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M E M O R A N D U M

Date:	July 17, 2010
To:	City of Fort Bragg
CC:	Darcey Rosenblatt and Lesley Lowe, ESA
From:	Lindsey Sheehan, David Revell, PhD. and Bob Battalio, P.E.
PWA Project #:	2030.00
Subject:	**Tsunami Assessment for the City of Fort Bragg, CA**

Introduction

This technical memo provides an initial assessment of the potential impacts of tsunamis for the City of Fort Bragg in Mendocino County. The purpose of this assessment is to review recent research on tsunamis, examine historic impacts from tsunamis for this stretch of California coast, and to identify risks to the City of Fort Bragg. As part of this initial assessment, we make some recommendations for some additional studies and preparedness that could be conducted to further reduce risk and improve the understanding of tsunami hazards.

Background

The word tsunami comes from two Japanese words: *tsu* which means harbor, and *nami* which means wave. Tsunamis (inappropriately referred to as "tidal waves") are a series of potentially large waves which are caused by catastrophic events including: earthquakes, underwater landslides, volcanic eruptions, and infrequently, asteroids. Tsunamis are categorized based on the source of the generating event. Nearfield tsunamis occur in relative close proximity to the site while farfield tsunamis are generated at longer distances typically on the opposite side of ocean basins.

The formation mechanisms for a tsunami are illustrated in Figure 1. First a catastrophic event vertically displaces a volume of water as illustrated in the first stage of Figure 1. The second stage shows how waves are split and sent outward across the ocean. In the open ocean, these waves have small heights (amplitudes), but long periods (10-20 minutes) and fast speeds (350-500 mph) (Komar, 1997). (Note that Figure 1 is exaggerated for illustrative purposes). For comparison, a typical swell wave observed at the coast is called a surface gravity wave with periods of 13-20 seconds and speeds of 30-75 mph. Viewed at sea, a tsunami is barely noticeable; however, as the waves reach the coast, they shoal on the continental shelf with water piling up as the sea floor rises, and the height of the wave increasing dramatically as shown in stage 3. The first sign of an impending tsunami is often an unusual lowering of the water below a typical negative low tide level. This is the trough between wave crests and is followed by stage 4 where the wave runs up the coast raising water levels which cause flooding and erosion.

Northern California is threatened by both near and farfield tsunamis with the city of Crescent City one of the most susceptible coastal communities in California. Sources of nearfield tsunamis would be largely a result of a submarine (underwater) landslide and/or a large earthquake on the Cascadia Subduction Zone (CSZ). The CSZ which extends from Cape Mendocino, CA north past Vancouver Island in Canada, is one of the leading potential sources of nearfield events (Figure 2). Along this subduction zone, the Juan de Fuca and Gorda plates subduct under the North American plate and create a deepsea trench and a megathrust area which have the potential of producing earthquakes of magnitude 9 or greater. This magnitude of earthquake is similar to that experienced in December of 2004 which initiated the catastrophic Indian Ocean tsunami. The close location of the CSZ to the west coast of the US and Canada would allow a tsunami to reach land within 25 minutes of an earthquake event (Uslu *et al.*, 2008). From Japanese records of historic tsunamis, the CSZ last produced a major earthquake in 1700. With a recurrence rate estimated on the order of 500 years, but possibly ranging anywhere between 200-1300 years, an earthquake from the CSZ should be considered for tsunami planning (Uslu *et al.*, 2008; Clague, 1997). Sediment cores extracted from estuaries in the Pacific Northwest suggest that the recurrence interval of the CSZ earthquakes is more precisely between 200-500 years (Darienzo *et al.*, 1994). Using a unimodal recurrence distribution, Mazzotti and Adams (2004) estimate the 50-year conditional probability of an event along the CSZ to be 0-12%, while Petersen, Cramer, and Frankel (2002) using a time independent Poisson model estimate the probability at 10-14%. Kelsey *et al.* argue that there is a pattern to the recurrence of the events by looking at the geologic history of a lake in Oregon (2005). They found that the CSZ repeats a pattern of producing 3-4 tsunamis in approximately 1000 years followed by another ~1000 year period with no activity. They conclude that if this cycle continues, the tsunami in 1700 could be the beginning of a new cluster of events.

Another potential cause of a nearfield tsunami could be the Mendocino Fault. On September 1, 1994, a 7.0 earthquake triggered a small tsunami (less than 3 feet), which was detected in the Crescent City water level gauge 45 minutes after the earthquake (Dengler *et al.*, 2008). Given the close proximity of Fort Bragg to the Mendocino fault and the potential for a larger magnitude earthquake in the area, this is also considered a potential source of a nearfield tsunami.

Farfield tsunamis that would threaten the Fort Bragg coast could originate anywhere along the Pacific Rim, Alaska, or South America. A tsunami originating from Japan would take 10-15 hours to reach Fort Bragg while an event in South America could take up to 20 hours to reach the area. While such an incident would provide substantial time for evacuations, the effects could be as damaging as a nearfield event. One example is the Kuril earthquake (M8.3) which occurred on November 15, 2006 and generated a ~3ft tsunami at Crescent City that caused over $9.2 million dollars in damages to the boat basin (Dengler *et al.*, 2008). Figure 3 shows data from the Crescent City water level gauge during this event and illustrates the exaggerated heights of the waves overlying the longer period tidal oscillations.

State of the Art Numerical Models

Tsunami research has improved our understanding of tsunami risk through the use of numerical models. Using nested grids in a numerical model of tsunamis allows the coastal area to be more well-defined than the open ocean. This saves computational time while maintaining the detail necessary to determine wave and run-up heights. With complex bathymetry, as along the Fort Bragg coast, using a combination of interactive and non-interactive grids conserves energy in the coastal zone for increased accuracy in that area (Kowalik, 1991). Yamazaki, Kowalik, and Cheung (2009) showed that using an upwind flux approximation allows a numerical model to account for the discontinuity of wave breaking to fully model a tsunami wave bore.

Knowing the probability of tsunami run-up occurrences is also essential in evaluating risk. Tsunami wave heights at different locations along a coast are largely dependent on bathymetry and can therefore be modeled with a log-normal distribution (Choi, 2002). The cumulative frequency-size distribution of run-up heights at a single location is best described with a power-law or truncated power-law (Burroughs, 2005). However, if the tsunami catalog does not have sufficient data, using these patterns can lead to significant error. Geist and Parsons (2006) recommend using an insufficient catalog exclusively as background to a numerical model. Orfanogiannaki and Papadopoulos (2007) propose using earthquake time series with a ratio of tsunami occurrence to predict the frequency-size distribution of run-up heights since these series are generally more complete. One study conducted by USGS, FEMA, and NOAA developed a probabilistic assessment of tsunamis for Seaside, Oregon (Tsunami Pilot Study Working Group, 2006). This study established the new standard in probabilistic tsunami risk assessment for FEMA although this methodology has yet to be applied elsewhere in the United States. One key finding was that the largest tsunami impacts were expected to result from a nearfield tsunami associated with the Cascadia Subduction Zone, and not a farfield source (Tsunami Pilot Study Working Group, 2006).

The California Emergency Management Agency, the California Geologic Survey, and the University of Southern California have partnered to create statewide tsunami inundation maps. These maps were created by first examining tsunamis originating from the Pacific Rim or Cascadia subduction zones, underwater earthquake or landslide events, and past tsunamis and then running them through the MOST (Method of Splitting Tsunami) model using a coarse grid to determine which events would have the greatest impact on the California coast. Once identified, these events were run through the model again using nested grids down to 100 feet for three sea ports and 300 feet for the rest of the coast. The results of each modeled event were then combined to create a worst-case scenario wave and run-up estimate. Using

USGS 30 feet and interferometric radar 10 feet high resolution digital elevation models (DEMs), the inundation line was refined and verified in the field. This mapping effort which is ongoing provides the best information on the tsunami risk in the City of Fort Bragg (Figure 4). PWA has obtained the preliminary mapping results and has conducted some additional analysis to provide insights into the potential tsunami risk for the City of Fort Bragg.

One thing to note is that none of these models include erosion impacts from a tsunami. Coastal erosion along cliff backed shorelines is a process which is usually associated with high waves and water levels during storm events. A tsunami wave has much more wave energy than a swell wave and so erosion could be expected to occur during such an event.

History of Tsunamis in Fort Bragg

Three notable tsunamis have affected the Fort Bragg area in the twentieth century. On April 1, 1946, an 8.0 magnitude earthquake in the Aleutian Islands, AK spurred a tsunami that reached Noyo Harbor 5 hours and 31 minutes later (NOAA). The water level rose 4.5 feet above the predicted tide level of 2 feet for a total height of approximately 6.5 feet NAVD88 (NOAA). Docks in the harbor were damaged and 100 boats were thrown as high as 5.9 feet on the bank (Eisner et al.).

On May 22, 1960, a farfield tsunami originating in Chile, South America from an 8.7 magnitude earthquake reached Noyo Harbor 20 hours later (NOAA). Six boats were lost in the harbor and California suffered two deaths and damages from $500,000 to $1,000,000 (Eisner et al.).

The worst tsunami in Fort Bragg to date occurred on March 3, 1964. An 8.9 magnitude earthquake in Anchorage Alaska resulted in run-up heights of 12.5 feet in Noyo Harbor (NOAA). Tides were predicted to be 2 feet, but water levels instead reached an estimated 14.5 feet NAVD88. 10 boats were sunk and at least 100 boats were damaged (Eisner et al.) with total costs estimated at ~$1,000,000 in Fort Bragg alone (NOAA).

It is important to note that most of the tsunamis that have impacted Noyo Harbor occurred during a medium low tide. If these tsunamis had struck at high tide, damages could have been more severe.

City of Fort Bragg and the Mill Site Tsunami Risk

Factors that will affect the impact of tsunami run-up are tide level and sea level elevation at the time of arrival. These are independent factors that may reduce or exacerbate the impacts from such an event.
Investigation of the state tsunami hazard lines overlain on a high resolution LIDAR derived DEM shows that potential tsunami inundation elevations range up to 30 feet NAVD88. Figure 5 shows the tsunami inundation map for the Fort Bragg area. The range is partially established by the distance inland from the

beach as well as the accuracy associated with the state mapping, which use a coarser scale DEM. Areas located at or below this elevation should be considered to be inside a tsunami hazard zone.

While this information from the state was not intended for planning purposes it represents the best statewide tsunami mapping effort to date. This elevation information does not include wave run-up velocities which would be important in predicting potential erosion impacts.

Most parts of the coastline in front of Fort Bragg are protected by sea cliffs and will not flood from a tsunami. Soldier Bay is the most at-risk area for flooding and could see waters reaching 500 feet inland. Parts of Soldier Point could also flood, but the steep cliffs would keep waters from flowing very far onshore. The northern beach of Noyo Bay would also see inundation, with potential risk similar or increased to damages that have been observed historically. Future sea level rise may increase this risk as well. Photos in Figure 6 illustrate some of the areas that would be most affected by flooding.

City of Fort Bragg

The city of Fort Bragg currently has a Tsunami Contingency Plan for emergency response staff. This document identifies that the emergency services and City Hall are at low risk to tsunami run-up. This plan also identifies evacuation routes and low-lying areas within the City of Fort Bragg which include all areas below the 60-foot elevation level (Miller and Higdon, 2006), including but not limited to, the following:
All areas at and north of the Pudding Creek Bridge, including:

- Pudding Creek Beach and ocean beach areas
- Ocean Lake Adult Mobile Home Park (1184 North Main Street)
- All hotel / motel facilities on the west side of North Main Street
- All areas north of West Elm Street and west of North Main Street to Pudding Creek
- All areas along the Mill Site Coastal Trail within the city limits
- Portions of the Noyo Harbor (north side) and the Noyo Beach Jetty areas
- All areas within Pomo Bluffs Park
- All areas generally west of Pacific Drive and south of Bay View Drive in the Todd’s Point area
- All areas at and under (both west and east of) the Hare Creek Bridge
- The Fort Bragg Municipal Improvement District’s Wastewater Treatment Plant

It should be noted that this 60 foot elevation described in the contingency plan is well above the state modeled elevations (nearly double), but identifying the sources of these discrepancies is beyond the scope of this analysis and would require further modeling and technical information regarding both the source of the elevation information for the City’s Contingency Plan and the statewide efforts.

Mill Site

Tsunami inundation would most likely not reach the Mill Site. Within the site, the coastal trail and parkland area would be the most at-risk lands. Some of the ponds inland of Soldier Bay could also flood as well. Erosion should be expected in the event of a tsunami, although further modeling is necessary for specific locations and distances.

Tsunamis in Federal, State, and Local Policies, and Environmental Impact Reports

The Federal Emergency Management Agency would have involvement in any post disaster recovery. It is also important to note that FEMA currently does not have any specific tsunami inundation information for Fort Bragg and only has guidelines for inclusion of tsunami hazards in the Flood Insurance Studies (FEMA 2005). This risk is based on a 0.2% annual-chance-event tsunami from a farfield event. The most recent FEMA flood study (Ott 1984) mentions Noyo Harbor in as an approximate area which means no detailed analysis were conducted. However the closest detailed analysis at Point Arena Cove identifies a 500 year event to be approximately 20 feet NAVD88.

The California Coastal Act, which implements the Federal Coastal Zone Management Act in California, does not mention tsunamis in the Natural Hazard Section where most hazards information such as flooding and erosion are discussed. However, the Coastal Act does include a mandate to avoid and /or minimize risk to life and property in areas of high flood and geological hazards. The identification of specific geologic and flood hazards are thus left to the local jurisdictions to identify and interpret. This has been done partly through the environmental review process and partly through the local coastal programs (LCPs). Designation of tsunami hazard zones are primarily done through site or jurisdictional specific geotechnical studies and implemented through a General Plan or Local Coastal Program update.

One notable policy inclusion of tsunami hazards occurs in the City of Monterey LCP element regarding the planning for the Del Monte Beach Shoreline Segment (City of Monterey, 2003). This language states "new development must be set back from the eroding coastal dunes sufficiently to protect it for the 100-year economic life of the project and is not allowed in ***tsunami runup*** or storm wave inundation areas (excepting coastal dependent uses and public access improvements),"(*emphasis* added).

The Crescent City General Plan EIR merely noted the history of tsunamis in the area and the local factors that make the city so at risk to the big waves (Mintier & Associates, *et al.*, 2001). The combination of nearshore bathymetry and the protruding coastline near the city make it extremely susceptible to wave resonance that could create larger waves than anywhere else along the California coast. Following the 1964 quake, Crescent City experienced tsunami run-up up to 2000 feet inland causing $168 million in damages. Instead of rebuilding, much of the old downtown was turned into a park (Griggs et al 2005).

While Fort Bragg also extends into the ocean, the coastline has a smoother curve than near Crescent City and is somewhat protected by Humboldt County in the case of a tsunami arriving from the north.

While many Environmental Impact Reports (EIRs) for projects on the west coast of the United States refer to tsunamis, most ignore them as a threat because the project is located inland (County of Sonoma, 2008; CirclePoint, 2010; Leighton Consulting). However, EIRs for projects at risk of tsunami damage vary widely in the amount of details included in the report. In San Mateo, the Big Wave Wellness Center and Office Park project included an EIR that described the three major tsunami events in recent history at that site and included a tsunami evacuation map for the area. The report only went so far as to recommend that, "…any development in this area would need to take into account the effects of tsunami action on structures and people," (San Mateo County, 2009).

The city of Torrance in southern California included a draft EIR in the city's General Plan. Tsunamis were defined and potential sources that would create tsunamis in the area were cited in the report. The only conclusion drawn was that, "a landslide-induced tsunami directly offshore of Torrance is plausible," (City of Torrance, 2010). Similarly, the city of Goleta wrote an EIR for the General Plan and included a definition of tsunamis and a record of past tsunami events. An inundation map was included along with a summary of potential flooding.

In Tiburon, California, the Library Expansion project used an EIR that noted the possibility of tsunamis in the area and included an inundation map. The report then described the flooding that could result from a tsunami event, but concluded that, "mitigation practices for tsunami… are often best handled on a local or regional (rather than project) scale" (Christopher Joseph & Associates, 2010).

Conclusions

Some of the greatest historical tsunami impacts have occurred in harbors and port cities. Fort Bragg and Noyo Harbor have historically experienced larger tsunami impacts than most of the California Coast. Most of the historic tsunamis have occurred during mid to low tide reducing the overall impact. Low lying areas in and around Fort Bragg especially Soldier Bay, Noyo Harbor, and Pudding Creek are particularly susceptible to tsunami hazards as documented by recent State mapping efforts. Since much of the City is located on sea cliffs that range in height from 40 to 70ft the overall tsunami risk is reduced for many of the residents.. Emergency services are also at low risk from tsunami hazards (although earthquake readiness was not investigated). However, the velocity associated with a tsunami is likely to increase cliff erosion, so development and infrastructure near the cliff edges may be susceptible to erosion impacts even though they are at low risk of wave run-up and flooding impacts. Several recommendations for improving emergency preparedness and understanding of tsunami risk are provided to the City.

Figures

List of Preparers

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Recommendations

Further develop tsunami evacuation plan (Miller and Higdon, 2006)
Time at the actual instance of a tsunami is precious. A tsunami from the CSZ could take as few as 20 minutes after an earthquake to arrive on the coast. While the tsunami contingency plan sets evacuation routes as seen in Figure 7, and procedures for notifying officials and the public to improve preparedness, conduct drills on the emergency response plan, train new staff, expand educational signage along the coastal trail, work with tourist industries to inform visitors, and expand evacuation signage. Collaboration with surrounding coastal and bay areas on tsunami evacuation procedures and best practices will eliminate any local inconsistencies.

Support community specific tsunami wave modeling
The state has invested in numerical models that can provide planning level coastal hazard maps such as in Figure 4. These, along with other erosion and flooding models such as the probabilistic assessment developed in Oregon can be used to improve the understanding of tsunami and other coastal hazards both now and into the future. The city should write to FEMA and ask for financial and technical support to include more detailed analysis in future updates of Flood Insurance Rate Maps (DFIRMS).

Develop an ordinance which reduces vulnerability by avoiding future development and redevelopment in the tsunami and other coastal hazard zones.
Several jurisdictions have good examples of coastal hazard avoidance policies which include tsunamis. This should include avoidance of both flooding and erosion hazards. One such example is Del Monte Beach in Monterey, CA (City of Monterey, 2003).

Develop an outreach and education strategy targeting the key community constituents
Tsunami information, education, and training should be made available to residents (both full time and part time), tourists serving industries, especially hotels, motels, and bed and breakfasts, and any businesses in inundation zones. Due to the potentially short arrival times of a tsunami, the need to respond quickly is essential.

Develop a post disaster redevelopment plan
The recovery after a disaster is a hard time for any jurisdiction; however it can also be an opportunity to change the direction, location or character of a community. This is best achieved if the community has a current shared vision before the event. This facilitates the use of recovery funds to be used to shift infrastructure and development to achieve the vision.

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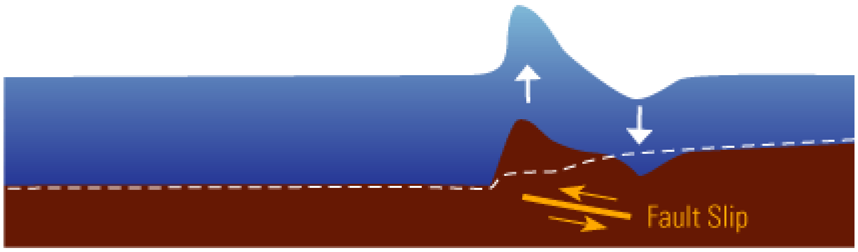
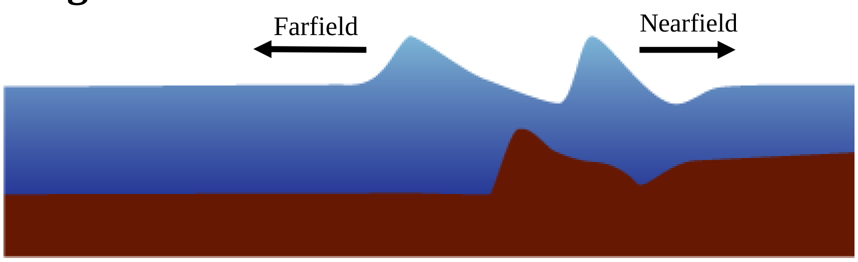
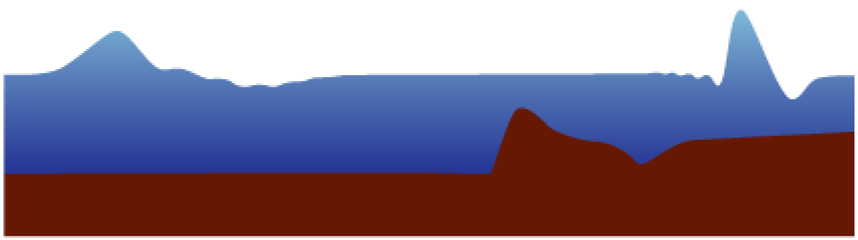


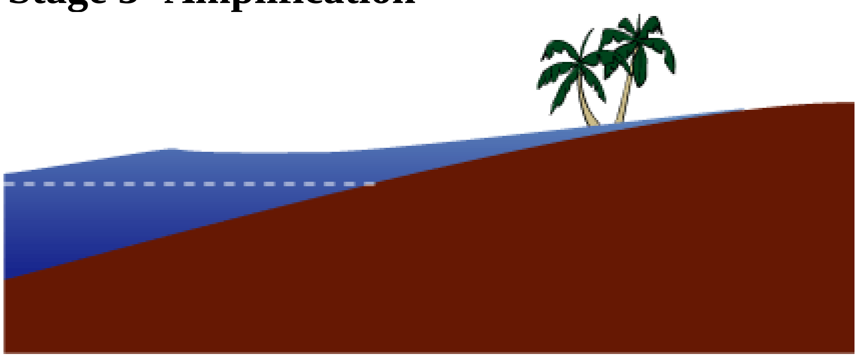
Stage 1- Initiation



Stage 2- Split



Stage 3- Amplification



Stage 4- Run-up

The height of the waves above are exaggerated for illustrative purposes.

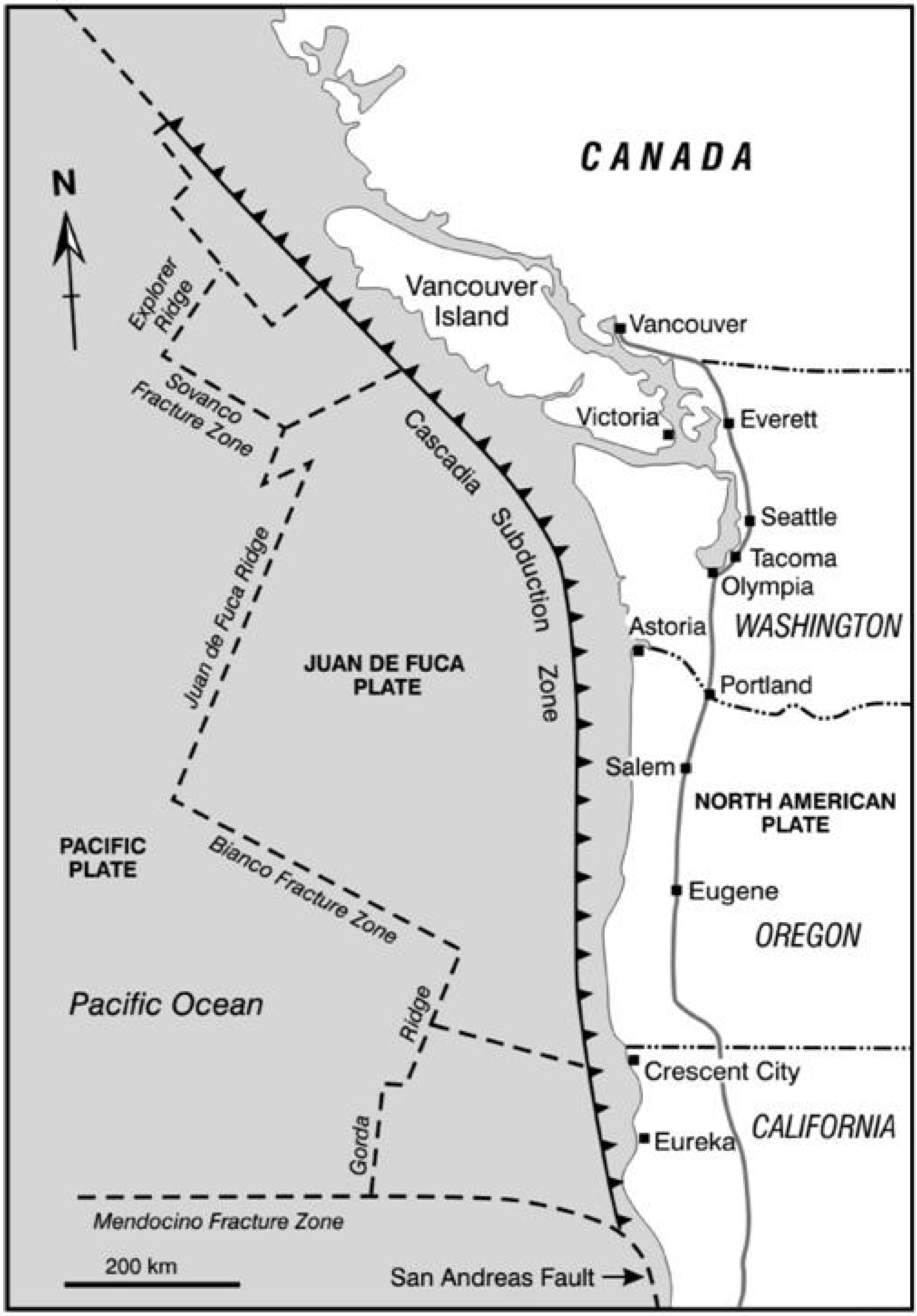
Source: Adapted from USGS. Life of a Tsunami.
http://walrus.wr.usgs.gov/tsunami/basics.html.

figure 1
Tsunami Assessment for the City of Fort Bragg, CA

Tsunami Formation

PWA Ref# 2030-04

PWA



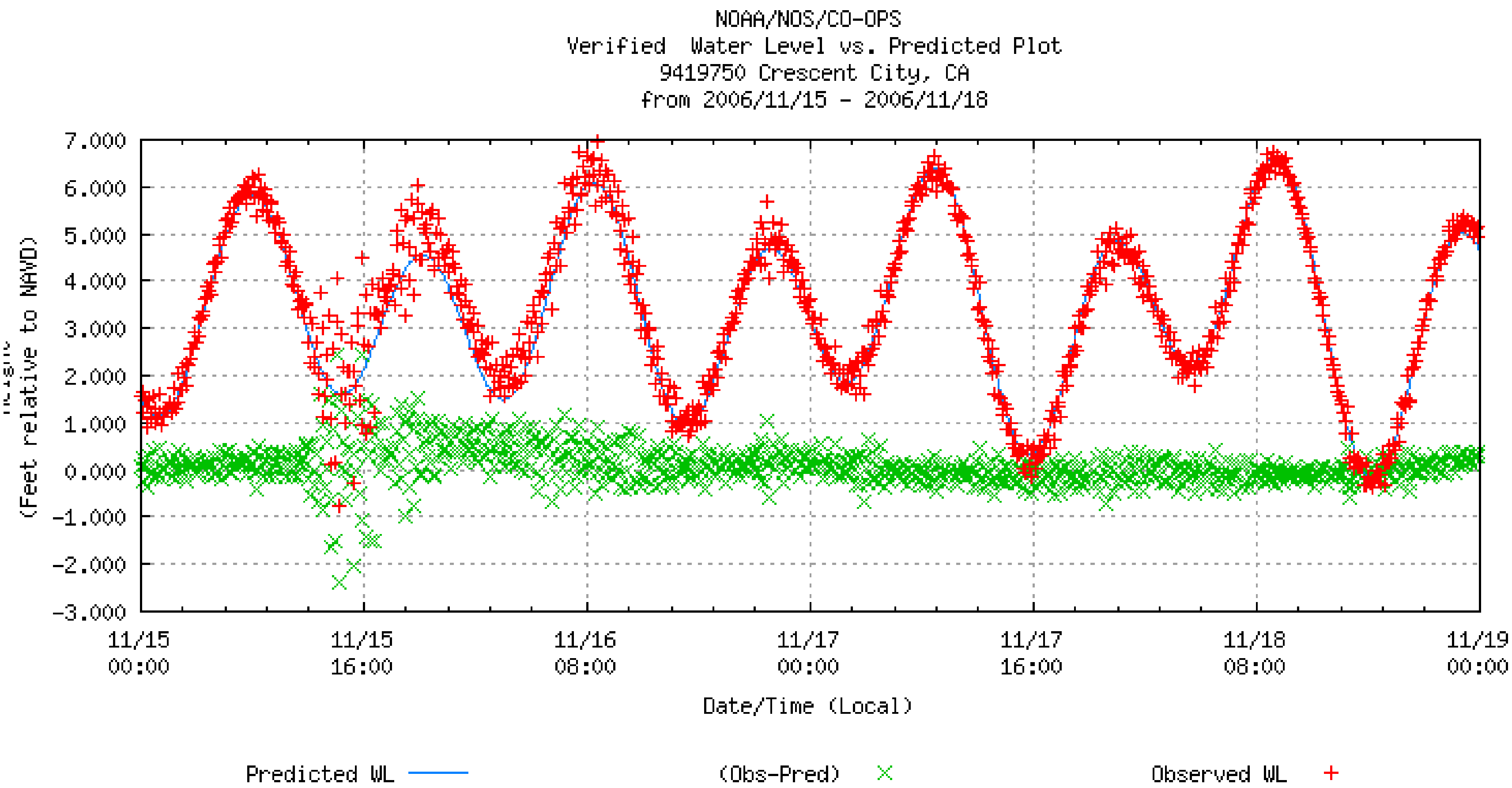
Source: Adapted from the Cascadia Region Earthquake Workgroup. (2005).

figure **2**

Tsunami Assessment for the City of Fort Bragg, CA

Cascadia Subduction Zone

PWA Ref# 2030-04



Source: NOAA Tides and Currents.
http://tidesandcurrents.noaa.gov/data_menu.shtml?type=Historic+Tide+Data&mstn=9419750.

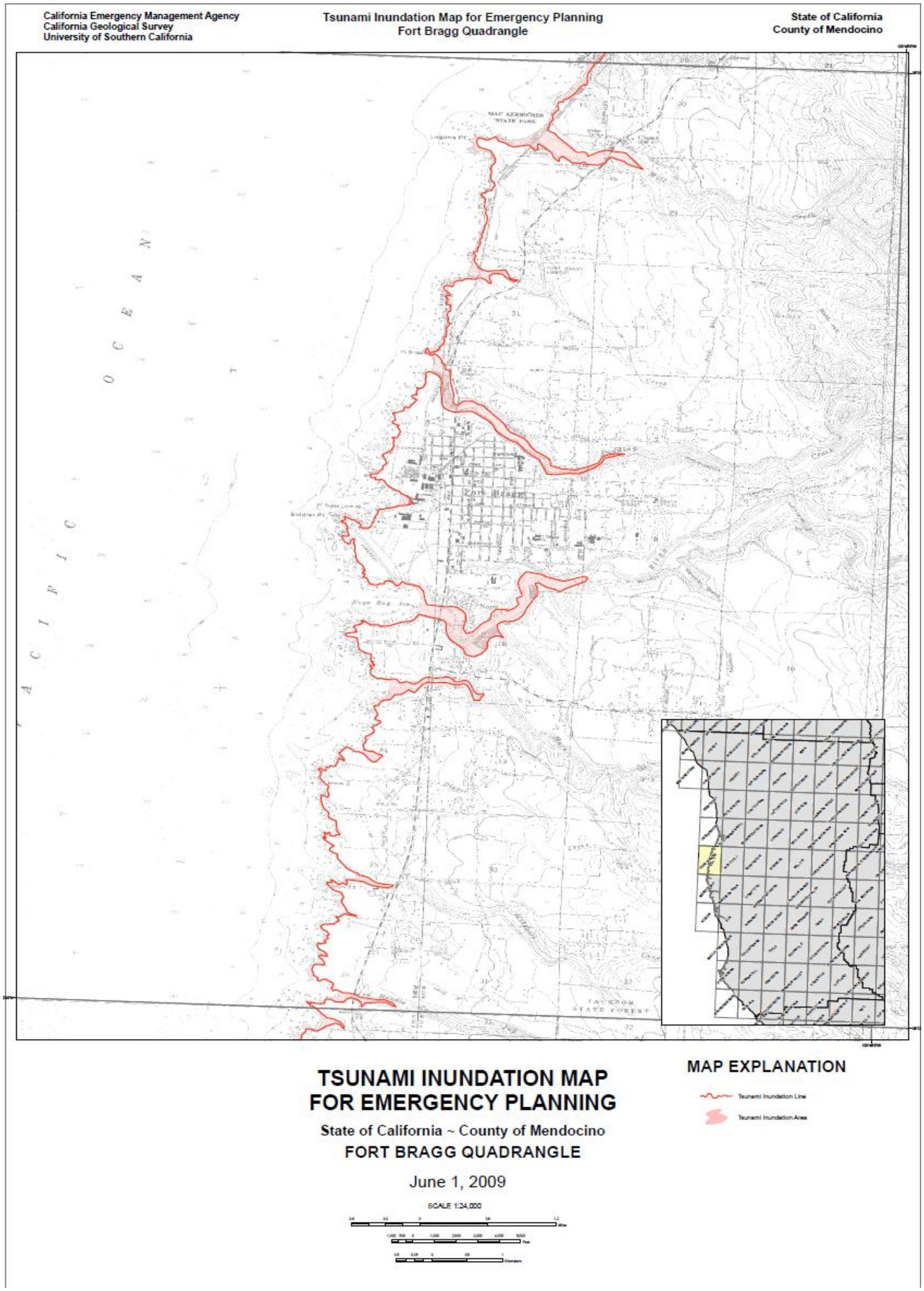
figure **3**

Tsunami Assessment for the City of Fort Bragg, CA

Crescent City Water Level Data
for the Tsunami on 11/15/06

PWA Ref# 2030-04

PWA



Source: State of California. (2009). Tsunami Inundation Map for Emergency Planning, Fort Bragg Quadrangle, Mendocino County; produced by California Emergency Management Agency, California Geological Survey, and University of Southern California – Tsunami Research Center; dated June 1, 2009, mapped at 1:24,000 scale.

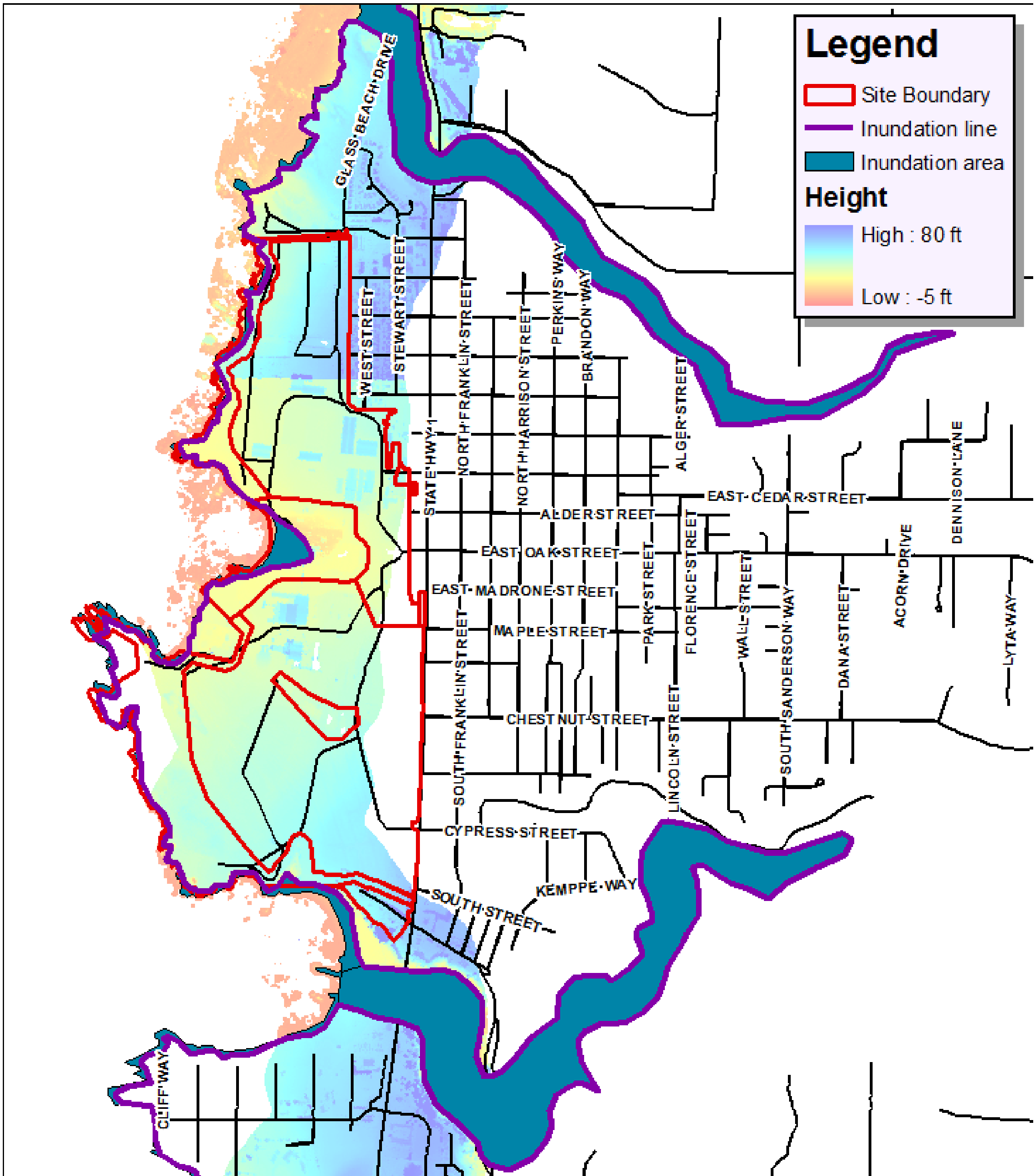
figure **4**

Tsunami Assessment for the City of Fort Bragg, CA

State Map of Tsunami Inundation

PWA Ref#: 2030-04

PWA



Source:

Note:

N

0 1,000 2,000 4,000 Feet

figure 5

Fort Bragg Tsunami Technical Memo

PWA Map of Tsunami Inundation

PWA Ref# 2030-04

PWA

filepath for mxd

Mouth of Pudding Creek, 2009

Soldier Bay (and Soldier Point in bottom right), 2009

Noyo Harbor and River, 2009

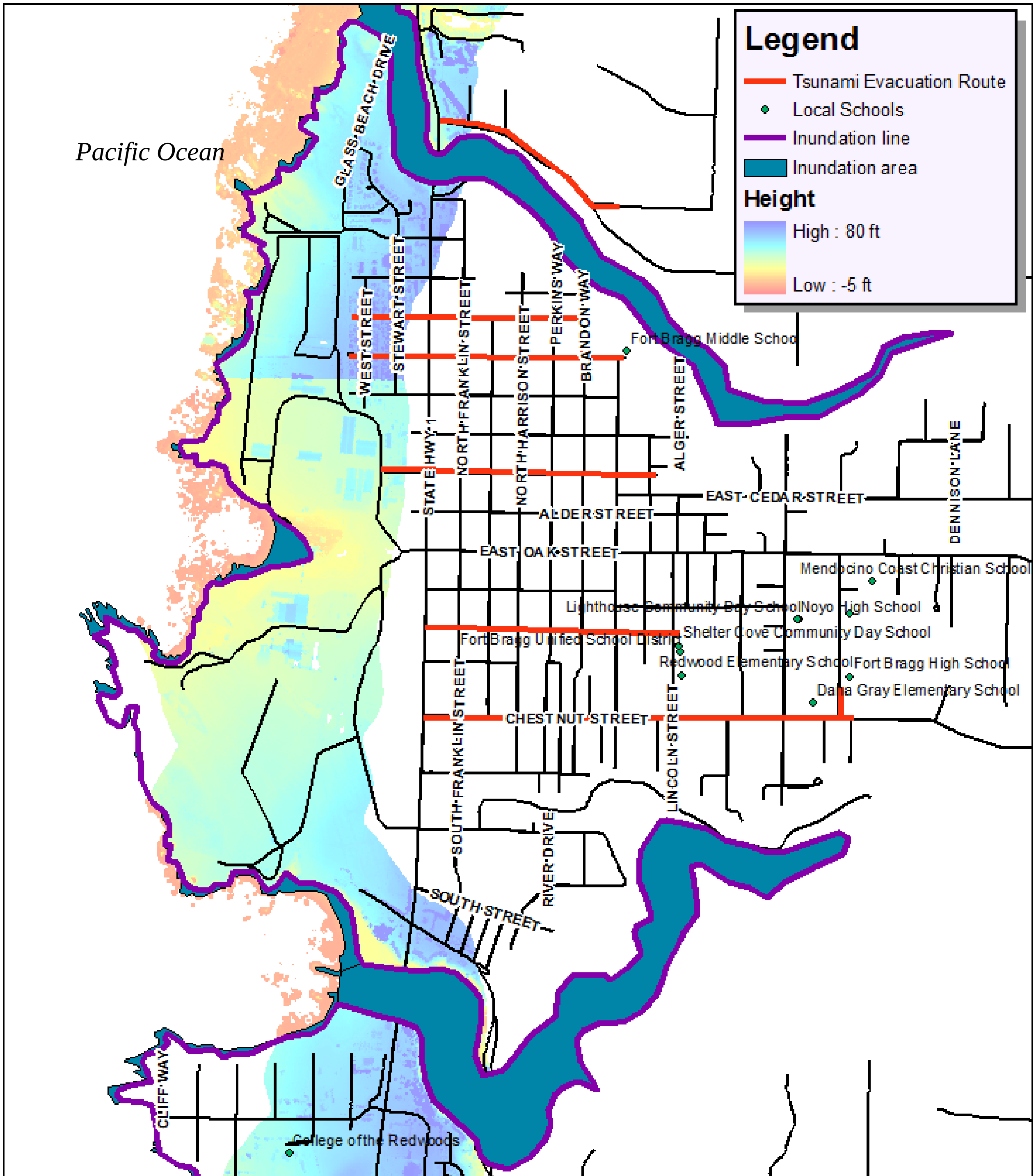
Source: California Coastal Records Project
http://www.californiacoastline.org

figure ***6***
Tsunami Assessment for the City of Fort Bragg, CA

Photos of the Fort Bragg Coast

PWA Ref# 2030-04

PWA



Note: All routes lead east away from the ocean

N

0 1,000 2,000 4,000 Feet

figure 7

Fort Bragg Tsunami Technical Memo

PWA Map of Fort Bragg Evacuation Routes

PWA Ref# 2030-04

PWA

filepath for mxd