New Maximum Tsunami Inundation Maps for Use by Local Emergency Planners in the State of California, USA

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ABSTRACT: A consortium of tsunami modelers, geologic hazard mapping specialists, and emergency planning scientists has produced maximum tsunami inundation maps for California, covering most residentially and transient populated areas along the state's coastline. The new tsunami inundation maps are an upgrade over the existing maps for the state, improving on the resolution, accuracy, and coverage of the maximum anticipated tsunami inundation line. Thirty-three separate map areas covering nearly one-half of California's coastline were selected for tsunami modeling using the MOST (Method of Splitting Tsunami) model (FIGURE 1). Based on a preliminary evaluation of over fifty local and distant tsunami source scenarios, those with the maximum expected hazard for a particular area were input to MOST. The MOST model was run with a near-shore bathy-topo grid resolution varying from three arc-seconds (90m) and one arc-seconds (30m), depending on availability. Maximum tsunami "flow depth" and inundation layers were created by combining all modeled scenarios for each area. A method was developed to better define the location of the maximum inland penetration line using higher resolution digital onshore topographic data from interferometric radar sources. The final inundation line for each map area was validated using a combination of digital stereo photography and fieldwork. One-hundred and thirty inundation maps were made available at www.tsunami.ca.gov. Local governmental agencies have used these tsunami inundation maps to develop or update their evacuation routes and emergency response plans. The state will continue to evaluate the tsunami inundation hazard for the state by comparing the existing mapping and modeling results to inundation modeling using newly completed high-resolution (10m) bathy-topo grids, ongoing evaluation of tsunami sources (seismic and submarine landslide), and comparison to the location of recorded paleotsunami deposits.

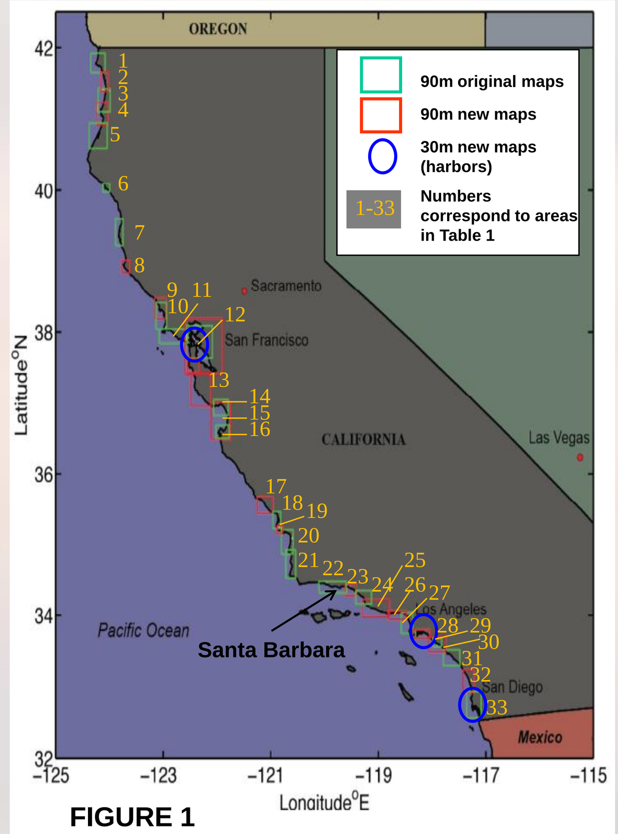


FIGURE 1

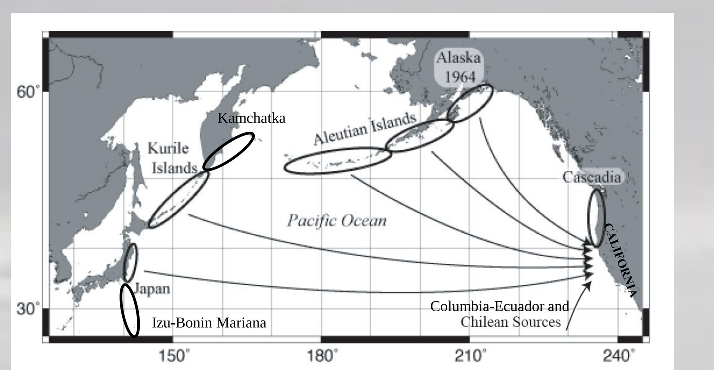


FIGURE 2

Area	Cascadia	Alaska 1964 Event	Aleutian Islands East	Aleutian Islands West	Kamchatka	Kurile Islands	Japan	Izu-Bonin Mariana North	Izu-Bonin Mariana Central	Izu-Bonin Mariana South	Chile 1960 Event	Chile North	Columbia-Ecuador Central	Columbia-Ecuador South
1 - Crescent City	3.0-4.0	2.0-3.0	2.0-3.0	0.8-1.0	0.6-0.8	0.4-0.6	1.0-2.0	1.0-2.0	2.0-3.0	0.8-1.0	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
2 - Yurok Reservation	3.0-4.0	1.0-2.0	1.0-2.0	0.8-1.0	0.4-0.6	0.4-0.6	0.8-1.0	1.0-2.0	2.0-3.0	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
3 – Orick	3.0-4.0	1.0-2.0	0.8-1.0	0.8-1.0	0.4-0.6	0.4-0.6	0.8-1.0	1.0-2.0	1.0-2.0	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	< 0.1
4 – Trinidad	3.0-4.0	1.0-2.0	1.0-2.0	0.6-0.8	0.4-0.6	0.4-0.6	0.8-1.0	1.0-2.0	1.0-2.0	0.6-0.8	0.4-0.6	0.2-0.4	0.2-0.4	0.1-0.2
5 – Humboldt	> 4.0	1.0-2.0	3.0-4.0	0.8-1.0	0.4-0.6	0.4-0.6	1.0-2.0	1.0-2.0	2.0-3.0	0.6-0.8	0.6-0.8	0.4-0.6	0.4-0.6	0.2-0.4
6 - Shelter Cove	0.8-1.0	1.0-2.0	1.0-2.0	0.6-0.8	0.4-0.6	0.4-0.6	0.6-0.8	0.6-0.8	0.8-1.0	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	< 0.1
7 – Mendocino	0.8-1.0	1.0-2.0	3.0-4.0	1.0-2.0	0.4-0.6	0.2-0.4	0.4-0.6	0.8-1.0	1.0-2.0	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	< 0.1
8 - Point Arena	0.8-1.0	1.0-2.0	1.0-2.0	0.8-1.0	0.4-0.6	0.4-0.6	0.4-0.6	0.8-1.0	1.0-2.0	1.0-2.0	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
9 - Pt Reyes North Ex	0.6-0.8	0.8-1.0	1.0-2.0	0.6-0.8	0.4-0.6	0.2-0.4	0.2-0.4	0.8-1.0	0.8-1.0	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
10 - Pt Reyes North	1.0-2.0	1.0-2.0	2.0-3.0	1.0-2.0	0.4-0.6	0.2-0.4	0.4-0.6	0.6-0.8	1.0-2.0	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
11 - Pt Reyes South	0.6-0.8	0.6-0.8	2.0-3.0	0.6-0.8	0.4-0.6	0.4-0.6	0.4-0.6	0.8-1.0	0.6-0.8	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
12 - San Francisco	1.0-2.0	1.0-2.0	2.0-3.0	0.8-1.0	0.6-0.8	0.4-0.6	0.6-0.8	0.8-1.0	0.8-1.0	1.0-2.0	0.4-0.6	0.4-0.6	0.4-0.6	0.1-0.2
13 – Pescadero	0.8-1.0	0.8-1.0	1.0-2.0	0.4-0.6	0.4-0.6	0.2-0.4	0.4-0.6	0.4-0.6	1.0-2.0	0.8-1.0	0.4-0.6	0.2-0.4	0.2-0.4	0.1-0.2
14 - Santa Cruz	0.4-0.6	0.6-0.8	1.0-2.0	0.6-0.8	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
15 - Monterey Bay	0.8-1.0	1.0-2.0	2.0-3.0	1.0-2.0	0.4-0.6	0.4-0.6	0.4-0.6	0.8-1.0	1.0-2.0	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.1-0.2
16 – Monterey	0.4-0.6	0.6-0.8	1.0-2.0	0.8-1.0	0.4-0.6	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
17 - North Morro	0.4-0.6	0.8-1.0	1.0-2.0	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.6-0.8	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
18 – Morro	0.4-0.6	0.8-1.0	1.0-2.0	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.6-0.8	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
19 - San Diablo	0.6-0.8	0.8-1.0	1.0-2.0	0.6-0.8	0.4-0.6	0.4-0.6	0.4-0.6	0.8-1.0	0.4-0.6	1.0-2.0	0.4-0.6	0.4-0.6	0.2-0.4	0.1-0.2
20 - Port San Luis	0.6-0.8	0.8-1.0	1.0-2.0	0.6-0.8	0.4-0.6	0.4-0.6	0.4-0.6	0.6-0.8	0.4-0.6	1.0-2.0	0.4-0.6	0.4-0.6	0.2-0.4	0.1-0.2
21 – Lompoc	0.4-0.6	0.8-1.0	1.0-2.0	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.6-0.8	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
22 - Santa Barbara	0.2-0.4	0.4-0.6	0.8-1.0	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.1-0.2
23 - SB-Ventura	0.4-0.6	0.4-0.6	0.6-0.8	0.2-0.4	0.1-0.2	0.2-0.4	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.8-1.0	0.6-0.8	0.1-0.2
24 – Ventura	0.4-0.6	0.6-0.8	1.0-2.0	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.2-0.4	0.4-0.6	0.8-1.0	0.6-0.8	0.2-0.4
25 – Pt Hueneme	0.4-0.6	0.2-0.4	1.0-2.0	0.2-0.4	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	0.4-0.6	0.8-1.0	0.6-0.8	0.2-0.4
26 – Malibu	0.2-0.4	0.2-0.4	0.4-0.6	0.2-0.4	0.1-0.2	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4
27 - Santa Monica	0.2-0.4	0.2-0.4	0.8-1.0	0.2-0.4	0.2-0.4	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4
28 - Los Angeles	0.2-0.4	0.4-0.6	0.8-1.0	0.2-0.4	0.2-0.4	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4
29 - Newport Ext	0.2-0.4	0.4-0.6	0.6-0.8	0.2-0.4	0.1-0.2	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4
30 – Newport	0.2-0.4	0.4-0.6	0.6-0.8	0.2-0.4	0.1-0.2	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4
31 - Dana Point	0.2-0.4	0.4-0.6	1.0-2.0	0.2-0.4	0.2-0.4	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.6	0.4-0.6	0.2-0.4	0.1-0.2
32 – Oceanside	0.2-0.4	0.4-0.6	1.0-2.0	0.6-0.8	0.2-0.4	0.1-0.2	0.2-0.4	0.4-0.6	0.4-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2
33 - San Diego	0.2-0.4	0.4-0.6	0.6-0.8	0.2-0.4	0.1-0.2	0.1-0.2	0.1-0.2	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.4	0.1-0.2

TABLE 1: Index offshore tsunami heights in meters, based on sensitivity analysis using NOAA's FACTS website and coarse bathymetry grids. Scenario input conditions, ~M9 events and 20 meter slip, may be unrealistic in some areas but were held consistent for each source for comparison purposes. More realistic magnitude and slip values were used for the actual final scenarios modeled.

SOURCE DEVELOPMENT AND SELECTION:

- To help protect its nearly one-million coastal residents and seaports vital to the US economy, the California Tsunami Program is developing statewide tsunami inundation maps that improve on the resolution, accuracy and coverage of the existing maps for the state.
- California's coast is vulnerable to tsunami sources that are distant, Pacific Rim subduction events and local, submarine seismic and landslide events. The Cascadia Subduction Zone is also a local source for the northern part of the state.
- Over 50 potential "worst-case" scenarios representing both local and distant tsunami sources were considered for 33 coastal populated areas (Borrero, 2002; Uslu, 2008). FIGURE 1 shows each coastal populated area mapped, FIGURE 2 shows distant source areas considered, and TABLE 1 shows the relative impact (incoming tsunami height offshore) of different distant source regions on each coastal area; these results address directivity effects from distant sources.
- The source scenarios showing the greatest impact for each coastal section were selected for hydrodynamic tsunami modeling.

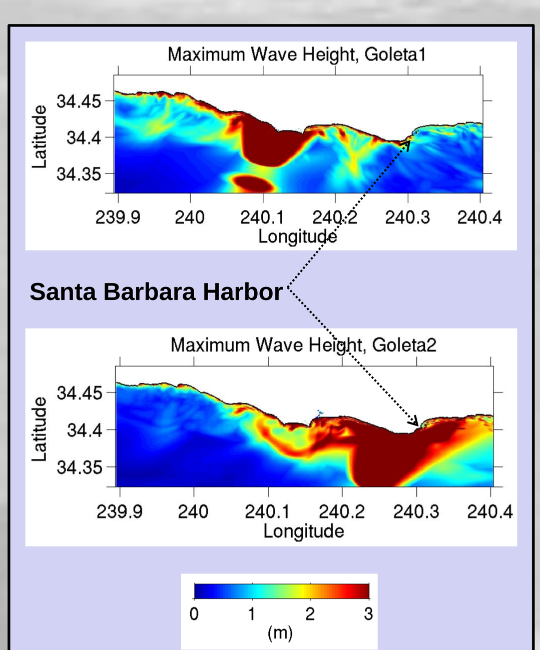


FIGURE 3

MODELING AND MAXIMUM WAVE ELEVATION CREATION

- The Tsunami Research Center at USC ran each scenario through the MOST hydrodynamic model program (Titov and Synolakis, 1997), propagating the tsunami through nested, lower- to higher-resolution bathymetric grids resulting in output grids of one arc-second (~30m) for three seaports and three arc-seconds (~90m) resolution for rest of California. FIGURE 3 shows results from two landslide scenarios near the existing submarine Goleta Landslide.
- For each source scenario run for a particular area, three output grids are available for use: the initial bathymetric grid, a tsunami flow-depth grid, and a tsunami inundation grid.
- Through simple grid manipulation and processing, these three grids are used to create individual wave elevation, or runup, grids for each scenario source.
- As shown in the FIGURE 4, the wave elevation grids for each source are combined into a single, maximum wave elevation grid.
- This maximum wave elevation grid represents the worst of all the scenarios for each individual grid cell.

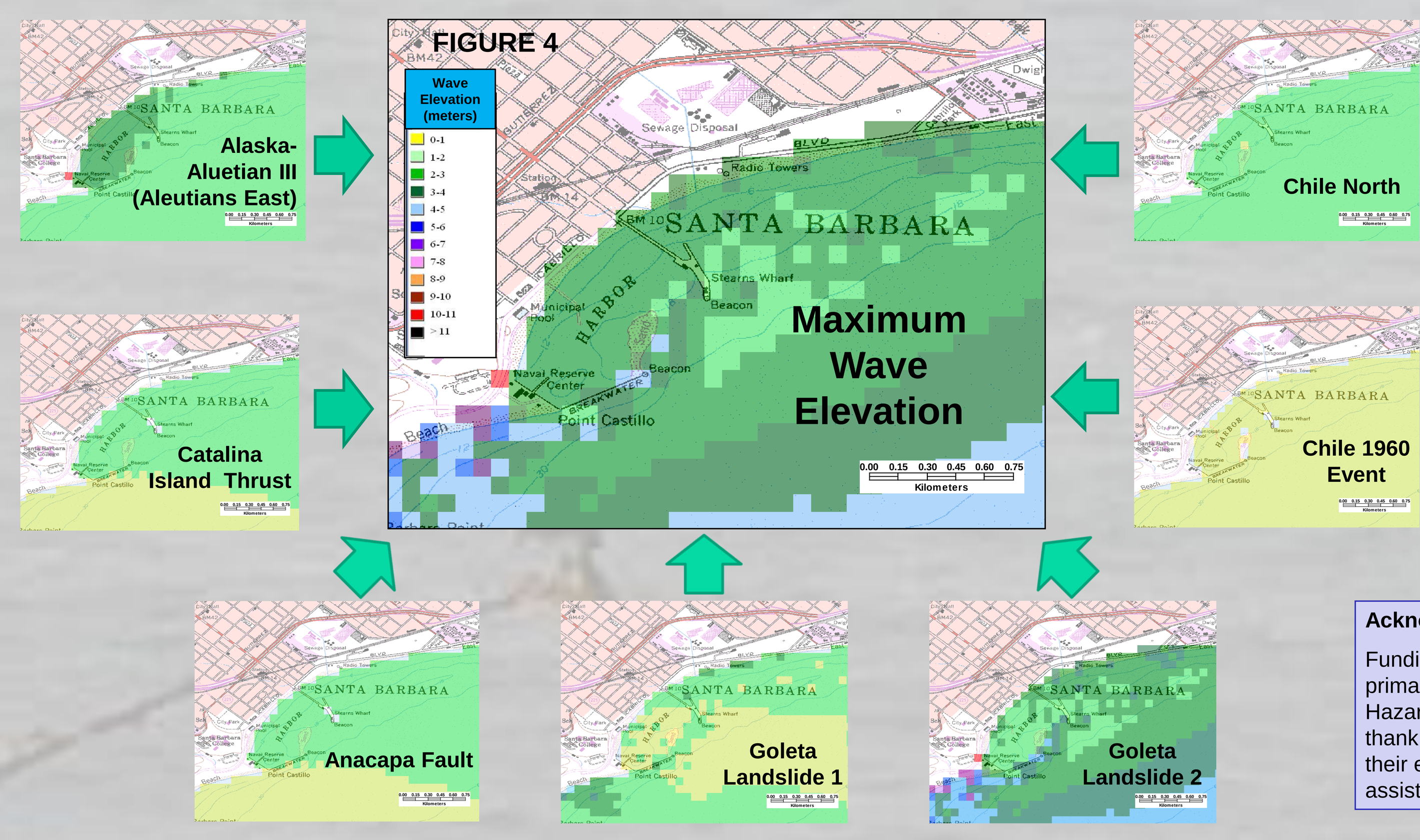
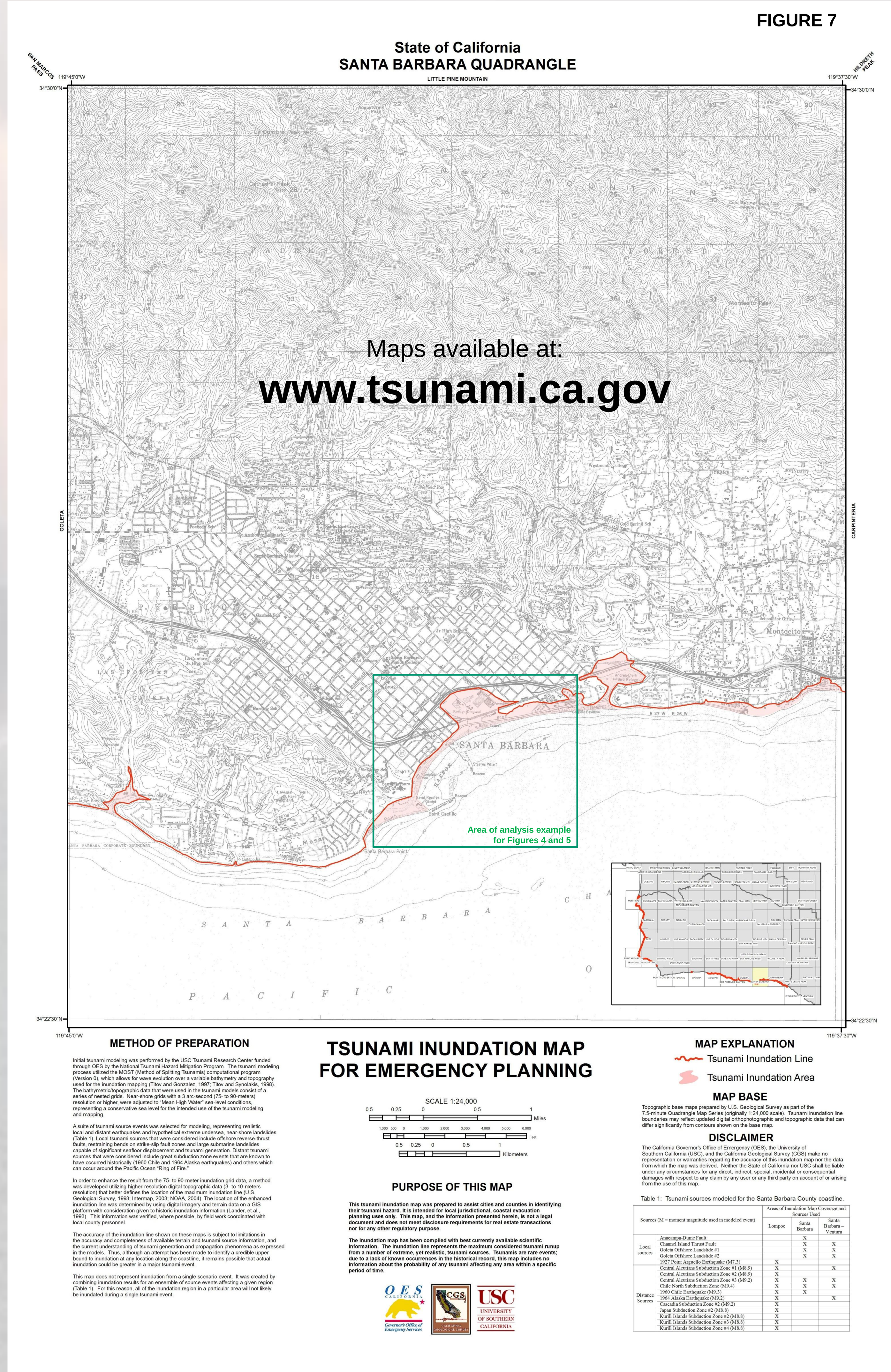


FIGURE 4



FUTURE MAPPING WORK BY THE STATE TSUNAMI PROGRAM

FIGURE 9

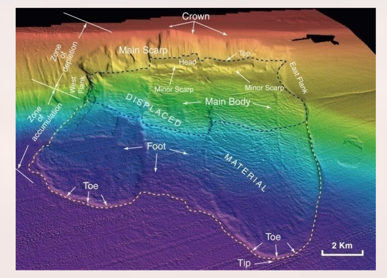


FIGURE 10

- Existing paleotsunami deposit information (FIGURE 9) will be entered into a database, compatible with the National Geophysical Data Center Global Tsunami Deposit Database, and used to verify the results from the hydrodynamic tsunami models.
- A tsunami source scenario database and discussion forum will be created to allow geoscientists and hydrodynamic modelers to discuss and help validate tsunami sources that could impact California.
- Tsunamigenic landslides (like FIGURE 10 showing the submarine Goleta Landslide, a potential tsunamigenic source for Santa Barbara; from Greene *et al.*, 2006) and offshore faults will be inventoried and hazard potential maps produced for improving tsunami mitigation efforts.
- To fulfill mandates by the National Tsunami Hazard Mitigation Program and the State Seismic Hazard Mapping Act of 1990, two Pilot Studies will be developed to produce tsunami hazard information and/or maps (showing inundation, flow depth, and flow velocity) to assist local jurisdictions in making land-use planning decisions.

LOCAL EMERGENCY RESPONSE PLANNING APPLICATIONS

- Draft inundation maps are checked in the field with emergency planners from local jurisdictions (FIGURE 6).
- Post-field draft tsunami inundation maps are sent to the local lead agencies for review and comments are collected and considered.
- Final inundation maps are sent to the local lead agencies and posted on state tsunami program websites (FIGURE 7).
- Workshops are held by state tsunami program representatives and local agency personnel to discuss how to best use the new inundation maps and what other needs local agencies might have.
- The state tsunami program may assist local agencies in development of new emergency and/or evacuation plans and placement of signage (FIGURE 8).
- Regional tsunami "working groups" (similar to the Redwood Coast Tsunami Working Group in the north part of the state) composed of state, local, and academic representatives will be initiated to maintain community-based tsunami hazard mitigation and outreach efforts.

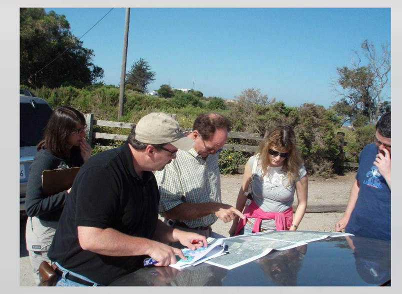


FIGURE 6

FIGURE 8

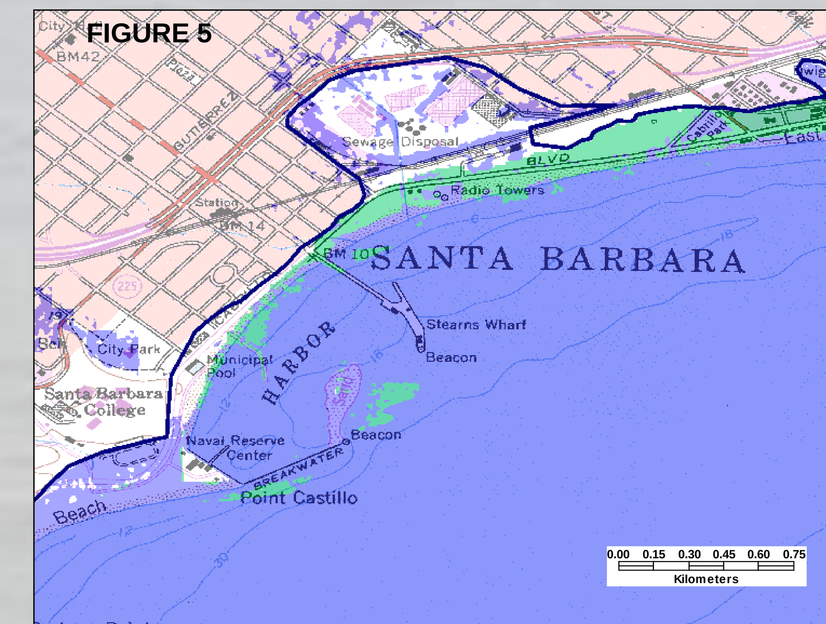


FIGURE 5

MAXIMUM TSUNAMI INUNDATION LINE PRODUCTION

- High resolution digital elevation models (DEMs) are used to enhance the location of the maximum inundation line.
- The maximum wave elevation grid is extended onshore and transferred from the coarse grid onto the USGS 10m DEMs (green) and interferometric radar 3m DEMs (blue) to show were flooding from the tsunami might occur (FIGURE 5).
- A draft inundation line is digitized (also FIGURE 5). Because the topography used to create the USGS DEMs is out-of-date and the more up-to-date (2005) interferometric radar DEMs shows structures or vegetation, careful consideration is given to these potential problems with both high-resolution DEMs.
- The inundation line is checked in the field and adjusted where appropriate.

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Websites

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