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March 10, 2016

Mr. Paul Cole
Assistant Chief, Operations/Special Operations
Coastside Fire Protection District
CAL FIRE – San Mateo – Santa Cruz Unit

Subj: Site Specific Tsunami Study – Rev1
Relocation of El Granada Fire Station 41

Dear Mr. Cole:

We are pleased to provide this site-specific tsunami assessment for the proposed El Granada Fire Station Relocation Site (EGFSR) in San Mateo County, shown on Figure 1, and referred to as the EGFSR site such throughout the report. This revised report addresses comments that were received from the Coastal Commission.

We understand that the Coastside Fire Protection District proposes to relocate the existing Station 41 in El Granada. The proposed relocation site is a 2.5 acre parcel, known as Assessor Parcel Number 047-261-030, which is approximately 600-feet southeast of the existing Station 41. This parcel in bounded by Avenue Portola, Obispo Road, Coronada Street and a portion of Avenue Alhambra.

In 2009, the California Emergency Management Agency (Cal-EMA) developed tsunami inundation maps for emergency planning purposes that show inundation limits defined as an aggregate of the maximum runup caused by simulating hypothetical tsunami events assuming a tide level equal to or greater than Mean High Water (MHW). The EGFSR site, currently lies within a tsunami inundation area, as does the existing Station 41, per the Cal-EMA tsunami hazard maps.

Moffatt & Nichol (M&N) has conducted a site-specific tsunami study for the EGFSR site to understand the historical and scientific background, as well as the statistical significance of the Cal-EMA and other relevant tsunami hazard maps.

The main findings of the study are:

1. A review of topographic information for the site, literature, and discussions with authors of the Cal-EMA maps, indicate that the maximum inland limit of runup shown on the maps is based on tsunamis that have a return period of over 500 years. The proposed EGFSR site is close to the inland limit of the inundation shown on the Cal-EMA map for this area. Therefore, the probability of tsunami-induced inundation at the EGFSR site as shown on the 2009 Cal EMA tsunami hazard map is quite low, and very likely even lower than that of typical seismic design criteria for buildings (generally equates to about 475 year return period).

2. The 2013 U.S. Geological Survey map (SAFRR scenario), which is estimated to have a return period of 200 – 250 years, shows the EGFSR site well outside the inundation zone.

3. When compared to typical coastal flood hazard analysis using, for example, FEMA guidance (100-year return period or 1% annual chance), the site has a significantly small risk of inundation from tsunamis. Extrapolation of available tsunami runup elevations resulted in a 100-year tsunami runup elevation range of 8 to 10 ft (NAVD88). Ground elevations at the EGFSR site range from 25 to 44 ft (NAVD88), with finish floor of the new fire station proposed at elevation 32.5 ft; therefore, the 100-year event is not expected to cause flooding. Also, the probability of a 100-yr or larger return period tsunami event occurring at a tide level equal to or greater than MHW is much lower than 1 in 100 years.

4. In a review of the applicable section of the Local Coastal Plan (LCP) relevant to tsunami hazards – *Section 6326.2: Tsunami Inundation Area Criteria* – it is not clear what probability of tsunamis is referenced therein. In other words, was the intent of the language to show events with return periods as large as the Cal-EMA maps? If yes, do other sections that deal with similar low probability geologic events, including earthquakes and landslides, also reference similar probabilities?

5. Our understanding via discussions with you is that the fire station will be occupied by first responders and support staff that operate on a *shift* basis, and that the building will not provide long-term or even short-term *living quarters* for anyone. It is not clear to us if operating on a shift basis qualifies the fire station for human occupancy as referenced in the LCP, and County officials should clarify the intent. An important point for consideration relevant to this subject is the fact that the large tsunami-causing events that would result in inundation of the EGFSR site are all far field, which implies that there will be several hours of advance notice before the inundation occurs.

The assessment is divided into four sections: 1) Introduction; 2) Review of site characteristics, including ground elevations, water levels, and waves; 3) Review of literature on tsunami hazards in California; and 4) Site-specific probabilistic analysis of tsunami occurrence at tide levels equal to or higher than MHW.

1.0 INTRODUCTION

The existing El Granada Fire Station 41 is located in El Granada, San Mateo County, just north of the City of Half Moon Bay. The fire station building is located approximately 400 ft inland from the Half Moon Bay shoreline. Relocation of the fire station is currently being contemplated to a site about 600 ft southeast of the present location, north of Obispo Road, in an undeveloped 2.5 acre parcel owned by the Coastside Fire Protection. Figure 1 shows the approximate footprint of the relocation site (blue), and the footprint of the fire station (red line).

The San Mateo County Local Coastal Program (LCP) Policies (County of San Mateo, 2013) defines a hazard area as an area (including land) subject to dangers from, among other phenomena, tsunamis. These areas are identified by flood and natural hazard maps. Therefore, per the 2009 Cal EMA tsunami hazard map, the EGFSR site would be in a hazard area.

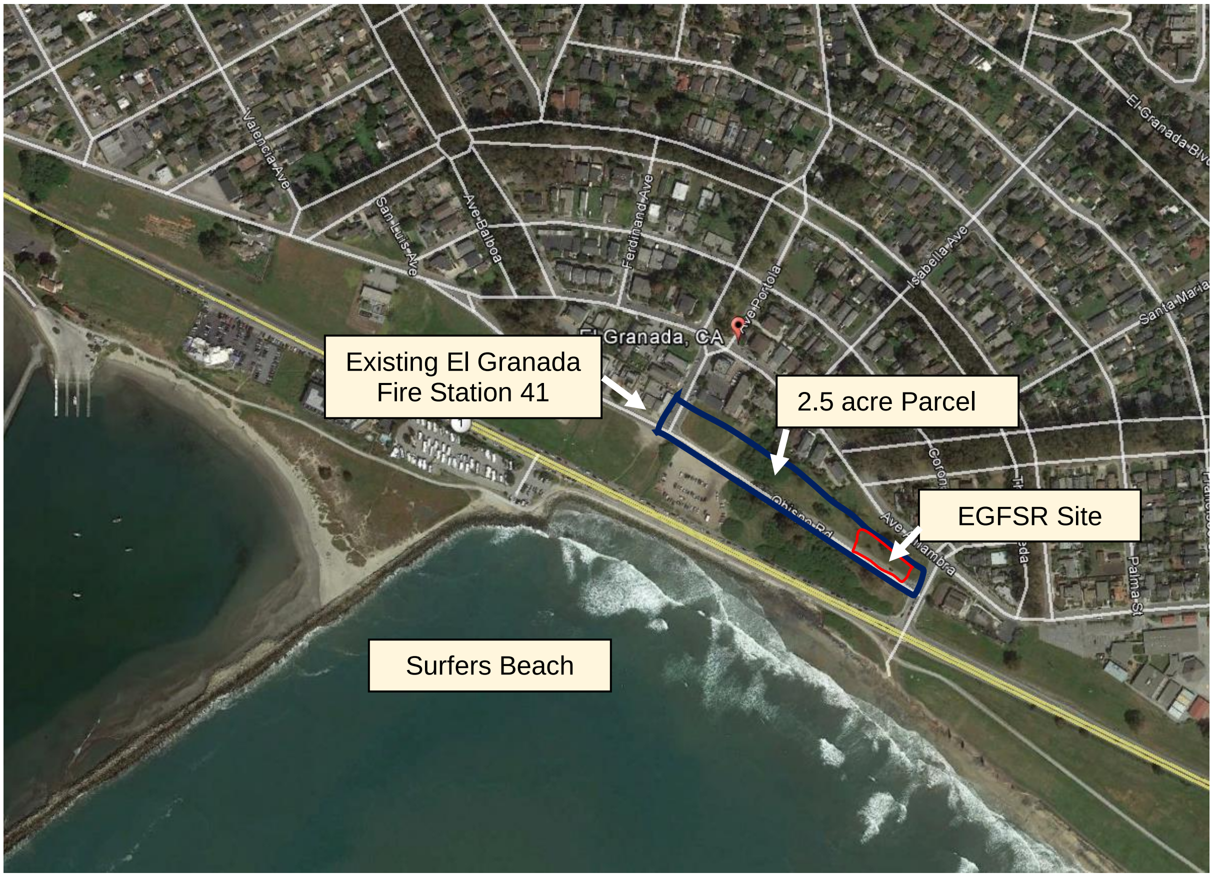


Figure 1: Existing El Granada Fire Station 41 Site and Proposed EGFSR Site

(Source: Google Earth)

The LCP points to the Resource Management Zoning Ordinance for criteria applicable to designated hazard areas. The regulations relevant to tsunami hazard are described in Section 6326.2 Tsunami Inundation Area Criteria. In essence, this section limits the development of infrastructure in tsunami hazard areas unless a site-specific study is submitted and approved by the Planning Commission.

The guidance makes no distinction between a “tsunami hazard area” (area subject to a design event, such as a typical FEMA 100-yr return period event) and an “inundation area” (area subject to a hypothetically plausible extreme event). This study presents technical information with a primary objective of evaluating the magnitude in terms of tsunami runup of a typical FEMA type design event in the area the EGFSR site.

2.0 SITE CHARACTERISTICS

2.1 Ground Elevations

A Digital Elevation Model (DEM) containing topography and bathymetry for San Francisco Bay area was obtained online from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information. The DEM was completed in July 2010 and has a cell size of 1/3 arc-second (roughly 33 ft). Figure 2 shows a rendition of the DEM. The ground elevation around the existing El Granada Fire Station 41 is about 26 ft (NAVD88). In the EGFSR relocation area, ground elevations range from 25 to 44 ft (NAVD88), generally increasing to the north and towards the east end of the parcel. With the proposed grading, the fire station structure, parking lot, and eastern access road will all be above elevation 30 ft.

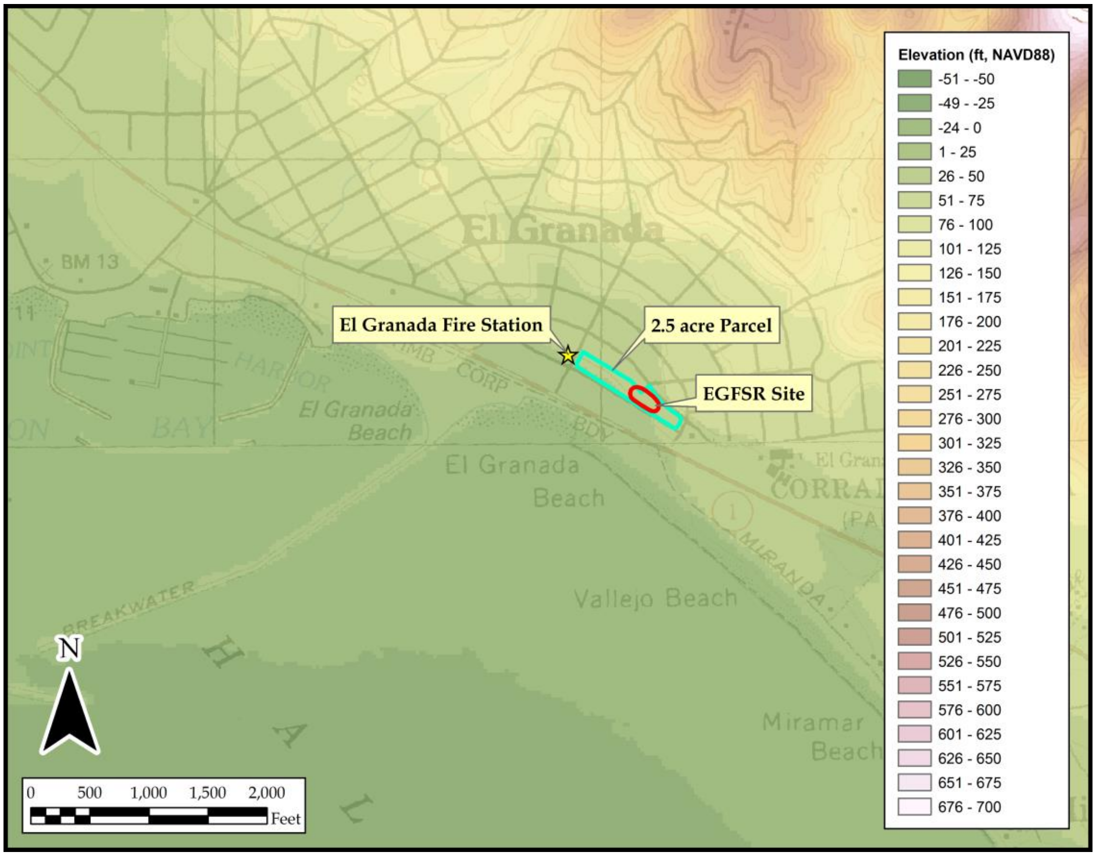


Figure 2: Bathymetry and topography around El Granada

2.2 Water Levels

Water level data in proximity to the relocation site was obtained from the NOAA Tides & Currents website. Table 1 presents information about these stations and the stations selected for analysis as shown on Figure 3.

The tidal datums reported by NOAA for each station are presented in Table 2. The datums that would be most applicable to Half Moon Bay are those from Station 9414290 San Francisco, simply based on proximity. Based on the mean tidal range at all the stations, it is reasonable to assume that the mean tidal range in Half Moon Bay is between 3.5 and 4.0 ft.

The best dataset to estimate extreme water levels is that of Station 9414290 San Francisco because it is the longest (~114 years). An extreme value analysis was performed following the methodology outlined in Goda (2000) where a set of extreme values is identified using the peak-over-threshold method, with a threshold defined as the 99.5 percentile value. The method identifies events using the threshold and then selects a single maximum for each event.

Table 1: Description of stations selected for analysis of water levels

Source	Station ID	Station Name	Location	Reporting Interval	Record Length
NOAA Tides & Currents	9415020	Point Reyes, CA	37° 59.8'N 122° 58.6'W	60 min	11/08/1973 – 08/31/2015
	9414958	Bolinas, Bolinas Lagoon, CA	37° 54.5'N 122° 40.7'W	60 min	07/01/2009 – 08/31/2015
	9414290	San Francisco, CA	37° 48.4'N 122° 27.9'W	60 min	01/01/1901 – 08/31/2015
	9413450	Monterey, CA	36° 36.3'N 121° 53.3'W	60 min	11/08/1973 – 08/31/2015

Figure 4 presents the results of the extreme value analysis. The 10-year water level is 4.86 ft (MSL), while the 100-year water level is only 0.68 ft higher. The small variability is indicative of an area where the residual or storm surge component of the measured tide signal is very small.

However, the California coastline is vulnerable to extreme water levels caused by tsunamis generated from local and distant sources as a result of the seismically active crustal plates underlying the Pacific Ocean. Tsunamis are addressed in Section 3.0.

Figure 3: Location of stations selected for analysis of water levels

Table 2: Tidal datums at stations selected for water level analysis
(feet, 1983 – 2001 epoch)

Datum	Description	9415020 Point Reyes	9414958 Bolinas	9414290 San Fran.	9413450 Monterey
HAT	Highest Astronomical Tide	+4.37	NA	+4.15	+4.20
MHHW	Mean Higher-High Water	+2.66	+2.08	+2.72	+2.51
MHW	Mean High Water	+2.00	+1.47	+2.11	+1.81
MSL	Mean Sea Level	0.00	0.00	0.00	0.00
MLW	Mean Low Water	-1.92	-1.53	-1.99	-1.74
MLLW	Mean Lower-Low Water	-3.10	-2.32	-3.12	-2.83
LAT	Lowest Astronomical Tide	-5.31	NA	-5.21	-4.80
MN	Mean Tidal Range (MHW – MLW)	3.92	3.00	4.10	3.55

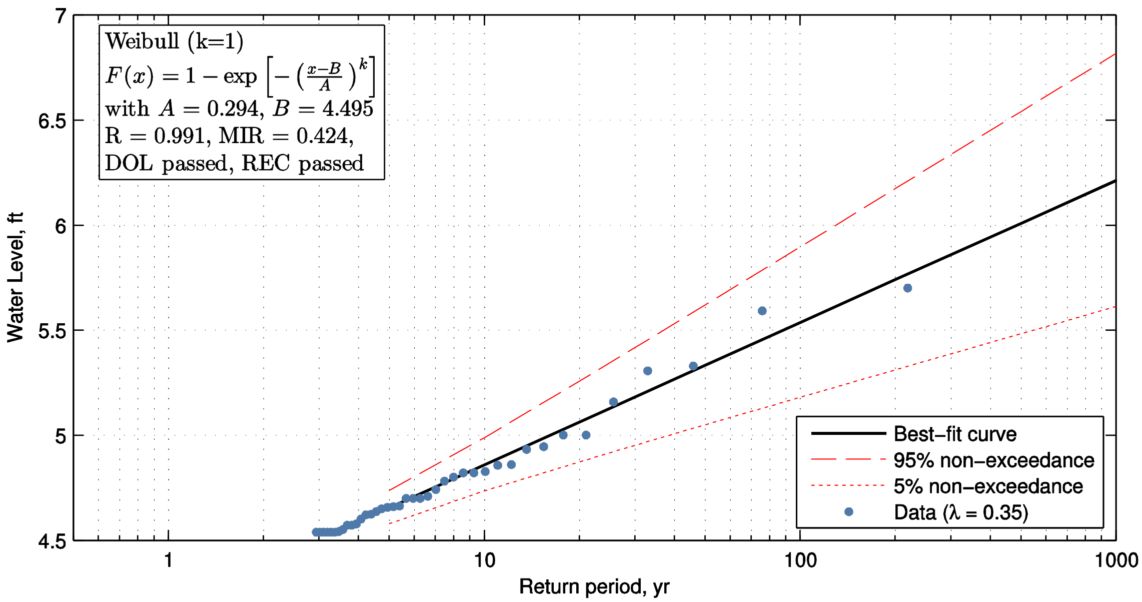


Figure 4: Best-fit distribution to extreme water levels measured (Station 9414290 San Francisco, CA)

2.3 Waves

Wave data from two offshore buoys were obtained online from the NOAA National Data Buoy Center. Table 3 presents information about the buoys and Figure 5 shows their location. The data consists of significant wave height, peak wave period, and mean wave direction. In the case of buoy 46012 Half Moon Bay, the data also includes wind speed and wind direction.

The Half Moon Bay buoy is located far offshore at a water depth of 685 ft; thus, it will not provide an accurate representation of nearshore conditions. The San Francisco Bar buoy, located at a water depth of 56 ft, was selected to assess the changes to the waves as they near the shore. Water depths of about 60 ft are found just outside Half Moon Bay.

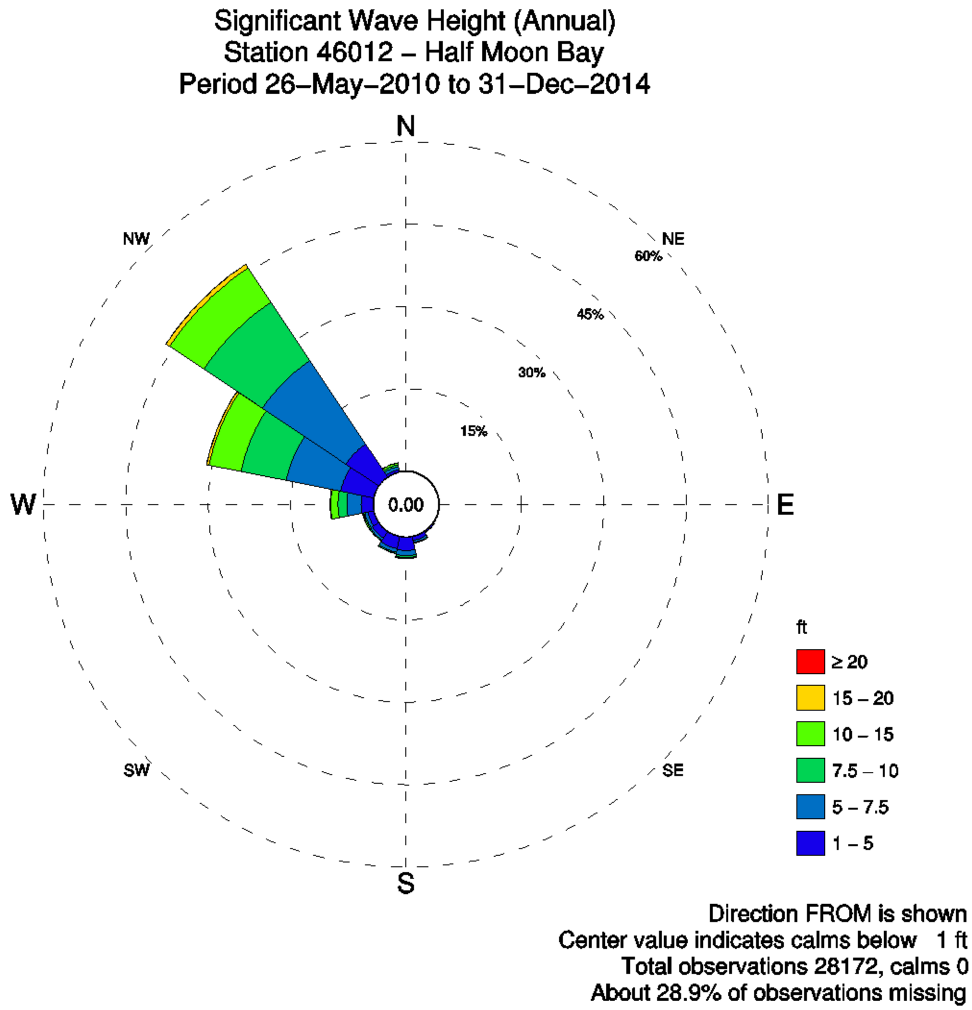
Table 3: Description of stations selected for analysis of waves

Source	Station ID	Station Name	Location	Reporting Interval	Record Length
NOAA National Data Buoy Center	46237	San Francisco Bar	37° 47.2'N 122° 38.1'W	60 min	07/25/2007 – 10/26/2015
	46012	Half Moon Bay	37° 21.75'N 122° 52.9'W	60 min	05/26/2010 – 12/31/2014

Figure 5: Location of stations selected for analysis of waves

The figures provided in the following (Figures 6 to 11) present annual wave roses and joint histograms developed based on the wave data. The following are some key observations:

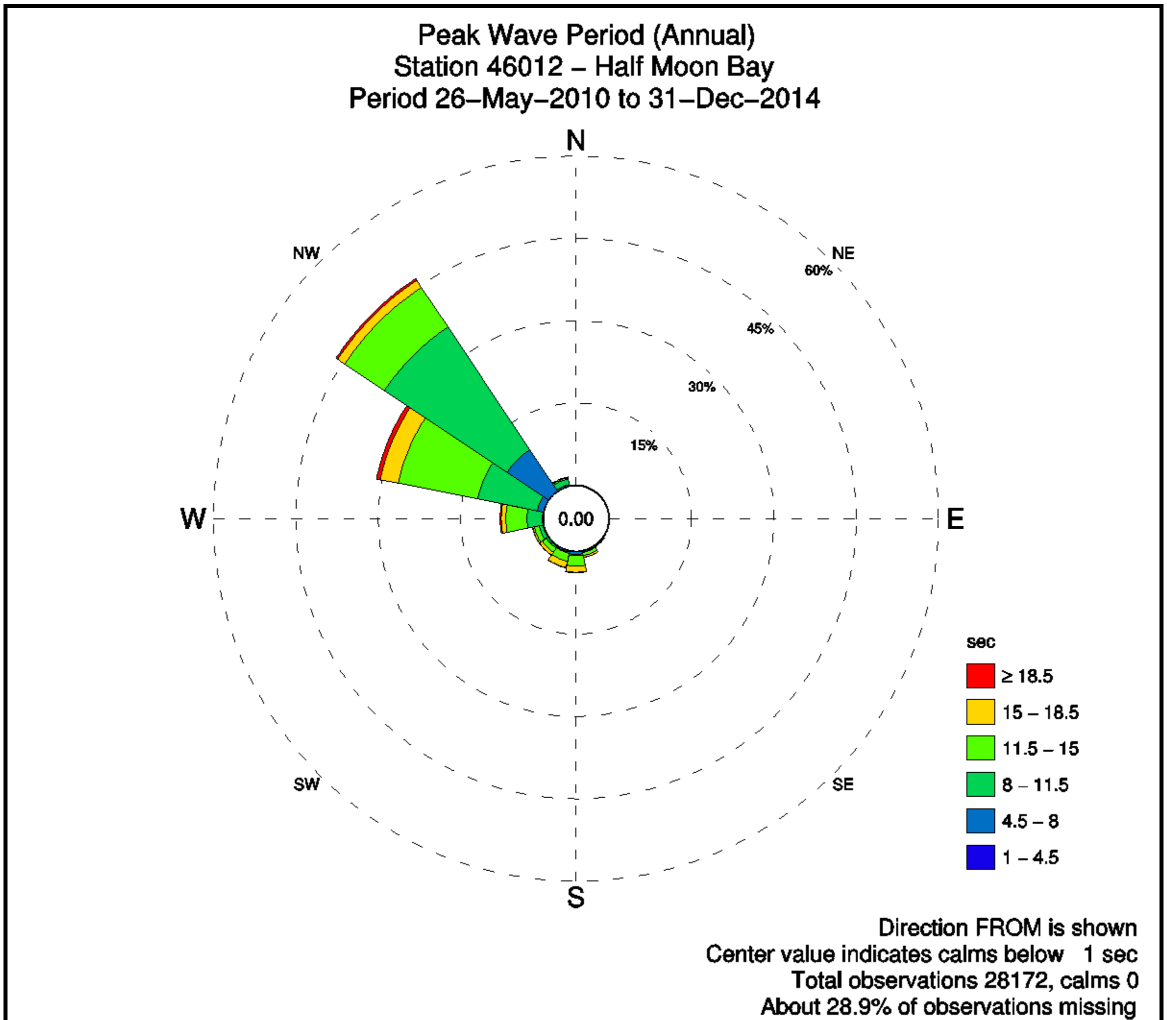
- Waves primarily approach from the northwest to west sector. Predominant waves (over 80% of the waves) range from 1 to 10 ft in height, and 8 to 15 seconds in period. This range of wave periods indicates that the wave field is dominated by swell; that is, waves of long period not locally generated by the wind, but by other systems in the Pacific Ocean.
- Closer to shore, predominant waves are lower in height, with the same wave periods. In the vicinity of El Granada, the wave climate is expected to be characterized by waves 1 to 7.5 ft in height and 8 to 15 seconds in period.
- Waves from the south are also appreciable, but have a low frequency of occurrence.



Percentage of Occurrence

Significant Wave Height, ft	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total							0.24	1.24	3.85	3.15	2.03	2.06	7.84	31.00	46.56	1.73	100.00
15–20													0.15	0.44	0.79		1.47
10–15									0.17			0.20	1.27	5.95	7.50	0.33	15.55
7.5–10								0.16	0.35	0.21	0.18	0.20	1.62	8.38	12.80	0.33	24.26
5–7.5								0.38	0.88	0.64	0.43	0.55	2.66	10.10	18.26	0.58	34.59
1–5							0.17	0.68	2.42	2.23	1.38	1.09	2.13	6.11	7.18	0.44	24.06

Figure 6: Annual wave height rose for wave buoy 46012 Half Moon Bay



Percentage of Occurrence

Peak Wave Period, sec	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total							0.24	1.24	3.85	3.15	2.03	2.06	7.84	31.00	46.56	1.73	100.00
≥ 18.5										0.11			0.23	0.69	0.39		1.79
15 – 18.5								0.35	1.14	1.16	0.58	0.29	0.86	3.35	1.53		9.53
11.5 – 15								0.56	1.84	1.47	0.95	0.90	3.85	14.74	8.70	0.24	33.44
8 – 11.5									0.29	0.18	0.34	0.70	2.78	11.03	26.86	1.02	43.30
4.5 – 8								0.19	0.47	0.22		0.12	0.13	1.19	9.07	0.30	11.88
1 – 4.5																	

Figure 7: Annual wave period rose for wave buoy 46012 Half Moon Bay

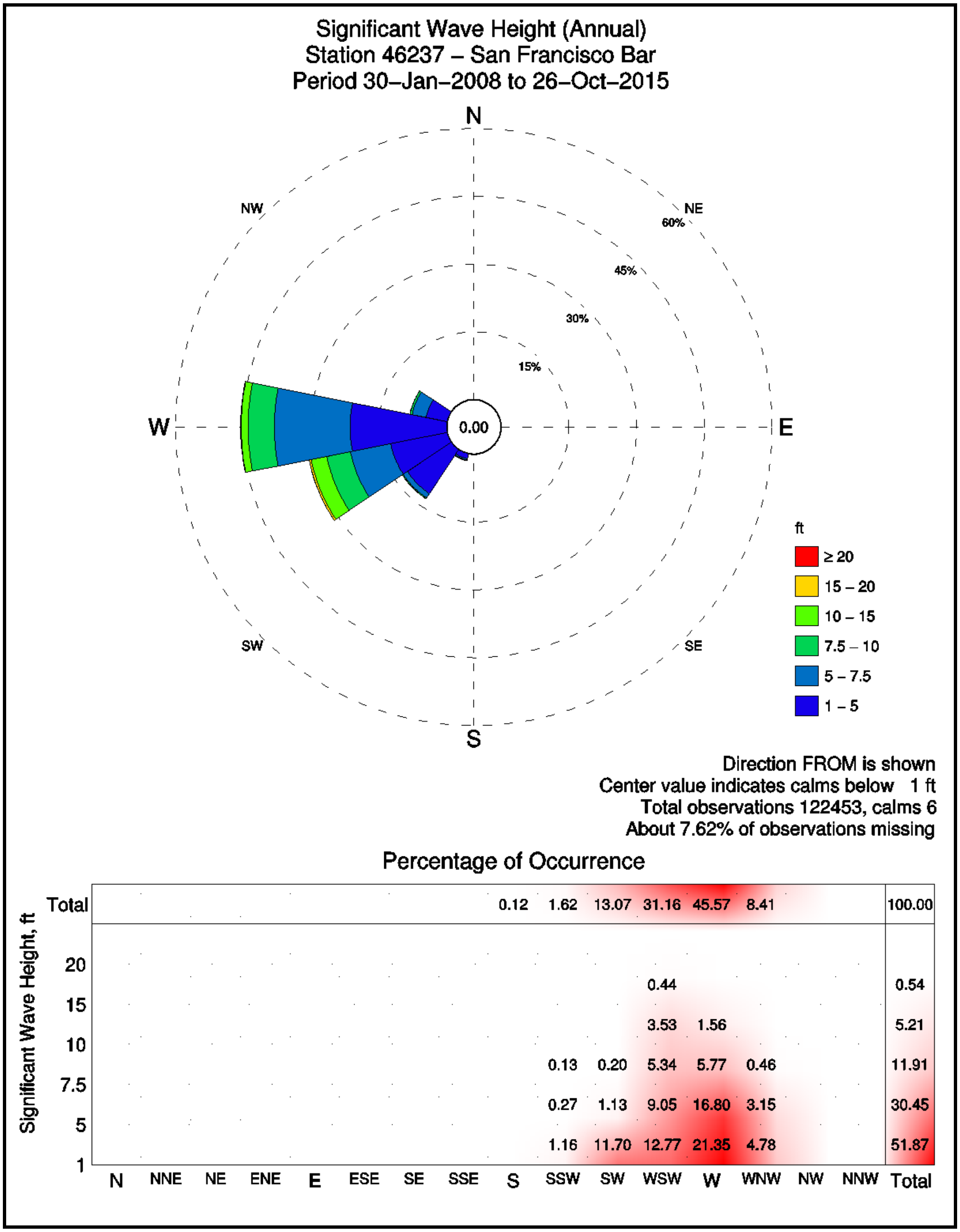


Figure 8: Annual wave rose for wave buoy 46237 San Francisco Bar

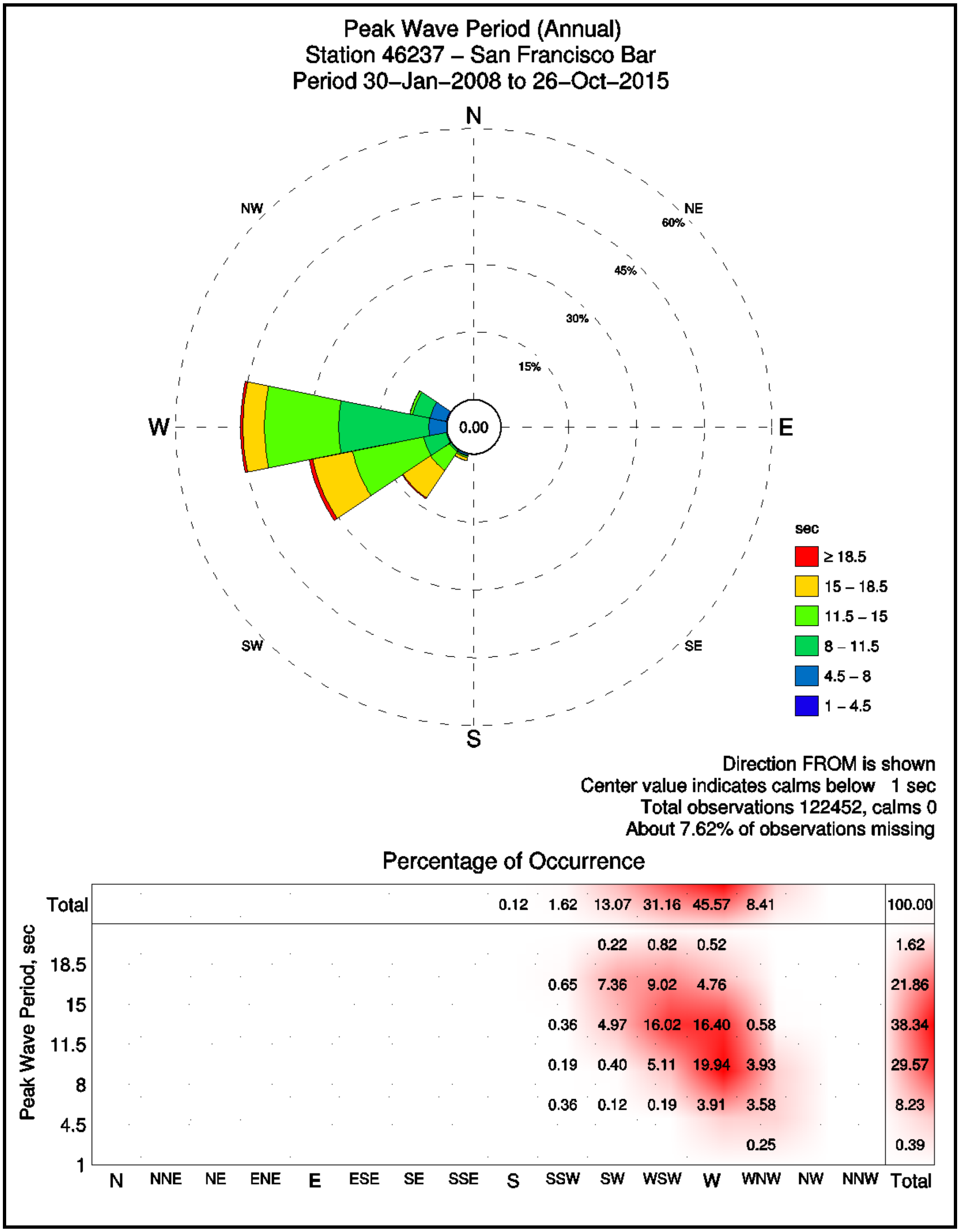


Figure 9: Annual wave period rose for wave buoy 46237 San Francisco Bar

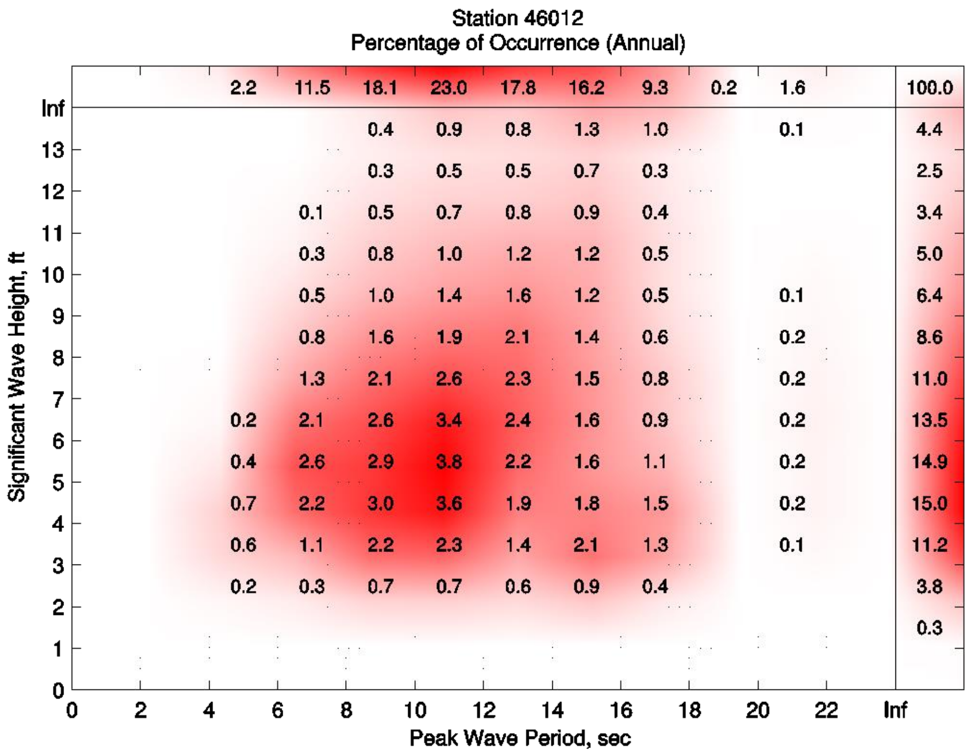


Figure 10: Joint histogram of waves for wave buoy 46012 Half Moon Bay

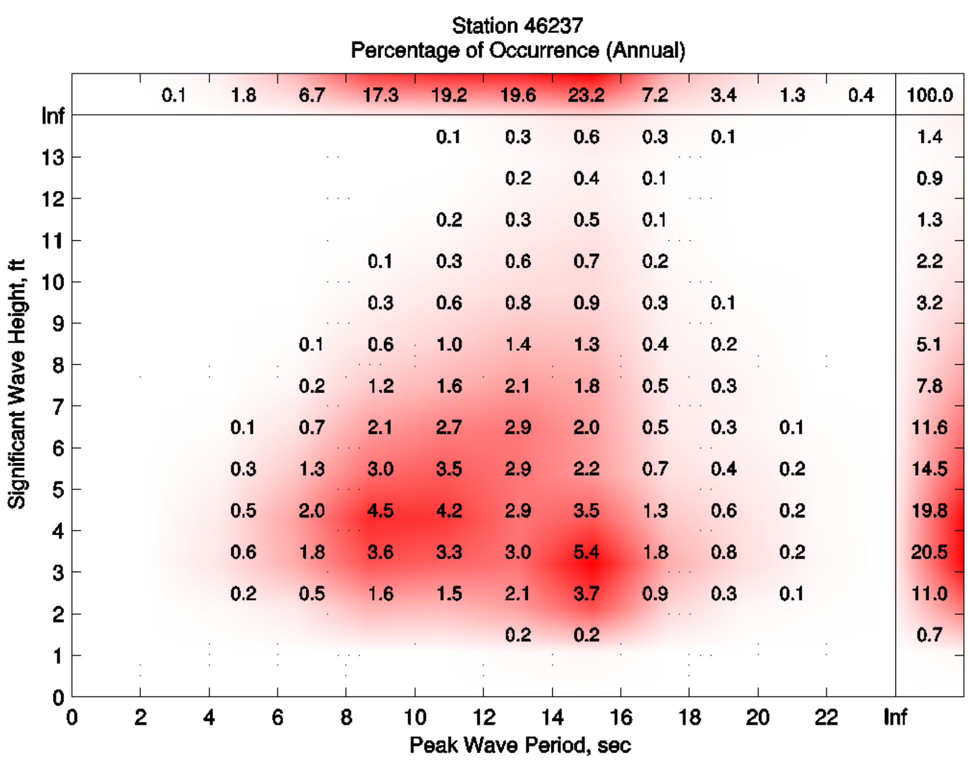


Figure 11: Joint histogram of waves for wave buoy 46237 San Francisco Bar

3.0 TSUNAMI STUDY

3.1 Definitions

Technical terms that repeatedly appear in this section are defined below (Eisner et al. 2001; NOAA NWS).

Tsunami: A series of long-period waves (on the order of minutes to hours depending on source location) generated by impulsive geological events, such as earthquakes, subaerial and submarine landslides, and volcanic eruptions.

Wave Height: Distance from wave trough (lowest part of the wave) to wave crest (highest part of the wave).

Wave Period: Time between consecutive wave crests past a fixed point, typically given in seconds.

Runup: The uprush of water over a beach or structure above the still water level. Figure 12 provides an illustration of this definition for the case of a tsunami.

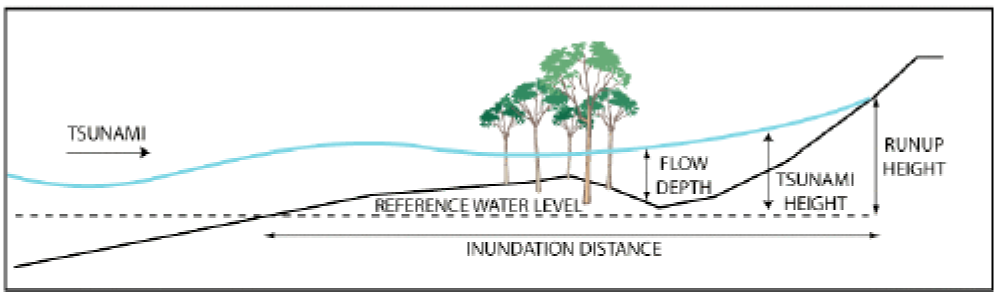


Figure 12: Tsunami runup illustration (UNESCO-IOC, 2012)

Nearfield or local source (relative to the California coastline): A geographical area or feature capable of generating a tsunami just offshore of the California coastline.

Farfield or distant source (relative to the California coastline): A geographical area or feature, particularly subduction zones, capable of generating a tsunami along the Pacific Rim.

3.2 Literature Review

Site specific tsunami studies for the Half Moon Bay have not been conducted; therefore, other relevant tsunami studies that would be applicable to the study area were reviewed and are summarized in this section.

3.2.1 Tsunami Hazards in San Francisco Bay

Borrero et al. (2006) conducted a study to deterministically assess the tsunami hazard at marine oil terminals in San Francisco Bay. The study consists of a literature review of the record of tsunami events in San Francisco Bay from distant and local sources and the execution of numerical hydrodynamic modeling of historic and hypothetical events.

The literature review of Borrero et al. (2006) covers tsunami events recorded in San Francisco Bay between 1851 and 2001 (157 years), allowing them to identify sources and triggering mechanisms that pose a potential threat to marine oil terminals. The majority of the tsunamis recorded in the Bay have been generated by earthquakes taking place in subduction zones around the Pacific Rim, specifically in South America, Russia, Japan, and Alaska. The greatest tsunami-induced runup in the record was caused by the 1964 earthquake in Prince William Sound, Alaska of magnitude M_w = 9.2. This event resulted in runup exceeding 1 m in some locations in San Francisco Bay. The historic record also shows landslides as tsunami sources for a few local events occurring in Northern California; however, the runup induced by these events was of lower magnitude.

Borrero et al. (2006) also discuss previous efforts to assess tsunami hazard in San Francisco Bay. A brief summary of these studies is presented below:

- Magoon (1966) used runup data inside the Bay from the 1960 Chilean tsunami and the 1964 Alaskan tsunami to develop an attenuation model which predicts the reduction in wave height as the tsunami propagates through the Golden Gate into the San Pablo and San Francisco bays.

- Based on five co-seismic tsunami events occurring in 1946, 1952, 1957, 1960, and 1964, Wiegel (1970) developed a maximum tsunami wave height frequency of occurrence graph for Crescent City and the Presidio (Golden Gate).

- Ritter and Dupre (1972) created a tsunami inundation map for the Bay for a far-field tsunami by imposing a 20 ft water height at the Golden Gate. This condition was adopted based on the peak inundation at Crescent City after the 1964 Alaskan tsunami. They used the attenuation model of Magoon (1966) to model the effect inside the Bay. Furthermore, they extended the frequency of occurrence graph of Wiegel (1970) to assign a return period to the 20 ft water height at the Golden Gate. The resulting return period was 200 years.

- Garcia and Houston (1975) used a finite-difference long wave model to simulate tsunami events originating in the Aleutian Trench, with the objective of determining 100- and 500-year runup in Monterey and San Francisco Bay. Outside San Francisco Bay, the model-computed tsunami amplitude was taken and propagated into the Bay with a set period of 38 minutes. Their approach was probabilistic, in the sense that they included the effect of astronomical tides.

From their review of historic tsunami events, Borrero et al. (2006) defined 23 scenarios (historical and hypothetical) to be numerically modeled. They utilized the MOST (Method of Splitting Tsunami) model, which solves the nonlinear shallow water equations, to simulate generation, propagation, and runup. Model resolution in the nearshore areas of interest was refined to resolve runup and inundation more accurately. The far-field seismic sources included the subduction zones of Alaska – Aleutian Islands, Cascadia (Northern California to Vancouver Island), Kuril – Kamchatka (Russia), Chile – Peru, and Japan. The local sources included the San Gregorio and Rodgers Creek faults as co-seismic events and the Farallon Islands as a landslide-generated event.

For the far-field events triggered by earthquakes, Borrero et al. (2006) defined the source (rupture) characteristics using the National Oceanographic and Atmospheric Administration (NOAA) Facility for Climate Assessments (FACTS) database. This database is a compilation of numerical simulations of extreme events, including tsunami from segments of the main subduction zones in the Pacific Rim. These subduction zones are divided into 2 parallel rows of 100 km in length by 50 km in width and a 1 m unit slip. Borrero et al. (2006) combined the necessary segments to obtain the desired earthquake magnitude for each one of these scenarios. The results were then used as initial condition on the ocean boundaries of the outermost grid of their model.

The modeled scenario that was found to cause the greatest impact in San Francisco Bay was the Aleutian III scenario (M_w = 9.15, 800 km rupture) which produced wave heights in San Francisco Bay 2 to 3 times greater than those observed in the 1964 Alaskan earthquake. The return period of the 1964 Alaskan earthquake is estimated to be 350 to 800 years; thus, the return period of the Aleutian III scenario can be expected to be on the upper end of this range.

Borrero et al. (2006) concluded their study by making recommendations for the marine oil terminals in terms of wave height and current speed, including a safety factor of 1.5 since the ecological consequences of a large oil spill in San Francisco Bay would be disastrous.

3.2.2 2010 Chilean and 2011 Tohoku Tsunami

Since the completion of the work of Borrero et al. (2006), two far field tsunami events of relevance to the California coast have occurred, namely the 2010 Chilean, and the 2011 Tohoku (Japan) tsunami.

The 2010 Chilean tsunami was generated by a magnitude 8.8 earthquake in the Maule region of central Chile on February 26, 2010. The earthquake occurred on the Nazca Plate – South American Plate subduction zone, about 300 km north of the 1960 event. Tide conditions were low at the time of the tsunami arrival on the California coast. In San Francisco Bay, the maximum tsunami amplitude recorded on tide gauges was 0.32 m (1.0 ft). Although no observations are available for Half Moon Bay, estimates of the maximum tsunami amplitude range from 0.6 to 0.96 m. No damage was reported in Half Moon Bay as a result of the tsunami (Wilson et al., 2010).

The March 11, 2011 Tohoku tsunami was generated by a magnitude 9.0 earthquake off the island of Honshu, Japan, along the subduction zone created between the Pacific and North American plates. At the San Francisco Marina, which is just east of the entrance to San Francisco Bay (Golden Gate), the maximum measured amplitude was 0.62 m (2.0 ft). At Pillar Point Harbor near Half Moon Bay, the maximum observed and maximum forecasted amplitudes were 0.7 and 0.92 m, respectively. Maximum currents speeds at this location range from 7 – 15 knots (Ewing, 2011). The return period of this event ranges from 500 to 1,200 years, with more literature leaning towards 1,000 years (Tsimopoulou, 2011; EERI, 2011; Tsimopoulou et al., 2013).

3.2.3 M&N Treasure Island Coastal Flooding Study

In 2009, M&N conducted a study to establish flood elevations around Treasure Island. The study was completed before the release of the Cal EMA tsunami hazard maps in June 2009. This study is relevant and applicable to El Granada because it incorporated tsunami contribution relative to the tide level, using probabilistic analyses[1].

Based on the work of Borrero et al. (2006), three historic tsunami events were identified based on the measured runup in the San Francisco Bay area. These events are: 1898 Northern

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[1] *Probabilistic analysis is where the probabilities of occurrence of various infrequently occurring phenomena are combined together to estimate the net result of an outcome, rather than using discrete measurements, because simultaneous measurements may not exist.*

California Rogers Creek fault, 1960 South Central Chile, and 1964 Alaska. The wave height variation near Treasure Island, which served as boundary condition for a Boussinesq Wave Model, was digitized from Appendix 1 of Borrero et al. (2006) for each event. A probabilistic interpretation of tsunami runup relative to the tide level was conducted using results from the Boussinesq wave model in a Monte-Carlo simulation.

The 1898 and 1960 tsunami events were assumed to occur, on average, once in 157 years which is the length of the historic tsunami record (Borrero et al., 2006). The 1964 event was assumed to have a 314 year return period, twice that of the other two events. Borrero et al. (2006) suggest the return period of the 1964 event is between 350 and 800 years.

The water levels used were those measured at the San Francisco Presidio tide gage for the period from 1945 to 2008 (63 years). The Monte-Carlo simulations consisted of repeating the 63 year water level record 16 times for a total of 1,008 years while randomly determining the occurrence and type of tsunami event based on the three events and their associated return period as previously described. The annual maxima were then used to estimate extreme values.

Aspects of this study to highlight due to their applicability to the site specific tsunami hazard study for EGFSR site are:

- The methodology of using a measured long-term record of water levels in the site proximity as the base for water levels.

- The analysis of historical tsunami events in the San Francisco Bay area by Borrero et al. (2006). This list of events may have to be supplemented with post-2005 tsunami events relevant to the San Francisco Bay area.

- The Monte-Carlo simulation approach to quantify maximum water levels associated with tsunamis relative to tide levels.

3.2.4 Tsunami Inundation Maps for Emergency Planning

The University of Southern California (USC) Tsunami Research Center conducted a series of numerical model simulations for the development of tsunami inundation maps for emergency planning for the State of California. The project was funded by the National Tsunami Hazard Mitigation Program through the California Emergency Management Agency (Cal EMA). By defining the tsunami inundation area, the maps are intended to aid cities and counties in identifying areas vulnerable to tsunami hazard and in developing adequate emergency and evacuation practices.

The map that is relevant to the EGFSR site is the map corresponding to San Mateo County, Montara Mountain Quadrangle, published on June 15, 2009 (State of California, 2009). Per this map, as shown in Figure 13, the EGFSR site is practically entirely within the projected tsunami inundation extent. According to the DEM shown in Figure 2, the inundation extent reaches elevations of about 37 – 42 ft (NAVD88) in the relocation area.

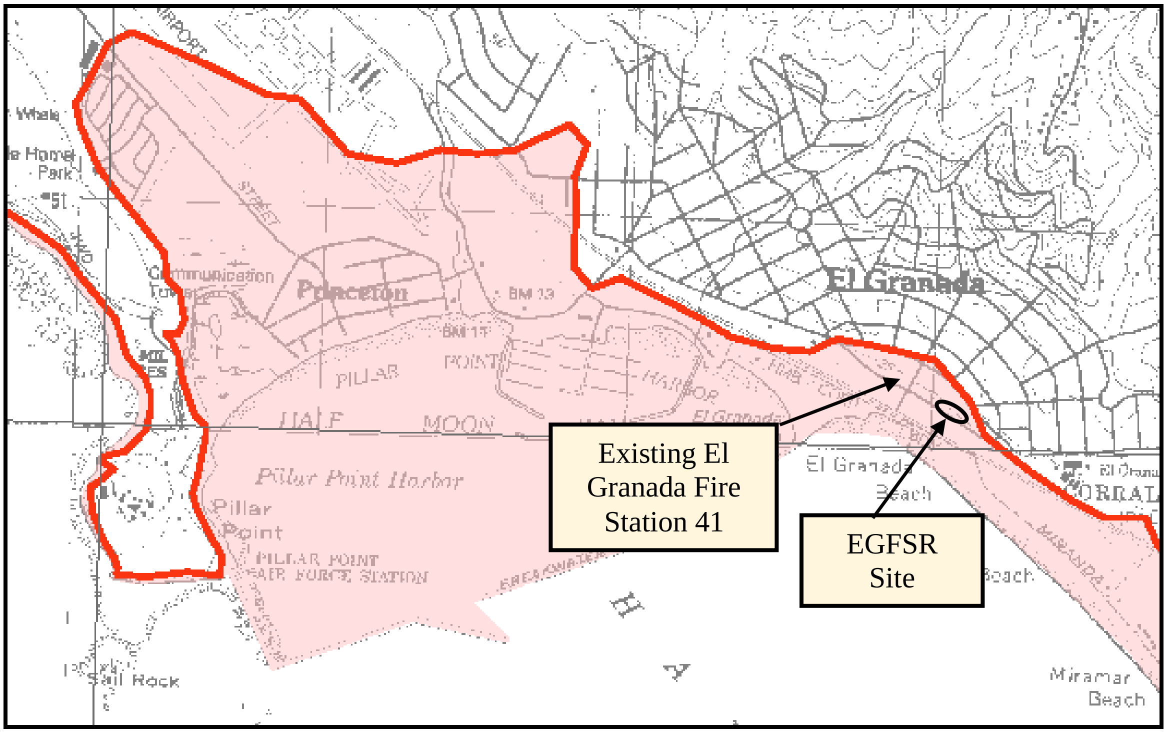

Figure 13: Tsunami hazard map for San Mateo County, Montara Mountain Quadrangle (State of California, 2009)

The maps show the tsunami inundation line and the inundated inland areas. These are defined based on the aggregated maximum tsunami runup from a group of extreme tsunami events modeled using the MOST model with a Mean High Water tide condition. These events are listed in the maps,and the event that results in the maximum runup may vary depending on the quadrangle. Table 4 shows the events modeled for San Mateo County.

Table 4: Events modeled for San Mateo County (State of California, 2009)

Sources (M = moment magnitude used in modeled event)		Areas of Inundation Map Coverage and Sources Used	
		San Francisco Bay	Pescadero
Local Sources	Point Reyes Thrust Fault	X	
	Rodgers Creek-Hayward Faults	X	
	San Gregorio Fault	X	
Distant Sources	Cascadia Subduction Zone-full rupture (M9.0)	X	
	Central Aleutians Subduction Zone #1 (M8.9)	X	X
	Central Aleutians Subduction Zone #2 (M8.9)	X	
	Central Aleutians Subduction Zone #3 (M9.2)	X	X
	Chile North Subduction Zone (M9.4)	X	
	1960 Chile Earthquake (M9.3)	X	
	1964 Alaska Earthquake (M9.2)	X	X
	Japan Subduction Zone #2 (M8.8)	X	
	Kuril Islands Subduction Zone #2 (M8.8)	X	
	Kuril Islands Subduction Zone #3 (M8.8)	X	
	Kuril Islands Subduction Zone #4 (M8.8)	X	
	Marianas Subduction Zone (M8.6)	X	X

The most recent tsunami of 2010 Chile and 2011 Tohoku, Japan, are not specifically part of the suite of events that compose the tsunami hazard map for San Mateo County. However, events of similar or even more conservative characteristics are included. Thus, the specific inclusion of these events is not expected to incur significant changes to the inundation extent in this map.

The events presented in Table 4 are consistent with the study of Borrero et al. (2006) in terms of the location of the sources, earthquake magnitudes, and historic events of relevance. Table 5 presents a comparison of earthquake magnitudes between the events modeled by Borrero et al. (2006) and those in the Cal EMA map of interest. From the similarities in magnitudes and event names observed in Table 5 it is inferred that the events share similar rupture characteristics (length, width, slip, etc.). One distant source and one local source that were not modeled in Borrero et al. (2006) that are present in Table 4 are the Marianas Subduction Zone (western Pacific) and the Point Reyes Thrust Fault (northern California). The return period associated to the events shown in Table 4 is not available from the Cal EMA maps and, to M&N's knowledge, is information that has not been published.

Given the similarities evident in Table 5, it is reasonable to assume that the same event that Borrero et al. (2006) found to generate the greatest runup in San Francisco Bay, the Aleutian III event, is the same event that pushes the inundation line inland the farthest on the Cal EMA map for San Mateo County. For this event, the mapped area would be associated with a minimum return period in the 350 – 800 year range (most likely in the upper end of this range). Nevertheless, because the inland limit of inundation is defined in a maximum of maximums approach, the composite return period associated with the map can be higher than that of the Aleutian III event alone. Dr. Patrick Lynett from the USC Tsunami Research Center provided feedback on the return period associated with the Cal EMA maps, indicating that ongoing probabilistic modelling has shown that the inundation line has a return period in the range of 1,000 years.

Table 5: Comparison of events modeled by Borrero et al. (2006) and events modeled for Cal EMA tsunami hazard map for San Mateo County

Type	Borrero et al. (2006)		Cal EMA Map for San Mateo County, Montara Mountain	
	Event	M_w	Event	M_w
Historical Event	Alaska 1964	9.26	1964 Alaska Earthquake	9.2
	Chile 1960	9.26	1960 Chile Earthquake	9.3
Hypothetical Distant Source	Aleutian I	8.78	Central Aleutians Subduction Zone #1	8.9
	Aleutian II	8.78	Central Aleutians Subduction Zone #2	8.9
	Aleutian III	9.15	Central Aleutians Subduction Zone #3	9.2
	Cascadia III	9.2	Cascadia Subduction Zone-full rupture	9.0
	Chile North	9.35	Chile North Subduction Zone	9.4
	Japan II	8.72	Japan Subduction Zone #2	8.8
	Kuril II	8.72	Kuril Islands Subduction Zone #2	8.8
	Kuril III	8.72	Kuril Islands Subduction Zone #3	8.8
	Kuril IV	8.72	Kuril Islands Subduction Zone #4	8.8
Hypothetical Local Source	San Gregorio	7.1	Point Reyes Thrust Fault	NA
	Hayward-Rodgers Creek	6.61	Rodgers Creek-Hayward Fault	NA

3.2.5 SAFRR Tsunami Scenario

The Science Application for Risk Reduction (SAFRR) tsunami study was conducted in order to evaluate a single hypothetical, yet plausible far-field tsunami event numerically modeled to map inundation along the coast of California for emergency, mitigation, and evacuation purposes. The work was carried out by the United Stated Geological Survey (USGS) in collaboration with NOAA, the California Geological Survey (CGS), and the California Office of Emergency Services (Cal OES). The study was published in 2013 (Ross et al. 2013).

Defined by the USGS Tsunami Source Working Group, the scenario is set in the Semidi subduction sector off the Pacific coast of the Alaska Peninsula, with a moment magnitude (M_w) of 9.1 and a rupture length of 360 km. This geographical setting was selected based on the knowledge that tsunamis originating from this region of Alaska (e.g., 1946 and 1964 events) pose the greatest threat to the California coastline. The tectonic source properties were chosen to resemble those of the 2011 Tohoku tsunami in Japan. The scenario was set to occur on the 50th anniversary of the 1964 Alaskan earthquake at high tide (MHW plus 0.2 m or 0.66 ft).

The SAFRR tsunami scenario does not entirely replicate one of the Aleutian scenarios modeled by Borrero et al. (2006) or USC. The Aleutian I event, while similar in source location, has an M_w = 8.78 and a rupture length 500 km. The Aleutian III event has a slightly greater M_w than the SAFRR scenario, but a much longer rupture length of 700 km.

The SAFRR tsunami scenario inundation line does not extend as far inland as Cal-EMA's inundation line in the El Granada area, as shown in Figure 14. The inundation extent of the SAFRR scenario reaches elevations of around 15 to 22 ft (NAVD88), leaving a distance of about 90 ft from the farthest inland reach of the inundation to the southern boundary of the EGFSR site. The inundation associated with the SAFFR scenario at El Granada is estimated to have a return period between 200 and 250 years.

3.2.6 Discussion

The literature review indicates that deterministic studies have been the primary means to assess tsunami hazard in the San Francisco Bay area and the rest of the California coastline. These studies have relied on validated numerical models to simulate historical and hypothetical events of far field and near field sources (earthquakes and landslides) to define the extent of inland inundation for emergency purposes. Far field tsunamis generated by subduction earthquakes, primarily from the Alaska – Aleutian Islands zone, have been consistently found to pose the greatest threat.

The modeling performed to develop the 2009 tsunami hazard maps is still relevant today, despite the occurrence of post-2009 events, because of the comprehensive suite of events that were modeled. In addition, these events were modeled with the state-of-the-art MOST model which incorporated bathymetry and topography datasets that are generally representative of the existing conditions. Therefore, the Cal EMA tsunami hazard maps are reliable and conservative in the "emergency planning framework" for which they were designed.

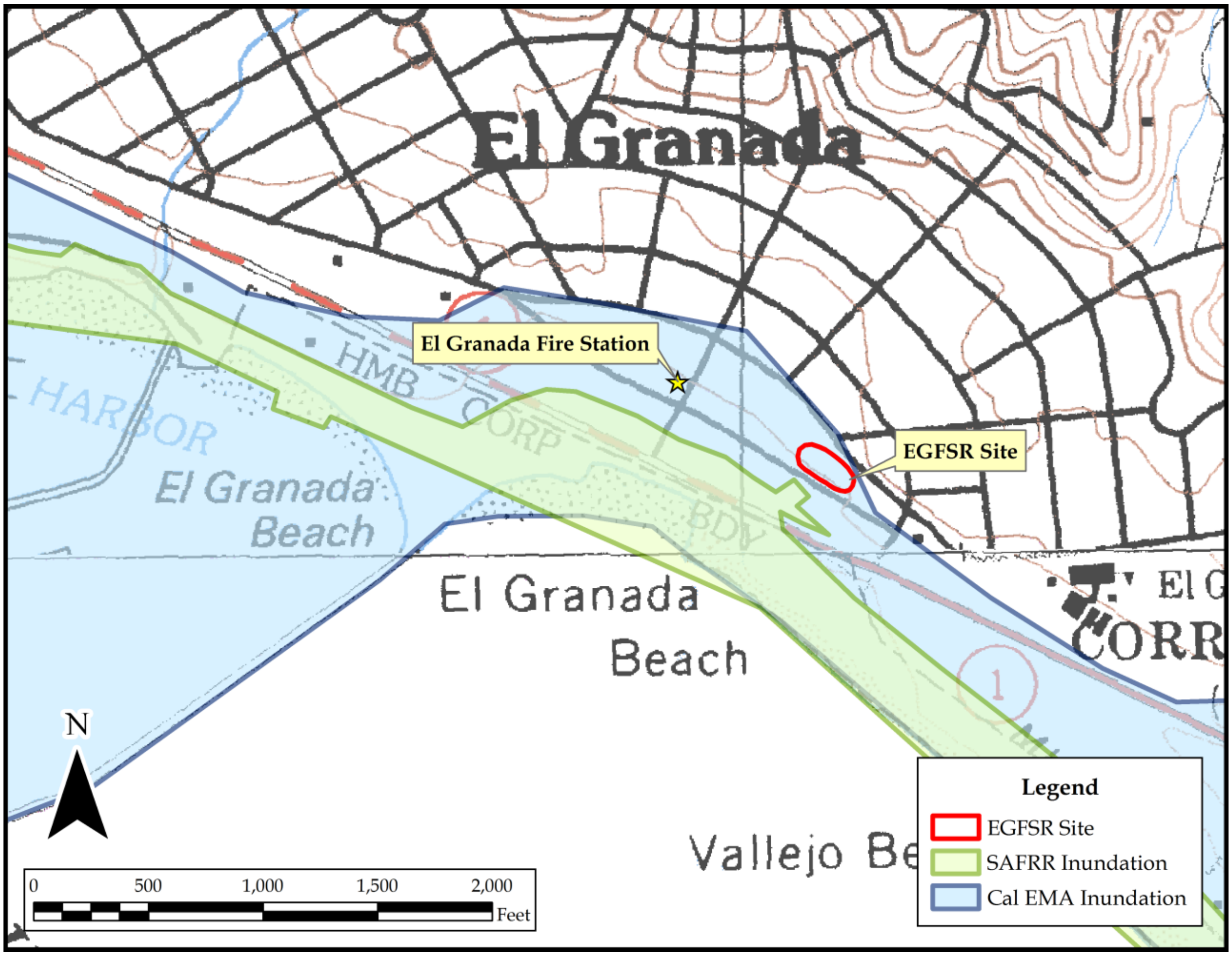

Figure 14: SAFRR and Cal-EMA inundation lines in El Granada

The mapped inland inundation shown on the Cal-EMA map has a very small probability associated with it (500-yr return period or even smaller than that) which is significantly smaller than say a typical 100-year return period (1% annual chance) event typically required for flood hazard analysis under FEMA guidance. Similarly, the inundation extent associated with the SAFRR scenario has a return period between 200 and 250 years which is closer to but still smaller than FEMA requirements. This scenario was also modeled using state-of-the-art techniques and recent ground elevations, making it also a reliable, accurate, and conservative reference which was also intended to be used for emergency purposes.

The SAFRR scenario shows the EGFSR site outside the inundation limit. Therefore, it is reasonable to conclude that tsunami events with return periods of 100 years and less will not cause inundation at this site. To validate this conclusion, extrapolation was conducted as part of this assessment to estimate the runup elevation for the 100 year return period event. Table 6 shows the runup values and corresponding return periods used, as obtained from the literature review, including the resulting 100-year return period range. Figure 15 presents the extrapolation of these points from which the 100-year return period range was obtained.

Table 6: Range of runup elevations at the EGFSR Site

	Lower Range		Upper Range		EGFSR Site (ft, NAVD88)
	Return Period (years)	Runup El. (ft, NAVD88)	Return Period (years)	Runup El. (ft, NAVD88)	
Cal EMA	350	35.0	1000	44.0	25 - 44
SAFRR	200	18.0	250	22.0	
100-yr	100	9.0	100	10.7	
MHHW	1	2.5	1	3.0	

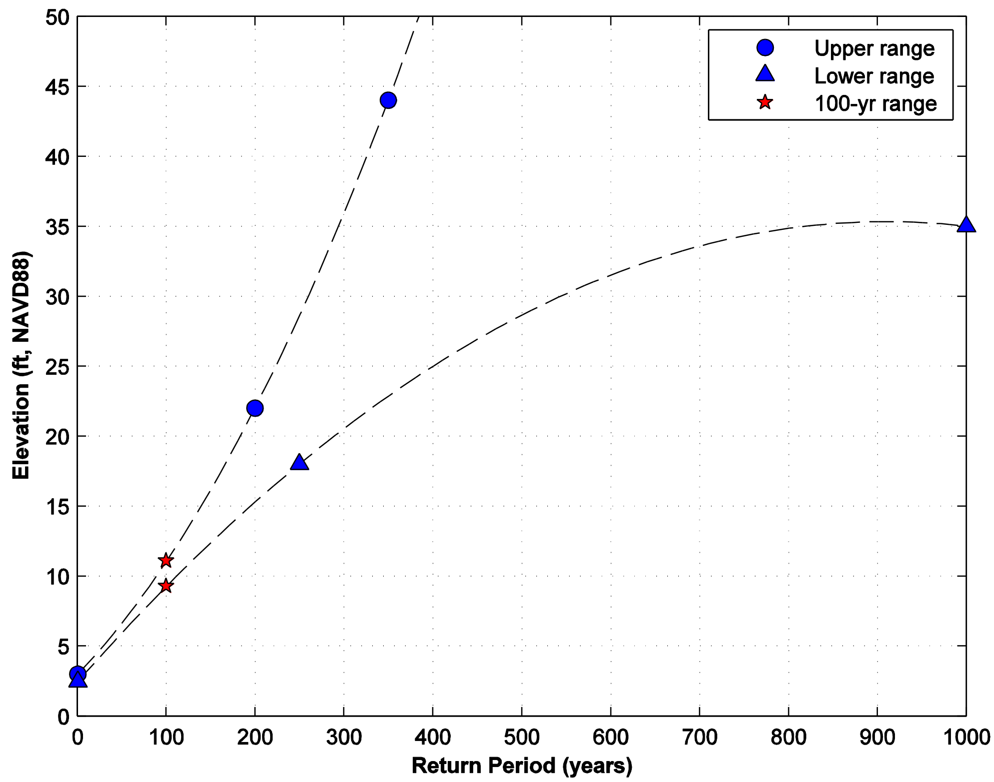

Figure 15: Extrapolation of available tsunami runup to estimate 100-year runup elevation

For illustrative purposes, the information presented in Table 6 was overlaid along a transect shown on Figure 16. This transect was laid out to capture the farthest inland area inundated by the SAFRR scenario in the relocation site vicinity, as well as the portion of the relocation site shown as inundated in the Cal-EMA map. Results of this analysis are shown on Figure 17. The figure shows the extent of inundation estimated for the SAFRR and Cal-EMA efforts, as well as for the relocation site (see yellow stars). The important observation from Figure 17 is that the seaward limit of the EGFSR site is higher than, and inland of, the estimated 100-year return period tsunami inundation zone as well as the SAFRR inundation zone.

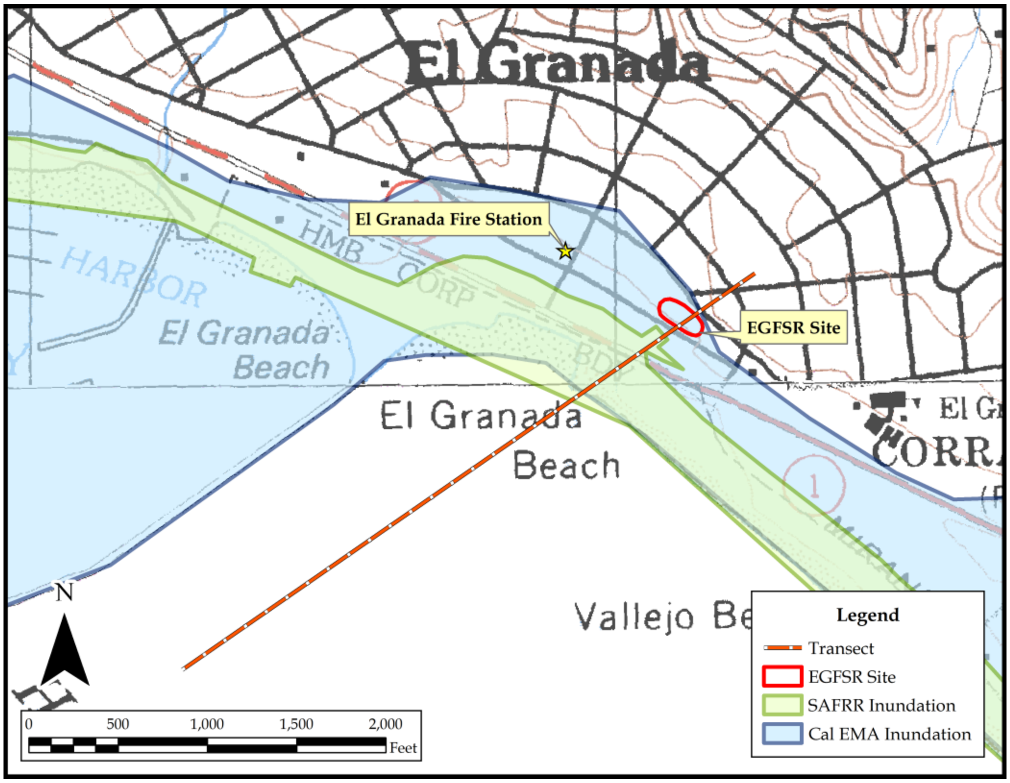

Figure 16: Transect utilized for illustration of runup elevations (Figure 17)

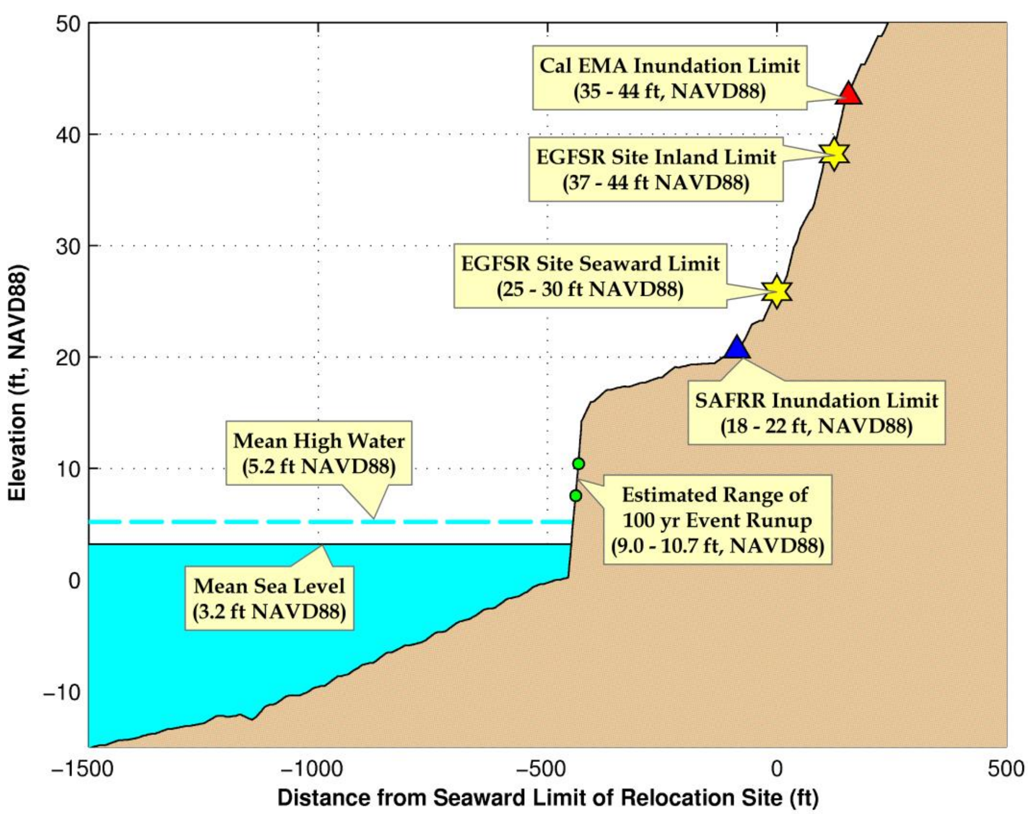

Figure 17: Available and estimated tsunami runup elevations at the EGFSR site

3.3 Probabilistic Analysis of Tsunami Occurrence

The previous sections have provided an indication of the probability of occurrence and return period associated with the inundation extents shown in the Cal EMA and SAFRR tsunami hazard maps. Both of these maps assume the tsunami event(s) occur at a tide level equal to or higher than Mean High Water (MHW). The analysis presented in the following was carried out to estimate the likelihood of a tsunami event occurring under these conditions, which in turn affects the estimated probability of occurrence of the Cal EMA and SAFRR maps as a whole.

Tide levels are an important aspect of tsunami hazard evaluation because a higher tide level in combination with a tsunami wave can result in a higher flood elevation, and thereby a wider flooding extent. Studies conducted for emergency planning purposes, such as the Cal EMA and SAFRR studies adopt a fixed high water level (MHW) in order to produce conservative estimates of potential inundation areas. In reality, the wave period of tsunamis will be on the order of minutes, while variations in tide level occurs over a number of hours. This means that while it is not implausible that the highest wave associated with a tsunami could occur right at the peak of the highest tide, it has a lower probability than the tsunami occurring at an average water level (for example mean tide level).

The analysis is based on the concept applied by M&N for Treasure Island to determine extreme water levels including tsunami contribution. The concept can be divided into three main components: selection of water level record, identification of tsunami events and their contribution to water levels, and selection of a random process to determine the occurrence of those tsunami events.

NOAA Station 9419750 at Crescent City provides a record of measured water levels. The record extends from 1933 to 2015 in hourly intervals. Despite its location near the Oregon border, Crescent City is a location historically affected by tsunamis and, in general, known for experiencing more pronounced tsunami effects than the rest of the California coast. Therefore, by using this record of water levels, a level of conservatism is added to the analysis.

A search in the U.S. National Geophysical Data Center World Data Service for Geophysics (NGDC/WDS) Global Historical Tsunami Database for tsunami events causing runup in Crescent City was conducted to define the tsunami events. The database returned 38 events between 1933 and 2015 that were definite tsunami events.

Each of those events was analyzed in the measured record of water levels and the residual determined as the maximum residual within a 6 hour window (3 hours prior to and 3 hours after the time of the event). Then, extreme value analysis of the residuals was conducted, following the methodology outlined in Goda (2000). A set of extreme values were identified using the peak-over-threshold method, with a threshold defined as the 99.5 percentile value. The method identifies events using the threshold and then selects a single maximum for each event.

Figure 18 shows the results of the extreme analysis of residuals at Crescent City and Table 7 presents the residuals of selected return events as obtained from the best-fit curve. It is noted that this analysis was also conducted for San Francisco Bay and the results were very similar.

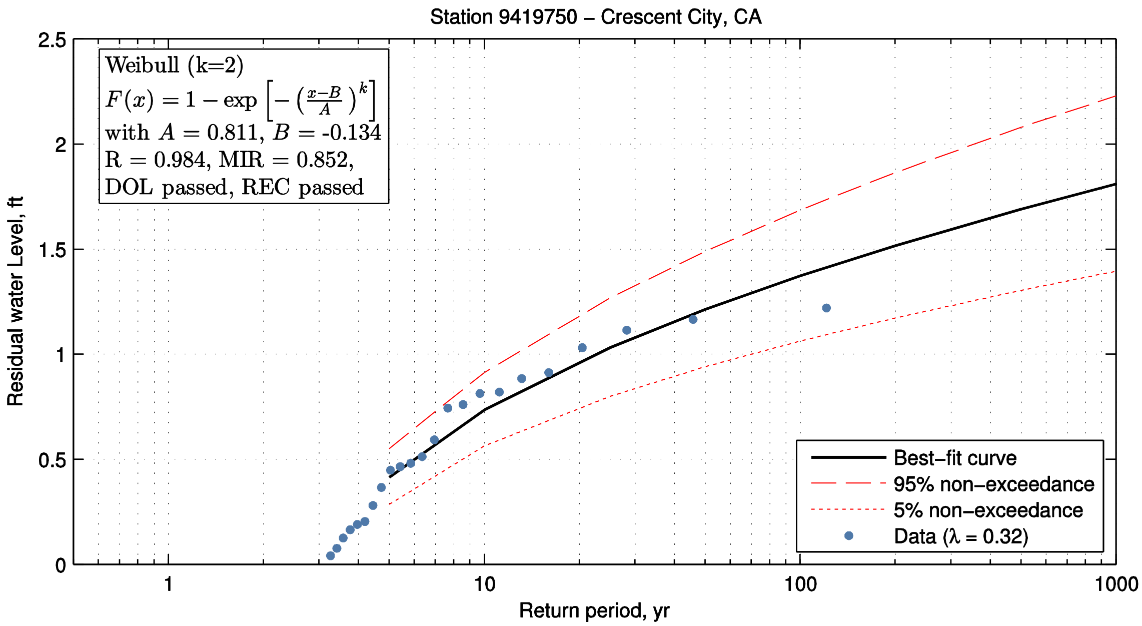

Figure 18: Extreme analysis results of residuals caused by tsunami events

Table 7: Selected extreme values included in simulation

Return Period of Tsunami Event (years)	Expected Residual Water Level (ft)
5	0.42
10	0.74
25	1.03
50	1.21
100	1.37
250	1.55
500	1.69
1,000	1.81

A 1,000-year long time series of astronomical water levels was generated for the simulation, using tidal constituents calculated from the measured record at Crescent City.

The events shown in Table were determined to occur at any time in a year of the simulation by using a random number generator that follows the Poisson distribution. The Poisson distribution gives the probability of a given number of events to occur in a fixed time span if the average rate at which the events occur is known. Since this average rate (return period) is known for selected events from the extreme analysis, this approach allows the random selection process to be weighted so that smaller return periods have a greater likelihood of occurrence than longer return periods. However, as the simulation progresses, the chance for the larger events to occur increases.

At any given time an event occurs, the residual associated with that event was added to the astronomical water level. It is possible to have more than one event occur at the same time; their residuals are simply superimposed on the tide.

For the purpose of analyzing the simulation results it was estimated, using the information in Table 2, that MHW is 2.0 ft above MSL in the Half Moon Bay area. The probability of a tsunami occurring at a tide level equal to or higher than MHW was calculated as the mean of ten (1,000 year) simulations, which were found to yield similar results (which is in turn indicative of good convergence using 1,000 years as the simulation length). The results are presented in Table 8. These results illustrate how the likelihood of occurrence of a given return period event can be lower when factoring in tide levels; for example, the annual probability of a 100-year tsunami occurring at a tide level equal to or higher than MHW was found to be 0.15% which is approximately equivalent to the annual probability of a 650-year return period event. It can therefore be concluded that the probability of a tsunami capable of affecting the EGFSR site is very low.

Table 8: Results from simulation of water levels and random tsunami events

Return Period of Tsunami Event (years)	Probability of Occurrence in a Year at a Tide Level Equal to or Greater than MHW (2 ft above MSL), %
5	3.60
10	1.62
25	0.83
50	0.25
100	0.15
250	0.07
500	0.03
1,000	0.02

4.0 SUMMARY

Key findings of this tsunami study for the EGFSR site are summarized below:

1. The California coastline is vulnerable to tsunamis. Historically, far field tsunamis of seismic origin have caused the greatest impact; in particular, tsunamis originating in the Alaska – Aleutian Island subduction zone.

2. As of the completion of this report, two references define the tsunami inundation potential at El Granada: the Cal-EMA tsunami inundation maps and the SAFRR tsunami inundation map. Both use state-of-the-art modeling techniques, high resolution near the coastline, and recent ground elevations. The maps define only the inundation caused by tsunami events, without providing information about flow depth or return period. This is because the maps were created for emergency and mitigation purposes and not to provide a regulatory design guideline as is the case of FEMA flood maps.

3. The 2009 Cal-EMA tsunami inundation map is the result of modeling a suite of historical and hypothetical tsunami events at Mean High Water (MHW). The extent of inundation shown on the map is an aggregate of maximum runup from several events, with the farthest landward inundation being subject to tsunamis that have return periods as high as 1,000 years. According to this map, the EGFSR site is close to the upland limit of

inundation, which implies that it would be inundated primarily when these low probability events occur.

4. The SAFRR scenario is a single, hypothetical tsunami event with a source in the Alaska – Aleutian Island subduction zone. Even though it was modeled at high tide (MHW plus 0.66 ft), the inundation from this scenario, which corresponds to a 200 – 250 year return period, does not reach the EGFSR site nor does it reach the existing firestation 41 site.

5. Extrapolation of the available tsunami runup elevations resulted in a 100-year tsunami runup elevation range of 8 to 10 ft (NAVD88). The EGFSR site is at elevations ranging from 25 to 44 ft, with most of the proposed facility at about 32 ft; therefore, the 100-year event is not expected to cause flooding of the site.

6. Results of a probabilistic analysis of historical tsunami events indicate that the risk of occurrence of a large tsunami event at MHW (2 ft above Mean Sea Level) or higher is low. A 100-year return period tsunami event occurring at MHW, for example, was found to have a probability of occurrence in a given year of 0.15% which is equivalent to a 650-year return period event. Based on these results, it is reasonable to infer that the probability of a tsunami capable of affecting the EGFSR site is significantly lower than 1 in a 100 years.

7. The low-probability, far-field tsunamis that the EGFSR are vulnerable to travel over great distances over the Pacific Ocean before they arrive at the site, which typically takes over 4 hours from the time that a seismic activity occurs. Given that the fire station is proposed to be occupied by first responders and able support staff, the risk of a tsunami causing life safety concerns could be considered to below. The building itself could be designed to sustain loads associated with a tsunami; guidance from ASCE that is forthcoming will include design criteria for buildings subject to tsunamis.

8. The section of the Local Coastal Plan (LCP) relevant to tsunami hazards, *Section 6326.2: Tsunami Inundation Area Criteria,* is not clear about the level of probability to be used in the evaluation. In other words, is the intent of the language to show events with return periods as large as the Cal-EMA maps? It would be instructive to review other sections that deal with similar low probability geologic events, including earthquakes and landslides, to achieve consistency for such design criteria. For example, seismic design criteria for non-essential buildings per the California Building Code allows the use of a 10% probability of occurrence over 50-years, which equates to about a 475-yr return period. If a parallel to this is drawn for tsunamis, the maximum inland extent of inundation would be lower than this design criteria.

9. We concur with Commission staff’s recommendation that the project consider the implications of the Cal-EMA study for siting and design of the fire station. Specifically, design elements addressing location of bunk rooms for personnel relative to inundation and designing structures consistent with standards for coastal high hazard areas outlined in LCP Section 6825.3. This study used LiDAR elevational data and approximate inundation depths by comparing the Cal-EMA map to the LiDAR data to complete the assessment. To assist in siting and design of building structures within the proposed site, additional analyses may be warranted to estimate inundation depths and resultant tsunami forces. The analysis could take the form of a detailed site-specific tsunami study that would result in design criteria.

10. It would also be instructive to comment on the potential vulnerability of this facility to sea level rise over a typical lifespan (assumed to be 50 to 100 years for the relocated firestation). Comparing the lowest existing site elevation of 25 ft to the elevation reached by a typical design tsunami event of 8 to 10 ft, as shown in this analysis, there is about 15 feet of freeboard at this location. Assuming the most conservative projection of sea level rise of 5.5 ft by 2100, per the National Academy of Sciences 2012 report, there is sufficient allowance such that a design tsunami event would not result in inundation of the site. Even for tsunamis in the 200 to 250-yr return period (such as the SAFRR scenario), where the runup could be in the 18 to 20-ft range, there is sufficient allowance for the future.

Thank you for giving us the opportunity to provide our services on this important local project. Should you have any questions or comments, please contact me at your convenience.

Sincerely,

MOFFATT & NICHOL

A. Jimenez   Mads Jorgensen   Dilip

Arturo Jimenez, P.E.	Mads Jorgensen, P.E.	Dilip Trivedi, Dr. Eng., P.E.
Coastal Engineer	Project Manager	Vice President

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