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FIGURES

1 OVERVIEW OF TSUNAMI HAZARDS FOR THE HUMBOLDT REGION

Tsunamis are anomalous waves "triggered by earthquakes, volcanic eruptions, submarine landslides, and by onshore landslides in which large volumes of debris fall into the water… [They] typically consist of multiple waves that rush ashore like a fast-rising tide with powerful currents (USGS, 2020). For the North Coast and other areas adjacent to subduction zones, tsunami sources fall into two categories: (1) local or nearfield tsunamis generated by seafloor displacement associated with a rupture along the subduction zone megathrust, or landslides set in motion by seismic shaking, to include submarine landslides and massive coastal landslides that fall into the sea; and (2) distant-source or far-field tsunamis (also called teletsunamis, e.g. Wilson et al., 2013) originating from seismic disturbances, particularly along subduction zones, in other locations as far as 1000s of kilometers away.

The North Coast area faces risk from both nearfield and far-field tsunamis. Geophysical modeling and geological field data show that the CSZ has ruptured in estimated M8-M9 earthquakes in the past, and that similar to other subduction zones worldwide, tsunamis have attended a number of these past earthquakes (Heaton and Hartzell, 1987; Abramson, 1998; Carver et al., 1998; Garrison-Laney, 1998; Atwater et al., 2003, 2005; Patton, 2004; Kelsey et al., 2005; Peterson et al., 2011; Hemphill-Haley et al., 2019). For the Highway 101 Safety Corridor project tsunami concerns include on-land inundation, coastal and shallow bay erosion, and potential impacts to highway infrastructure from strong currents during on-land inundation. The major effect of far-field tsunamis would be strong, possibly erosive currents in Humboldt Bay's North Bay (Admire et al., 2011, 2014; Admire, 2013; Wilson et al., 2013b), whereas nearfield tsunamis would likely involve all three areas of impact.

The primary authorities on tsunami hazards for the North Coast are the California Geological Survey (CGS, 2020) and the Redwood Coast Tsunami Work Group (RCTWG, https://rctwg.humboldt.edu) who produced the tsunami inundation map shown in Figure 1. In addition, the US Geological Survey produced a map indicating land usage and maximum inundation (Wood et al., 2013) (Figure 2).

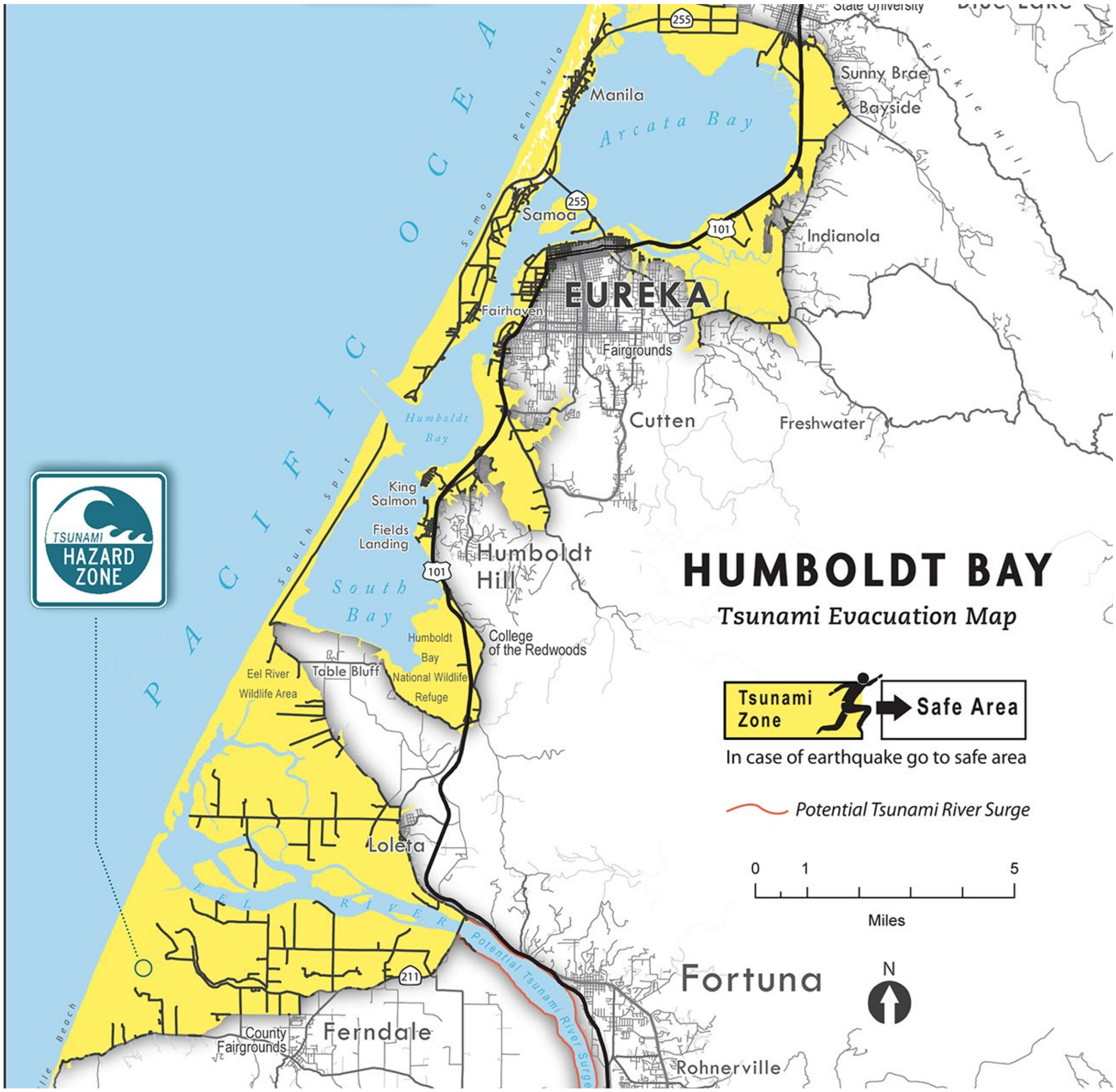

Figure 1. Map of tsunami inundation zone for area of Humboldt Bay (Modified from RCTWG, 2020, Humboldt Bay Tsunami Evacuation Map, <https://rctwg.humboldt.edu/sites/default/files/regional-crop.pdf>.)

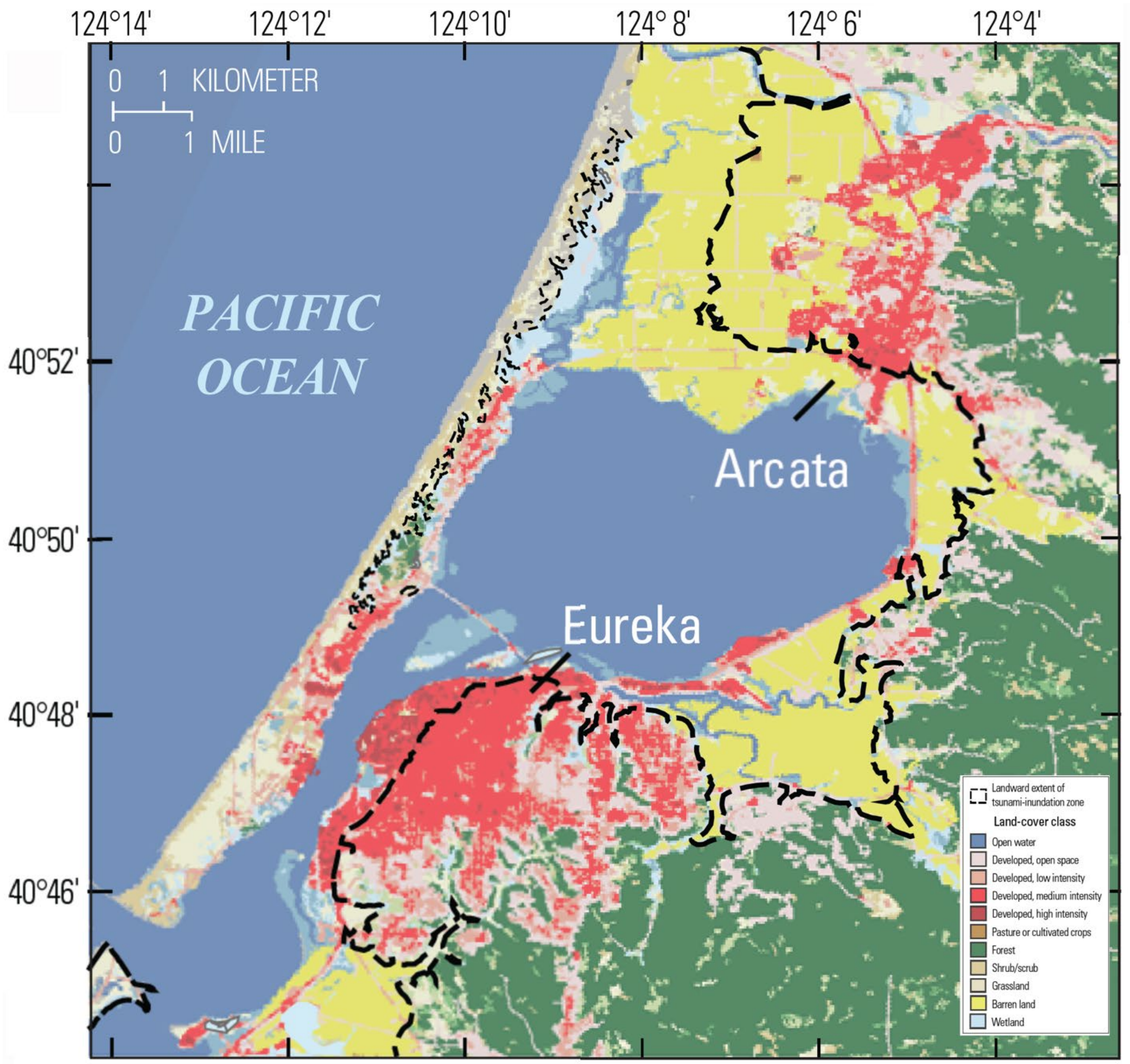

Figure 2. USGS map showing potential tsunami inundation map of northern Humboldt Bay superimposed on land use (Wood et al., 2013).

Thio (2019) produced statewide tsunami inundation maps as part of a Probabilistic Tsunami Hazard Analysis (PSHA) that include Humboldt Bay (Figures 3 and 4). These two maps represent evaluation of a 2475 year recurrence model that considers all potential tsunami sources (Figure 3a) and only far-field sources (Figure 3b). The State of California (2021), using Thio (2019) modeling produced an inundation map considering a 975-year average return period tsunami event model with a 5% probability of exceedance in 50 years. Of these maps only Thio (2019) provides an estimate of inundation depth (Figure 3a and b). These maps suggest the inundation would be less than one m along the Hwy 101 corridor. It should be noted that Thio is currently creating new inundation maps for Humboldt Bay using new bathymetry models (Hun Ki Thio, personal communication, September 2024).

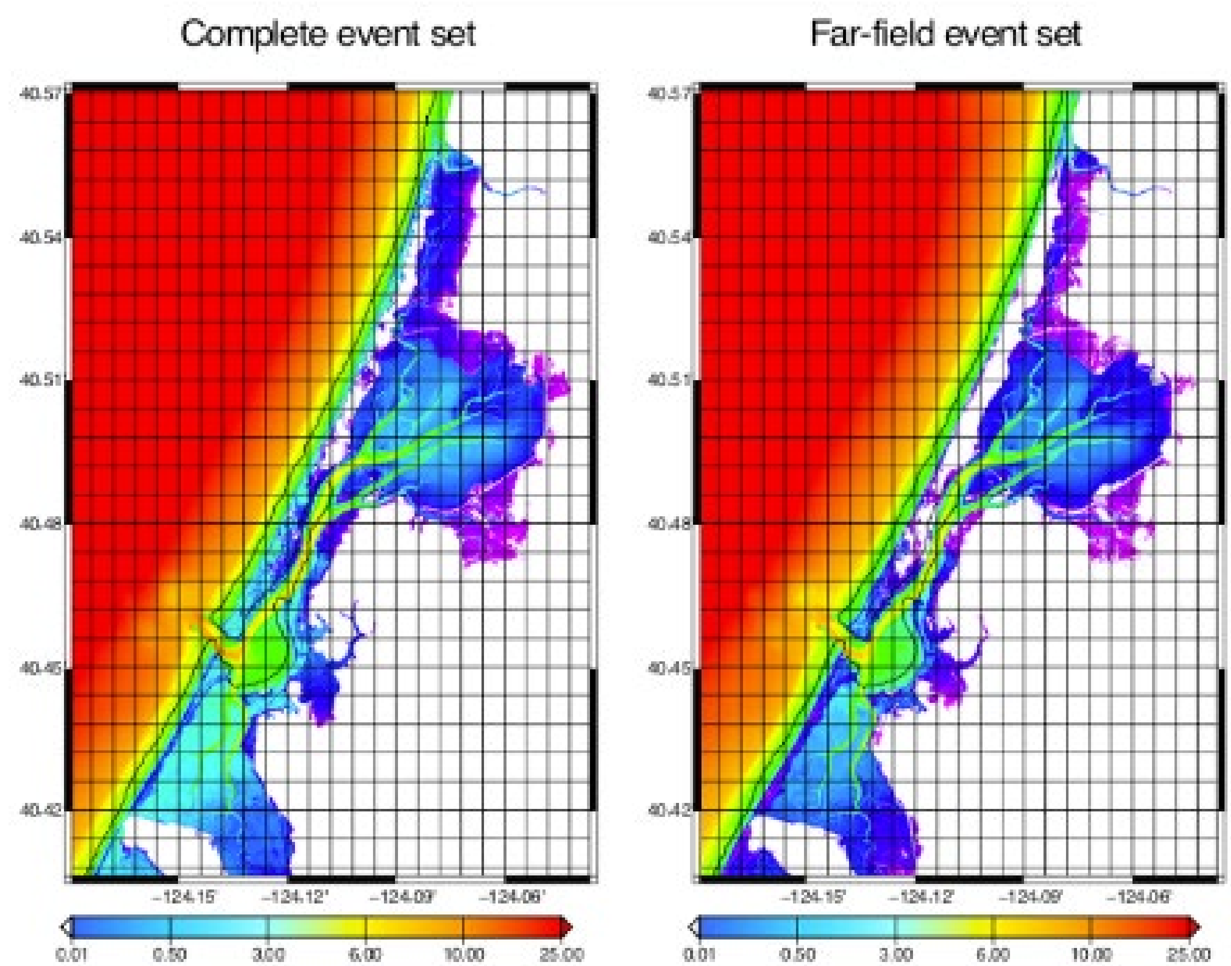

Figure 3. Probabilistic tsunami flow depths for Humboldt Bay considering a 2475 year model (from Thio, 2019). Left map includes local and far-field sources while the map on the right considers only far-field sources. There is not substantial difference in the inundation pattern between the two source models. Elevation units are in meters.

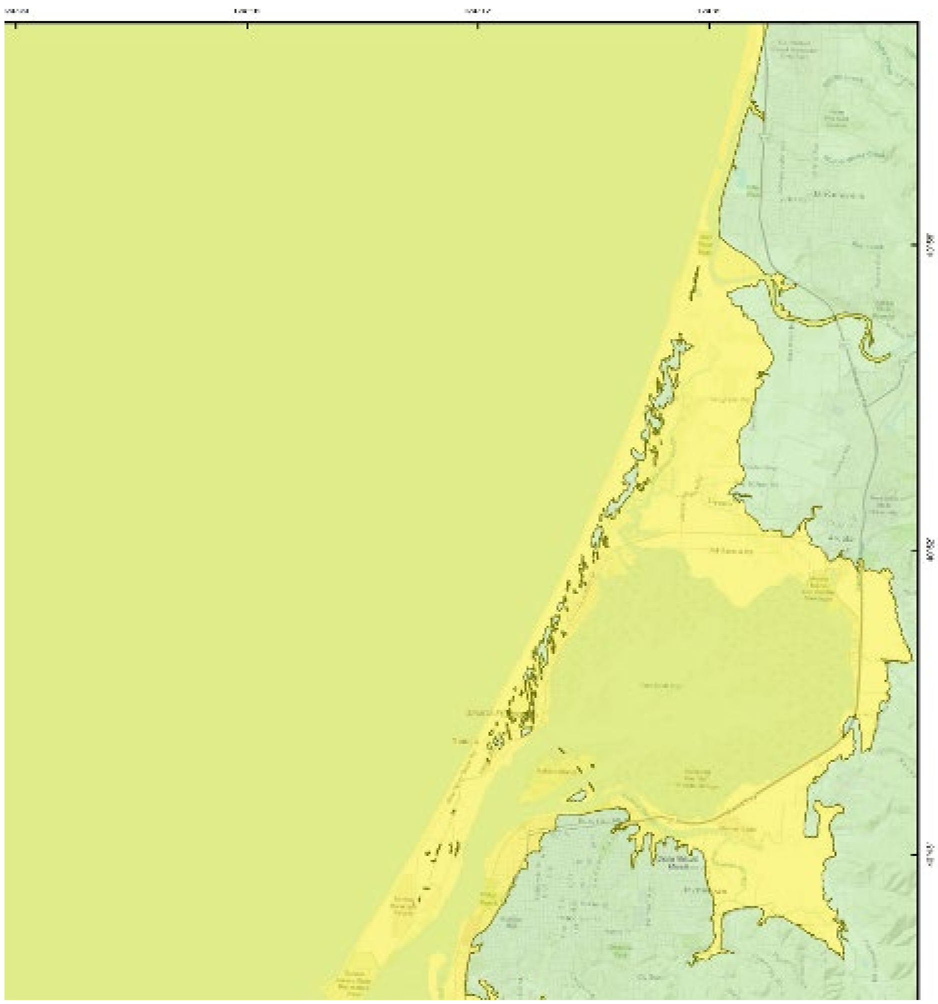

Figure 4. Portion of Humboldt Bay tsunami inundation map (State of California, 2021). Areas highlighted in yellow are considered likely to be inundated corresponding to a 975-year average return period tsunami event model with a 5% probability of exceedance in 50 years. This map is based on modeling by Thio (2019).

The aftermaths of tsunamis associated with the subduction zone earthquakes in 2004 M9.1 Indonesia (e.g., Kurian et al., 2006; Szczuciński et al., 2006), 2010 M8.8 Chile (e.g., Fritz et al., 2011; Palermo et al., 2013) and 2011 M9.0 Japan (e.g., (Mori et al., 2011; Suppasri et al., 2012; Fraser et al., 2013; Hazarika et al., 2013) attest to the level of destruction that can accompany such events. For the 1964 M9.2 Alaska earthquake, 116 of the 131 reported fatalities were caused by tsunami inundation, much attributed to submarine landslides, along the coast and fjords of southern Alaska (Haeussler et al., 2007, 2014; Suleimani et al., 2011; Brothers et al., 2016). On the North Coast and elsewhere along the coast of the Pacific Northwest and British Columbia, the far-field tsunami from the 1964 earthquake caused significant damage. Crescent City, California, was impacted the most severely with 29 city blocks damaged and 11 people killed (Griffin, 1984; Dengler and Magoon, 2005). For the 2011 Tohoku-aki M9.0 earthquake, even though the earthquake shook a large part of the island of Honshu—including large urban areas—for as much as six minutes, most of the destruction and majority of the >20,000 deaths were attributed to the tsunami rather than the shaking (Nakahara and Ichikawa, 2013).

Tsunamis usually are not observed as a single wave, but the arrival of a series of waves with the crests separated by an amount of time determined by their wavelength and distance from source, ranging from a few minutes to hours (NOAA, 2020). Often the first wave to arrive is not the largest (Dengler and Magoon, 2005; Okal and Synolakis, 2016). The destructive forces of tsunamis not only include the far-field tsunamis are a fairly frequent occurrence landward force and flooding of the incoming waves, but also the erosion and deposition by backwash as debris-filled water rushes back to the ocean, typically at high flow velocities (Bahuguna et al., 2008; Feldens et al., 2009; McAdoo et al., 2011; Hazarika et al., 2013; Udo et al., 2016). As described by Lemmons (2016), the "*force of the tsunami backwash can be just as strong, and in some cases stronger than the initial impact. Some waves take five minutes or more to move inland, and less than two minutes to wash back out to sea, so the outgoing velocity may be greater than the initial surge. The outgoing waves often take the loose debris from the destruction of the incoming wave with them, placing projectiles in the water for the next crest to launch when it moves inland*." The combined landward flow and subsequent backwash can result in areas of coastal erosion and deposition in the nearshore (Feldens et al., 2009; MacInnes et al., 2009; Tanaka et al., 2012; Udo et al., 2012; Hazarika et al., 2013; Ikehara et al., 2014), as well as sediment scour in ports and harbors (Wilson et al., 2012; SAFFR Tsunami Modeling Working Group, 2013; Borrero et al., 2015; Son et al., 2020).

There have been 33 tsunamis recorded since the installation of the first tide gauge at Crescent City in 1933 (Admire et al., 2013, 2014). To date, Humboldt Bay has not suffered damage from fa- field tsunamis, although higher current velocities have been recorded. In Humboldt Bay, Acoustic Doppler Current Profilers (ADCP) have been installed (Figure 5) to measure tsunami and other currents (Admire et al., 2014). The ADCPs were operational during the 2010 M8.8 Chile and 2011 M9.0 Tohoku-Oki, Japan earthquakes and were able to calculate peak tsunami wave amplitude and peak current speeds for both events (Figure 6). Admire et al. (2014) report that tsunami currents from the 2010 Chile earthquake lasted within Humboldt Bay for approximately 30 hours with peak velocities of about 0.35 m/s and peak water amplitudes of about 0.23 m. The 2011 Japan earthquake resulted in a tsunami signal that lasted more than 40 hours in the bay with water velocities between 0.6 and 0.84 m/s measured during the first two hours and a peak amplitude of 0.81 m. The Physical Oceanographic Real-time System (PORTS) project (which included some of the ADCP locations reported by Admire (2014), a collaborative effort at Humboldt Bay between NOAA and Cal Poly Humboldt (https://tidesandcurrents.noaa.gov/ports/index.html?port=hb) currently maintains a continuous monitoring system in Humboldt Bay in the event of tsunami activity to acquire "*Better estimates of the currents generated by tsunamis [which] can be used to improve numerical modeling and to provide better understanding of the hazards in ports and harbors caused by currents* (Admire et al., 2014, p. 3402).

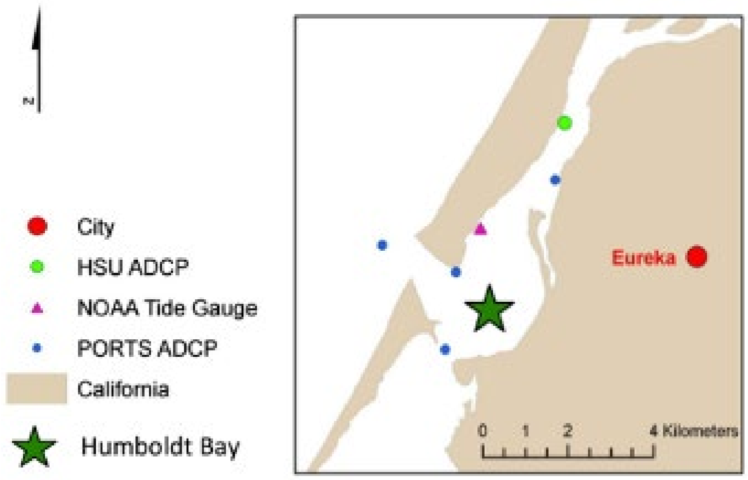

Figure 5. Humboldt Bay with NOAA tide gauge site (pink triangle), Acoustic Doppler Current Profiler (ADCP) (green dot), and ADCP sites deployed as part of ongoing NOAA PORTS project (blue dots). Modified from Admire et al., (2014).

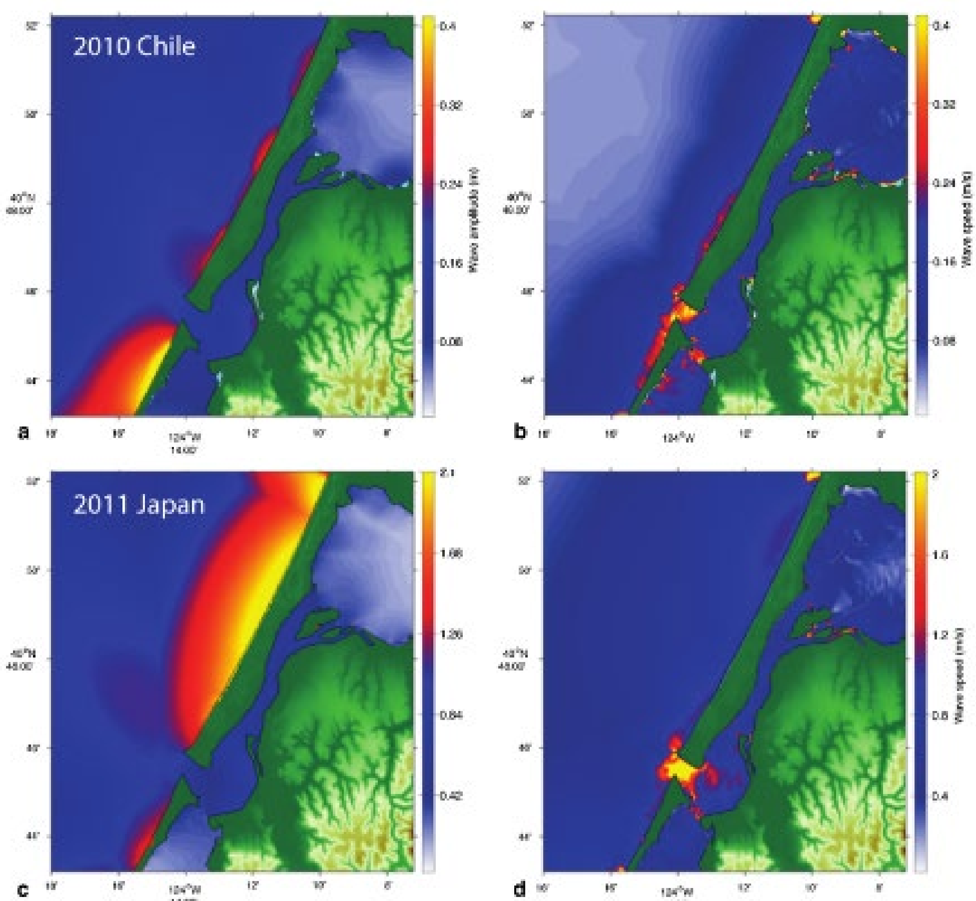

Figure 6. Peak tsunami wave amplitudes (a, c) and peak current speeds (b, d) computed by the MOST model for the 2010 Chile and 2011 Japan tsunamis for the coast and entrance to Humboldt Bay. Amplitudes were predicted to be largest on the coastal side of the North Spit with increased currents focused at the harbor entrance (from Admire et al. (2014)).

Mori et al. (2011) documented inundation along more than 2000 km of Japan's shoreline after the 2011 M9.1 Tohoku-aki earthquake and associated tsunami. They found maximum runup heights in excess of 30 m and commonly 10 – 20 m heights along long stretches of the coast. The highest runup heights were recorded along steep coastal stretches or within confined bays. Although there was no similar harbor or bay to Humboldt Bay, which has a very shallow bay protected by a relatively large, vegetated barrier such as North Spit, Mori et al. (2011) did document the difference in runup height between two closely spaced, deep water (~50 m) bays, one with open access to the ocean (Ohtsuchi Bay) and one (Kamaishi Bay) that had tsunami wave barriers installed about two km oceanward of the bay mouth. At Ohtsuchi Bay, initial runup heights entering the bay were in excess of 17 m at the bay entrance and were 15 – 19 m within the bay. At Kamaishi Bay the runup height was approximately 22 m oceanward of the barrier and diminished to about 10 m within the bay. We can infer that similarly large tsunami waves generated by a CSZ event would lose significant energy as it encountered the broad, rough and high dune fields of the North Spit, a narrow bay entrance, and a shallow, energy dissipating bay basin.

2 TSUNAMI RECORD FOR THE NORTH COAST AT HUMBOLDT BAY

The record of tsunamis for the Humboldt Bay/North Coast area includes prehistoric tsunamis from CSZ megathrust earthquakes (Carver et al., 1998; Patton, 2004), a local but non-destructive tsunami driven by the 1992 M7.2 earthquake at Cape Mendocino (González et al., 1995; Dengler et al., 2008a), and numerous tsunamis from distant-source events documented by tide gauges or other instrumentation (Admire et al., 2011, 2014).

Previous paleoseismic studies at Humboldt Bay that report evidence for tsunami inundation from past CSZ earthquakes include Carver et al. (1998) and Patton (2004). Both of these studies were located in southern Humboldt Bay. To date, no definitive tsunami deposits have been identified at study locations along northern Humboldt Bay (Arcata Bay), which is relatively sheltered from the Pacific Ocean by intervening high sand dunes between the mouth of Humboldt Bay and the Mad River (Pritchard, 2004; Engelhart et al., 2016; Hemphill-Haley, 2017; Padgett et al., 2021, 2022). Carver et al. (1998) described sandy deposits on the bayward side of South Spit that they interpreted as possible tsunami deposits from CSZ earthquakes, although their chronology was based on few radiocarbon ages. In the Hookton Slough area on the east side of southern Humboldt Bay about 5 km (3 mi) from the Pacific Ocean, Patton (2004) identified evidence for past instances of coseismic subsidence from prehistoric CSZ earthquakes in the form of layers of former marsh soils buried by intertidal mud. Two of the buried soils, indicating earthquakes about 1,500-1,700 years ago and 2,300-2,700 years ago, were capped by coarse silt and sand, consistent with a tsunami having inundated the area in conjunction with the earthquake that caused the land subsidence. This coincidence of layers of silt and sand in direct juxtaposition with buried soil deposits has been similarly identified at numerous other locations along the length of the CSZ, and interpreted as evidence for tsunami inundation from past CSZ earthquakes (Atwater et al., 1995; Nelson et al., 1995, 2006; Atwater and Hemphill-Haley, 1997; Kelsey et al., 2002; Witter et al., 2003, 2012; Hemphill-Haley et al., 2019).

Patton (2004) found no evidence at Hookton Slough for a tsunami deposit associated with the ~ M9.0 CSZ earthquake in 1700 C.E., and evidence for the 1700 C.E. deposit at the South Humboldt Bay sites studied by Carver et al. (1998) is possible but equivocal because of the proximity of the study sites to the ocean and overlapping radiocarbon ages with the age of destructive coastal storms in the late 19th century (e.g., Hemphill-Haley et al., 2019). However, it is likely that the coast at Humboldt Bay was impacted by the CSZ tsunami in 1700 C.E. as there is abundant evidence for this event at coastal sites to the north at Crescent City and elsewhere in coastal Del Norte County (Abramson, 1998; Carver et al., 1998; Garrison-Laney, 1998; Peterson et al., 2011; Hemphill-Haley et al., 2019).

Farfield tsunamis are a fairly frequent occurrence on the North Coast, with 33 tsunamis recorded since the installation of the first tide gauge at Crescent City in 1933 (Admire et al., 2011, 2014). Five of these farfield tsunamis caused major damage to the harbor at Crescent City, but compared to Humboldt Bay, Crescent City is “particularly vulnerable to tsunamis” (Admire et al., 2014, p. 3385) because of its geographic position, offshore morphology, and configuration of the harbor area that serves to magnify tsunami energy (Dengler et al., 2008; Dengler & Uslu, 2011; Kowalik et al., 2008; Uslu et al., 2008). To date, Humboldt Bay has not suffered damage from farfield tsunamis, although higher current velocities have been recorded, for example, 0.6 m/sec to 0.84 m/sec in 2011 from the Tohoku farfield tsunami (Admire et al., 2011, 2014; Admire, 2013). The “Physical Oceanographic Real-time System (PORTS) project, a collaborative effort at Humboldt Bay between NOAA and Humboldt State University (https://tidesandcurrents.noaa.gov/ports/index.html?port=hb) currently maintains a continuous monitoring system in Humboldt Bay in the event of tsunami activity to acquire “*Better estimates of the currents generated by tsunamis [which] can be used to improve numerical modeling and to provide better understanding of the hazards in ports and harbors caused by currents* (Admire et al., 2014, p. 3402). As undertaken in other ports in California (e.g., Borrero et al., 2015; SAFFR Tsunami Modeling Working Group, 2013), an evaluation of potential effects of tsunami-driven currents in Humboldt Bay should be included in infrastructure designs for large scale projects in the bay.

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