitat in the Sacramento River (National Oceanic and Atmospheric Administration, Office of Protected Resources, 2013b).

Other Tsunami-Vulnerable Threatened, Endangered, or Protected Species

Other species that have the potential to be affected by the SAFRR Tsunami Scenario include the endangered tidewater goby (*Eucyclogobius newberryi)*. Its preferred habitat is in estuaries or marshes, in brackish lagoons with fairly shallow water, a sandy bottom and cool temperatures (U.S. Fish and Wildlife Service, 2013b).

Critical habitat for leatherback sea turtles (*Dermochelys coriacea*) extends along the coast from Point Arena to Point Arguello and includes shores that are vulnerable to SAFRR Tsunami Scenario damage and erosion.

The Pacific Eulachon or Smelts (*Thaleichthys pacificus*) *(southern DPS listed as threatened under ESA)* are anadromous fish that typically spend 3 to 5 years in saltwater before returning to freshwater for spawning from late winter through mid-spring. Threats are habitat loss and changes in sediment quality. However, these fish have been shown to carry high pollutant loads potentially affecting their survival. Any contaminants introduced into their habitat by the tsunami are likely to exacerbate risks to the species health and survival (National Oceanic and Atmospheric Administration, Office of Protected Resources, 2013c).

Numerous coastal plant species are listed as threatened or endangered and/or vulnerable to damage in California. They include endangered seablite (*Suaeda californica*), historically known from beaches and marshlands of San Francisco Bay and Morro Bay; the endangered salt marsh bird's beak (*Cordylanthus maritimus maritimus*) found just above the high tide line in salt marshes in San Diego County, and many plants confined to coastal dune habitats (Pickart and Barbour, 2007; Pickart, 2008). Invertebrates (insects, butterflies, etc.) and vertebrates that depend on these plants also are at risk.

The California Grunion (*Leuresthes tenuis*)

The grunion is not a listed species but is of special cultural significance to California. A licensed fishery is in effect in the state. Grunion distribution ranges from Point Conception, California, to Point Abreojos, Mexico, occasionally extending farther north to Monterey Bay, California. They spawn at night on sandy beaches during spring tides from March through September, and late March–June are peak spawning months (California Department of Fish and Wildlife, 2013b). The SAFRR Tsunami Scenario models the tsunami arriving on a peak spawning month and close to the start of the spawning nights. SAFRR Tsunami Scenario indicates that grunion reproduction will be affected along most of their spawning beaches in California. Despite locally high concentrations, grunion are not abundant, and the most critical problem they face is loss of spawning habitat caused by beach erosion, harbor construction, and pollution (California Department of Fish and Wildlife, 2013b).

California Marine Mammals and Protected Marine Organisms

Marine mammal (seal and sea lion) haul out sites may be damaged. Along the coast, most of the breeding elephant seals (*Mirounga angustirostris*) found at places like Ano Nuevo State Park and Big Sur have gone back to sea by the end of March; however, weaned pups remain until April and may be vulnerable to the tsunami. Marine mammals and other marine creatures may be affected by contaminants including crude oil, various fuels, petroleum products, and various other pollutants transported by the tsunami into the ocean (Plumlee and others, 2013).

Fisheries and Other Natural Resources

Commercial marine fisheries, particularly nearshore and invertebrate fisheries are at risk. The main fishing harbors, including Los Angeles/Long Beach, Ventura, Santa Cruz, Half Moon Bay, and Crescent City, will be inundated by damaging currents and wave amplitudes. In Santa Cruz, the inundation line extends 2 km inland, and at Half Moon Bay, surge overruns docks and extends another 100 m inland. The commercial fishery is covered separately in Section 3.

Shellfish beds, including commercial oyster farms distributed along central and northern California may be vulnerable to sedimentation and/or surge. These include shellfish in Tomales Bay. Native shellfish restoration sites in San Francisco Bay are unlikely to be affected by currents but may be at risk from tsunami-transported sediments.

Conclusions for Practical Approaches and Additional Research

Tsunami damage to ecological and natural resources affects more than the natural systems themselves. It impacts the lives of communities who use and depend on them and in a multitude of ways, including economically, psychologically, and recreationally. We are poorly equipped to manage the potential damage to natural systems, and the knock-on effects on humans, envisioned under the SAFRR Tsunami Scenario for the California coast. But there are planning and emergency frameworks in place that can be utilized to quickly improve preparedness, education, and mitigation. In addition to immediate practical actions, there is need for research on the relationship among ecological systems, multi-hazards and stability of human communities in order to inform decisions.

Ecological systems will suffer damage from the forces of the tsunami and complex debris. Formally taking action now to recognize, assess, evaluate, and develop plans for ecological damages will be beneficial. This type of planning and response will not be possible when a tsunami strikes and creates a sticky web of overwhelming and pressing societal needs.

Ecosystems may not be sufficiently resilient to recover naturally and human intervention may be needed. This potential need can be addressed now. For instance, managers and regulators of vulnerable parks and reserves can implement a scenario situation in order to identify the types of debris and ecological challenges they are likely to face. Formally working through key questions can be valuable. For instance, this would include envisioning the scale of damage and which resources are most vulnerable; identifying the equipment and personnel needs, and whether these are likely to be available (for example, in these scenarios, it is quickly apparent that volunteers cannot clean up complex and hazardous debris). It also would include evaluating the range of applicable regulatory statutes, for example, those that apply for contaminants, identifying the agencies or other institutions that would be involved in response and clean up, and preparing in advance order to avoid lengthy regulatory quagmires. Realistically, they will not have the time or resources to adequately manage these tasks when a tsunami strikes.

In the SAFRR Tsunami Scenario, many beaches are vulnerable to sand erosion and to inundation that will flood and destroy property. Communities and regulators will benefit from formally considering protection measures that address the potential effects of a single major erosion and natural hazard event. Creative but effective solutions that may involve ecological and engineering methods could potentially be transformative and meet multiple goals. These are questions that can be more effectively addressed in advance and before the community faces millions of dollars in losses and additional tsunami-driven crises.

Endangered species and restoration sites are nature's equivalent of the most vulnerable segments of a human population. They are by definition fragile, close to the ecological edge, and have little resilience against additional stresses. Utilizing emergency planning and response frameworks already in place for those most vulnerable elements offers a practical and useful approach. Envisioning "what if" scenarios for endangered species and identifying, in advance, any actions that will be necessary in the event of a tsunami may improve recovery and help to prevent species' extinction. Scenario planning for restoration sites also would minimize damage. The knowledge gained by extensive scientific, community, and regulatory investment in restoration planning is likely to be a valuable source of information that can be incorporated in tsunami-planning and mitigation for those sensitive areas.

There is increased interest in the role of ecosystems as bioshields against climate-change events such as extreme storms. Evaluating the conditions under which ecosystems provide protection against both climate-change and tsunami events will greatly benefit decision makers. Unfortunately, There is almost no information on the threshold levels that determine when ecosystems can shield natural resources, property and vulnerable communities against a tsunami or similar large-hazard events. Investing in gathering this knowledge for practical use can result in great savings and benefit to humans and natural resources.

Ecological and engineering solutions may need to be combined to ensure the safety and sustainability of the coastal zone and communities. More creative and transformative approaches to combining these two solutions is needed and pilot projects that test options can prove useful.

Most areas and communities face multiple hazards. Mitigation measures developed against a single hazard in isolation are rarely effective. Multi-hazard planning and mitigation is more complex, but we have expertise and tools available that allow for more effective approaches to multi-hazards and to integrate conceptual level thinking, modeling and the development of practical solutions.

Table S2-1. Summary of plausible SAFRR Tsunami Scenario Impacts on California's Ecosystems, Natural Resources, and Endangered Species.

Ecosystem/natural resource	Ecological or resource features	Plausible damage
Habitats and Ecosystems		
Beaches	Prime natural and recreational resource. When dynamically healthy beaches provide protection against storms and surge.	May provide limited coastal shielding. Most beaches will be inundated. Heavy sand loss is likely, especially on southern beaches. Debris will include contaminants especially on beaches with beachfront property and adjacent to urban areas. Recovery times may be long. Recovery options and actions likely to be contentious, and involve regulatory quagmires.
Sand dunes	Depending on wave amplitude and dune height, dunes can be a natural defense against tsunamis.	Damage varies along the coast. Some dunes appear to offer a natural line of defense, but others are likely to be damaged
Marshlands, sloughs, estuarine wetlands, and riverbanks	Productive habitats, absorb wave energy and slow current speeds. Narrow channels and rivers focus tsunami energy and can funnel waves and debris inland.	Marshes appear to slow down the surge, but many are fully inundated by the tsunami surge extending 10 km inland. Rivers and inlets funnel the waves, and may channel surge to inundate areas behind the dunes. Debris and contaminants will enter marshes that are adjacent to ports, industrial, and residential areas. Debris will be trapped in marshes when waters recede. Some damage to vegetation where there is lengthy saltwater intrusion. Recovery Times: Variable depending on scale of damage, presence of contaminants etc.
Rocky shore, tidepool, and cliff habitats	Act as a natural barrier against inundation.	Debris may be scattered on tidepools and lower elevation cliffs, especially those near towns or buildings. Other types of damage are likely to be minimal.
Low-lying islands	Overtopping of low-lying islands likely, including man-made islands. Other islands will experience some perimeter inundation.	Debris and contaminant issues are likely from overtopping of industrial and human-made islands. Debris may wash ashore on other islands.
Nearshore shallow water habitats (generally <20 m)	Ecologically diverse in habitats and species composition. Valuable resources include commercial fisheries, and recreation (diving, fishing etc.) Subject to strong currents, scour, sedimentation, water borne debris and contaminants. Tsunamis can dislodge marine plants animals.	Significant impacts likely in some nearshore waters from scouring, sedimentation, debris and contaminants. Strong waves could dislodge marine plants and animals resulting in ecological loss. Kelp beds may be ripped out. Recovery time would be variable. May be slower or impeded if damage is widespread and/or if keystone species are affected.

Ecosystem/natural resource	Ecological or resource features	Plausible damage
Special and Sensitive Areas		
Parks, reserves, including coastal sites, offshore islands, and submarine habitats.	Represent a major investment in natural systems, designated for conservation, recreation, fisheries etc.	Several coastal and shallow water habitats of parks and reserves are vulnerable to ecological, debris, and contaminant damage. Clean up could be significant. High elevation islands will not be inundated. Loss of the natural insurance provided by protected areas. Recovery times would be variable
Restoration sites	Several marshes, beaches, and islands are undergoing major ecological restoration. Restoration sites are fragile.	May require particular attention regarding securing equipment and managing restoration activities, to protect habitats that are generally more vulnerable during restoration. Recovery times may be long depending on restoration stage and type of damage.
Sensitive, Protected, and Endangered Species		
California Snowy Plover (*Leuresthes tenuis*) Grunion Black abalone *Haliotis cracherodii* and white abalone *(Haliotis sorenseni)* Clapper Rail (*Rallus Longirostris obsoletus)* Sacramento River Spring-Run Chinook, and later salmon runs (*Oncorhyncus spp.*) Marine mammals and other marine organisms	Nesting season on beaches March–September Breeds on beaches March–September Critically endangered Restricted range in marshes and sloughs Late March to September run Various	Breeding likely to be disrupted. Breeding likely to be disrupted. Will be very sensitive to population losses.. Main habitat not inundated, others are vulnerable. Unknown but damage not predicted. Affected by damage to haul-out sites, and by debris, contaminants, etc.
Other species including Tidewater goby *Eucyclogobius newberryi*; Eulachon/Smelt *Thaleichthys pacificus*; green sturgeon, *Acipenser medirostris;* leatherback sea turtle *Dermochelys coriacea* critical habitat. Many threatened and sensitive coastal plants, including dune species	Habitat are likely to be damaged Inhabit vulnerable habitats	Local and coast wide impacts likely depending on the species. Vulnerable to tsunami surge, salt water inundation and debris/contaminants.
Marine mammals	Migrating and resident species.	Minimal direct impacts, but mammals may be affected by debris and/or contaminants.

Ecosystem/natural resource	Ecological or resource features	Plausible damage
Natural Resources		
Fisheries—invertebrates and nearshore fisheries	Invertebrate	Commercial invertebrate species are susceptible to damage and dislodgement by surge, debris, sedimentation contaminants. Little direct impact likely on coastal pelagic species, but few data available.
Shellfish beds	Most located in central/northern coast for example, San Francisco Bay shellfish restoration sites; Oyster Industry in Tomales Bay.	May be affected by scour and sedimentation, and contaminant debris.
Fishing habitat	Rocky and sandy seabeds. Shallow and inshore habitats more vulnerable.	Nearshore habitat and species are vulnerable to strong surge and debris Offshore, debris and lost gear may impact species in deeper waters.
Fishing gear	Deployed gear at risk.	Some losses.
Fishing fleet/fishing	Most of the main fishing ports are inundated and will be damaged. Ports of Los Angeles/Long Beach heavily affected. Ventura, Santa Cruz, Half Moon Bay, Crescent City inundated and will suffer damage.	Greater impact to boats in harbor. Except for dive and shallow inshore fishing, boats at sea unlikely to be damaged. Most damage in harbors, and economic losses due to port, processing plant and transportation disruptions. Impacts will vary greatly among individual fishermen.

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Section 3. Tsunami Impacts on the Commercial Fisheries and Fishing Fleet in San Pedro Bay, Ports of Los Angeles/Long Beach in the SAFRR Tsunami Scenario

Deborah Brosnan[1], Anne Wein[2] and Rick Wilson[3]

Introduction

A goal of the Science Application for Risk Reduction (SAFRR) Tsunami Scenario is to provide scientific information to help educate and mobilize at risk communities on ways to protect themselves against a tsunami event. A unique feature of the SAFRR approach is that it envisions a specific large tsunami, which is within the scientifically identified range of plausible events. This allows for a realistic scientific evaluation of the consequences and an exercise that is meaningful to planners and responders. This SAFRR Tsunami Scenario is based on a hypothetical earthquake with a moment magnitude of 9.1 occurring offshore from the Alaskan Peninsula at 11.57 a.m. on March 27, 2014. The generated tsunami is modeled to arrive along the coast of California between 4 and 6 hours after the earthquake. Scientific analysis shows that the tsunami striking the coast is not a single wave but an extended series of tsunami surges accompanied by strong and erratic currents that last for several hours to days. Similar extended tsunami events are characteristic of many tsunamis that have struck coastlines around the world. For instance, along the southwest coast of Sri Lanka, residents experienced the Southeast Asia tsunami as a 6-hour tsunami-surge event (P. Fernando, Center for Biodiversity Conservation, Sri Lanka, oral commun., 2005).

During and after these events, specialized natural resources-based communities and industries have unique risks and vulnerabilities. These include commercial fishing and fisheries. Evaluating the risks and likely impacts in advance can help inform planning and response in order to build greater resilience. To address this need, this report explores the SAFRR Tsunami Scenario impacts on commercial fishing in San Pedro Bay, California, where the Ports of Los Angeles and Long Beach (hereafter referred to as POLA/LB) are situated.

Our assessment, presented here, integrates the results from SAFRR's inter-disciplinary scientists for tsunami wave and current models and for oceanographic and seismological models. The assessment is based on estimates of damage to coastal infrastructure, ecological/environmental issues, and social vulnerabilities.

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[2]U.S. Geological Survey.

[3]California Geological Survey.

Monthly SAFRR team meetings allowed for discussion and integration across the disciplines. In developing the specific scenario for commercial fishing, we also relied on existing data from previous tsunami impacts. A series of discussions and meetings with port authorities, harbormasters, and fishermen along the Californian coast who have experienced tsunamis in the course of their work, and meetings with representatives of the Ports of New York and New Jersey (post Super-storm Sandy) provided valuable information for this assessment.

This report focuses on the SAFRR scenario in relation to southern California fisheries, but we designed it as a resource for all ports and harbors in California and for use as a global model. For this reason and to set the stage, we begin with an overview of past tsunami impacts on fishing fleets, using Crescent City as a primary California example but also drawing on experiences of port-based fishing fleets around the Pacific. We describe the key features of the POLA commercial fishing fleet and industry in order to illustrate the range of potential tsunami impacts. We conclude with opportunities for mitigating the effects of a tsunami and for enhancing resilience.

Overall, the unique vulnerabilities of fishing fleets and the fishing industry are complex and have not been well studied. The complexity is driven by the nature of the fishing industry that depends on several interconnected factors each of which is individually vulnerable to a tsunami (fig. S3-1). Thus, the greatest impacts to fishermen may not be from the tsunami surge or direct damage to the fishing vessels, but may come from the tsunami's destruction of landing and mooring docks, or from changes in fisheries laws and policies as part of the disaster-response. As a result, there is great variation in how fishermen in the same port can be affected by the same tsunami. For instance, a fisherman whose vessel and dock are damaged may be unable to fish for several months, while a neighboring fisherman, whose boat and dock are unscathed may benefit in the tsunami aftermath from reduced competition and higher catch prices. Fishermen can prepare and plan for many of the impacts, but some factors are beyond their control and require coordinated community planning and response. One of our goals in this section is help coastal communities and ports better evaluate which factors are likely to be most important to them and so that they can plan accordingly.

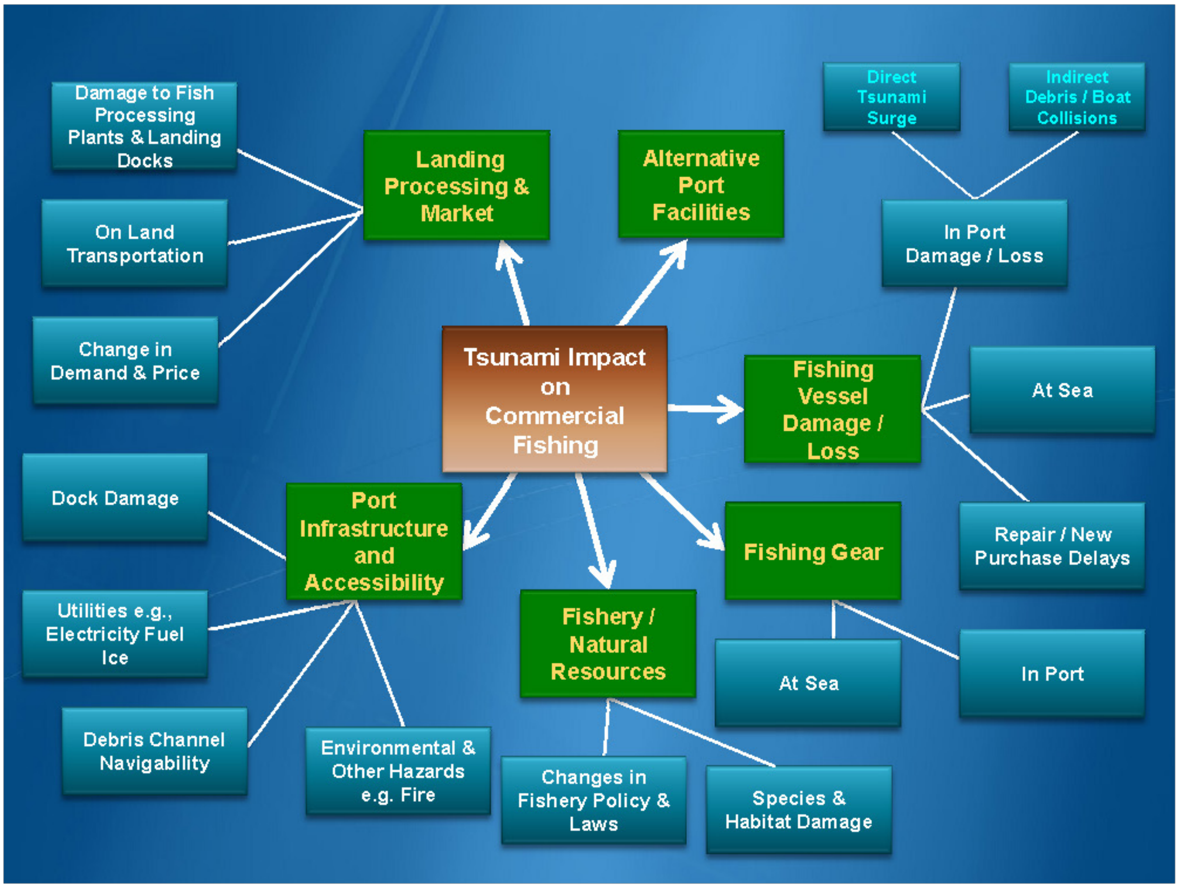

Figure S3-1. A tsunami's impact on a commercial fishery: This chart presents the main categories of factors that influence a tsunami's impact on fishermen and the fishing industry. For clarity, we present this as a simplified chart and have not included all interactions among the elements. However, we discuss them where relevant in the text. We use this chart to help identify areas of vulnerability for fishermen based in POLA/LB. We also envision this chart as a general guide to the industry and others in considering how to plan and respond to tsunami events.

Tsunami Effects on California's Fishing Fleets and Fisheries

Although California's ports have not experienced tsunami devastation on the scale of central Chile in 2010 or Japan in 2011, serious, potentially damaging tsunamis are not rare along its coast. Their effects on the State's ports and harbors have been localized and have varied widely in severity. For example, since 2006 there have been three tsunamis that have caused damage to maritime communities in California (National Geographic Data Center, 2013). Wilson and others (2012) identifies 27 harbors that sustained damage during either the 2010 or 2011 tsunamis at a cost of more than $100 million. Previous larger, distant source tsunamis have damaged POLA/LB small boat marinas and harbors—the 1960 Chilean tsunami caused 800 small boats to become unmoored, 200 of these were damaged, and 40 were sunk; during the 1964 Alaska tsunami, 100 boats were unmoored, and 6 were sunk (Lander and Kozuch, 1993).

The SAFRR Tsunami Scenario is approximately three to four times the size in wave height of the March 11, 2011 event for the California coast. Based on the SAFRR modeling results and inundation maps, each of the more than 100 main ports, harbors, and marinas along the coastline will be damaged and many boats docks and piers will be damaged and destroyed. This applies generally and not just to fishing boats and docks. The amount of damage will depend on many factors including in part on the preparedness and response efforts in each harbor, which is difficult to predict currently (2013).

Crescent City, California

In 1960, a tsunami generated after a M9.5 earthquake off the coast of Chile caused localized inundation in Crescent City, damaged wharfs and docks, and sank three commercial fishing boats (Lander and Kozuch, 1993). In 1964, 29 blocks of the city were inundated, 21 boats were sunk, and 11 people lost their lives during a tsunami that was generated by the M9.2 Great Alaska Earthquake. In March 2011, the Tohoku tsunami's near destruction of all docks and the accumulation of 150,000 m^3 of sediment in the small boat basin virtually shut down the harbor (Wilson and others, 2012). This affected the fishing fleet moored in Crescent City, which is one of the region's main commercial fishing ports. Its commercial seafood catch between 2000 and 2009 was valued at $12.7 million. Dungeness crab fishing (*Cancer magister*) is a mainstay of the fishing fleet (California Department of Fish and Wildlife, 2012) and the harbor is one of the West Coast's top crab exporters. The 2011 tsunami significantly affected revenues and operations for the harbor and the fishing fleet. However, the impacts were complex and not necessarily apparent to planners prior to the tsunami.

Crescent City Harbor suffered heavy financial losses as a result of structural and sediment damage from the tsunami (R. Young, Harbormaster. Crescent City Harbor District. Crescent City, California, oral commun., 2013). Because of dock damage, post-tsunami mooring revenues were down by one-third. It took more than 10 months for the sediment to be removed (Wilson and others, 2012; R. Young, Harbormaster, Crescent City Harbor District, Crescent City, California, oral commun., 2013). Other California ports also suffered significant and cost damage in the Tohoku tsunami (Wilson and others, 2012). For example, Wilson and others (2012) report that for Crescent City and Santa Cruz, a full year's delay in recovery was caused by engineering issues with damaged ships, docks, and infrastructure, in addition to environmental issues as a result of petroleum/chemical contamination and sediment removal/disposal (Weston Solutions Inc, 2013). Wilson reports that there also were delays because of overlapping regulations and confusing/redundant permitting. The scale and impact of environmental regulatory challenges were not fully anticipated in either planning or response. While Crescent City Harbor suffered heavy financial losses, other industries profitted from post-tsunami construction projects (R. Young, Harbormaster, Crescent City Harbor District, Crescent City, California, oral commun., 2013).

A robust alert system in place at Crescent City gave warning to harbor tenants and fishermen of the approaching tsunami (R. Harbormaster. Crescent City Harbor District. Crescent City, California Young, oral commun., 2013). Most boats heeded the alert and these vessels went out to sea. Some of the fleet was already offshore and fishing when the warning was issued and when the tsunami arrived. Despite multiple alerts, other boats remained in the harbor because their owners were either out of town, did not believe the threat to their vessels was significant, or their boats were derelict and unable to leave the harbor. One fisherman who had hesitated to leave the harbor barely managed to exit and only by precariously navigating the extreme currents after the first tsunami wave. On the morning of the tsunami and as the first surges were coming ashore in Crescent City, officials reported that 35 boats that had remained in the harbor had been damaged or sunk (Times-Standard, March 3, 2011).

During the tsunami, boats at sea reported unusual ocean conditions. Crab fishermen experienced intense and erratic currents and those retrieving pots had to constantly reposition their boats to be able to approach them, a phenomenon widely reported by fishermen from around the World during other tsunamis (Brosnan, 2006). A few fishermen found that their pots were initially stuck but reported that they were able to eventually retrieve them (J. Wallace, fisherman, oral commun., 2013).

Because of the extensive damage to Crescent City Harbor, fishing boats were discouraged from returning there in the immediate aftermath of the tsunami (R. Young, Harbormaster. Crescent City Harbor District. Crescent City, California, written commun., 2013). Most were directed to Eureka Harbor [136 km (84 mi) south)]. Several boats temporarily relocated to Eureka while their home port of Crescent City was under repair. Fishermen bore the cost of longer driving commutes, as well as any additional distances to fishing grounds. Their mooring fees were diverted from Crescent City to Eureka thus providing a benefit to the port of Eureka at the expense of Crescent City. However, a number of fishermen chose to return to Crescent City. To cope with the scarcity of docks and slips, temporary moorings were installed in the harbor, requiring fishermen to row or motor in and out to access their boats. Despite the lack of dock facilities, the boats were otherwise able to conduct their fishing business because the fuel dock, ice house, repair facilities, and unloading facilities were not damaged by the 2011 tsunami.

Fishermen who operated from Crescent City in the tsunami's aftermath felt that they had higher revenues at least initially because there were fewer boats fishing for the same limited resource (B. Fahning, fisherman, oral commun., 2013). However, a controversial California Department of Fish and Wildlife policy decision changed that perception. Fishermen who had lost boats in the tsunami were allowed to transfer certain permits without restrictions to other boats. The pre-tsunami regulations imposed several restrictions including that a license issued for a 10 m (32 ft) boat was valid only for a 10 m boat (B. Fahning, fisherman, oral commun., 2013). With that restriction lifted, fishermen with permits for their boats, and who had lost use of those boats in the tsunami were able to transfer their permit without these restrictions and benefit economically from the transfer. As a result, fishermen reported tension when several larger [for example, >25 m (>82 ft)] commercial boats from outside the area, capable of fishing 24 hours/day competed with local fishermen and took larger catches after picking up the licenses. This policy lasted only 1 year and then was withdrawn. Some fishermen felt that, although unintentional, the indirect effect of the policy caused them greater economic losses than the more direct inconveniences from the tsunami (B. Fahning, fisherman, oral commun., 2013).

The 2011 tsunami struck during the crab fishing season. Crab fishing grounds range from nearshore to offshore and from depths of slightly less than 10 m (32 ft) to well in excess of 40 m (131 ft). In the tsunami, only the shallower fishing habitats (generally less than 10 m) would have experienced any direct wave impacts. Anecdotal evidence indicates that the crab population did not suffer any direct effects during the 2011 tsunami. Other effects, such as changes in fishing pressure or effects on recruitment or juvenile survival are unlikely to be detected for several years and as far as we know there are no ongoing studies. Without adequate data, it will be hard to ascribe any long-term changes in crab populations to the tsunami as compared to other factors. However, the year following the tsunami was a high yield year for Dungeness crab and prices were high. The increased catches are unlikely to be related to the tsunami, and more probably reflect the biological and other oceanographic conditions from the time of cohort settlement to the crabs entering the fishery, about a 5-year span. However, the high prices paid to fishermen for the catch the following year may have been a lingering effect of the tsunami.

Previous Pacific Rim Tsunami Impacts

Elsewhere around the World, fishing fleets and the fishing industry have suffered greater tsunami damage in nearshore and harbor environments. The 2010 earthquake and tsunami that struck Chile destroyed 1,400 boats and 70 percent of the country's south-central fishing fleet (World Fishing and Aquaculture, 2012). However, an additional and significant source of fishery damage was the destruction of several fish processing plants, which prevented any processing and sale of the catch and thereby inhibited recovery. At-sea conditions for some of the nearshore boats actively fishing when the tsunami struck were hazardous. During the 2004 Southeast Asia tsunami, fishermen reported tsunami currents strong enough to drag the nets they were hauling and destabilize their boats, others reported having to cut their lines to prevent from capsizing; and in the aftermath there were many reports and underwater sightings of lost gear (Meadows and Brosnan, 2008).

The 2011 Tohoku tsunami had serious impacts on the Japanese fishing industry. According to government data, overall losses to the fishing industry in the disaster zone came to more than 1.2 trillion yen ($14.8 billion). In all, 319 fishing ports and 22,000 fishing boats were damaged by the March 11 tsunami (Global Post, 2012). Major fishing ports in the three hardest-hit prefectures experienced a 60 percent decrease in total hauls in 2011 from the previous year (Global Post, 2012). A year after the Tohoku earthquake and tsunami, tuna and oyster fishermen had returned to fishing but the fleet and fishing effort was much reduced. In Miyagi prefecture, almost one-third of fishermen surveyed said they had no intention of returning to the sea. Under the SAFRR Tsunami Scenario, the scale of damage is not predicted to be as severe at POLA/LB as compared to that experienced by Chile and Japan's fishing fleets. However, tsunamis across the globe appear to affect fleets and fisheries in much the same ways even if the severity of impact varies from incident to incident, and from port to port. As a result, past tsunamis play a valuable role in illustrating the scope of potential sources of damage and identifying critical points of vulnerability.

The SAFRR Tsunami Scenario: San Pedro Bay and the Commercial Fishery

Located in San Pedro Bay, the Ports of Los Angeles and Long Beach (POLA/LB) comprise the fifth-busiest port facility in the World and the busiest in the Western Hemisphere. POLA occupies 3,000 ha (7,500 acres) of land and water along 69 km (43 mi) of waterfront (Pitchon, 2011). A multi-purpose facility, POLA handles commercial fishing and fish processing, cargo ships, cruise ships, industrial storage, and transportation. These activities collectively generate annual revenues on the order of $406.8 million. POLB ranks as the second busiest container port in the USA after POLA, and is a major gateway for U.S.-Asian trade. POLB has 40 km (25 mi) of waterfront in the city of Long Beach, California, and annual trade valued at approximately $140 billion dollars in goods transported (Pitchon, 2011).

Within the POLA, commercial fishing is not the primary activity or revenue generator when compared to the combined industrial and cruise ship activities. However, it is a major part of the State's commercial fishing industry and fisheries revenue. It also is acknowledged as a vital cultural and biological asset to POLA. The commercial fishing industry generally is divided into activities on Terminal Island (Fish Harbor) and San Pedro (for example, 73 S.P. Slip, Berth 72). (See fig. S3-2 for locations of fishing activities in POLA.) Although boats from each area fish heavily for coastal pelagic species (CPS), most of the smaller vessels are moored in Fish Harbor and many of these specialize in nearshore invertebrate fisheries, including sea urchins and sea cucumbers. The two fishing communities are described as culturally distinct in terms of boat size, a sense of safety, and ethnicity (Pitchon, 2011).

Approximately 60 percent of the POLA fleet is berthed in the Fish Harbor area. The 0.9 ha (2.3 acres) has an aggregate berth length of 13.4 km (8.3 mi) and is a focal point for commercial fishing, seafood processing, and maritime support. A small floating dock north of Dock 267 is used mostly to load and unload supplies, fish, and gear. Fishing boats primarily are berthed along three fixed piers that line the harbor at Docks 267A, 268 A&B, 268 C&D (dock 267A is innermost and docks 268 C&D are outermost to the harbor) and also close to two full-time fish processing plants (Bob Bertelli, fisherman and chair of the California Sea Urchin Commission, written commun., 2013). San Pedro, once a major deep-netting port, is home to larger purse-seine vessels that fish for CPS. Pier 167 is designated for vessels 12 m (40 ft) and larger. In addition, some of the larger fishing boats unload at Berth 72 and tie up at 73 S.P. Slip located on the western side of Main Channel, eastern side of Pier No 1 at the foot of Twenty-Second Street.

Although the number of fishing vessels moored varies with the time of day and season, the Wharfinger Division estimates the resident fleet size at 100,120 vessels and Pitchon (2011) generally confirms the same. Twelve fishermen reported living on their boat full time and a similar number live on-board part time, when they are actively fishing (Pitchon, 2011).

In Fish Harbor, on Terminal Island, there are two full-time fish processing facilities, and a third facility that is involved in abalone aquaculture development (Wise, 2011). The catch brought into Fish Harbor is unloaded from the mooring docks as well as from the docks that span two-thirds of the perimeter of Fish Harbor. Fish are either taken to fish processing facilities in Fish Harbor, are picked up by trucks for processing elsewhere, or taken to markets in the greater Los Angeles area outside of the port complex. There are additionally several fish houses on the Main Channel, just before entering the mooring area of Berth 72 (also known as “The Forty Thieves") in San Pedro and in the area where most of the larger boats unload their catch. Bob Bertelli (written commun., May 16, 2013) reports that the fish houses on the Main Channel have been too busy to be able to accommodate additional business from Fish Harbor.

Commercial Fishery

Commercial boats, processors, and receivers in Terminal Island and San Pedro target primarily coastal pelagic species (CPS). These include Pacific sardine, market squid, northern anchovies, Pacific (chub) mackerel, jack mackerel, and as of 2010, catches of jack smelt and Pacific herring (table S3-1A). In addition, Fish Harbor is home to several boats that target dive and invertebrate fisheries and these species make up a large percentage of catch landed at Fish Harbor and revenue to the industry (table S3-1B).

The coastal pelagic species fishery is a high volume fishery where processing primarily consists of de-watering, grading/sorting, boxing/packaging, blast freezing, and cold storage. The catch is highly perishable and needs to be frozen, transported quickly, and kept at low temperatures. The majority of the catch is exported, and only 2-5 percent is consumed in the United States. For example, much of the squid is shipped to China for use in soup-base, and sardines are used as bait in Eastern Pacific longline tuna fisheries.

Table S3-1. Commercial vertebrate fishery information for Terminal Island and San Pedro, 2011.

A.				
Commercial fishery	**Total fishery landing (lb)**	**Value**	**Coastal pelagic species as percentage of total landing**	**Percentage of total value from coastal pelagic species**
Terminal Island	90,797,297	$20,854,880	53.2	70.6
San Pedro	90,826,599	$21,128,029	99.3	91.4

B.						
Commercial fishery	**Sea urchin landing (lb)**	**Sea urchin catch value**	**Sea cucumber landing (lb)**	**Sea cucumber catch value**	**Spiny lobster landing (lb)**	**Spiny Lobster catch value**
Terminal Island	879,138	$824,236	195,694	$802,121	26,507	$450,925
San Pedro	767	$7,797	9,683	$39,804	46,426	$805,404

Sea urchins and sea cumbers are commercially harvested mostly by divers. They are fished in nearshore rocky reefs, generally kelp environments and at depths ranging from 20 to 80 ft. Harvesting of the sea cucumber fishery is 80 percent by divers and 20 percent by trawl fishing.

In 2011, California reported total landings of 416 million lb valued at $218 million. Annual catch and revenue figures demonstrate the economic importance of the commercial fishing industry (table S3-1). In 2011, POLA/LB combined reported total landings of 181,623,896 lb valued at $41,982,909. This represents 44 percent of the State's landings and 19.25 percent of its value.

The 2009 ex-vessel value, or EVV, which is the price paid to fishermen at the dock, for CPS catches was $11 million on Terminal Island and $13 million at San Pedro (Hackett and others, 2009; California Department of Fish and Wildlife, 2012). Combined, these represented 22 percent of State commercial fishing annual earnings of around $110 million. A portion of the reported earnings from Terminal Island go to fishermen from other harbors/ports (for example, Ventura) who, frequently transport their catch to Terminal Island (Pitchon, 2011; Wise, 2011).

Commercial fishermen and the industry are heavily dependent on other port tenants for supporting infrastructure and supplies. Because of the focus on CPS, processors on Terminal Island and San Pedro are reliant on nearby boat berthing space, a fish pump, and a dock hoist to offload catch. On Terminal Island, one facility uses a 45 m (150-ft) long floating dock that can accommodate one vessel. They are able to offload, dewater, weigh, sort, and pack 500 ton/day. A second facility estimates that they can handle 120–130 ton/day at their dock and facility (Wise, 2011). A total of 62 percent of fishermen in Fish Harbor reported that they depend on other tenants for essential supplies, notably Western Fish and Tri-Marine for ice and bait, while 65 percent report that they sell all or part of their catch to processors in POLA (Pitchon, 2011).

San Pedro Bay: Tsunami Scenario Conditions

Inundation, Wave Height, and Water Flow

The SAFRR tsunami will be experienced over southern California as tsunami surges combined with strong and erratic currents lasting more than 24 hours (SAFRR Tsunami Modeling Working Group, 2013). SAFRR Tsunami scenario inundation for portions of POLA/LB (figs. S3-2, S3-3) show that fishing boat moorages, docks, and nearshore areas along Fish Harbor and San Pedro will be inundated to a distance of 20–50 m from the water front. By comparison, more inland parts of Terminal Island and other areas of POLA/LB are spared significant inundation. The tsunami scenario predicts maximum tsunami wave velocity of 2–3 m/s in the channels and gaps around Fish Harbor (fig. S3-3). However, current speeds vary greatly and erratically over the duration and throughout the harbor. Figure S3-4 is a snapshot of the variability in current speeds throughout POLA/LB 60 minutes into the tsunami event. Tsunami wave heights, the peak to trough of the tsunami wave, above mean high water (Max D) reach 2 m. In the initial pulse of the tsunami, the leading single wave height is between 1.2 and 1.4 m occurring over 15–25 minutes. The maximum individual wave height in Fish Harbor is forecast to be about 2 m, and occurs over about 20 minutes. (This is the equivalent to a 40-minute wave period, but the maximum change occurs over one-half of that time). This maximum wave occurs at near low tide at around at 2 a.m. PDT on March 28, 2014, 8 hours into the event. The highest individual crest (amplitude) elevation occurs near the first high tide, with an elevation of 1.0 m above mean high water (MHW), at approximately 8 p.m. PDT, 2 hours into the tsunami event.

The rate of change in water elevation is especially noteworthy to demonstrate and describe the strength of the tsunami; the rapid change generates most of the strong currents. For instance, models forecast that one wave event will result in a 1 m change in tidal amplitude over a 30–40 minute duration, (here the water rises by >0.6 m above MHW datum and declines to -0.4 m below MHW datum), and later on there will be a 2 m change occurring in 40 minutes. Figure S3-5 provides two snapshots of ocean surface-elevation simulations 20 minutes apart. Mean tidal amplitude, or the average difference between mean high and low water in POLA/LB is 1.2 m, occurring gradually over a 6 hour tidal cycle. During the tsunami event, boats in POLA will, in effect, experience the typical 6 hour tidal extremes in 30–40 minutes. Fishing vessels and all boats moored in the ports will be rolled and pitched erratically and unpredictably.

Figure S3-2. SAFRR Tsunami Scenario inundation line in POLA and locations of fishing activities on Terminal Island and San Pedro. (Source: SAFRR Tsunami Modeling Working Group.)

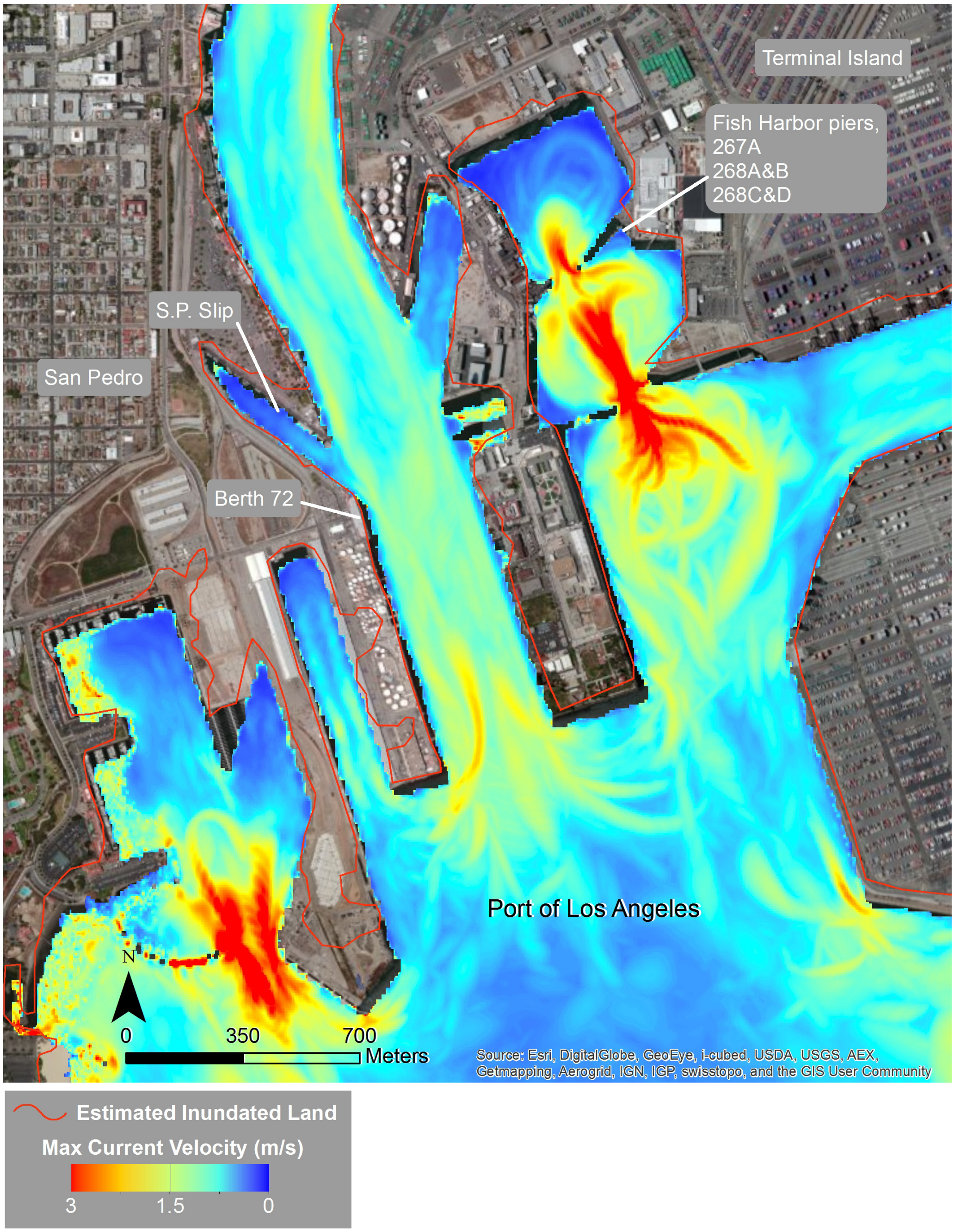

Figure S3-3. SAFRR Tsunami Scenario maximum current velocities and inundation line in POLA and locations of fishing activity on Terminal Island and San Pedro. (Source: Lynett, University of Southern California, written commun., 2013.)

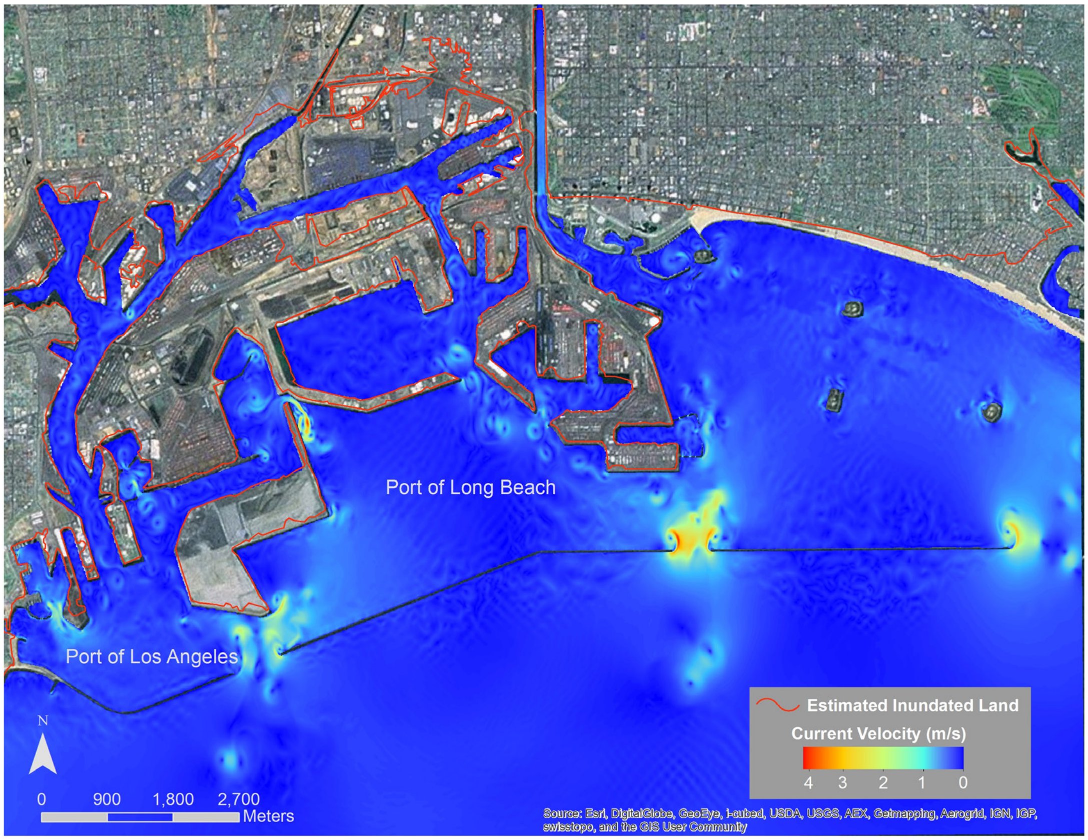

Figure S3-4. A snapshot of the variation in current velocity around POLA/LB and the nearshore waters 1 hour after the SAFRR Tsunami arrives (source: Patrick Lynett, University of Southern California, written commun., 2013). Animated simulation (Lynett, 2013a) show how these current speeds fluctuate over time and across location in POLA/LB.

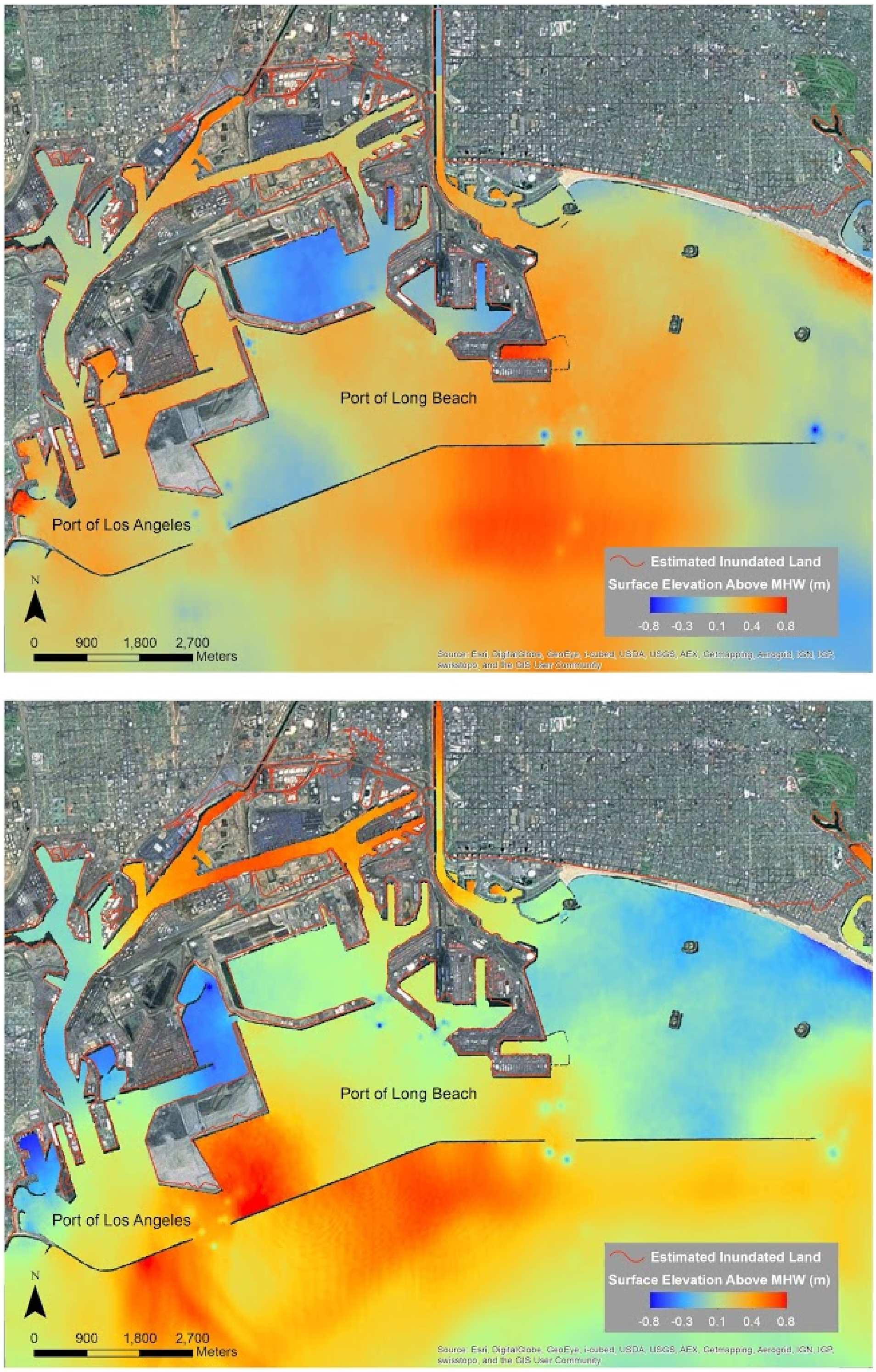

Figure S3-5. Snapshots of wave height 30 and 50 minutes after the SAFRR Tsunami Scenario arrives at POLA/LB (Source: Patrick Lynett, University of Southern California, written commun., 2013). A comparison of water elevation at 6:20 p.m. and 6:40 p.m. PDT on March 27, 2014, illustrates the rapid changes in ocean surface elevation as the tsunami waves begin to come onshore. See Lynett (2013b) for the complete time series.

Currents in excess of 2–3m/s are known to cause damage to piers and docks (Usulu and others, 2010; Wilson and others, 2012). Current velocities of 4–5 m/s typically cause more significant damage to docks and boats (Wilson and others, 2012). However, damage to boats, marinas, and docks also have occurred at lower velocities associated with tsunamis (Wilson and others, 2012). In tsunami conditions, it is important to recognize that boats experience a unique combination of conditions that include extreme currents from different directions, erratic tidal surges and waves. Typically, boats that are tied to non-floating docks (as many are in POLA) or fixed-depth buoys are considered to be at greater risk during inundation surges because the boats will move separately from, and collide with the docks/buoys. Additionally, Porter and others (2013) caution that small craft harbors are at higher risk of damage in this scenario than are larger ones.

Other evidence supports the vulnerability of POLA/LB's fleet and fisheries. Porter and others (2013) note that during the 2010 Chilean tsunami, POLA/LB operations and vessel navigation were halted as a result of the advanced tsunami warning. Strong currents were observed by the port pilots in some of the constricted channels and persisted for several days, making navigation somewhat more difficult. POLA/LB has experienced damage in previous tsunamis (Porter and others, 2013). During strong storms, moored boats have occasionally been damaged in Fish Harbor (Bob Bertelli, fisherman and chair of the California Sea Urchin Commission, written commun., 2013). Fishermen in Terminal Island voiced safety concerns with regard to winter storm surges, particularly at Pier 268 A and B, and reported that wakes from heavy boat traffic in San Pedro can damage smaller fragile fishing craft (Pitchon, 2011). In the SAFRR Tsunami Scenario, conditions will be more severe than any of these previous examples.

Debris

Debris will come from several sources and will include damaged vessels, dock fragments, and industrial materials from the wharfs. During tsunamis and extreme storms, boats are frequently damaged by collisions with adjacently moored boats, boats that have broken free from their moorings, and debris in waterways. R. Young (Harbormaster, Crescent City Harbor District, Crescent City, California, written commun., 2013) reported that these were significant sources of damage to boats in Crescent City in the 2011 tsunami, and Porter and others (2013) identify similar risks for this scenario.

Floating debris can be hazardous. Depending on the material they contain, some debris are prone to fires, posing greater risks (Porter and others, 2013). Floating debris as well as sunken debris (e.g. sunken vessels) can pose a navigation hazard. The U.S. Coast Guard oversees removal of navigational-hazard debris and would have responsibility for debris clean up.

In the SAFRR Scenario, debris models (Lynett, 2013c) show an accumulation of debris near the entrance to Fish Harbor from several areas in the bay. Immediately outside Fish Harbor a counter-clockwise debris vortex forms and 9 hours after the tsunami strikes San Pedro Bay a large area of relatively dense debris is well-established (fig. S3-6). Such areas are likely to impede the return of fishing vessels to the port to land their catch or to moor at docks. Based on the importance of the port's freight traffic to the U.S. trade, commerce, and transportation, we anticipate that clearing navigation routes will be a top priority. But if priorities must be made for navigation or repairs, the needs of freight shipping will likely have priority over the needs of State and local commercial fisheries needs. Porter and others (2013) estimate that the port will be fully closed for 2 days, but this does not imply that after a 48-hour closure debris will be cleared, channels navigable, or that operations will resume as normal.

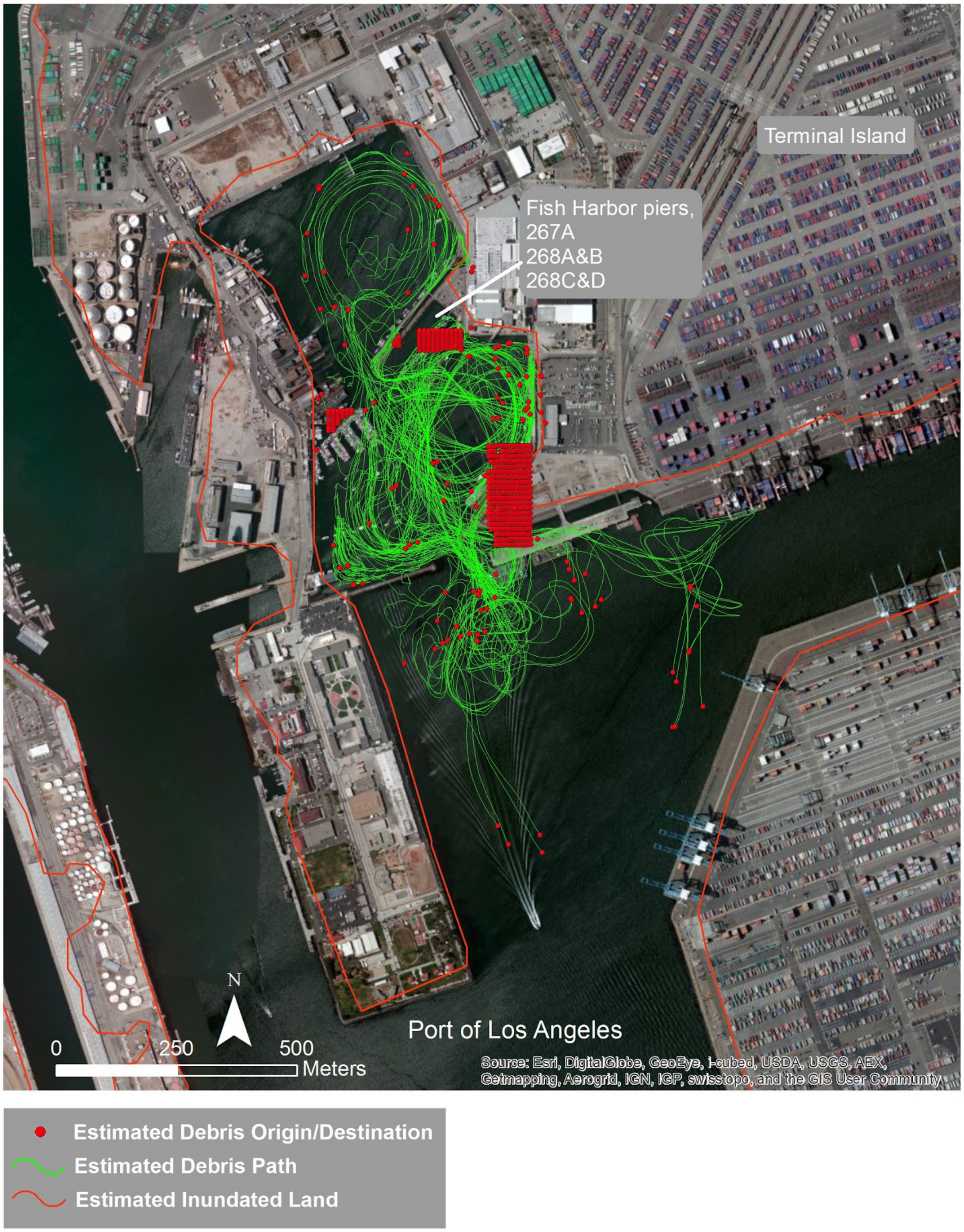

Figure S3-6. Hypothetical debris flow patterns in Fish Harbor a few hours after the SAFRR Tsunami arrives (snapshot taken at 8 p.m. PDT on March 27, 2014). Debris are assumed to originate from three selected sources (clustered red dots) and disperse along the green paths. Source: Patrick Lynett, University of Southern California, written commun., 2013).

Evaluating Tsunami Impacts on the Commercial Fishing Fleet

Tsunami Damage to Fishing Vessels

Fishing Vessels at Sea

March (when the SAFRR tsunami occurs) is an active fishing month in southern California. Many day fishing boats are likely to be at sea when the tsunami warning is issued earlier in the day and when the first waves arrive during the afternoon. Studies repeatedly indicate that boats offshore are usually unharmed during tsunamis. However, vessels that are net or pot fishing inshore and in waters experiencing strong tsunami currents may experience hazardous conditions. A tsunami alert will likely be issued but it not clear what advisories for boats in harbor or at sea will be issued. Boats at sea are likely to learn of the approaching tsunami from radios or alert systems. For example, the port of Los Angeles has a mass alert system and is in the process of rolling out a smart phone application called "PortWatch" (Curtis Thompson, POLA Port Police, written commun., 2013) to enhance the alert system. Because the tsunami lasts several hours, and dangerous currents persist for 1–2 days, fishing vessels may have to remain at sea for some time. Because boats located offshore during past tsunamis have suffered minimal or no damage, we anticipate that similarly in the SAFRR Scenario there will be negligible damage to boats that are and remain at sea.

Fishing Vessels in Harbor

Porter and others (2013) determined that most marinas will experience some damage from current velocities. They note that marinas located at the nexus of the East Basin and Cerritos Channel will experience significant impacts. For damage estimates, they derive probable small-craft harbor damage from $20 million of damages incurred during the Tohoku tsunami event on March 11, 2011, in Crescent City and Santa Cruz harbors reported by Wilson and others (2011, 2012).

The tsunami begins in POLA/LB in the afternoon of March 27, 2014. Boats that concentrate on squid fishing, generally a nighttime fishery, are more likely to be in port when the tsunami first strikes. Most of these vessels are moored in locations that are vulnerable to tsunami surges. In addition, not all commercial boats fish regularly, and there is an inherent randomness to how many boats will be in port when the tsunami warning is issued or the surge arrives.

Fishing boats moored in POLA/LB will have limited opportunities to leave the harbor prior to the tsunami. The first tsunami waves will arrive within 4–6 hours of the earthquake, which after the warning has been confirmed and issued could leave boat owners with less than 3.5 hours to evacuate. This is about one-third to one-half the time available to the fishermen in the Tohoku Tsunami. In a more rural setting, this might be ample time for fishermen to get to their boats and move offshore, but some POLA/LB fishermen live farther away from port where housing is more affordable. Traffic in the vicinity of the ports is heavy and will be even heavier in the event of a tsunami warning. Moreover, closure of the port and land-based evacuation orders will restrict access to the waterfront and the port itself. However, even with enough warning time, not all boats may leave. During the 2011 Japanese event, fewer than 10 percent of the fishing boats that were in Fish Harbor or 73 S.P. Slip left the harbor (Bob Bertelli, fisherman and chair of the California Sea Urchin Commission, written commun., 2013), even though it appears that they were aware of the impending event. However, fishermen, with a perishable catch, may feel compelled to attempt to enter port and dock during the tsunami, especially if they are not fully educated on the severity of conditions. Wilson and others (2012) document several emergencies caused when vessels attempted to enter or exit port during a tsunami. The unusual and treacherous currents put the lives of those on board, as well as emergency responders at risk.

In conclusion, boats moored in the harbor are at risk from tsunami wave amplitudes and currents, and they also are at risk from collisions with dislodged infrastructure and debris. In the SAFRR Scenario, larger craft have a relatively low risk of being tossed onto land by the tsunami, but smaller vessels are an exception and are vulnerable to being transported inland by the inundation wave surges (Porter and others, 2013). Most of the fishing vessels in POLA/LB fall into this vulnerable size class. As previous events have shown, tsunami-damage to fishing boats in harbors is often severe, see figures S3-7 and S3-8 from Crescent City in 2011.

Based on fisheries reports and discussions with fishermen, we roughly estimate that as many as 25 boats will be left in harbor when the SAFRR Scenario Tsunami strikes, and that many of these will be the larger seine boats. We expect that all will suffer a degree of damage, and that some could be rendered irreparable or completely destroyed.

Repair and Replacement

In ideal circumstances, a fisherman's insurance and availability of reliable boat repair facilities would allow for a relatively quick recovery. But in the aftermath of a disaster like a tsunami assessing damage and processing claims is a notoriously slower process if only because of the number of people in need. In addition, choosing, purchasing, and outfitting a new fishing vessel is time consuming and costly. Replacement costs of fishing vessels vary greatly depending on size and type of fishing (crab versus net-fishing). For instance, the average price for a 12 m (40 ft) custom-built deck trawler was $399,950 in 2012. New purpose-built aluminum boats range from $300,000 to $400,000 per fishing boat to $800,000 to more than $2 million for commercial crab boats (D. Pease, Dock St Brokers 2013, oral commun.; Athearn Marine Agency, 2013; Boat Trader, 2013). Prices for small [c.9 m (30ft)] and older fishing boats (pre 1998) well exceed $150,000. If for example, 20–25 boats need major repair or replacement and full gear refitting, the total costs could amount to or exceed $10 million (D. Pease, oral commun., Dock St Brokers 2013; Athearn Marine Agency , 2013; Boat Trader, 2013; National Fisherman, 2013). Repairing damaged boats is easier but there will likely be competition for repair facilities and parts, all of which contribute to time lost from fishing and to repair costs. Most fishermen do not have business loss insurance (Allianz Insurance, oral commun., 2013) and are unlikely to recover the time and income lost for boat repair or replacement, which could extend for several months.

Figure S3-7. Fishing dock at Crescent City, California, showing one of the vessels sunk by the 2011 Tohoku-oki tsunami. Most tsunami-damaged boats sink at the dock where they were docked, but some vessels are carried into the main channels where they sink and become navigational hazards. (Image courtesy of R. Wilson, California Geological Survey, 2011.)

Figure S3-8. Fishing dock, Crescent City, California, showing damage to fishing boat and the dock caused by the 2011 Tohoku tsunami. (Image courtesy of R. Wilson, California Geological Survey, 2011.)

Fishing Gear

Fishing gear in use during the season and when not deployed generally is kept on board. Therefore, the potential for gear loss in harbor is likely to be small. However, several studies report significant loss of fishing nets and pots deployed during a tsunami event (Meadows and Brosnan, 2008; MacFadyen and others, 2009; Miththapala, 2009). Tsunami currents can drag nets and pots from their fishing grounds. Those deployed nearshore, and especially around reef habitats or rocky outcrops appear most vulnerable. Gear loss can add significantly to economic losses. For instance, an average net costs in the region of \$10,000. In addition, lost gear can become derelict “ghost” gear, that is, lost gear that continues to trap fish and other marine creatures indefinitely. In previous tsunamis, derelict gear became a severe problem and threat to marine species and their habitats (Meadows and Brosnan, 2008). Since 2006, more than 60 tons of lost fishing gear, and 1 million ft of monofilament line has been recovered from ports and waters off the California coast (Gilardi and Renzullo, 2013). Studies show that a single ghost net can kill approximately 1,000 invertebrates (mostly crabs), 150 fish, and 80 birds a year. Over a decade, the economic cost of a ghost net on the Dungeness crab fishery was estimated at \$20,000 (Gilardi and Renzullo, 2013). The State of California, under the auspices of the Ocean Protection Council and the Coastal Conservancy, has a derelict gear removal/recovery program and one of its ultimate goals is to transfer the program to commercial fishermen. In the aftermath of a SAFRR Tsunami Scenario, the program could potentially be mobilized with the cooperation of the commercial fishing industry in POLA/LB to help find and retrieve gear lost due to the tsunami. Once located, it can either be recovered and returned to fishermen or at least removed in order to protect marine habitat and species and prevent hazards to navigation.

Landing, Processing, and Marketing the Catch

The SAFRR Tsunami will affect the landing, processing and marketing of fishery catches. The severity of impacts will depend on interactions among several factors—extent of tsunami damage to port infrastructure and accessibility, damage to processing plants and landing docks, navigability of port channels, and duration of down-time (fig. S3-1). The inundation lines beyond the boundary of Fish Harbor (fig. S3-3) indicate flooding and potentially other damage to some of the fish processing plants and shipping facilities. Damage to the processing plants will affect their ability to receive and process the catch. Land transportation to and from San Pedro Bay also is likely to be affected, and this in turn will affect the ability of the processing plants to transport catch within the region.

Because CPS must be landed and processed immediately, any factors that prevent landing will result in catch loss and income losses to fishermen. Fishermen will lose 2 days of port and processing facilities, and may experience additional delays in being able to return to harbor. Many boats may not be able to return to their normal dock until debris is cleared. The catch from March 27–28 would likely be lost, and the landing and processing of the CPS catch is likely to be affected for some time after the tsunami.

Dive and invertebrate fishing boats also will be impeded from returning to port from landing and selling their catch at POLA/LB. In addition, the erratic and strong nearshore currents will make dive fishing dangerous. Numerous reports document divers experiencing powerful currents and/or being swept considerable distances from their boats during a tsunami event (for example, Divernet, 2013). Tsunami currents are not evident to fishermen or divers on the surface, and fishermen may not be aware of them until they start to descend. Based on information from other tsunamis including 2010 and 2011 in California, these tsunami currents may last 1–2 days. California fishermen diving in nearshore environments, many of whom use surface-supplied air, will need to be aware of the risks.

The total value of landed catch averages $3.1 million per month (California Department of Fish and Wildlife, 2012). The average, Ex Vessel Value (EVV, which is the amount paid directly to fishermen at the pier) is $916,677 per month for CPS fishery in POLA. Data were not readily available for other fisheries. If, for the purposes of the SAFRR Scenario, we estimate that 25 percent of the fishing fleet is inoperable post-tsunami, that docks are damaged as predicted, that debris clogs the channel and entrance to fishing harbors for weeks after the 2-day closure, and port operations are impeded for weeks, a significant decrease in landing and EVV will occur. For this study purpose only, it is not unreasonable to envision that the port and fishery could lose a month of landings, valued at approximately $3.1 million. This however, assumes that fishing effort, landing, and transportation capabilities are all back to pre-tsunami levels 1 month after the disaster. As we have learned from other harbors, for example, Crescent City and Santa Cruz, after the less severe 2011 tsunami, it was many months before the fishing ports were fully operable. For example, 10 months after the Tohoku tsunami, Crescent City announced that it would not be able to honor all of its 50 pending slip applications as repairs had not been completed (R. Young, Harbormaster, Crescent City Harbor District, Crescent City, California, written commun., 2013). There do not appear to be good alternatives for mooring and landing catches given that fishermen from neighboring ports, including Ventura, tend to use POLA/LB to land their catch. However, under the SAFRR Tsunami Scenario, Ventura Harbor will be inundated by the tsunami as well.

Some of the estimated potential fishery losses at POLA/LB mentioned here, including $3.1 million in landing ($916,677 EVV) and $10 million in boat/gear losses, serve only to provide a gross-level benchmark for the fishery; actual costs were difficult to estimate. Moreover, the estimates do not describe the full costs nor do they illustrate the range of experiences that affect individual fishermen. Although overall fishing revenues may be down, a percentage of fishermen will see increased income if they are able to fish and sell their catch. This was the case for fishermen in northern California after the 2011 Tohoku tsunami, who reported they benefited from less competition because other boats had been destroyed or damaged in the tsunami, and because they received higher prices for their catch. Thus, the industry-level effects of the tsunami mask the variance in impact to individual fishermen. At one end of the spectrum, a fisherman may lose his/her vessel, mooring dock, and ability to earn income from fishing, while on the other end, a neighboring fisherman who experiences no boat or dock damage, may report increased fishery income after the tsunami.

Fishery/Natural Resources and Fishing Habitat

Damage to Commercially Important Species and Habitats

There are two main types of fisheries associated with the San Pedro Bay complex, the CPS and invertebrate fisheries caught by divers, trawl, and pots. Of the two fisheries, invertebrate species and their habitats are the most vulnerable in the Tsunami Scenario.

There are few, if any, long-term studies on tsunami impacts on economically important marine species and fewer that distinguish among tsunami impacts, fishing pressures, and natural dynamics. Studies on short-term impacts (Food and Agricultural Organization, 2007) suggest that CPS are not significantly directly affected by tsunamis, but that post-tsunami changes in fishing pressure can temporarily benefit these species. For example, surveys carried out on demersal (near-bottom) fish along the Andaman Coast of Thailand over seven cruises in 2004 and 2005 showed an overall increase in catch per unit of effort (CPUE) and stock densities after the tsunami (Food and Agriculture Organization, 2007). Differences were significant for total catches of demersal fish, cephalopods, and crabs. However, there was considerable variation among site samples, for instance marine fish decreased to one-third of pre-tsunami levels in Phuket and Phang-nga Provinces, Thailand. A separate study off the Malaysian coast reported a temporary increase in density and diversity of up to 286 percent for fished species, including demersal fish and demersal and pelagic invertebrates. This increase occurred 2 months after the tsunami, but values returned to expected levels after 5 months, leading the authors to conclude that the changes were more likely due to reduced fishing pressure immediately after the tsunami (Food and Agricultural Organization, 2007).

To the contrary, research cruises that sampled CPS around Aceh, Indonesia, from 2003 to 2005 (Food and Agricultural Organization, 2007) reported that the total catch of pelagic fish, species composition and size distribution decreased in Aceh during this period. However, they concluded that these changes were unlikely to be due to the 2004 tsunami. In post-tsunami surveys of perceptions of local fishermen from the Maldives outer atolls, 122 respondents perceived no tsunami effects on bait fisheries, and only five perceived tsunami-related decreases. However, another 69 respondents near Male, the Maldives, reported that bait fishing was poor and attributed it to a combination of post-tsunami increases in turbidity, perceived habitat damage, and normal seasonal effects (Gunn and others, 2005; Food and Agricultural Organization, 2007).

Under the SAFRR Tsunami Scenario, we expect that most of the coastal pelagic species are unlikely to be directly affected by the tsunami, but may respond to changes in fishing pressure. For example, significant reduction in fishing pressure may, at least in the short term, benefit these species. Water quality and turbidity can potentially affect coastal pelagic and other species, but there are few data available to indicate the importance of these effects here.

Nearshore habitats including rocky reefs and kelp beds, and the commercial species that live in these environments are more vulnerable to direct tsunami impacts. Their habitats tend to be more affected by strong currents, accumulation of tsunami debris, turbidity and sedimentation (Brosnan, 2006; Meadows and Brosnan, 2008). Sea urchin and abalone populations were seriously affected during the Tohoku tsunami. In some areas of the affected coastline in Japan, adult densities of abalone decreased by more than one-half in the aftermath of the tsunami, and juvenile abalone and sea urchins decreased to 14 and 5 percent of their abundance just prior to the tsunami (Choi, 2013). Research by the National Research Institute of Fisheries, reported that the number of young wild abalone in the waters off Miyagi Prefecture decreased more than 90 percent after the tsunami, apparently having been swept away by the tsunami, and that adult abalone had decreased 30 to 50 percent (Hays, 2012). In Ishinomaki, the population of the northern sea urchin decreased by more than 90 percent of its pre-tsunami abundance. These prime fishery habitats also were affected by high amounts of debris (fishing gear, wood, and iron frames) and by sedimentation on the seabed and in the water column (Hays, 2012). A slow recovery is forecast—the time to first capture for these species is around 5 years, implying that the populations will show evidence of the tsunami's damage well into the following decade.

Sea urchins, sea cucumbers, and spiny lobsters are among the main fishery species that are likely to be affected by the SAFRR Tsunami Scenario. A large part of the Fish Harbor fleet specializes in invertebrate species. Sea urchins, sea cucumbers, and spiny lobster landings generate $2,930,287 annually (Fish Harbor and San Pedro), and the fishery is critical to the livelihoods of those boats that target these species. Fishermen guard the secrecy of their fishing grounds in the face of competition for these valuable and limited resources. In the SAFRR Tsunami Scenario, these habitats and fisheries are vulnerable to tsunami-surge damage, debris, sedimentation, and chemical or other contamination. As cited above, strong currents are likely to prevent dive fishing, and also may result in loss of pots or other gear. Tsunami debris that accumulate in Fish Harbor area may not be a priority for clean-up. Even when sensitive fishing habitats have been buried in debris, ecosystem clean-up has rarely if ever been a major focus in tsunami recovery (Meadows and Brosnan, 2008). Consequently, it may be left to the community to restore the fishing habitat. Depending on the exact locations of the fishing sites, recovery times for these fisheries could be several years. Rocky reef habitats are not extensive along the coast, so even if a few of these habitats and their fisheries are damaged, the remaining reefs habitats are likely to experience higher fishing pressure. The impact of increased pressure on these already limited resources will be of concern in the long term.

Changes to Policy

There is often regulatory confusion and paralysis in the aftermath of disasters like tsunamis (Wilson and others, 2012; R. Young, Harbormaster, Crescent City Harbor District, Crescent City, California, written commun., 2013) because the scale and novelty of the disaster is unprecedented. Relaxations of existing policies or changes in environmental policies are not uncommon after disasters. In the aftermath of tsunamis and other extreme events, there has been less stringent application of sediment toxicity testing in order to open ports and harbors that are critical for boat traffic, trade and commerce. The relaxation of boat permit transfers in the State of California in response to the Tokohu tsunami affected how fishing was conducted. Some fishermen perceived that the policy change caused them greater income losses than the tsunami. There is, as yet, no information on how this policy may have affected the resource. These policy changes are reactive to particular disasters and consequently are hard to predict ahead of time. However, scenario planning can help agencies and communities to identify what pressing needs are likely to arise and develop plans that are less likely to require ad hoc regulatory changes.

Recovery

Recovery times are frequently underestimated because they fail to account for the cumulative effects of the disaster (see fig. S3-1) due to blockage of coastal access roads, shortages in personnel and resources, and regulatory quagmires. In the SAFRR tsunami scenario, Porter and others (2013) addressed the need to properly power down electrical systems, and dry them out. California's experiences with tsunamis, especially the more recent ones of 2010 and 2011, show that port repairs and rebuilding can be extremely slow.

The fishing industry is one of many industries located in the ports of San Pedro Bay complex. Recovery of U.S. national trade and commerce flow from the freight industry in POLA/LB will be a priority in a SAFRR scenario. The commercial fishing industry will have to compete for industry-specific resources necessary for its recovery and fisheries will be indirectly influenced by damage and recovery trajectories of other industries and other tenant-occupants in ports. The potential for long recovery times and the effect of cumulative impacts are an important component of planning and resilience building for the fishing community.

Summary and Conclusions

The SAFRR Tsunami Scenario identifies the following vulnerabilities:

- Highest risks are to boats in harbor and from cumulative damage (for example, docks, debris, and port infrastructure).
- Fisheries and fishermen will not be uniformly affected.
- Coastal pelagic species are less likely to be impacted but the invertebrate and diver fisheries are vulnerable to damage from the tsunami surge as well as from debris and sediments.
- Overall recovery time will be long and is likely to be underestimated.

Opportunities to Enhance Mitigation and Resilience

1. The fishing industry can enhance resilience by leveraging the experiences of fishermen and fisheries that have been documented from other tsunamis. This includes actively identifying specific vulnerabilities of the fishery, the scope of cumulative impacts, and planning accordingly. It also means understanding and anticipating the significant repair and recovery challenges in the aftermath of a tsunami.

2. California fishermen and harbormaster affected by previous tsunamis all stress the upmost importance of a robust and reliable local alert system and keeping contact information up to date.
3. Previous experience in Crescent City prompted several fishermen to train their crew and/or friends on how to start the boat engine and pilot the boat in the event of an emergency and the boat owner is not able to get to the boat in time to head to sea.
4. There are some specific and common sense actions and precautions that the fleet can consider immediately. During a tsunami, fishing boats at sea will likely be advised or alerted to remain offshore for the duration of the tsunami, and boats should not attempt to enter or exit the harbor or dock during the event. Dive fishermen will not be able to dive safely during the event and may need to consider suspending diving operations and if alerted, to take their boats out to sea. For some boats, staying offshore may mean that the catch will likely perish while entering harbor in a tsunami risks lives and vessels. Many boats may need to remain offshore for hours or even several days and should have ample supplies of water, fuel, and other emergency needs as on-board standards.
5. Strong and erratic currents persist in ports and at sea for several days after a tsunami. These will be stronger and unlike any currents to which fishermen are accustomed. These currents typically cause problems with fishing gear and are dangerous to dive fishermen. Good communication among fishermen on the location and strength of tsunami-currents or other tsunami-conditions can increase safety and save gear.
6. A tailored emergency and resilience plan can help the fishing community. In planning and preparedness, the fishing community at POLA/LB represents a specialized cultural and economic sector. But they also are a relatively small part of the Ports vast industry, and their needs may not be fully recognized or addressed in a tsunami. The information in this scenario can be used as a foundation for the fishing community to consider developing a tailored emergency plan (in conjunction with POLA/LB and emergency responders and agencies) that addresses the issues or questions specific to the fleet and fishery. A detailed walk-through scenario exercise of "a day in the life for the fishing fleet" will help to identify vulnerabilities that can be overlooked. For instance, is electricity needed to hoist the catch and will it be available? What if the dock itself has been destroyed? What other ports and fish processing plants are likely to be operational if POLA is inaccessible and the fleet cannot land their catches there? If only a small percentage of fishermen can reach POLA/LB and their boats before the tsunami strikes, are there actions that can and should be taken to protect the fleet and/or processing docks? Are there salvage and repair facilities that are adequate and reliable in a tsunami? What combined contingency plans between the processing plant and fishermen minimize damage to the catch, especially CPS?
7. Educational materials widely distributed, and awareness activities targeted to the fishing fleet and fishing community would be valuable. Multi-lingual materials to teach fishermen how to interpret tsunami warnings and information will facilitate more effective preparedness. Awareness includes education on the challenges of post-tsunami recovery including what fishermen and the fishing industry can expect and actions they can take to promote their own recovery and resilience. The State Tsunami Program has developed a maritime brochure that would help with this and plans to provide additional guidance to the maritime communities.

8. In the aftermath of a tsunami, there will be few resources available and competition for them will be high. Therefore, a plan to address how a fishing community will endure the tsunami's aftermath collectively would enhance the resilience of the community.
9. Consider potential tsunami impacts in port development planning to build resilience. POLA is finalizing plans for development and land use at Terminal Island. The proposed plan includes a 30 percent increase in container berth and land-use areas, expands rail capacity by a similar measure, and provides for the redevelopment of Fish Harbor for many smaller industrial and water-dependent tenants. It allows for development of truck service facilities and possible expansion of the boatyard service industry in the port. Non-maritime dependent and recreational facilities would be removed from the Terminal Island. It seems likely that discussions and planning have not evaluated potential for a tsunami-event at POLA. Incorporating tsunami-awareness will allow for analysis and discussion on how activities might alter risks to Fish Harbor and Terminal Island. Combining this evaluation on potential impacts coupled with emerging developments in tsunami-resistant construction, the ports in San Pedro Bay have an opportunity to ensure more resilient fishing industry and harbor facilities.
10. Little is known about the long-term impacts of tsunamis to native marine species and habitats. A pre-tsunami baseline inventory would help any post-event evaluation and help improve the understanding of damage including any chemical contamination and pollution of fish and other marine invertebrates.
11. As experienced in Crescent City after the 2011 Tohoku tsunami, lengthy delays in recovery were caused by environmental regulations. The POLA/LB and other ports and harbors can learn from this and develop plans that help streamline the regulatory process and that balance commercial and environmental concerns.

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