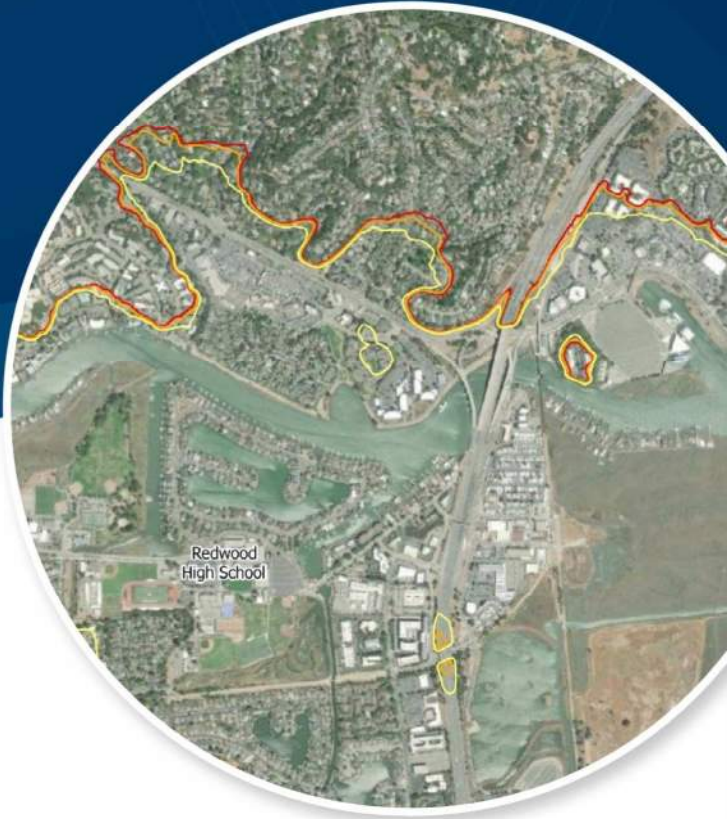


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Tamalpais Union High School District Sea Level Rise Vulnerability Assessment

June 30, 2021





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ABSTRACT

This vulnerability assessment study will focus on the sea level rise/coastal hazards analysis of the Tamalpais Union High School District sites in Marin County, CA. The Tamalpais Union High School District consists of five (5) high school parcels located in the “Coastal Zone” of Marin County, CA, as listed below:

1. Archie Williams High School (formerly Sir Francis Drake HS) (Figure 2)
2. Redwood High School (Figure 3)
3. San Andreas High School (Figure 4)
4. Tamiscal High School (Figure 5)
5. Tamalpais High School (Figure 6)

Archie Williams High School is located on high ground in the San Anselmo Creek water shed that merges with Ross Creek to form the larger Corte Madera Creek watershed. The complex of campuses comprised of Redwood, Tamiscal and San Andreas High Schools are clustered at low elevations in the floodplain of Corte Madera Creek. Tamalpais High School is located at low elevation adjacent to the Pickleweed Marsh Complex, (cf. cover photo).

For reasons of consistency with state-wide standards, and in order to err on the side of caution, this study has been prepared according to the sea level rise projections and requirements for a sea level rise/coastal hazards analysis as set forth in The California Coastal Commission’s *Sea Level Rise Policy Guidance Document*. Vulnerability and planning recommendations in this study were prepared in accordance with Federal Emergency Management Agency (FEMA) flood standards based on the 100-year event (1% joint probability of exceedance). Flooding and inundation analysis utilized a hybrid modeling approach based on the USGS , “Coastal Storm Modeling System (CoSMoS 2.1: San Francisco Bay) and the Scripps Coastal Evolution Model, (CEM). Refer to Section 2 – *Technical Approach* for a more detailed explanation of the hybrid modeling approach and why it provides a more accurate result.

The modeling results determined that the 1% flood event (return period of 100 years) results in flooding or inundation at present sea level up to + 9.12 ft. NAVD88 (NAVD). Sea level rise (SLR) projections were made for the planning horizons at years 2070 (50-yr), 2100 (80-yr), and 2120 (100-yr). Total water levels for the 1% flood event at the 50-year planning horizon (2070) are little changed from those at present sea levels, reaching +9.44 ft. NAVD. At the 80-year planning horizon (2100), the 1% flood event reaches + 11.44 ft. NAVD, while at the 100-year planning horizon (2120), total water levels during the 1% flood event rise to 12.14 ft. NAVD.

Only the Archie Williams High School (at the headwaters of the San Anselmo Creek at elevation +77 ft. NAVD) lies outside all of the 1 % flood event inundation contours; and therefore, remains immune to flooding or inundation at both present and future sea levels. The cluster of the three high schools (Redwood, San Andreas, and Tamiscal) located in or adjacent to the floodplain of the Corte Madera Creek, are particularly at risk, even for the 1% flood event at present sea level. Not only will the buildings and parking lots of these schools become flooded or inundated; but so will the road network over large areas surrounding these schools. Similarly, Tamalpais High School, which is located adjacent to the tidal channels and marsh plains of Pickleweed Inlet, will also be



flooded or inundated by the 1% flood event at both present and future sea levels, but only a short section of roadways to the west of the high school will be subjected to additional flooding or inundation.

A notable result is that there is little distinction between the flooding and inundation contours at present sea level vs. those at 2100 or 2120 sea levels. This arises because the 4 at-risk high schools are located on very flat floodplains or ancient marsh plains that are surrounded by higher ground. Consequently, the rise in sea level does not significantly change the flooded or inundated area, but rather merely increases the depth of flood waters or the depth of submergence in and around these high schools. At present sea level, flood depths around Redwood, San Andreas, and Tamiscal High Schools during a 100-year event would be on the order of 2 ft. and about 0.5 ft. at Tamalpais High School. At 2120 sea levels (100-year planning horizon), submergence depths due to inundation of Redwood, San Andreas, and Tamiscal High Schools could reach about 5 ft., and about 3.5 ft. on some portions of the Tamalpais High School campus.

After a discussion with the Tamalpais Union High School District CFO, it was determined that the fundable solution for protection against flooding and inundation by the 1% flood event at present and future sea levels is a local berm concept around the four at-risk campuses. The central objective would be protection of capital assets, primarily buildings, while sacrificing portions of playing fields and parking lots in order to minimize remedial costs. A hybrid solution would be utilized consisting of a vegetated earthen berm layout fortified with a buried seawall constructed of interlocking pre-cast concrete panels. In locations where a berm is not feasible due to site restrictions (i.e. right of way, property lines, etc.), a concrete seawall is proposed.

Access to the school campuses, both pre- and post- extreme event, would be accomplished using flood gates through the berm systems that are anchored to the pre-cast concrete seawall panels. Periods of extreme event floods would become times for *ZOOM classrooms* as was common throughout the COVID-19 pandemic.



1) INTRODUCTION

This study provides a Sea Level Rise/Coastal Hazards Vulnerability Analysis for the Tamalpais Union High School District located along the west shoreline in the north arm of the San Francisco Bay Estuary, (cf. **Figure 1**). In addition to the analysis, potential adaption measures are provided with preliminary concepts and cost estimates. Tamalpais Union High School District consists of five (5) high school parcels located in the “Coastal Zone” of Marin County, CA, as listed below. These schools and the geographic centroid of each geographic are:

- | | |
|--------------------------------|---|
| 1. Archie Williams High School | (Figure 2): 37°58'58.00"N; 122°34'21.26"W |
| 2. Redwood High School | (Figure 3): 37°56'15.09"N ; 122°31'27.23"W |
| 3. San Andreas High School | (Figure 4): 37°56'10.73"N ; 122°31'30.91"W |
| 4. Tamiscal High School | (Figure 5): 37°56'15.92"N ; 122°31'46.31"W |
| 5. Tamalpais High School | (Figure 6): 37°53'29.37"N ; 122°31'46.10"W |

Archie Williams High School (formerly Sir Francis Drake HS) is located on high ground in the San Anselmo Creek water shed that merges with Ross Creek to form the larger Corte Madera Creek watershed. The complex of campuses comprised of Redwood, Tamiscal, and San Andreas High Schools are clustered at low elevations in the floodplain of Corte Madera Creek (**Figure 1**) and are subject to occasional minor flooding during storms and king tides. Tamalpais High School is similarly located at low elevation adjacent to the Pickleweed Marsh Complex (**Figure 1**). The study is prepared in accordance with requirements of both the Marin County’s Bay Waterfront Adaptation Vulnerability Evaluation (BayWAVE) “Sea Level Rise Scenario Guidance document (BayWAVE, 2021), and the *California Coastal Commission Sea Level Rise Policy Guidance* document (CCC, 2018) for a sea level rise/coastal hazards analysis. The analysis includes assessment of vulnerabilities and remedial measures for these five Union High Schools as listed above.

2) TECHNICAL APPROACH

Several sea level rise (SLR) inundation models are available to estimate the extent of coastal flood inundation along the eastern Marin shoreline, i.e. the NOAA’s *Sea Level Rise Viewer (SLRV)* model and the USGS *Coastal Storm Modeling System (CoSMoS v. 2.1)*; each with particular advantages and disadvantages. With no officially recommended model; Marin County Staff have evaluated strengths and limitations of these two models; in addition to a hybrid approach, the *Richardson Bay Shoreline Model* that combines the Marin County’s more accurate Digital Elevation Model (DEM) with “bathtub” SLR scenarios. Marin County staff have conducted Geographic Information Systems (GIS) comparisons of flooding extent using the NOAA, CoSMoS and hybrid models throughout eastern Marin’s shoreline and at several critical locations known to flood at current King Tide elevations (approximately 12 inches above MHHW). Staff presented these findings at the November 23, 2015, BayWAVE Technical Group meeting. A vote on whether to use USGS CoSMoS, NOAA SLRV or the hybrid approach was conducted, with a determination that *CoSMoS* will be the primary model used for sea level rise/coastal hazards analyses. Note: CoSMoS v. 2.1 is specific to San Francisco Bay only, and uses the latest DEM



from Bay Lidar surveys. CoSMoS v. 3.1 is specific to the exposed open ocean coastline of Central California and is not the appropriate version to use for this sea level rise analysis within the Bay.

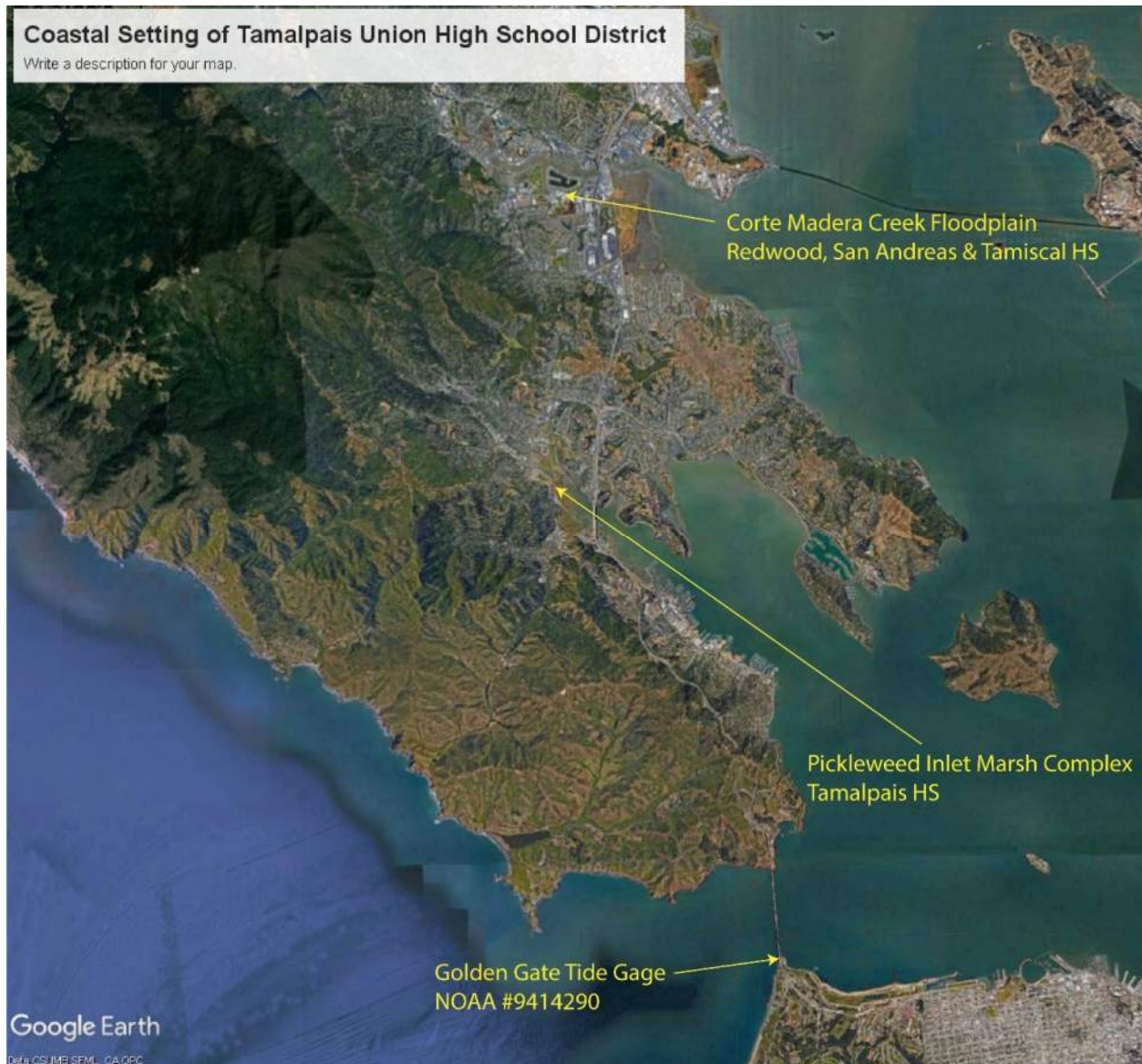


Figure 1: *Coastal Setting for the Tamalpais Union High School District Sites.*



Figure 2: Google Earth far-field image of Archie Williams (formerly Sir Francis Drake) High School location relative to the entrance to San Francisco Bay. Elevation of existing grade at Archie Williams High School is +77 ft. NAVD. Hence inundation by extreme events at future sea levels is not likely within the design life of the high school buildings.



Figure 3: Google Earth near-field image of Redwood High School locations relative to the shoreline of Corte Madera Creek. Elevation of existing grade at Redwood High School averages approximately +7 ft. NAVD.



Figure 4: Google Earth near-field image of San Andreas High School locations relative to the shoreline of a Corte Madera Creek tidal channel. Elevation of existing grade at San Andreas High School averages approximately +7 ft. NAVD.



Figure 5: Google Earth near-field image of Tamiscal High School locations relative to the shoreline of a of Corte Madera Creek tidal channel. Elevation of existing grade at Tamiscal High School averages approximately +7 ft. NAVD.



Figure 6: Google Earth near-field image of Tamalpais High School location relative to the shoreline of Pickleweed Inlet. Elevation of existing grade at Tamalpais High School is averages approximately +8.6 ft. NAVD.



The Technical Group selected a set of six (6) sea level rise scenarios to include:

1. 25 centimeters (0.82 ft.) – No storm
2. 25 centimeters (0.82 ft.)– 100-year storm
3. 50 centimeters (1.64 ft.) – No storm
4. 50 centimeters (1.64 ft.) – 100-year storm
5. 150 centimeters (4.9 ft.) – No storm
6. 150 centimeters (4.9 ft.) – 100-year storm

However, the decisions were made at the November 23, 2015, BayWAVE Technical Group meeting were based on previous Coastal Commission sea level rise guidance from on a 2012 study by the National Research Council, (NRC, 2012). Since that time, the California Ocean Protection Council (OPC) and the California Coastal Commission (CCC) have reviewed more recent climate model forecasts, (IPCC, 2018; OPC, 2018), and have updated state-wide sea level rise guidance and the requirements for a sea level rise/coastal hazards analyses in 2015 and again in 2018, (CCC, 2015; 2018). These updates have considerably increased sea level rise projections over the six discrete scenarios above that the BayWAVE Technical Group adopted in 2015. The new *State of California Sea-Level Rise Guidance: 2018 Update* (2018 OPC SLR Guidance) contains projections for 12 tide gauges throughout California, to account for localized variations in vertical land motion and other factors, for each decade from 2030 to 2150. The sea level rise projections specific for the San Francisco Bay Estuary were derived from the Golden Gate tide gauge shown in **Figure 1**. Those sea level rise projections are listed in **Table 1**. Inspection of **Table 1** indicates that the BayWAVE's year 2115 upper range sea level rise projection of 150 cm (4.9 ft) now corresponds to only a year 2068 projection according to the H++ scenario, which is based on the NOAA funded study by Sweet et al. (2017).

Even though the Bay Conservation and Development Commission (BCDC) has jurisdiction over the CCC within the San Francisco Bay Estuary, it is likely that BayWAVE and BCDC will be required to reassess and update their previous sea level rise guidance documents to be consistent with more aggressive projections in CCC (2018; and that the sea level rise projections listed in **Table 1** will be adopted as the regulatory standard within The Bay. Furthermore, the *California Coastal Commission Sea Level Rise Policy Guidance*, (CCC, 2018), details a specific series of analysis procedures for assessing the full range of combined impacts that may arise from the simultaneous occurrence of extreme storms, tsunamis, tides, ocean-bay water levels, and watershed flooding when superimposed on future sea level rise. For reasons of consistency with state-wide standards, and in order to err on the side of caution, this study has been prepared according to the sea level rise projections in **Table 1** following the vulnerability assessment protocols detailed in CCC (2018 & 2020).

A commonly used model when assessing sea level rise impacts in the Bay is the USGS model, CoSMoS version 2.1, which maps baseline predictions of coastal flooding due to both future sea level rise and storms. However, CoSMoS 2.1 has some limitations, particularly when integrating sea level rise impacts that must be adjusted for additional water level increases resulting from wave set-up and total wave runup of ultra-refracted storm waves that leak into bays from the open ocean. San Francisco Bay, one of the earth's largest and most protected natural harbors, is vulnerable to



ultra-refracted ocean waves, particularly southwest incident swells; and that ultra-refraction can produce wave heights in Marin Bay reaching 2 m (6.3 ft.) and higher. Capabilities to account for wave set-up, run-up, and erosion due to wave breaking of ultra-refracted ocean waves and locally generated wind waves in the Bay are apparently not yet functional in the CoSMoS 2.1 model.

Table 1: *Sea Level Rise Projections for the San Francisco Bay Estuary based on the Golden Gate tide gage Tide Gage, NOAA #9414290 (from OPC, 2018 & CCC, 2018)*

Projected Sea Level Rise (in feet): San Francisco			
	Probabilistic Projections (in feet) (based on Kopp et al. 2014)		R++ Scenario (Sweet et al. 2017)
	Low Risk Aversion	Medium-High Risk Aversion	Extreme Risk Aversion
	Upper limit of 'likely range' (~17% probability SLR exceeds...)	1-in-200 chance (0.5% probability SLR exceeds...)	Single scenario (no associated probability)
2030	0.5	0.8	1.0
2040	0.8	1.3	1.8
2050	1.1	1.9	2.7
2060	1.5	2.6	3.9
2070	1.9	3.5	5.2
2080	2.4	4.5	6.6
2090	2.9	5.6	8.3
2100	3.4	6.9	10.2
2110*	3.5	7.3	11.9
2120	4.1	8.6	14.2
2130	4.6	10.0	16.6
2140	5.2	11.4	19.1
2150	5.8	13.0	21.9

To address these deficiencies and refine the baseline predictions, CoSMoS 2.1 modeling with supplemented by a hybrid model, *Coastal Evolution Model (CEM)*, recently developed at the Scripps Institution of Oceanography (SIO). The CEM is public domain and available from the University of California Digital Library at: <http://repositories.cdlib.org/sio/techreport/58/>. The CEM employs algorithms consistent with the U.S. Army Corps of Engineers *Coastal Engineering Manual* but employs the latest generation equilibrium shore profile algorithms from Jenkins and Inman (2006) based on the elliptic cycloid and provides 3-dimensional predictive and mapping capability of the shoreline recession under the effects of wave climate variability and sea level rise. It also utilizes a hydroperiod approach to calculating extreme water levels arising from king tides and sea level anomalies resulting from El Nino/Southern Oscillation (ENSO) and climate cycles such as the Pacific Decadal Oscillation (PDO). The hybrid CEM model has recently been incorporated into the Caltrans *Highway Design Manual* for use in coastal highway and drainage design, (Jenkins and Taylor, 2015 & 2016).



The CCC Sea Level Rise Policy Guidance documents (CCC, 2013, 2015, 2018 & 2020) provide no specific guidance on the redline frequency for coastal flooding or inundation. In the absence of such guidance Michael Baker has adopted Federal Emergency Management Agency (FEMA) standards for flooding frequency and set redline planning frequency at the 100-year event (1% joint probability of exceedance). In the present application, the 1% flood event arises from the superposition of future sea levels with a combination of storm induced wave surge inside The Bay and extreme water levels in The Bay arising from king tides, ENSO and PDO. Consequently the 1% flood event is given by the joint probability of extreme total water levels and sea level rise, or:

$$P[\Delta\eta_{SLR}, \eta_{TWL}] = P(\Delta\eta_{SLR}) \cdot P(\eta_{TWL}) = \frac{1}{100} \text{ or } 1\% \quad (1)$$

Here η is The Bay water level; η_{TWL} is the total water level along The Bay shoreline at present sea level (including combined effects of ultra-refraction of storm waves into The Bay, superimposed on king tides and sea level anomalies resulting from climate cycles such as ENSO and PDO; $P(\eta_{TWL})$ is the exceedance probability of a particular total water level in The Bay; T is the return period of total water levels in years, $P(\eta_{TWL}) = 1/T$; and $P(\Delta\eta_{SLR})$ is the exceedance probability of a given sea level rise projection. The joint probability of the 1% flood event using equation (1) assumes that sea level rise and extreme total water levels at present sea level are independent events. This assumption is justified on the basis that extreme total water levels in The Bay are caused by the astronomic tidal extremes with smaller additional increases on the order of 1 ft. resulting from extreme event storms. The astronomic tidal extremes are controlled by the orbital dynamics of the earth moon and sun, and therefore totally independent of sea level rise processes. The storm induced component of total water levels in the Bay are influenced by the relatively short-term climate cycles of ENSO (average return periods of about 7 years) and the warm-wet phase of PDO, which has an average return periods of about 20 years. On the other hand, sea level rise is the result of the build-up of greenhouse gases in the atmosphere, a process that has been ongoing for at least the last 150 years. At present there is no known couple between ENSO or PDO and sea level rise.

The calculation of the 1% joint probability of flooding in equation (1) is bounded by the exceedance probability of the particular sea level rise scenario that is used. Because this study has adopted the FEMA 100-year flood design standard for developing protective measures for the Tamalpais Union High School District, the only sensible sea level rise scenario is the “Low-Risk Aversion” scenario in column-(1) of **Table 1**, which represents the upper limit of the likely range of sea level rise based on IPCC (2018) and OPC (21018). The exceedance probability of this scenario is $P(\Delta\eta_{SLR}) = 0.17$ or 17%. Exceedance probabilities for the other two scenarios in **Table 1** have exceedance probabilities more extreme than the FEMA 1% flood design standard. By adopting the *upper limit of the likely range of sea level rise projections* for the 1% flood event calculations in equation (1), the particular value for the probability for exceedance of Bay total water levels is set at $P(\eta_{TWL}) = 0.0588$ (5.88%) in order for the joint probability of extreme Bay water levels superimposed on sea level rise to yield a joint probability for flooding of 1% (100-year flood event). When assessing the joint probability for the 1% flood event at present sea level,



the exceedance probability for sea level rise becomes $P(\Delta\eta_{SLR}) = 1$ in equation (1), and the probability for exceedance of Bay total water levels is set at $P(\eta_{TWL}) = 0.01$.

To determine the particular extreme total water level in the Bay that has an exceedance probability of either 1% at present sea level or 5.88% at future sea levels, we invoke the hydroperiod and refraction algorithms from the CEM to augment flooding and inundation contours predicted by CoSMoS 2.1. The calculus of the total water level modeling is described in more detail in Section 4 below. The Bay water levels resulting from the 1% joint probability for flooding or inundation are then used to calculate the flooding and inundation contours around the Tamalpais Union High Schools using USGS DEM data bases derived from most recent Lidar surveys (cf. USGS, 2021).

3) SLR ANALYSIS – REGULATORY REQUIREMENTS

The *California Coastal Commission Sea Level Rise Guidance Policy Guidance* document (CCC, 2015) and CCC (2018) provides specific guidance on the analysis protocols of a sea level rise/coastal hazards analysis, which are provided in the list below:

- **Step 1: Develop temporally- and spatially-appropriate sea level rise projections**

In the original draft of the *California Coastal Commission Sea Level Rise Guidance Policy Guidance* document (CCC, 2015), two (2) methods were originally recommended for establishing sea level rise projections for a specific year: 1) linear interpolation, or 2) use the “best fit” equations that are provided below. At this time, both were acceptable for Coastal Commission purposes. However, in the latest policy draft, (CCC, 2018), these two methods have been replaced by a set of tables appearing in Appendix-G of that updated draft. The tabular estimates are specific for 12 different sea level provinces California

- **Step 2: Determine tidal range and future inundation**

This step requires the determination the future intersections of mean sea level or other tidal datums with the shoreline. Erosion must be accounted for in these determinations.

- **Step 3: Determine still water changes from surge, El Niño events, and PDOs**

Estimates of surge, El Niño, and PDO water elevation changes are to be developed primarily from historical records. There are no state-wide resources for this information,

- **Step 4: Estimate beach, bluff, and dune change from erosion**

There is no single specific accepted method for predicting future beach erosion. At a minimum, projects should assume that there will be inundation of dry beach and that the beach will continue to experience seasonal and inter-annual changes comparable to historical amounts. When there is a range of erosion rates from historical trends, the high rate should be used to project future erosion with rising sea level conditions (unless future erosion will encounter more resistant materials, in which case lower erosion rates may be used). For beaches that have had a relatively stable long-term width, it would be prudent to also consider the potential for greater variability or even erosion as a future condition.



- **Step 5: Determine wave, storm wave, wave runup, and flooding conditions**

Wave impacts to the coast, to coastal bluff erosion and inland development, should be analyzed under the conditions most likely to cause harm. Those conditions normally occur in winter when most of the sand has moved offshore leaving only a reduced dry sand beach to dissipate wave energy (this seasonal change in beach width is often referred to as short-term or seasonal erosion). On beaches that will experience long-term erosion, trends expected to occur over the entire expected life of the development should also be considered. Since water levels will increase over the life of the development due to rising sea level, the development should be examined for the amount of sea level rise (or a scenario of sea level rise conditions) that is likely to occur throughout the expected life of the development. Then, the wave impact analysis should examine the consequences of a 100-year design storm event using the combined water levels that are likely to occur with high water conditions and sea level rise, as well as a long-term and seasonally eroded beach.

- **Step 6: Examine potential flooding from extreme events**

Extreme events, by their very nature, are those beyond the normal events that are considered in most shoreline studies. Tsunami should be among the extreme events evaluated. Planning and project analysis need to consider and anticipate the consequences of these outlier events. Projections of potential flooding from extreme events are the principle outcome of Step 6.

4) BAY WATER LEVEL AND PROBABILITY ANALYSIS

The present analysis will use 2120 (100-year project lifespan) as the ultimate planning horizon, typical of an infrastructure project. The Tamalpais Union High School District lies in the San Francisco Bay Estuary sea level rise province, found in Table G-5 of Appendix G of CCC, (2018). The *upper limit of the likely range of sea level rise projections* appear in the first column of **Table 1** and represent a 17% probability that sea level rise will exceed the tabulated values. Sea level rise (SLR) projections for the planning horizons for years 2070 (50-yr), 2100 (80-yr), and 2120 (100-yr) are the scenarios that will be used to determine the evolution of the 100-year flood as a function of increasing sea level over time. These values will be used to specify the *temporally- and spatially-appropriate sea level rise projections* required by Step-1 of the CCC's sea level rise/coastal hazards analysis protocols, (cf. Section 3), and will ultimately drive the calculations of *extreme total water levels* (TWL's) in the Bay, that drive the final solution for the 1% (100-year) flood event at present in future sea levels according to equation (1).

In evaluating Steps 2, 3, and 6 of the CCC's sea level rise/coastal hazards analysis protocols, (cf. Section 2), this project benefits from being located only 6 to 9 miles from the NOAA tide gage (#9414290) at the Golden Gate Bridge, (cf. **Figure 1**). This tide gage was among those California tide gages that was leveled by NOAA with validation of its historic water level measurements for the most recent tidal epoch 1983-2001, and its updated elevation datum are listed in **Table 2**. Interesting enough, the most recent leveling of this tide gage found little evidence of accelerated sea level rise as compared to NOAA's previous tidal epoch, 1967-1978. This tide gage measures outer Bay water levels at 6-minute intervals and provides *in situ* data of historic occurrences of



local tidal muting or resonances, Tsunami surges and longer-term water level variations associated with El Niño, and PDO, thereby satisfying the requirements of Steps 2, 3, and 6 of the CCC's sea level rise/coastal hazards analysis protocols, (cf. Section 3).

Steps 4 and 6 of the CCC's sea level rise/coastal hazards analysis protocols, (cf. Section 2), address coastal hazards associated wave-driven processes, common along the open coast of California. However, the project sites are located in the inlets to Corte Madera Creek and the Pickleweed inlet marshes (**Figure 1**). Even though these inlets appear to be sheltered from open ocean swell waves entering The Bay, these open ocean swell waves can undergo changes in their direction of propagation (relative to deep-water) greater than 90° over relatively short spatial scales. This phenomenon referred to as ultra-refraction. Ultra-refracted swell waves can have a powerful influence on coastal areas that otherwise appear to be sheltered from ocean waves. **Figure 7** shows that San Francisco Bay, one of the earth's largest and most protected natural harbors, is vulnerable to ultra-refracted ocean waves, particularly southwest incident swell; and that ultra-refraction can produce wave heights reaching 2 m (6.3 ft.) and higher. Since heights of long period swell in shallow water become depth limited, increases in local water depths at future sea levels can increase breaking wave heights along the shoreline, potentially causing wave runoff to exceed the elevation of existing grade in the neighborhood of the high schools. Furthermore, ultra-refracted open ocean swells reaching the project site can be augmented by locally generated wind waves within the Bay, and the project site is fully exposed to wind waves generated by southerly pre-frontal storm winds. These pre-frontal wind waves inside The Bay are fetch limited, having extremely short-wave periods, on the order of 3 s to 4 s. The effects which ultra-refracted swells and local wind waves have on total water levels along the project shoreline are detailed in the modeling discussion in Section 4.1 below.

4.1) Hydroperiod and Total Water Level Modeling

Quantitative analysis of Steps 2, 3, and 6 of the Coastal Commission's sea level rise/coastal hazards analysis protocols, (cf. Section 3), begins with water level recurrence statistics derived from the period of record of historic water levels at the NOAA Golden Gate tide gage, NOAA #9414290. These recurrence statistics determine the likelihood of still water levels (SWL) in the Bay and are based on modeling a stage frequency curve called a "*hydroperiod function*", (cf. Jenkins and Wasyl, 1999; 2005). The hydroperiod function provides a continuous relationship between Bay still water levels measured at 6-minute time intervals and the recurrence probability of highest daily bay still water level.



Table 2: Station Datum for NOAA Tide Gage,(NOAA #9414290) *onto which sea level rise projections from Table 1 are linearly superimposed*

Station: 9414290, Golden Gate Bridge, San Francisco, CA
Status: Accepted (April 17, 2003)
Units: Feet
T.M.: 120
Epoch: 1983-2001
Datum: STND

<u>Datum</u>	<u>Value</u>	<u>Description</u>
MHHW	11.82	Mean Higher-High Water
MHW	11.21	Mean High Water
MTL	9.16	Mean Tide Level
MSL	9.10	Mean Sea Level
DTL	8.90	Mean Diurnal Tide Level
MLW	7.11	Mean Low Water
MLLW	5.98	Mean Lower-Low Water
NAVD88	5.92	North American Vertical Datum of 1988
STND	0.00	Station Datum
GT	5.84	Great Diurnal Range
MN	4.09	Mean Range of Tide
DHQ	0.61	Mean Diurnal High Water Inequality
DLQ	1.13	Mean Diurnal Low Water Inequality
HWI	7.53	Greenwich High Water Interval (in hours)
LWI	0.85	Greenwich Low Water Interval (in hours)
Maximum	14.64	Highest Observed Water Level
Max Date & Time	01/27/1983 09:30	Highest Observed Water Level Date and Time
Minimum	3.10	Lowest Observed Water Level
Min Date & Time	12/17/1933 18:00	Lowest Observed Water Level Date and Time
HAT	13.25	Highest Astronomical Tide
HAT Date & Time	12/31/1990 18:12	HAT Date and Time
LAT	3.89	Lowest Astronomical Tide

EHW = 8.73 ft NAVD
MHHW = 5.90 ft NAVD
MHW = 5.29 ft NAVD
MSL = 3.18 ft NAVD
MTL = 3.24 ft NAVD
ELW = -2.82 ft NAVD

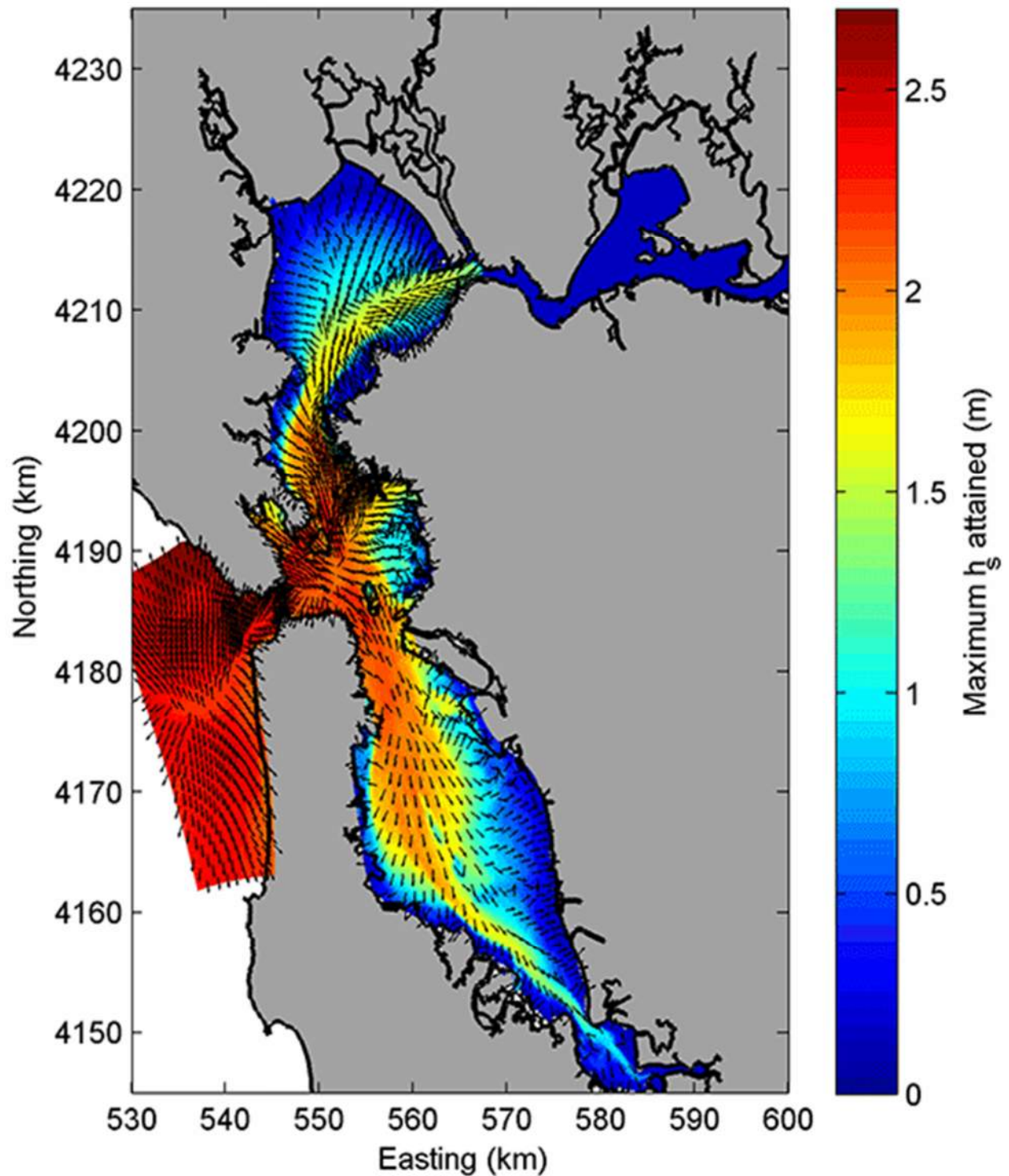


Figure 7: Refraction analysis of ocean storm swells entering San Francisco Bay, and undergoing ultra-refraction into San Francisco Bay, (from O'Neill, et al, 2017)



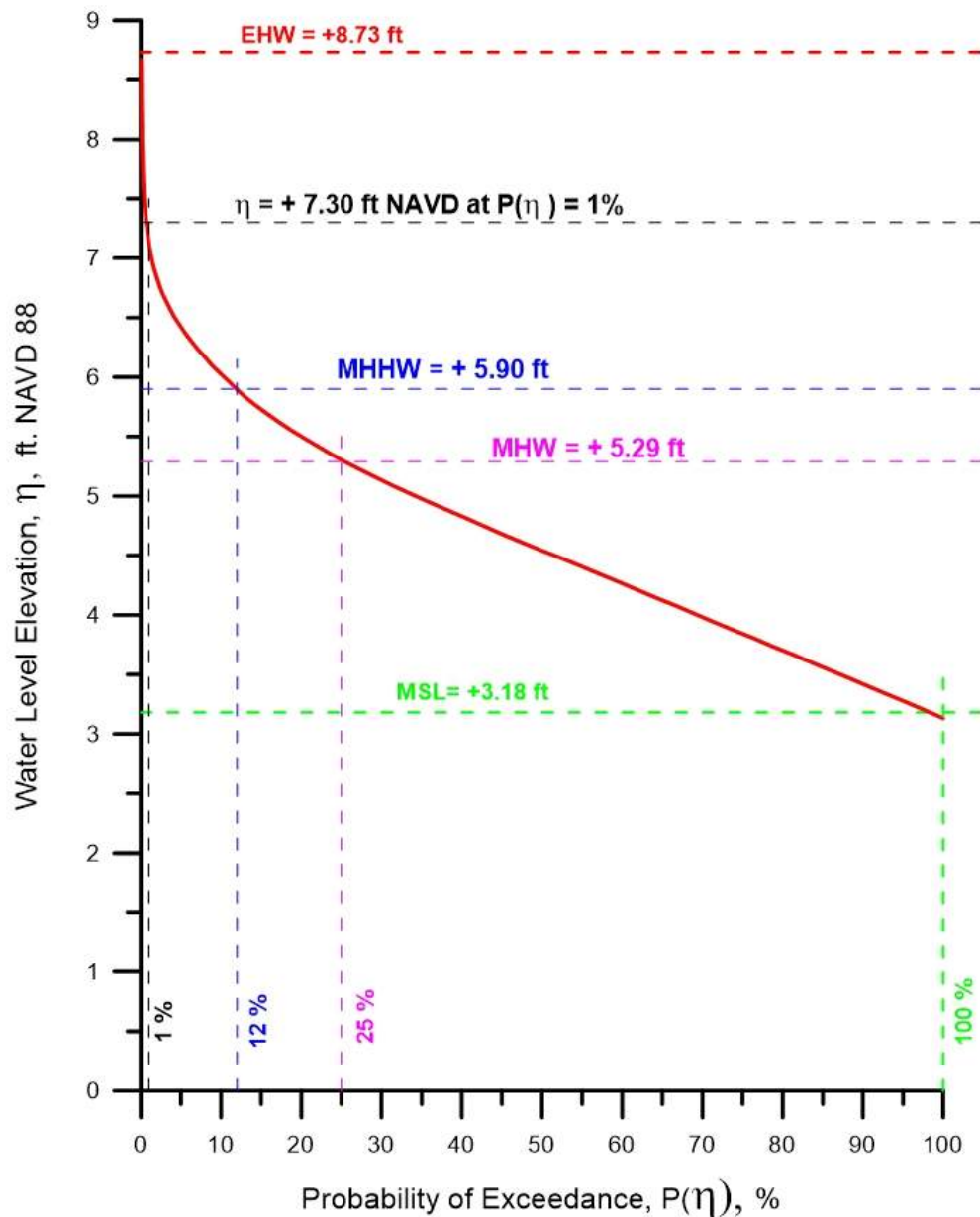
The computations involve a total of $N_0 = 6,939$ of daily maximum still water level measurements, $\bar{\eta}_{\max}$, in the 1983-2001 NOAA period of record from the most recent tide gage leveling procedure. Conditional *if-statements* embedded in counting loops of the CEM software (sub-routine *hydro-pr_caltrans*, Jenkins and Taylor, 2015) calculate the number days in the period of record, $N_i(\bar{\eta}_{\max} \geq Z_j)$ when the daily maximum still water level in the Bay reached or exceeded any given land elevation Z_j . The counting loops are repeated for a total of $M_0 = 100$ land elevations at 0.1 ft. increments between some minimum, $Z_{\min} = 0$ ft. NAVD, and some maximum land elevation of interest, $Z_{\max} = +10$ ft. NAVD. Thus, the exceedance probability of daily maximum still water levels in the Bay are calculated as:

$$P(\bar{\eta}_{\max}) = \frac{1}{M_o N_o} \sum_j^{M_o} \sum_i^{N_o} \left[N_i(\bar{\eta}_{\max} \geq Z_j) \right] \quad (2)$$

The red curve in **Figure 8** plots the exceedance probability of daily maximum still water levels in the Bay at present sea level that were calculated from equation (2) using the 1983-2001 period of record from the NOAA tide gage station #9414290 at the Golden Gate Bridge. No daily highest water level is ever less than mean sea level, which from **Table 2** is MSL = +3.18 ft NAVD. Therefore, mean sea level has an exceedance probability of $P(\bar{\eta}_{\max}) = 1.0$ or 100%. The highest historic water level ever observed in at the Golden Gate tide gage, (referred to as *extreme high water*, EHW) occurred on 27 January 1983, which has an exceedance probability of $P(\bar{\eta}_{\max}) = \frac{1}{N_o} < 0.01\%$. In **Figure 8**, there is a continuous distribution of exceedance probabilities

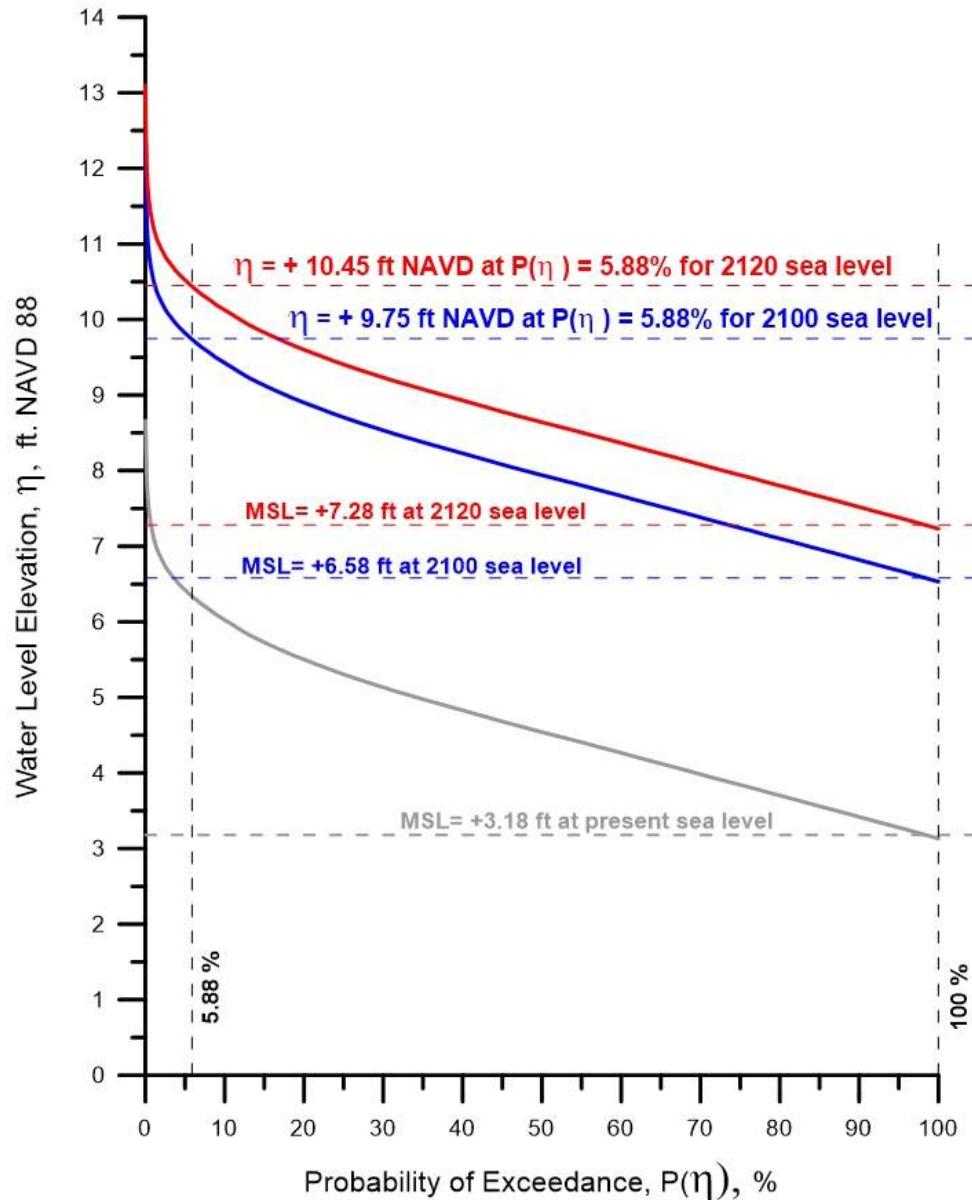
for daily highest still water levels between MSL and EHW that can be superimposed on any arbitrary sea level rise from **Table 2** to calculate a total water level (TWL). For example, mean higher high tides in the Bay (MHHW = + 5.90 NAVD) reach significantly lower still water elevation than extreme high water (EHW = + 8.73 ft. NAVD). Consequently, MHHW has a significantly higher probability of exceedance, $P(\bar{\eta}_{\max}) = 0.12$ or 12%. This indicates that 12% of the time still water levels in the Bay are higher than MHHW due to king tides and sea level anomalies associated with near-term climate cycles such as ENSO and PDO.

At future sea levels, still water elevations in the Bay are generated by the linear superposition of sea level rise projections from **Table 2** onto the hydroperiod function in **Figure 8**. Using the upper limit of the likely range of sea level rise (first column in **Table 2**) exceedance probabilities for still water elevations at 2100 sea levels (80-year planning horizon) and 2120 sea levels (100-year planning horizon), are modeled by the blue and red curves in **Figure 9**. Because projections for the upper limit of the likely range of sea level rise have a 17% probability of exceedance, the relevant still water elevations for computing the joint probability of the 1% flood events are those having a 5.88% exceedance probability.



Hydroperiod Function for NOAA Tide gage # 9414290, San Francisco, at present sea level

Figure 8: Exceedance probability of daily maximum still water levels in San Francisco Bay at present sea level (hydroperiod function). Based on Golden Gate Bridge tide gage, NOAA #9414290. Daily maximum water level corresponding to the 1% exceedance probability is $\bar{\eta}_{\max} = 7.30$ ft. NAVD.



**Hydroperiod Function for NOAA Tide gage # 9414290, San Francisco,
at present sea level and at 2100 and 2120 sea levels**

Figure 9: Exceedance probability distribution of daily maximum still water levels in San Francisco Bay at present sea level and future sea levels (hydroperiod function). Based on Golden Gate Bridge tide gage, NOAA #9414290, and sea level rise projections from CCC, (2018) Daily maximum water level corresponding to the 5.88% exceedance probability is $\bar{\eta}_{\max} = 9.75$ ft. NAVD at 2100 sea level, and $\bar{\eta}_{\max} = 10.45$ ft. NAVD at 2120 sea level.



As indicated in **Figure 9**, still water elevations to be used in the 1% flood event determination are $\bar{\eta}_{\max} = 9.75$ ft. NAVD at 2100 sea level, and $\bar{\eta}_{\max} = 10.45$ ft. NAVD at 2120 sea level. It is also notable that mean sea level in the Bay (the lowest possible daily maximum still water elevations) will rise to MSL = 6.58 ft. NAVD at 2100 sea level, and MSL = 7.28 ft. NAVD at 2120 sea level. The still water elevations in the Bay at present and future sea levels do not represent the total water levels that can potentially cause flooding or inundation of the Tamalpais Union High School District. Because of ultra-refracted ocean waves that leak into the Bay, combined with wind waves generated in the Bay during storms, the total water levels along the shorelines at the mouth of the Corte Madera Creek and Pickleweed Inlet are increased above Bay still water levels by the set-up and total wave run-up of breaking waves. Total water level (TWL) is the sum of still water levels (SWL) from **Figures 8 - 9**, set-up and total wave runup, or:

$$TWL = \langle \eta_s \rangle + \hat{\eta}_T + SWL \quad (3)$$

where $\langle \eta_s \rangle$ is the wave set-up due to water piled against the shore by the radiation stress of the shoreward propagating waves; and $\hat{\eta}_T$ is the total wave run-up due to wave breaking along the shore. Both of these wave-driven increases in water levels along the shoreline are dependent on the wave height of H'_0 , wave period of T_P , wave length of $L_0 = gT_P^2 / 2\pi$, and the average slope is m_{DIM} . Because the bottom slopes are relict features of the flood plain of the Corte Madera Creek or the marsh planes of the Pickleweed Inlet, the bottom slopes are very flat, $m_{DIM} \leq 3\%$. This allows the wave set-up and total wave run-up to be modeled using the direct integration method, (cf. USACE, 2011). By this method, the CEM calculates the wave setup according to:

$$\langle \eta_s \rangle = 4.0 \left(\frac{H'_0}{26.2} \right)^{0.8} \left(\frac{T_P}{20.0} \right)^{0.4} \left(\frac{m_{DIM}}{0.01} \right)^{0.2} \quad (4)$$

Similarly, the total wave runup is calculated as:

$$\hat{\eta}_T = 2.0 \sqrt{\eta_{rms}^2 + \sigma^2} \quad (5)$$

$$\text{where: } \eta_{rms} = 6.169 \left(\frac{H'_0}{26.2} \right)^{0.8} \left(\frac{T_P}{20.0} \right)^{0.4} \left(\frac{m_{DIM}}{0.01} \right)^{0.2} \quad (6)$$

$$\sigma_2 = 0.3 \xi_0 H'_0; \quad (7)$$

$$\xi_0 = \frac{m_{DIM}}{\sqrt{H'_0 / L_0}} \quad (8)$$



Historical wave data wave for the San Francisco Bay was compiled by O'Neill, et al. (2014) for the period 1975 – 2004, and subsequently projected for the period 2010-2100. Taking those historical and projected wave data for the central bay region (which incorporated the mouth of the Corte Madera Creek and Pickleweed Inlet), a wave height exceedance probability curve was constructed as shown **Figure 10**. The modeled significant heights of waves incident on the shorelines around the mouth of the Corte Madera Creek and Pickleweed Inlets are $H'_0 = 5.5$ ft. for a 1% probability of exceedance. These wave height values are used in equations (3) – (8) to determine total water levels when calculating the 1% event flood at present sea level using equation (1). When determining the 1 % flood event at future sea levels, a significant wave height of $H'_0 = 3.7$ ft. with a 5.88% probability of exceedance is used in the total water level calculations, since sea level rise projections have a 17% probability of exceedance. **Figure 10** also indicates that daily mean significant wave heights, with a probability of exceedance of 100% are $H'_0 = 0.96$ ft. along the shorelines around the mouth of the Corte Madera Creek and Pickleweed Inlets.

To complete the suite of variables needed to calculate total water levels from equations (3) – (8), wave periods (T_p) in the Central Bay are taken from **Table 2** in O'Neill, et al, (2017) while wave direction is derived from wave rose plots in **Figure 6** of O'Neill, et al, (2017). Nearshore bottom slopes in the shoaling wave regime, m_{DIM} , were obtained from the digital bathymetry data base obtained at the National Geophysical Data Center (NGDC) web site: (http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html) . With these input parameters, the exceedance probability distributions of total water levels at present sea level and 2100 and 2120 sea levels are calculated in **Figures 11-13**. At present sea level, the exceedance probability for sea level rise becomes $P(\Delta\eta_{SLR}) = 1$; and the 1% flood event (100-year event) are uniquely determined by the total water levels for the probability for exceedance is $P(\eta_{TWL}) = 0.01$, (1%). Thus, **Figure 11** teaches that flooding/inundation contours at present sea level along the shorelines of the Corte Madera Creek and Pickleweed Inlets occur at elevation $\eta_{TWL} = +9.12$ ft. NAVD. Furthermore, total water levels along these project shorelines are never less than $\eta_{TWL} = 3.33$ ft. NAVD, which is 0.15 ft. higher than present mean sea level at the Golden Gate Bridge tide gage, (cf. **Figure 8**). This slight increase is due to set-up and total runup resulting from shoaling and breaking of daily mean significant wave heights of $H'_0 = 0.96$ ft, (cf. **Figure 10**). At future sea levels, still water levels at mean sea levels rise to SWL = MSL = 6.58 ft. NAVD by year 2100, increasing to MSL = 7.28 ft. NAVD, based on the upper limit of the likely range of sea level rise projections according to **Table 2**. Since the probability of exceedance of these projections is $P(\Delta\eta_{SLR}) = 0.17$, (17%), the joint probability calculation of the 1% flood event (100-year event) peer equation (1) is determined by the elevations of total water levels having an exceedance probability of $P(\eta_{TWL}) = 0.0588$, (5.88%). Based on the 5.88% probability of total water level exceedance, **Figure 12** indicates that flooding/inundation contours at 2100 sea level along the shorelines of the Corte Madera Creek and Pickleweed Inlets occur at the elevation $\eta_{TWL} = +11.44$ ft. NAVD. Total water levels along the shorelines adjacent the project high schools at year 2100 are never less than η_{TWL}



= 6.73 ft. NAVD, or slightly higher than the projected 2100 mean sea level at the Golden Gate tide gage station, (cf. blue line in **Figure 9**). Flooding/inundation contours around the project high schools by year 2120 (100-year planning horizon) rise even further to $\eta_{TWL} = +12.14$ ft. NAVD, per the 5.88% exceedance elevation indicated in **Figure 13**. Total water levels along the project shorelines at year 2120 are never less than $\eta_{TWL} = 7.38$ ft. NAVD, again slightly higher than projected mean sea level at the Golden Gate tide gage station, (cf. blue line in **Figure 9**), due to additional water level increases associated with set-up and total runup of breaking waves along the shorelines of the Corte Madera Creek and Pickleweed Inlets adjacent to the project high schools.

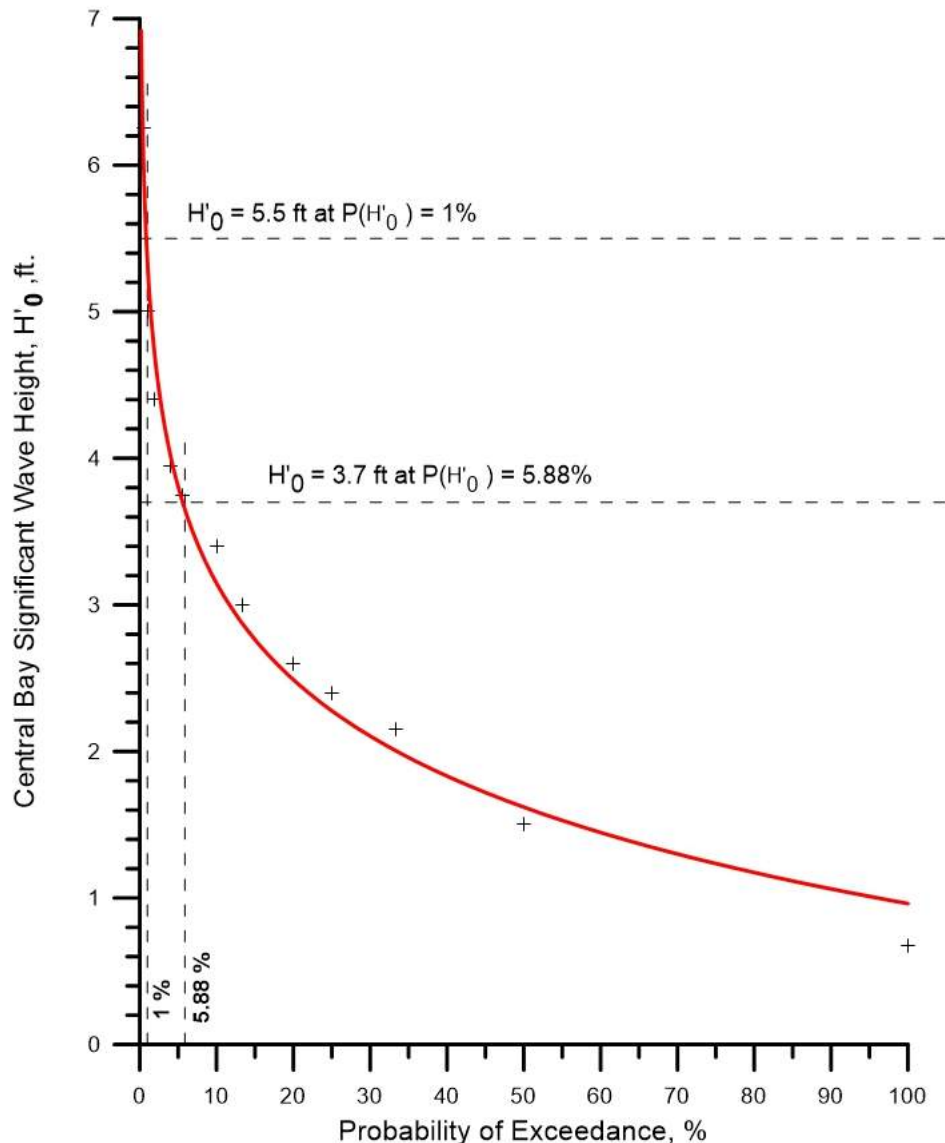


Figure 10: Probability of exceedance of significant wave heights in the Central Bay of the San Francisco Bay Estuary. Data from O’Neil, et al. (2017). Exceedance analysis based on Weibull Type III distribution with $K = 1.0$.

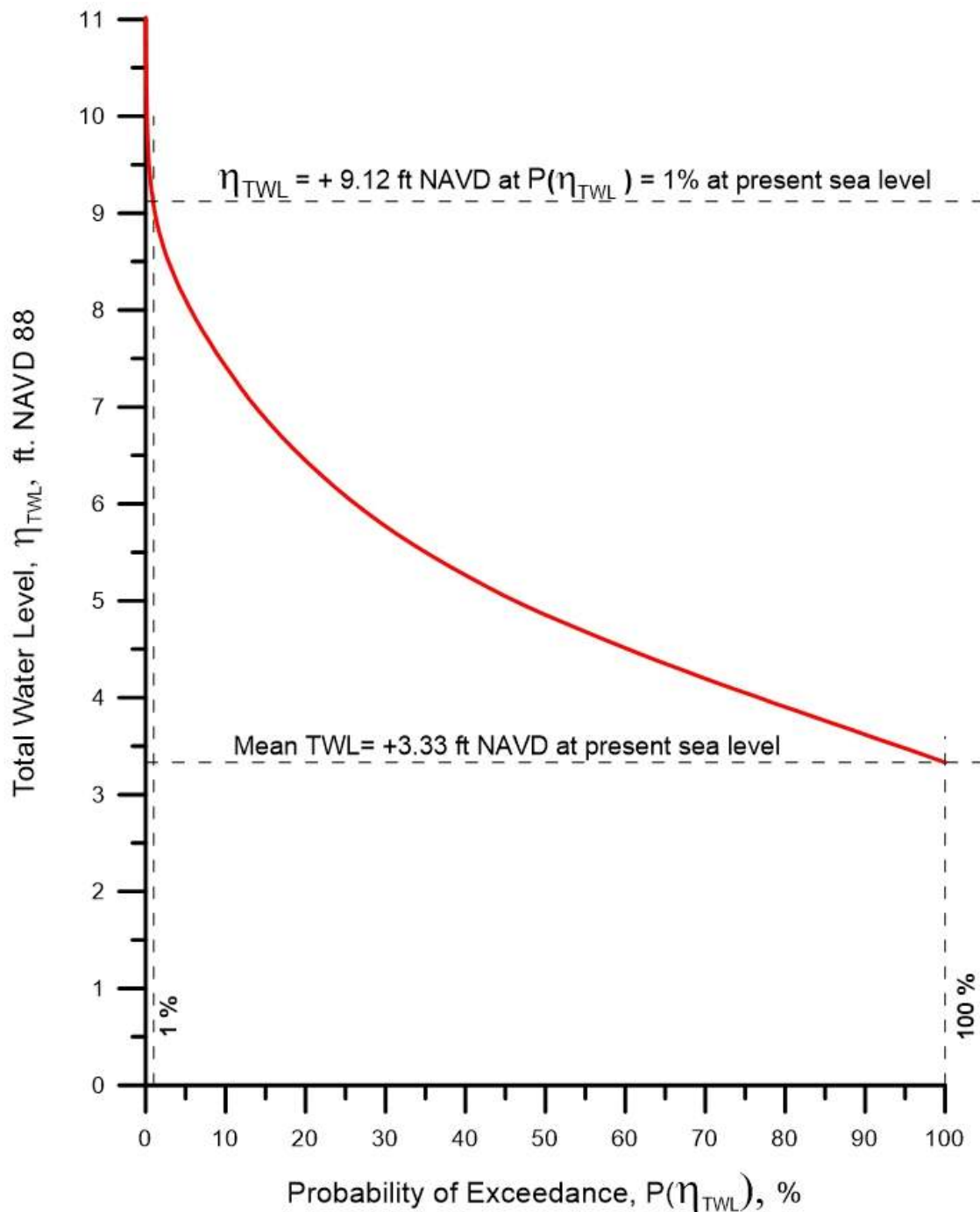


Figure 11: Exceedance probability distribution of total water levels at present sea level around the mouth of the Corte Madera Creek and Pickleweed Inlets. Total water level corresponding to the 1% exceedance probability is $\eta_{TWL} = 9.12$ ft. NAVD.

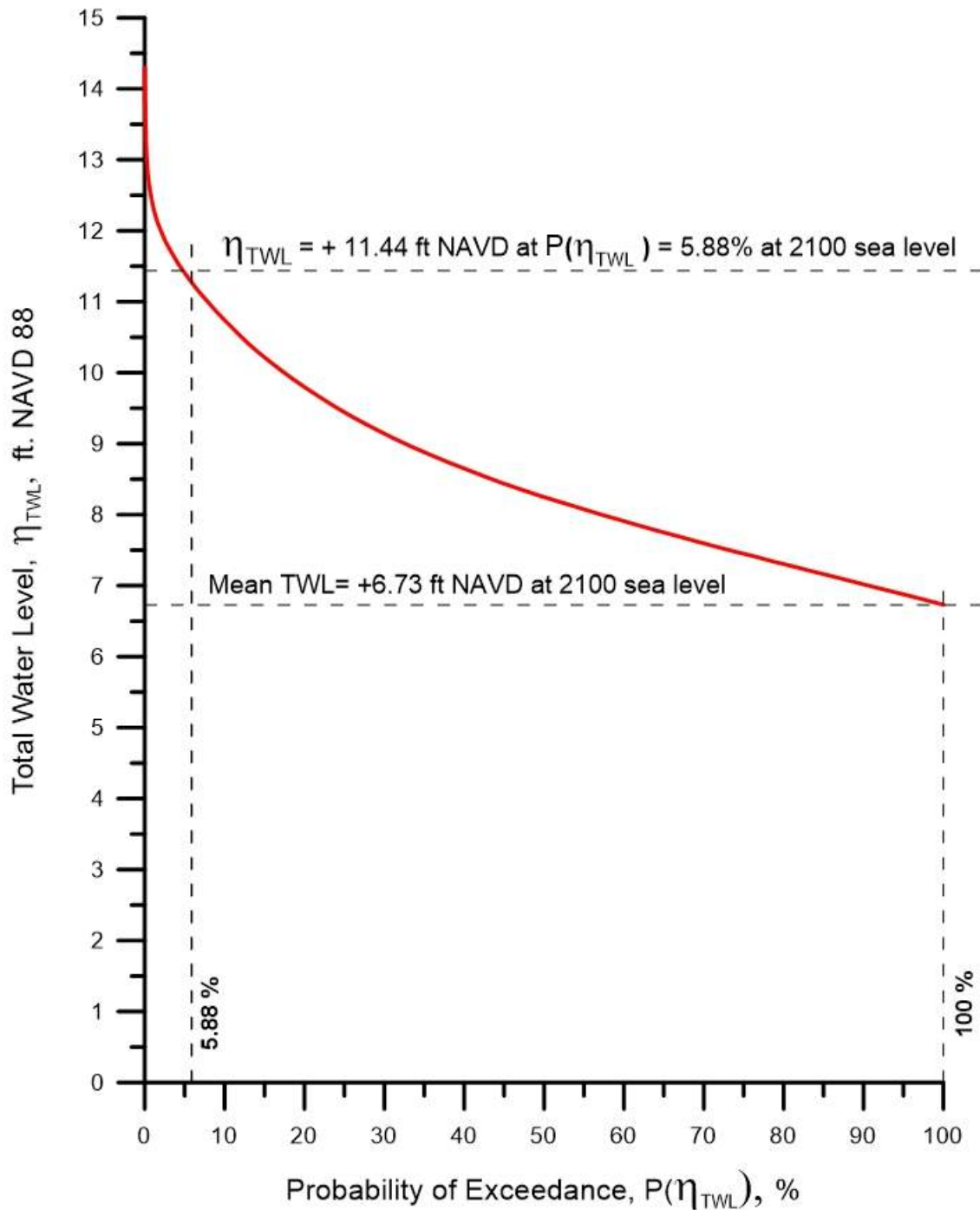


Figure 12: Exceedance probability distribution of total water levels at 2100 sea level around the mouth of the Corte Madera Creek and Pickleweed Inlets. Total water level corresponding to the 5.88% exceedance probability is $\eta_{TWL} = 11.44$ ft. NAVD.

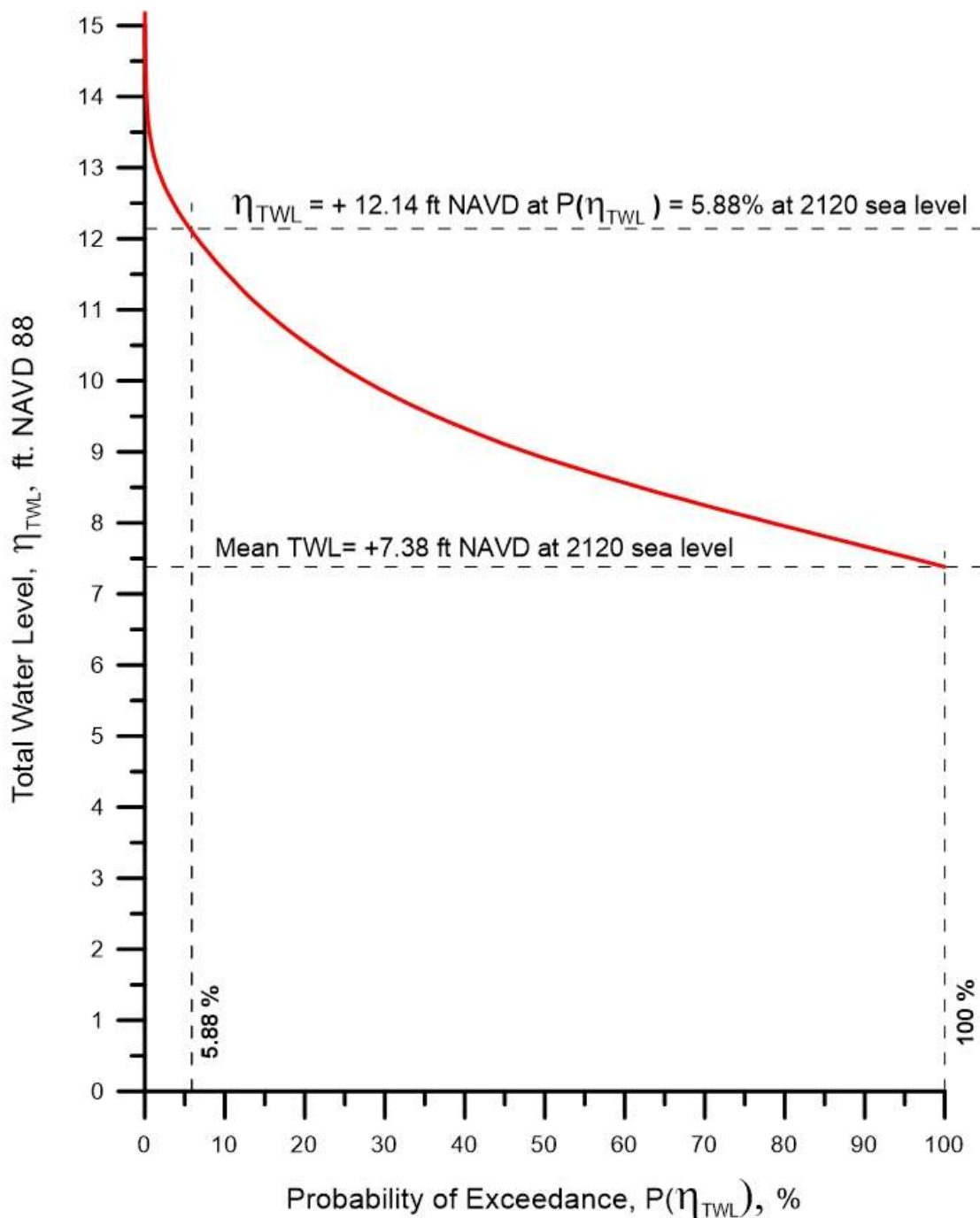


Figure 13: Exceedance probability distribution of total water levels at 2120 sea level around the mouth of the Corte Madera Creek and Pickleweed Inlets. Total water level corresponding to the 5.88% exceedance probability is $\eta_{TWL} = 12.14$ ft. NAVD.



5) SUMMARY OF INUNDATION RESULTS AND RECOMMENDATIONS

The *CCC Sea Level Rise Policy Guidance* documents (CCC, 2013, 2015, 2018 & 2020) provide no specific guidance on the redline frequency for coastal flooding or inundation at either present or future sea level. In the absence of such guidance, this study adopts FEMA standards for flooding frequency and set redline planning frequency at the 100-year flood event (1% joint probability of exceedance). In the present application, the 1% flood event arises from the superposition of future sea levels on top of a combination of storm induced wave set-up and run-up in the Bay and extreme still water levels arising from king tides, ENSO and PDO sea level anomalies. The modeling results determined that the 1% flood event (return period of 100 years) results in flooding or inundation at present sea level up to + 9.12 ft. NAVD88 (NAVD). Sea level rise (SLR) projections were made for the planning horizons at years 2070 (50-yr), 2100 (80-yr), and 2120 (100-yr). Total water levels for the 1% flood event at the 50-year planning horizon (2070) are little changed from those at present sea levels, reaching +9.44 ft. NAVD 88. At the 80-year planning horizon (2100), the 1% flood event reaches + 11.44 ft. NAVD, while at the 100-year planning horizon (2120), total water levels during the 1% flood event rise to 12.14 ft. NAVD.

Inundation/flood contours around the Tamalpais Union High School District schools are presented in **Figures 14-18**. These contours were developed from the USGS digital elevation data base developed from most recent Lidar surveys of the San Francisco Bay Estuary and downloaded from the website: <https://apps.nationalmap.gov/downloader/#1/>. Only the Archie Williams High School (formerly Sir Francis Drake HS), at the headwaters of the San Anselmo Creek at elevation 77 ft. NAVD, lies outside all of the 1% flood event inundation contours (cf. **Figure 14**); and therefore, remains immune to flooding or inundation at both present and future sea levels.

The cluster of the three (3) high schools (Redwood, San Andreas, and Tamiscal), located in or adjacent to the floodplain of the Corte Madera Creek, are particularly at risk, even for the 1% flood event at present sea level, (cf. **Figures 15 - 17**). Not only will the buildings and parking lots of these schools become flooded or inundated; but so will the road network over large areas surrounding these schools.

Similarly, Tamalpais High School, which is located adjacent to the tidal channels and marsh plains of Pickleweed Inlet, will also be flooded or inundated by the 1% flood event at both present and future sea levels, (cf. **Figure 18**), but only a short section of roadways to the west of the high school will be subjected to additional flooding or inundation.

A notable feature of **Figures 14-18** is that there is little distinction between the flooding and inundation contours at present sea level vs. those at 2100 or 2120 sea levels. This arises because the four (4) at-risk high schools are located on very flat floodplains or ancient marsh plains that are surrounded by higher ground. Consequently, the rise in sea level does not significantly change the flooded or inundated area, but rather merely increases the depth of flood waters or the depth of submergence in and around these high schools. At present sea level, flood depths around Redwood, San Andreas, and Tamiscal High Schools during a 100-year event would on the order of 2 ft., and about 0.5 ft. at Tamalpais High School. At 2120 sea levels (100-year planning horizon), submergence depths due to inundation of Redwood, San Andreas, and Tamiscal High Schools



could be approximately 5 ft., and approximately 3.5 ft. on some portions of the Tamalpais High School campus.

Not many practical solutions exist, that could remediate the potential for the inundation, even at present sea levels, of Redwood, San Andreas, Tamiscal, and Tamalpais High Schools. One option might be to relocate the student bodies of those 4 high schools to Archie Williams High School and significantly expand the facilities at that location on high ground at elevation +77 ft. NAVD, (cf. **Figure 14**). Surrounding Redwood, San Andreas, and Tamiscal High Schools with a local earthen berm would reduce those campuses to isolated islands during times of flooding because so much of the surrounding road network would remain flooded or inundated, (cf. **Figures 15-17**); and students would not be able to access or egress those campuses. Consequently, periods of extreme event floods would become times for *ZOOM classrooms* as was common throughout the COVID-19 pandemic. Local berm systems around Tamalpais High School would be less restrictive of access and egress due to proximity of the campus to nearby road networks located on higher ground above the flooding/inundation contours in **Figure 18**.

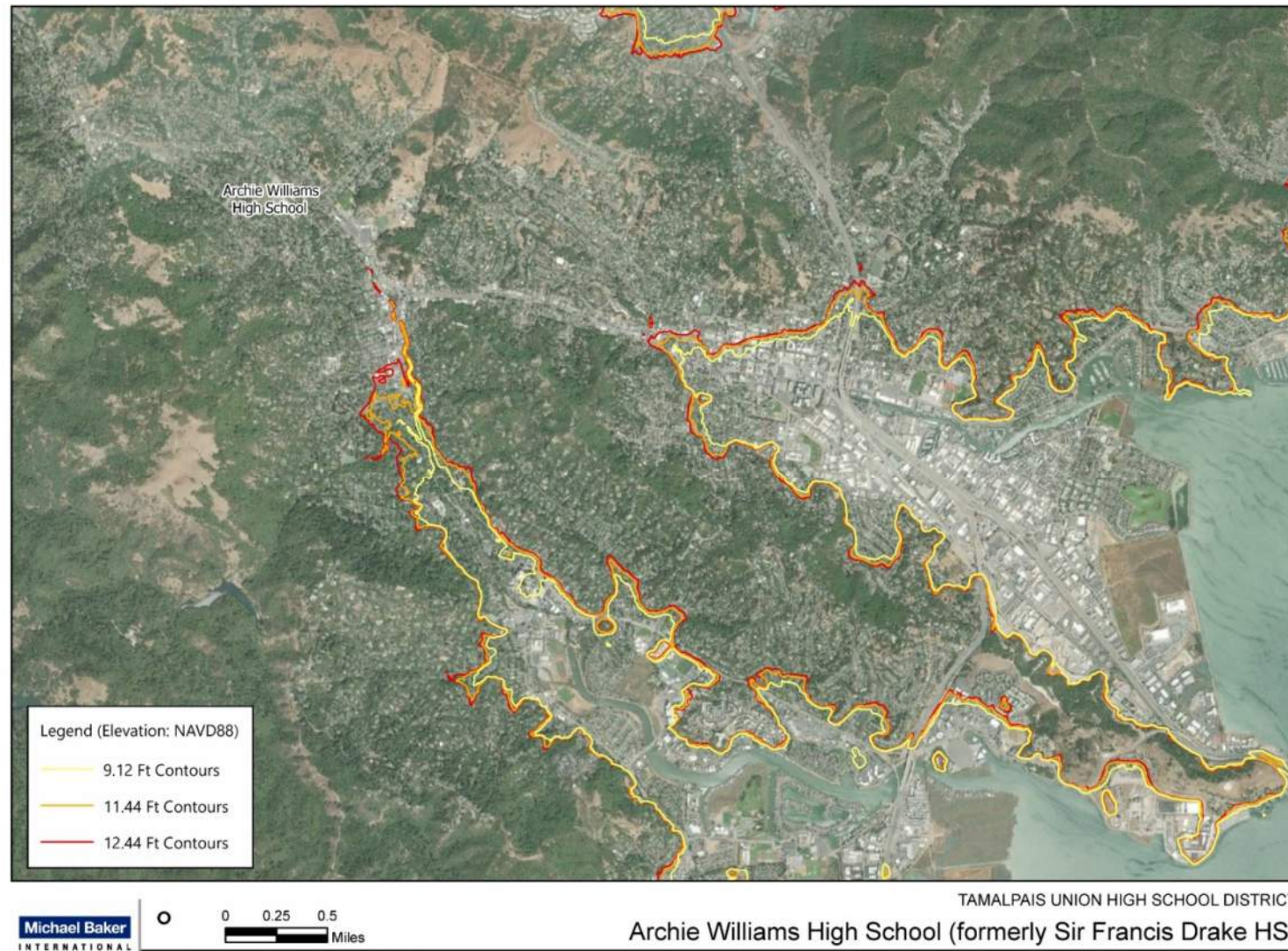


Figure 14: Inundation contours near the Archie Williams (formerly Sir Francis Drake) High School for the 1% flood event (return period of 100 years) at present sea level (yellow contour), at the year 2100 planning horizon (orange contour) and at the year 2120 planning horizon (red contour). Elevation of existing grade at Archie Williams High School averages about +77 ft. NAVD.

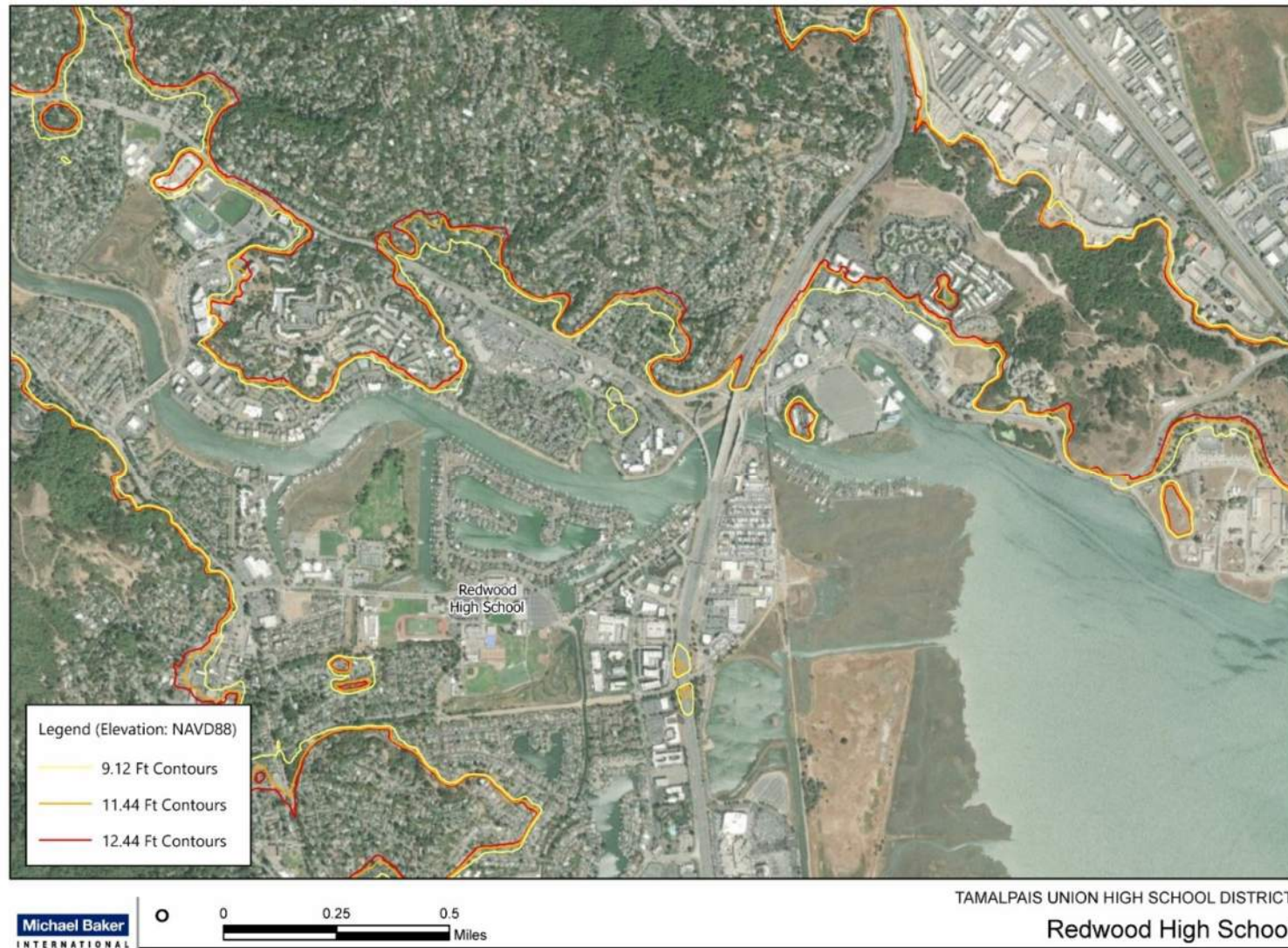


Figure 15: Inundation contours near the Redwood High School for the 1% flood event (return period of 100 years) at present sea level (yellow contour), at the year 2100 planning horizon (orange contour) and at the year 2120 planning horizon (red contour). Elevation of existing grade at Redwood High School averages approximately +7 ft. NAVD.

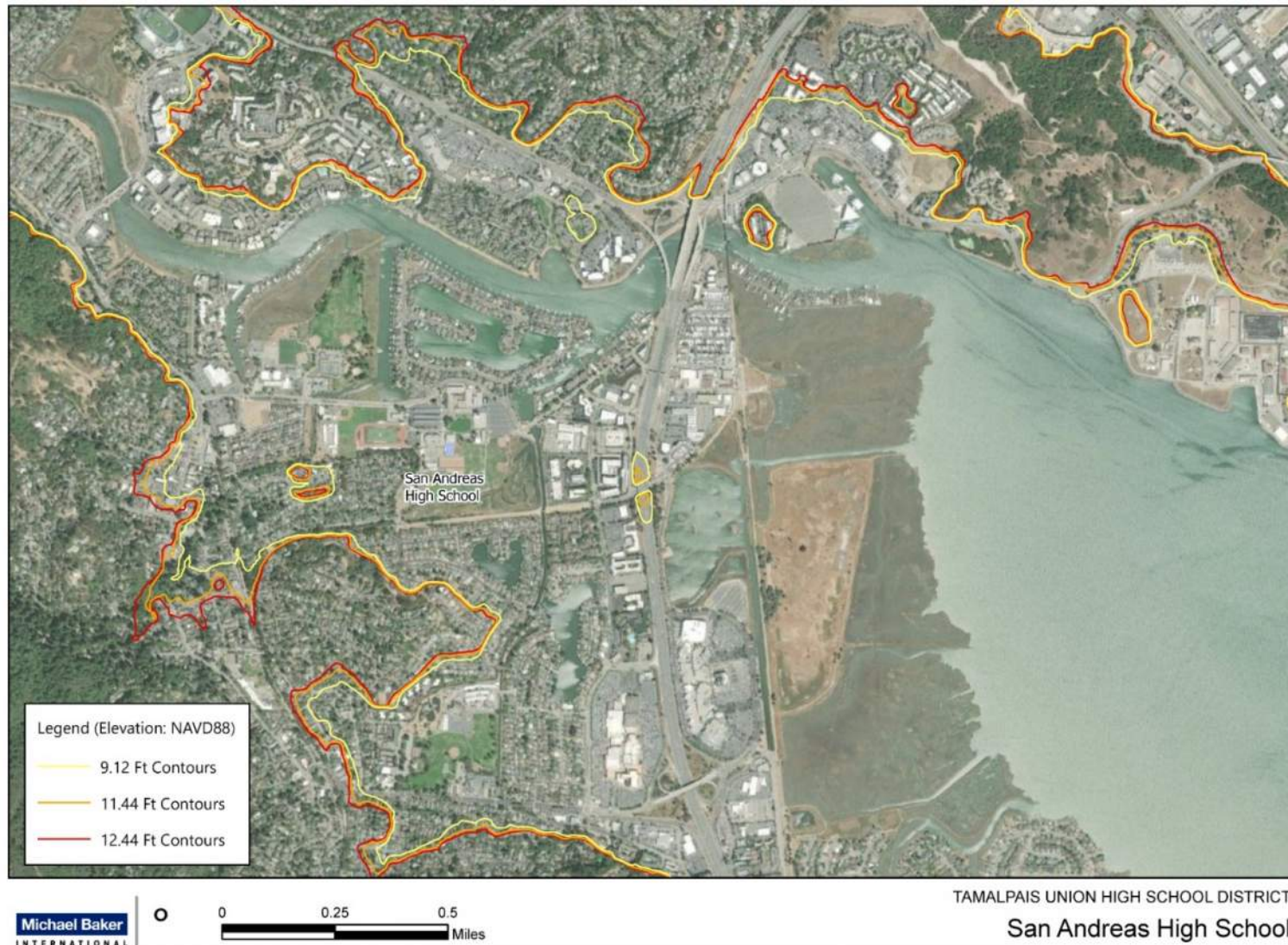


Figure 16: Inundation contours near the San Andreas High School for the 1% flood event (return period of 100 years) at present sea level (yellow contour), at the year 2100 planning horizon (orange contour) and at the year 2120 planning horizon (red contour). Elevation of existing grade at San Andreas High School averages approximately +7 ft. NAVD.

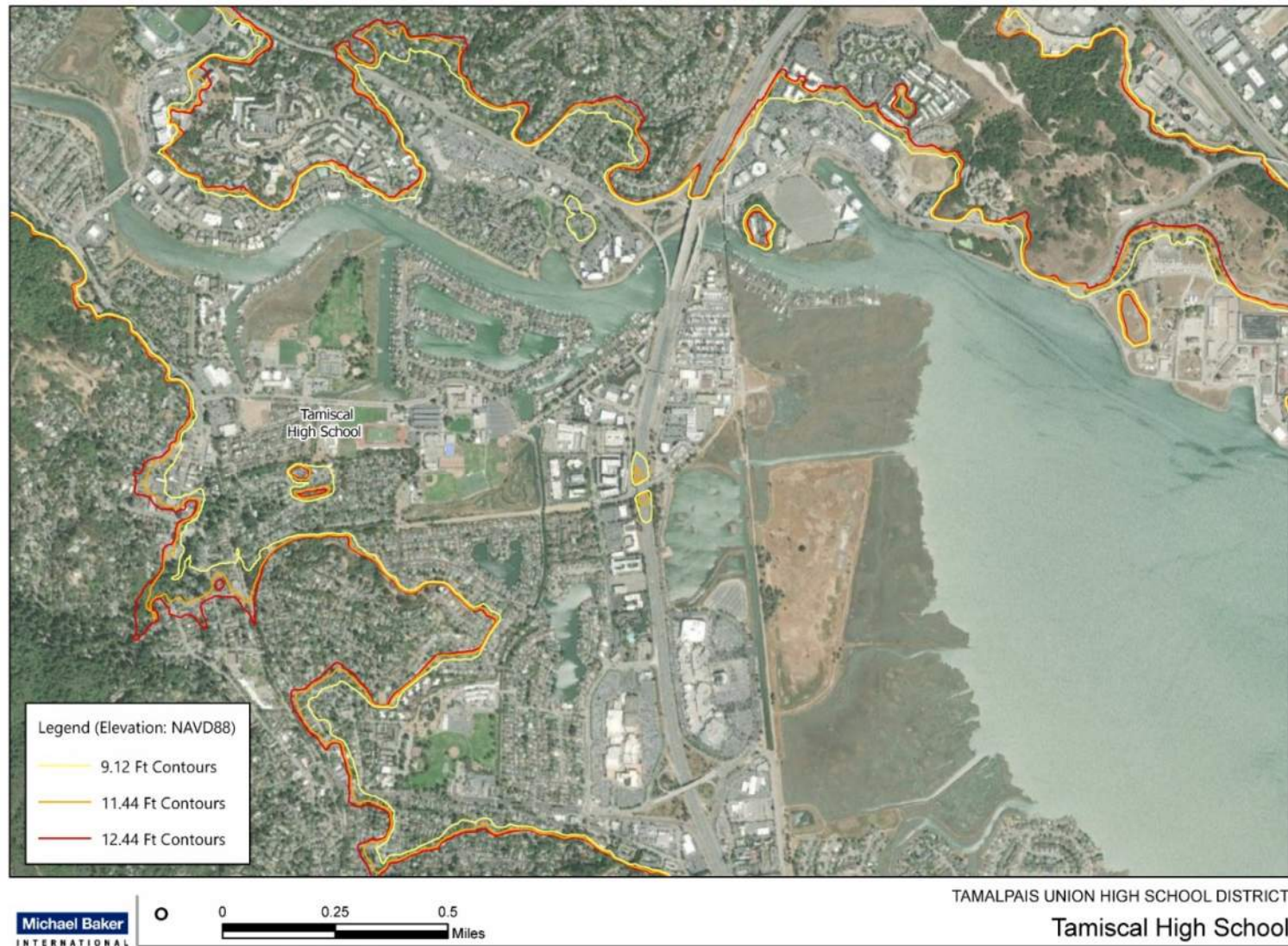


Figure 17: Inundation contours near the Tamiscal High School for the 1% flood event (return period of 100 years) at present sea level (yellow contour), at the year 2100 planning horizon (orange contour) and at the year 2120 planning horizon (red contour). Elevation of existing grade at Tamiscal High School averages approximately +7 ft. NAVD.

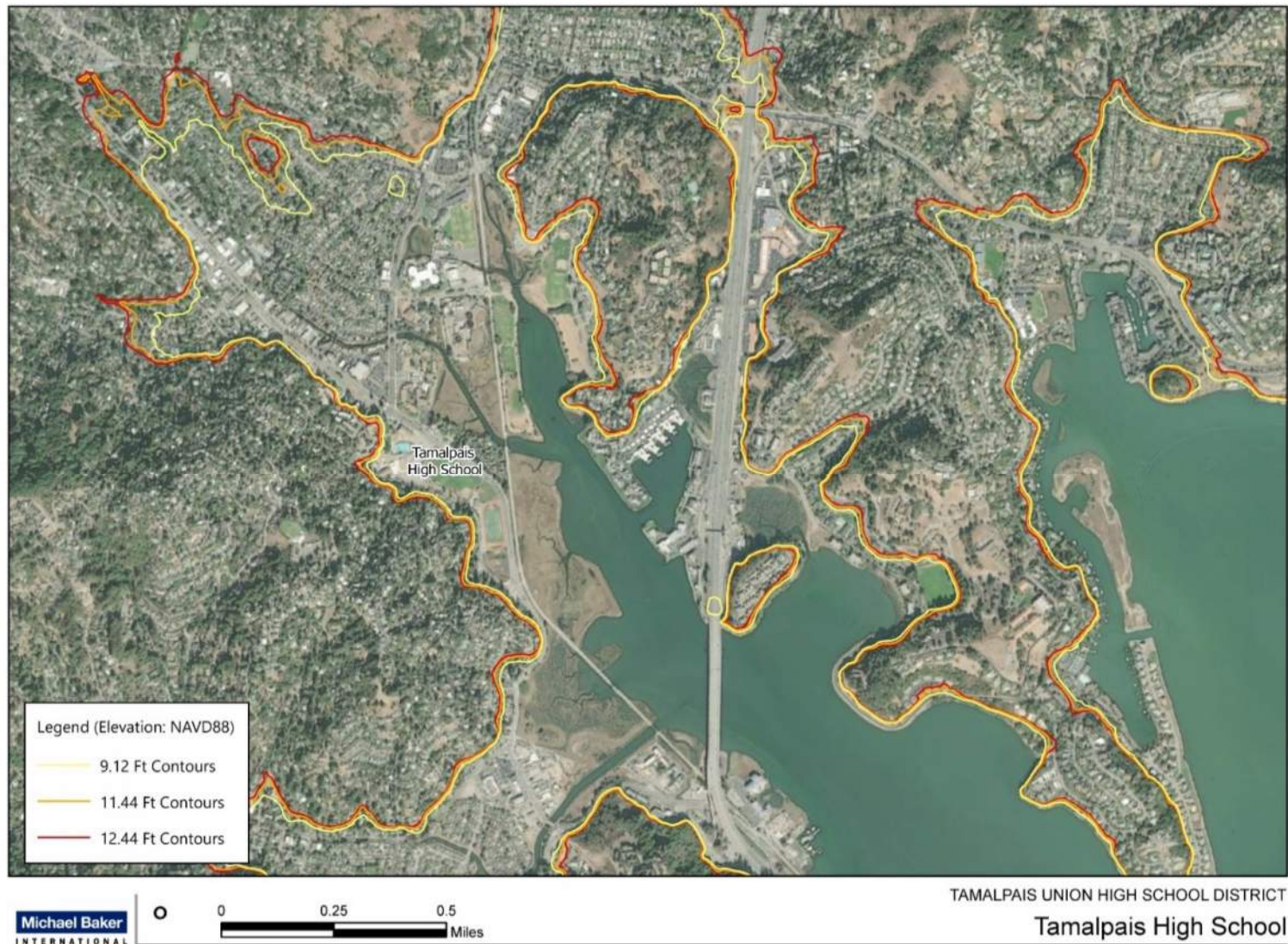


Figure 18: Inundation contours near the Tamalpais High School for the 1% flood event (return period of 100 years) at present sea level (yellow contour), at the year 2100 planning horizon (orange contour) and at the year 2120 planning horizon (red contour). Elevation of existing grade at Tamalpais High School is averages approximately +8.6 ft. NAVD.



An alternative solution for extending the operational life span of Redwood, San Andreas, and Tamiscal High Schools would be a Netherlands type of regional berm system that would protect these schools as well as the surrounding community. A schematic of this berm system is shown in **Figure 19**. The elevated roadbed of HWY 101 provides the seaward wall of this berm system, while the berms drawn in red prevent inundation of Redwood, San Andreas, and Tamiscal High Schools from storm surge, king tides, and rising sea level that would flow from the Bay up the flood corridor of Corte Madera Creek. The berm system would be built as a vegetated earthwork capping a buried shore protection structure; and must be built 4.5 miles up the Corte Madera Creek, beginning at the east side of the HWY 101 roadbed in order to reach closure with higher ground above the flood/inundation contours shown in **Figure 14**. This is a regional solution and therefore would require the inclusion of many stakeholders to implement and not considered feasible at this time.

The berm system illustrated in **Figure 19** is an example of what is termed a “*structural hybrid solution*” to sea level rise. Structural hybrid strategies were inspired by a Federal Highway Administration white paper, “White Paper: Nature Based Solutions for Coastal Highway Resilience” (FHWA, 2018). There is only one prototype of the structural hybrid solution in California; and that is the Cardiff Living Shoreline. This is a suitable prototype for either local or regional berm solutions for the Tamalpais Union High School District. The Cardiff Living Shoreline incorporates a buried revetment enclosed within a vegetated sand berm (aka, dune). A cross section of the berm and buried revetment is shown in **Figure 20**. The berm is 60 ft. in width and its crest elevation is 4 ft. above existing grade. The constructed and maintained berm feature acts to prevent extreme events overtopping onto HWY 101 (Coast Highway). The berm cross section is a broad-crested polygon with a compound double foreslope extending from existing grade of the back beach to the peak design crest elevation as shown in **Figure 20**.

Slopes on the polygon berm cross section range from 3:1 on the seaward-most foreslope, flattening to 5:1 on the final foreslope rise to the berm crest. The seaward 15 ft. of the berm are considered a *sacrificial erosion zone* that was fortified with a cobble berm buried beneath the foreslope along the seaward edge of the berm, built from native beach cobble and gravels excavated onsite. The buried cobble berm has a width of 20 feet, a height of 3 feet with a 3:1 foreslope and a 2:1 backslope and is buried by at least 6 inches of sand along the seaward edge of the berm profile. The landward 45 ft. of the polygon berm profile was intended to be slightly modified with berm hummocks for planting and recruitment of native berm vegetation. The berm of the Cardiff Living Shoreline required approximately 11 cubic yards per linear ft. of sand to construct, although the proposed regional berm system in **Figure 19** would utilize dredged mud from annual maintenance dredging in the San Francisco Bay Estuary (in particular dredged muds from Mare Island Straights on the lower Napa River). Plantings on the landward 45 ft. of the polygon berm profile create 0.01 acres per linear ft. of berm habitat using native berm plant cover. Planting is accomplished by a combination of seeding using broadcasting techniques combined with manual containerized plantings of the engineered hummocks using locally sourced palettes of native plants. The buried rock revetment was constructed of 5.2 tons per linear ft. of 2-4 ton riprap stone. The revetment is approximately 25 feet in width, and is 14 feet in height, sloping seaward at 1.5:1 grade. Because



the eastern 45 feet of the berms is vegetated, the rock revetment is buried by at least 18 inches of sand to allow for vegetation establishment on the overlying berms. The revetment was built prior to construction of the berm, beginning by digging a 35 ft. wide trench along the back beach to elevation + 4.0 ft. NAVD, removing existing roadside riprap and back-beach cobble. The shoreward slope of the trench was graded to a slope of 1.5 :1. The rip rap/cobble/sand mix that was excavated from the trench was piled shore parallel, beginning approximately 60 ft to 80 ft from the roadbed of Coast Highway 101. Geotextile fabric was laid in the formed trench. Approximately 5.2 tons of imported rock was then added and keyed in the trench, to form design revetment template on top of geotextile fabric, as shown in **Figure 20**. The Cardiff Living Shoreline was built for a cost of \$1,300 per linear ft of berm and buried revetment.



Figure 19: Schematic of regional berm concept to protect Redwood, San Andreas, and Tamiscal High Schools from inundation by the 1% flood event at present and 2120 sea levels. This concept is based on the Cardiff Living Shoreline hybrid solution concept for sea level rise adaptation and is a far-term solution with many regional stakeholders required.

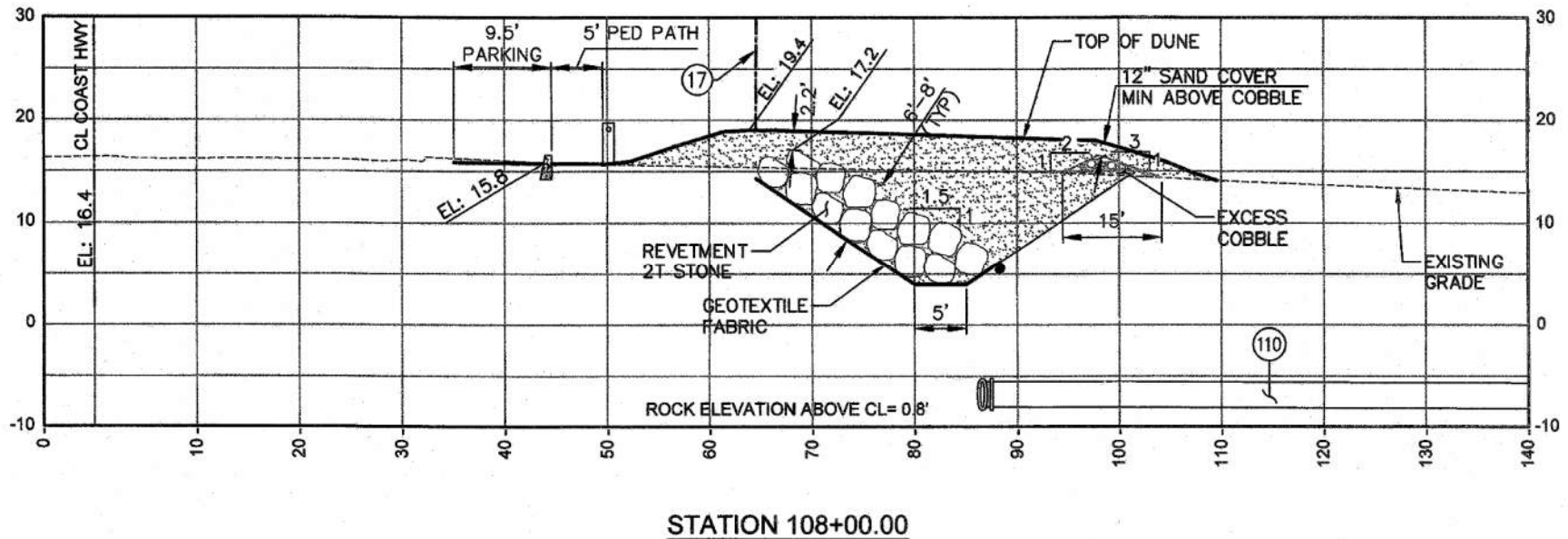


Figure 20: Cross section of the berm and buried revetment at Station 108 in the northern reach of the Cardiff Living Shoreline project. From Moffatt and Nichol, (2018). Crown elevation of Coast Highway 101 shown on the left-hand side of the plot



After a discussion with the Tamalpais Union High School District CFO, it was determined that the fundable solution for protection against flooding and inundation by the 1% flood event at present and future sea levels is the local berm concept. The central objective would be protection of capital assets, primarily buildings, while sacrificing playing fields and portions of parking lots in order to minimize remedial costs. A hybrid solution would be utilized based on a local earthen berm layout fortified with a buried seawall constructed of inter-locking pre-cast concrete panels. Earth works for the berm utilize cohesive fine-grained sediments obtained from maintenance dredge projects within San Francisco Bay Estuary. Exterior surfaces of the berm exposed to flood waters would be vegetated with local high-marsh and transitional species. Interior surfaces of the berms facing the school facilities would be vegetated with high-marsh and transitional species on its upper areas near the crest, and with local grass species on the lower interior surfaces where students could sit and relax before and after classes.

Figure 21 provides a typical berm cross section for implementation at Redwood, San Andreas, and Tamiscal High Schools. Here, where submergence depths could reach as much as 5 ft. at 2120 sea level, the berm is designed to an elevation of 7 ft. above existing grade in order to provide 2 ft. of free-board above flood waters. On all three campuses, clearances and available property is limited, so that the berm width is minimized as much as possible while maintaining slope stability, resulting on a berm width of 16 ft.

At Tamalpais High School, where existing grade is higher and submergence depths reach about 5 ft. at 2120 sea level, berm height is reduced to 6 ft. above existing grade while berm width is reduced to 14 ft, (cf. **Figure 22**). For all local berm layouts at these schools, (cf. **Figures 23-25**), access to the school campuses, both pre- and post- extreme event, would be accomplished using flood gates through the berm that are anchored to the pre-cast concrete seawall panels, (cf. **Figures 21 & 22**). Locations of these flood gates are illustrated schematically in the berm layouts at each high school in **Figures 23-25**. In locations where a berm is not feasible due to site restrictions (i.e. right of way, property lines, etc.), a concrete seawall is proposed.

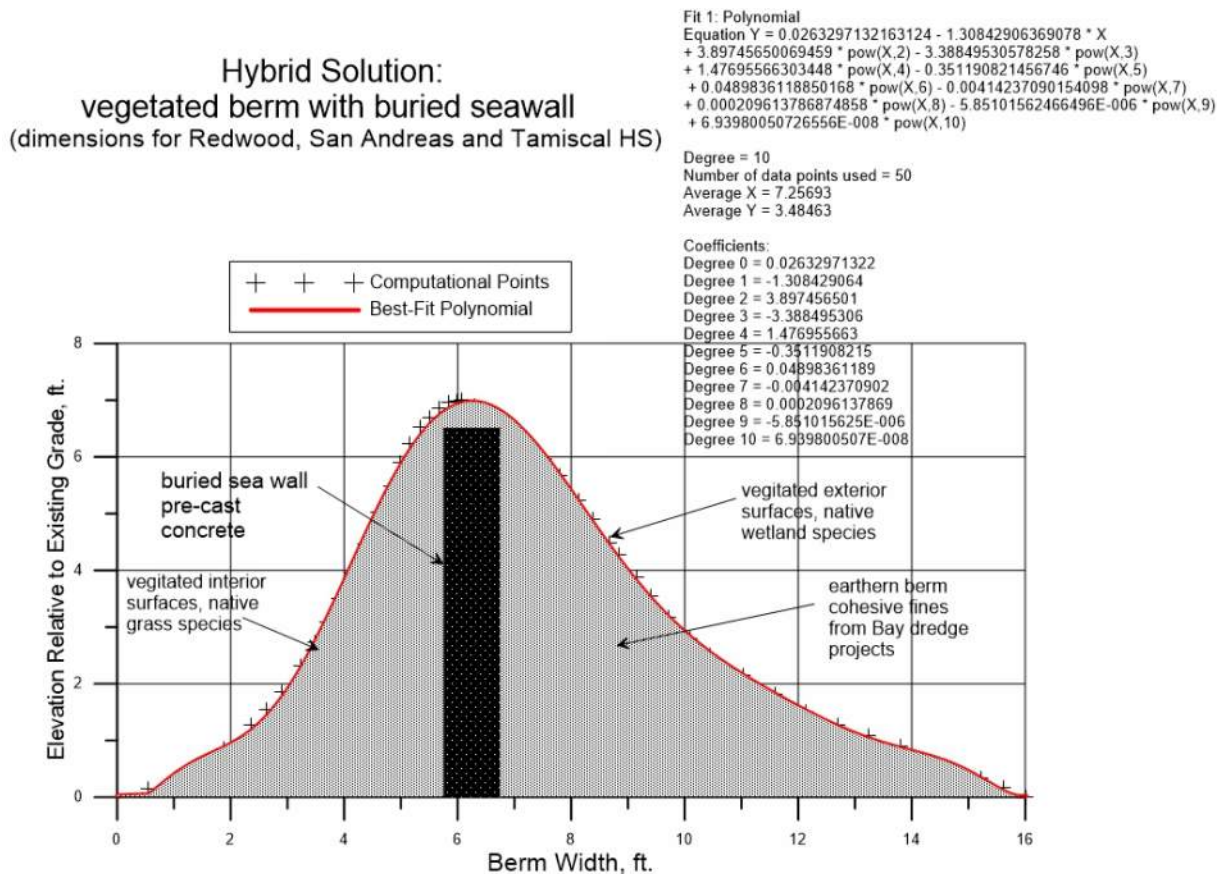


Figure 21: Dimensional cross section of the hybrid solution for Redwood, San Andreas and Tamiscal High Schools based on local earthen berm layout with buried pre-cast concrete seawall. Earth works for the berm utilize cohesive fine-grained sediments obtained from maintenance dredge projects within San Francisco Bay Estuary. Exterior surfaces of the berm are vegetated with local high-marsh and transitional species. Lower interior surfaces of the berms are vegetated with local grass species. Berm width is 16 ft.



Hybrid Solution:
vegetated berm with buried seawall
(dimensions for Tamalpais HS)

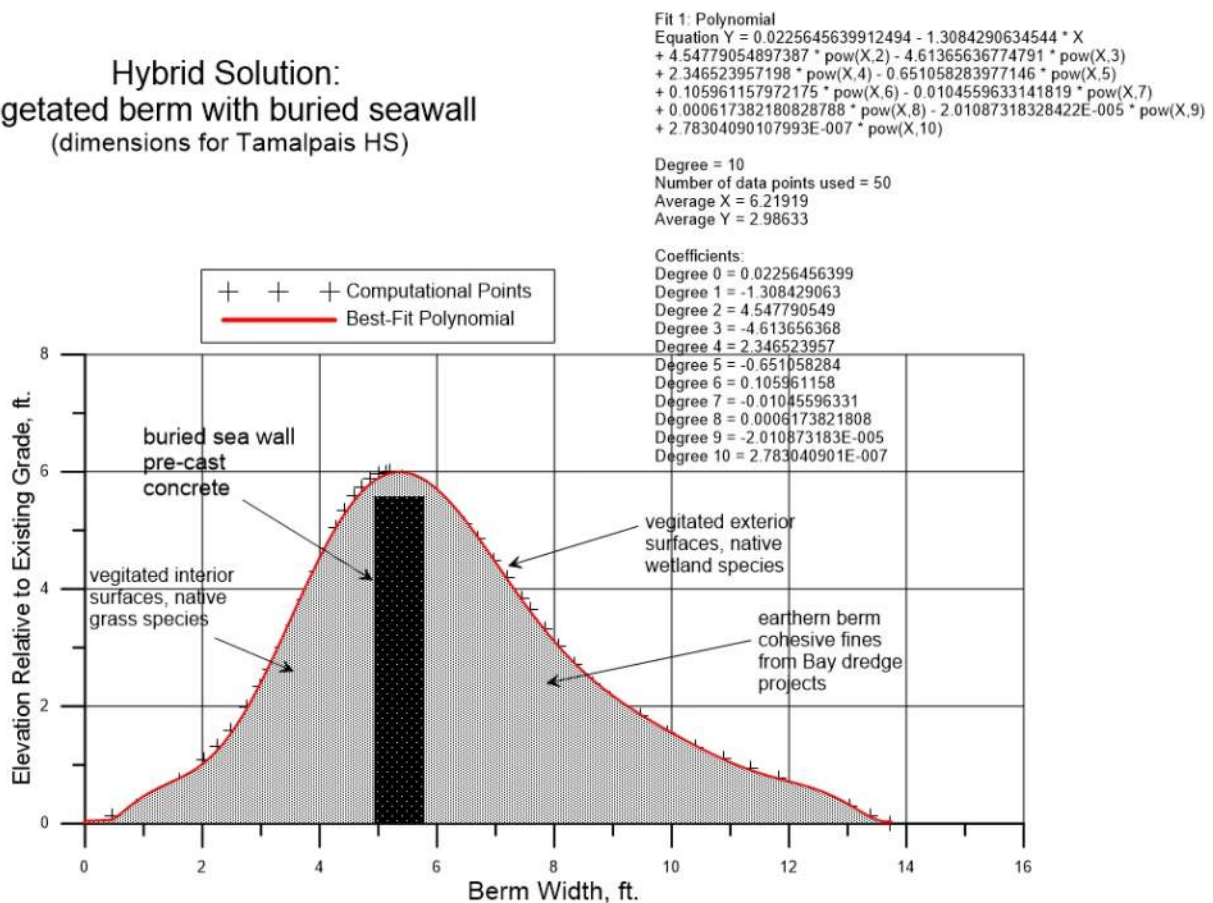


Figure 22: Dimensional cross section of the hybrid solution for Tamalpais High School based on local earthen berm layout with buried pre-cast concrete seawall. Earth works for the berm utilize cohesive fine-grained sediments obtained from maintenance dredge projects within San Francisco Bay Estuary. Exterior surfaces of the berm are vegetated with local high-marsh and transitional species. Lower interior surfaces of the berms are vegetated with local grass species. Berm width is 14 ft.



Figure 23: Layout of hybrid berm solution around the Redwood and San Andreas High School campuses. Flood gates indicated in cyan. Berm cross section is based on Figure 21.

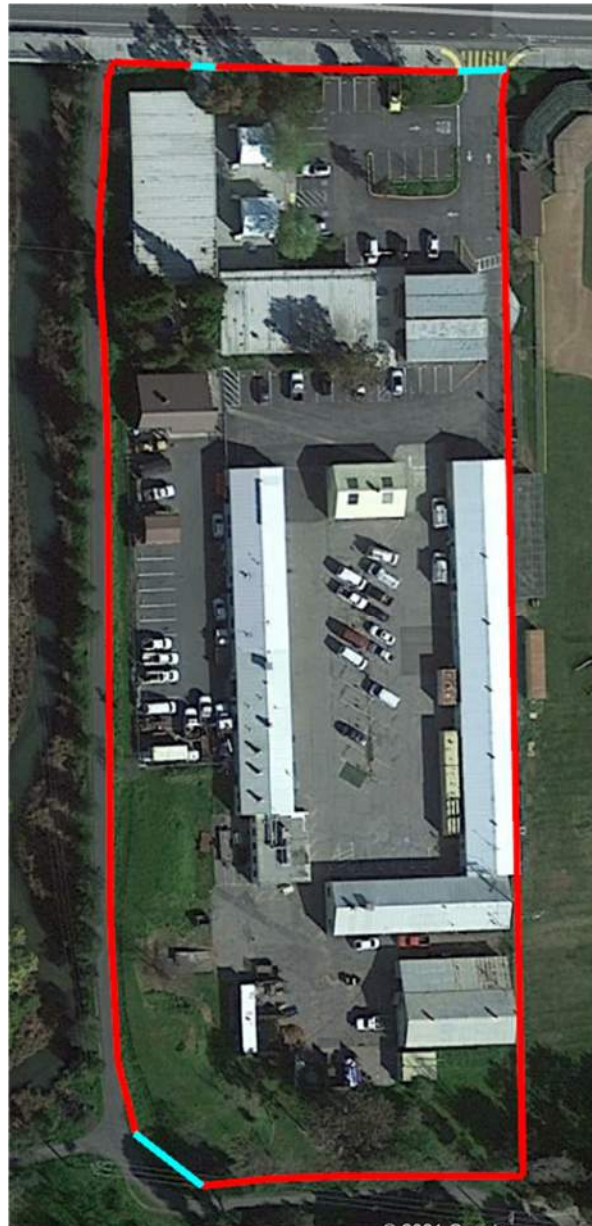


Figure 24: *Layout of hybrid berm solution around the Tamiscal High School campus. Flood gates indicated in cyan. Berm cross section is based on Figure 21.*



Figure 25: Layout of hybrid berm solution around the Tamalpais High School campuses. Flood gates indicated in cyan. Berm cross section is based on Figure 22.



6) CONCLUSIONS OF SLR VULNERABILITY ANALYSIS

This study is sea level rise/coastal hazards analysis of the Tamalpais Union High School District sites in Marin, CA. Union High School District consists of five (5) high school parcels located in the “Coastal Zone” of Marin, CA. Archie Williams High School is located on high ground in the San Anselmo Creek water shed that merges with Ross Creek to form the larger Corte Madera Creek watershed. The complex of campuses comprised of Redwood, Tamiscal and San Andreas High Schools are clustered at low elevations in the floodplain of Corte Madera Creek. Tamalpais High School is located at low elevation adjacent to the Pickleweed Marsh Complex.

For reasons of consistency with state-wide standards, and in order to err on the side of caution, this study has been prepared according to the sea level rise projections and requirements for a sea level rise/coastal hazards analysis as set forth in The California Coastal Commission’s *Sea Level Rise Policy Guidance Document*. Vulnerability and planning recommendations in this study were prepared in accordance with Federal Emergency Management Agency (FEMA) flood standards based on the 100-year event (1% joint probability of exceedance). Flooding and inundation analysis utilized a hybrid modeling approach based on the USGS , “Coastal Storm Modeling System (CoSMoS 2.1: San Francisco Bay) and the Scripps Coastal Evolution Model, (CEM).

The modeling results determined that the 1% flood event (return period of 100 years) results in flooding or inundation at present sea level up to + 9.12 ft. NAVD. Sea level rise (SLR) projections were made for the planning horizons at years 2070 (50-yr), 2100 (80-yr), and 2120 (100-yr). Total water levels for the 1% flood event at the 50-year planning horizon (2070) are little changed from those at present sea levels, reaching +9.44 ft. NAVD. At the 80-year planning horizon (2100), the 1% flood event reaches + 11.44 ft. NAVD, while at the 100-year planning horizon (2120), total water levels during the 1% flood event rise to 12.14 ft. NAVD.

Only the Archie Williams High School, at the headwaters of the San Anselmo Creek at elevation +77 ft. NAVD, lies outside all of the 1 % flood event inundation contours; and therefore, remains immune to flooding or inundation at both present and future sea levels. The cluster of the three high schools (Redwood, San Andreas, and Tamiscal), located in or adjacent to the floodplain of the Corte Madera Creek, are particularly at risk, even for the 1% flood event at present sea level. Not only will the buildings and parking lots of these schools become flooded or inundated; but so will the road network over large areas surrounding these schools. Similarly, Tamalpais High School, (which is located adjacent to the tidal channels and marsh plains of Pickleweed Inlet), will also be flooded or inundated by the 1% flood event at both present and future sea levels, but only a short section of roadways to the west of the high school will be subjected to additional flooding or inundation.

A notable result is that there is little distinction between the flooding and inundation contours at present sea level vs. those at 2100 or 2120 sea levels. This arises because the 4 at-risk high schools are located on very flat floodplains or ancient marsh plains that are surrounded by higher ground. Consequently, the rise in sea level does not significantly change the flooded or inundated area, but rather merely increases the depth of flood waters or the depth of submergence in and around these high schools. At present sea level, flood depths around Redwood, San Andreas, and Tamiscal High



Schools during a 100-year event would on the order of 2 ft. and about 0.5 ft. at Tamalpais High School. At 2120 sea levels (100-year planning horizon), submergence depths due to inundation of Redwood, San Andreas, and Tamiscal High Schools could reach about 5 ft., and about 3.5 ft. on some portions of the Tamalpais High School campus.

After a discussion with the Tamalpais Union High School District (CFO), it was determined that the fundable solution for protection against flooding and inundation by the 1% flood event at present and future sea levels is a local berm concept around the four at-risk campuses. The central objective would be protection of capital assets, primarily buildings, while sacrificing portions of playing fields and parking lots in order to minimize remedial costs. In locations where a berm is not feasible due to site restrictions (i.e. right of way, property lines, etc.), a concrete seawall is proposed. Access to the school campuses, both pre- and post- extreme event, would be accomplished using a flood gates through the berm systems that are anchored to the pre-cast concrete seawall panels. Periods of extreme event floods would become times for *ZOOM classrooms* as was common throughout the COVID-19 pandemic.



7) SUMMARY OF PERMITTING REGULATIONS

There are four (4) key agencies that regulate activities within coastal streams, wetlands, and riparian areas in California's San Francisco Bay, they include:

- **U.S. Army Corps of Engineers (Corps) Regulatory Division** that regulates activities pursuant to Section 404 of the Clean Water Act (CWA) and Section 10 of the Rivers and Harbors Act.
- **California Department of Fish and Wildlife (CDFW)** that regulates activities under Sections 1600 *et seq.* of the Fish and Game Code (CFGF).
- **Regional Water Quality Control Board (Regional Board)** that regulates activities pursuant to Section 401 of the CWA and Section 13263 of the California Porter-Cologne Water Quality Control Act (Porter-Cologne Act).
- **San Francisco Bay Conservation and Development Commission (BCDC)** that regulates activities throughout the San Francisco Bay under the McAteer-Petris Act and Section 307 of the Coastal Zone Management Act (CZMA). BCDC's jurisdiction extends to the mean high tide line in areas that do not contain tidal marsh and up to five feet above mean sea level in areas of tidal marsh. The 100-foot shoreline band extends inland for 100 feet from the shoreline of the Bay¹.

For projects in Marin County impacting watercourses that drain into the San Francisco Bay, completion and submittal of a Joint Aquatic Resource Permit Application (JARPA) would be required. The JARPA serves as a single comprehensive application package for the relevant regulatory agencies indicated above.

Archie Williams High School (formerly Sir Francis Drake):

In its current condition, the Archie Williams High School property does not appear to contain jurisdictional features. However, the property is bounded by two (2) blueline drainages:

- San Anselmo Creek which occurs along the southern boundary of the existing property.
- Sleepy Hollow Creek (historically also referred to as Ross Creek), which occurs along the eastern boundary of the existing school property.

Both San Anselmo Creek and Sleepy Hollow Creek are potentially considered jurisdictional resources regulated by:

1. Corps pursuant to Section 404 of the CWA,
2. Regional Board pursuant to Section 401 of the CWA or the Porter-Cologne Act,
3. CDFW pursuant to Section 1600 the CFGF.

Since Archie Williams is located beyond the 100-foot shoreline band of the BCDC, approval from the BCDC is not required. Therefore, if impacts to San Anselmo Creek or Sleepy Hollow Creek were to occur, it is anticipated the following approvals would be required:

¹ San Francisco Bay Conservation & Development Commission. 2021. *BCDC Jurisdiction and Authority*. Accessed online at: <https://bcdca.gov/bcdc-jurisdiction-authority.html>.



- Section Nationwide Permit (NWP) or Standard Individual Permit (IP) from the Corps,
- Section 401 Water Quality Certification (WQC) or Waste Discharge Requirements (WDR) from the Regional Board, and
- Section 1602 Lake or Streambed Alteration Agreement (LSAA) from the CDFW.

Tamiscal High School

The Tamiscal High School property does not appear to contain any potentially jurisdictional features in association with the school. However, the property is bounded by Larkspur Creek to the west and Larkspur Creek Tidal Channel to the north which is directly connected to the San Francisco Bay. In addition, an unnamed drainage feature appears to occur along the property's southern boundary. Larkspur Creek, Larkspur Creek Tidal Channel, and the unnamed drainage are potentially considered jurisdictional resources regulated by:

1. Corps pursuant to Section 404 of the CWA,
2. Regional Board pursuant to Section 401 of the CWA or the Porter-Cologne Act,
3. CDFW pursuant to Section 1600 the CFGC.

Since the aquatic features surrounding Tamiscal High School are either open water of the greater San Francisco Bay or are tributaries that flow directly into The San Francisco Bay, they are also considered potentially jurisdictional by the BCDC. Therefore, if impacts to these aquatic features were to occur, it is anticipated the following approvals would be required:

- Section NWP or Standard IP from the Corps,
- Section 401 WQC or WDR from the Regional Board,
- Section 1602 LSAA from the CDFW, and
- BCDC permit.

Redwood High School

Redwood High School adjoins Tamiscal High School to the east. No potentially jurisdictional features are located within the boundaries of the Redwood High School property. However, the property occurs in close proximity to Larkspur Marina Lagoon to the north, Larkspur Creek Tidal Channel to the west, and a small unnamed aquatic feature to the east and southeast. These aquatic resources are potentially considered jurisdictional resources regulated by:

1. Corps pursuant to Section 404 of the CWA,
2. Regional Board pursuant to Section 401 of the CWA or the Porter-Cologne Act,
3. CDFW pursuant to Section 1600 the CFGC,
4. BCDC pursuant to the McAteer-Petris Act and the CZMA.

Since the aquatic features surrounding Redwood High School are either open water of the greater San Francisco Bay or are tributaries that flow directly into the San Francisco Bay, they are also considered potentially jurisdictional by the BCDC. Therefore, if impacts to these aquatic features were to occur, it is anticipated the following approvals would be required:

- Section NWP or Standard IP from the Corps,
- Section 401 WQC or WDR from the Regional Board,



- Section 1602 LSAA from the CDFW, and
- BCDC permit.

San Andreas High School

San Andreas High School adjoins Redwood High School to the south of Redwood High School and to the southeast of Tamiscal High School. In its current condition, the San Andreas High School property does not appear to contain any potentially jurisdictional features. However, an unnamed channel and potential tidelands are located to the south and east of the school property. In addition, an unnamed drainage appears to occur along the southwestern property boundary adjacent to Lucky Drive. It is anticipated these aquatic features are tributaries that flow directly into the San Francisco Bay. Therefore, these aquatic features are potentially considered jurisdictional resources regulated by:

1. Corps pursuant to Section 404 of the CWA,
2. Regional Board pursuant to Section 401 of the CWA or the Porter-Cologne Act,
3. CDFW pursuant to Section 1600 the CFGC.
4. BCDC pursuant to the McAteer-Petris Act and the CZMA.

Therefore, if impacts to these aquatic features were to occur, it is anticipated the following approvals would be required:

- Section NWP or Standard IP from the Corps,
- Section 401 WQC or WDR from the Regional Board,
- Section 1602 LSAA from the CDFW, and
- BCDC permit.

Tamalpais High School

The Tamalpais High School property does not appear to contain any potentially jurisdictional features. However, the property is bounded by tidelands / wetlands to the south. In addition, tidelands of Richardson Bay and the greater San Francisco Bay are located to the east of the property adjacent to Miller Avenue. Therefore, these aquatic features are anticipated to be considered jurisdictional resources regulated by:

1. Corps pursuant to Section 404 of the CWA,
2. Regional Board pursuant to Section 401 of the CWA or the Porter-Cologne Act,
3. CDFW pursuant to Section 1600 the CFGC.
4. BCDC pursuant to the McAteer-Petris Act and the CZMA.

Therefore, if impacts to these aquatic features were to occur, it is anticipated the following approvals would be required:

- Section NWP or Standard IP from the Corps,
- Section 401 WQC or WDR from the Regional Board,
- Section 1602 LSAA from the CDFW, and
- BCDC permit.



8) PRELIMINARY DESIGN CONCEPTS

Two concepts were evaluated as potential solutions: a soft-armoring alternative and a hard-armoring alternative. The soft-armoring alternative consists of a vegetated berm similar to the recently constructed Cardiff Living Shoreline Project shown in Figure 20. Because the sites at the high school campuses have limited space, the footprint of the vegetated berm was reduced from a 60-ft width to approximately 15-ft wide with a buried precast element was substituted for the revetment stone utilized in the previous project. See Figure 26 for the conceptual vegetated berm cross section.

The hard-armoring alternative consists of a cast-in-place concrete seawall with interlocking sheet piling. The specific wall configuration will vary depending on wall height, site seismicity, and soil conditions. Figure 27 shows two potential wall configurations: one with a footing and precast concrete piles, and another founded completely on the proposed steel sheet pile.

The vegetated alternative is preferred due to environmental and cost advantages and should be utilized where possible. Because each site is unique in its constraints, it is likely that the design will consist of a combination of the vegetated berm and structural seawall options, utilizing the berm where possible and the seawall where constrained by site geometry.

According to the California Coastal Commission Sea Level Rise Policy Guidance (2015, 2018), a “soft” or “natural” adaptation strategy is identified as a preferred alternative for the protection of existing structures. A “living shoreline” is one such approach and is to be used as an alternative to the placement of hard shoreline protection in order to protect development or other resources and to enhance natural resource areas.

“Hard” coastal protection or engineered features such as seawalls, revetments, cave fills, and bulkheads that block the landward retreat of the shoreline should be avoided when feasible. Under current law, shoreline protection for existing structures in danger from erosion may be allowed if coastal resource impacts are avoided or minimized and fully mitigated where unavoidable.

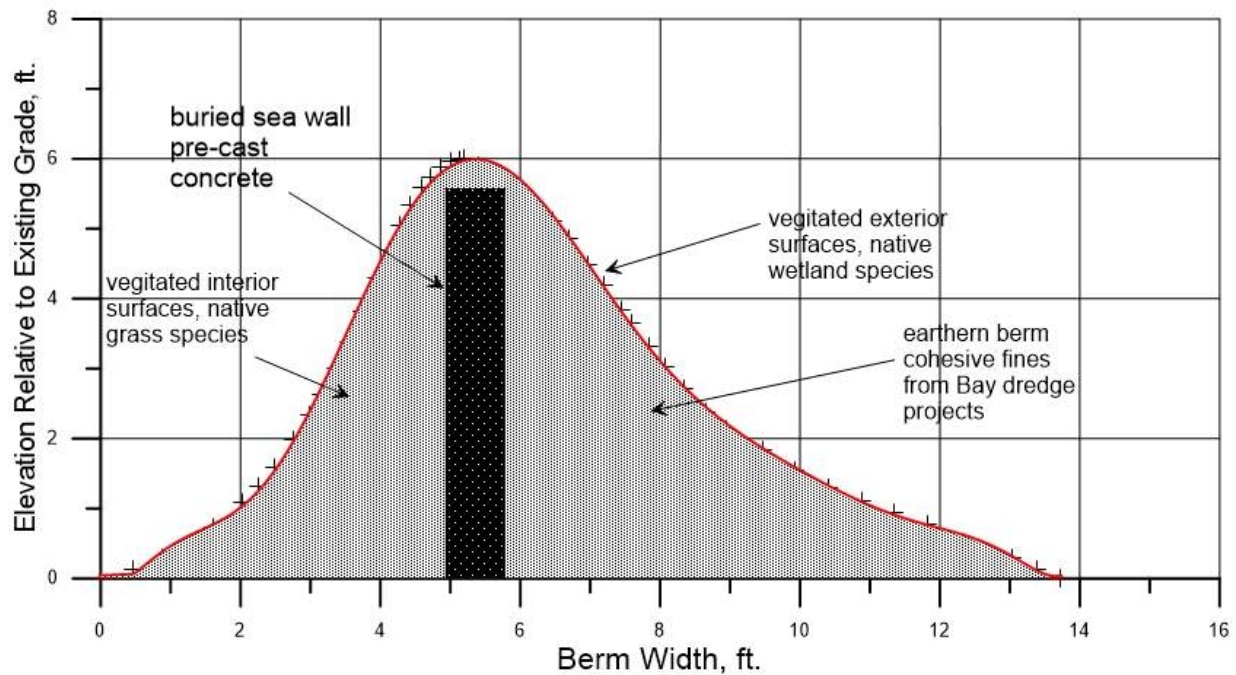


Figure 26: *Soft-Armoring Alternative is a vegetated berm with a buried precast element.*

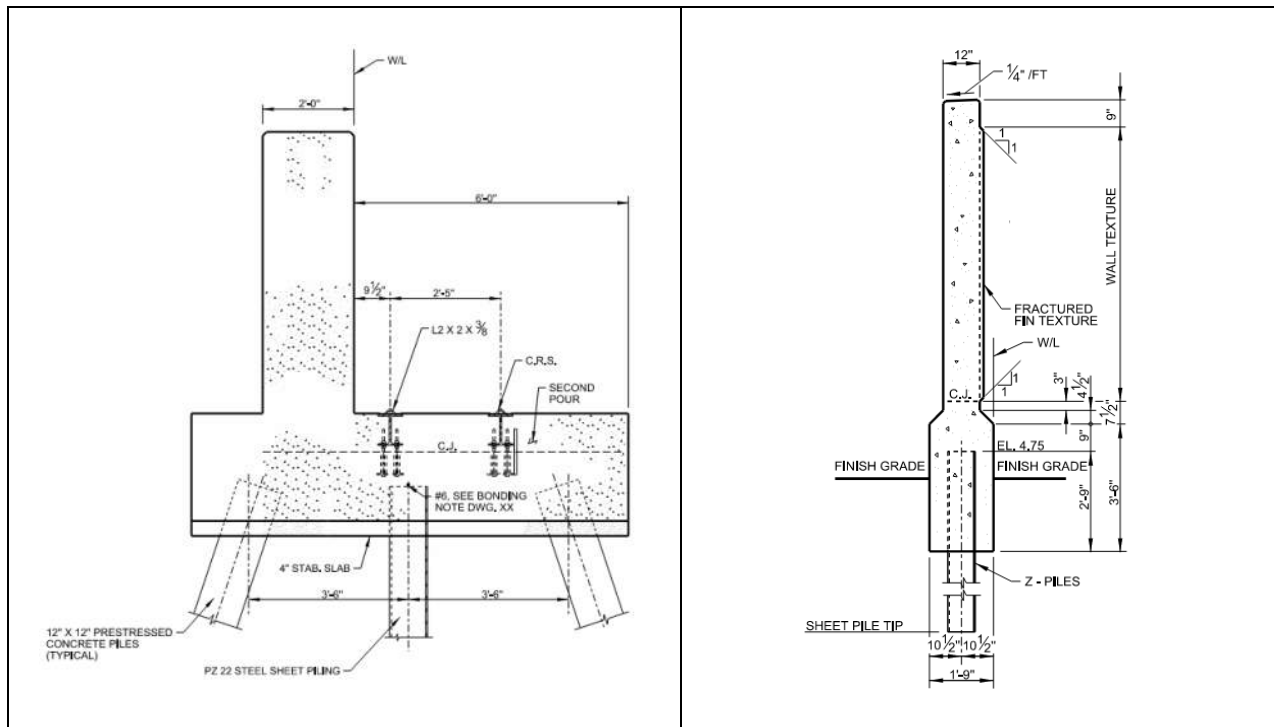


Figure 27: *Hard-Armoring Alternative is a cast in place concrete seawall with interlocking sheet pile. Left image shows a wall supported on a footing with precast piles and right image shows a wall supported on sheet pile. Wall configuration and geometry will vary depending on final design.*



9) PRELIMINARY COST ESTIMATE

Preliminary cost estimates were developed for soft-armoring and hard-armoring alternatives at each of the three locations: Tamalpais High School, Tamiscal High School, and Redwood / San Andreas High Schools. Although the design will likely incorporate a combination of the vegetated berm and structural seawall, the preliminary costs provide a useful range for planning and budgeting.

The cost estimates, shown in **Table 3**, were developed utilizing the conceptual wall and flood gate layouts shown in figures 23 thru 25.

Table 3: *Preliminary Cost Estimate for Alternative 1 – Vegetated Berm and Alternative 2 – Structural Seawall at Tamalpais High School, Tamiscal High School, and Redwood / San Andreas High Schools*

TAMALPAIS HIGH SCHOOL			
	Alternative 1 - Vegetated Berm		Alternative 2 - Structural Seawall (H = 5-ft)
Construction Cost	\$	6,890,000	\$ 8,810,000
Environmental and Preliminary Engineering	\$	206,700	\$ 264,300
Plans, Specifications, and Estimate	\$	689,000	\$ 881,000
Construction Management	\$	826,800	\$ 1,057,200
Escalation to 2025	\$	1,033,500	\$ 1,321,500
TOTAL	\$	8,613,000	\$ 11,012,500
TAMISCAL HIGH SCHOOL			
	Alternative 1 - Vegetated Berm		Alternative 2 - Structural Seawall (H = 6-ft)
Construction Cost	\$	4,792,000	\$ 7,070,000
Environmental and Preliminary Engineering	\$	143,760	\$ 212,100
Plans, Specifications, and Estimate	\$	479,200	\$ 707,000
Construction Management	\$	575,040	\$ 848,400
Escalation to 2025	\$	718,800	\$ 1,060,500
TOTAL	\$	6,708,800	\$ 9,898,000
REDWOOD/ SAN ANDREAS HIGH SCHOOLS			
	Alternative 1 - Vegetated Berm		Alternative 2 - Structural Seawall (H = 6-ft)
Construction Cost	\$	14,289,000	\$ 21,425,000
Environmental and Preliminary Engineering	\$	428,670	\$ 642,750
Plans, Specifications, and Estimate	\$	1,428,900	\$ 2,142,500
Construction Management	\$	1,714,680	\$ 2,571,000
Escalation to 2025	\$	2,143,350	\$ 3,213,750
TOTAL	\$	20,004,600	\$ 29,995,000

Construction costs are approximately \$3,000/LF for the vegetated berm alternative and \$4,300/LF for the structural seawall alternative. These costs include the construction of the proposed wall or berm, mobilization, traffic control, construction staking, roadway improvements, site improvements, and erosion control. Preliminary costs are based on bidding data from recent projects, including the California Department of Transportation Cost Database for construction cost data. Due to the preliminary nature of these concepts, a 50% contingency was included. This



is anticipated to incorporate utility relocation costs and other items that are not fully known at this time. Contingency will be reduced as the design progresses and more information is collected regarding each site. Note that Michael Baker International has no control over the actual cost of labor, material, equipment, or over the contractor's method of determining prices, or over the competitive bidding or market conditions at the time of bid, and therefore cannot guarantee that the construction cost will not vary from the pricing reflected in **Table 3**.

Environmental and preliminary engineering was assumed to be 3% of the construction cost. This includes environmental clearance, permitting, and preliminary design. Plans, Specifications and Estimate was assumed to be 10% of the construction cost. Construction management was assumed to be 12% of the construction cost. Escalation was estimated to be 3% per year, and the project construction date was assumed to be 2025.

Right of way costs were not included in this estimate. At this time, it is assumed that all improvements will be constructed on school property and that no easements will be necessary.



10) REFERENCES

BayWave, 2020, Marin County's Bay Waterfront Adaptation Vulnerability Evaluation: Sea Level Rise Scenario Guidance", <scenario-guidance-sheet_final.pdf> from: Sea%20Level%20Rise%20Scenarios.html

CCC, 2013 "California Coastal Commission Draft Sea Level Rise Policy Guidance", San Francisco, CA., No. PR-101420-13, 113 pp.

http://www.coastal.ca.gov/climate/slr/guidance/CCC_Draft_SLR_Guidance_PR_10142013.pdf

CCC, 2015, "California Coastal Commission Sea Level Rise Policy Guidance", adopted 12 August 2015, 254 pp.

CCC, 2018, "California Coastal Commission Sea Level Rise Policy Guidance: Draft Science Update", adopted July 2018, 305 pp.

CCC, 2020, "Critical Infrastructure Adaption Policy Guidance for Addressing Sea Level Rise", draft, March 2020, 95 pp.

FHWA, 2018, "White Paper: Nature Based Solutions for Coastal Highway Resilience", No. FHWA-HEP-18-037, February 2018, 42 pp.

IPCC, 2018, Intergovernmental Panel on Climate Change "Global Warming of 1.5° C", Chapter 3, *Intergovernmental Panel on Climate Change*, Special Report, No. sr15-FOD-Annex3-1, 63 pp.

Jenkins, S. A. and J. Wasyl, 2005, "Coastal evolution model," Scripps Institution of Oceanography Tech Report No. 58, 179 pp + appendices.

<http://repositories.cdlib.org/sio/techreport/58/>

Jenkins, S. A. & J. Wasyl, 1999, "Hydroperiod functions for habitat mapping of restoration alternatives for San Dieguito Lagoon," submitted to Southern California Edison Company, 15 pp.

Jenkins, S. A. and J. Wasyl, 2005, "Coastal evolution model," Scripps Institution of Oceanography Tech Report No. 58, 179 pp + appendices.

<http://repositories.cdlib.org/sio/techreport/58/>

Jenkins, S. A., 2015, "El Nino Vulnerabilities during Mission Beach Sea Wall Construction," submitted to the City of San Diego Parks and Recreation Department, submitted by Michael Baker International, San Diego, 8 pp.

Jenkins, S. A. and S. Taylor, 2015, "Storm and Tidal Conditions Determination for Coastal Drainage Design," submitted to Office of Highway Drainage Design Division of Design, MS 28, California Department of Transportation submitted by Michael Baker International, San Diego and Carlsbad, 42 pp.



- Jenkins, S. A. and S. Taylor, 2016, “Wave Run-up Determination for Coastal Drainage and Highway Design,” submitted to Office of Highway Drainage Design Division of Design, MS 28, California Department of Transportation submitted by Michael Baker International, San Diego and Carlsbad, 42 pp
- Moffatt & Nichol, 2016, “Rip Rap Reconfiguration Analysis for the Cardiff State Beach Living Shoreline Project, Final Feasibility Assessment”, submitted to the City of Encinitas September 21, 2016, 30 pp
- Moffatt & Nichol, 2016, “Cardiff Living Shoreline Project”, submitted to the City of Encinitas and California State Conservancy, February, 2016, 93 pp
- Moffatt & Nichol, 2017, “95% Basis of Design Report: Cardiff Beach Living Shoreline Project”, M&N Tech Rpt. # 8909-01, submitted to the City of Encinitas September 2017, 37 pp.
- Moffatt & Nichol, 2018, “Final Design Report: Cardiff Beach Living Shoreline Project”, M&N Tech Rpt. # 13553-G, submitted to the City of Encinitas September 2018, 89 pp.
- Moffatt & Nichol, 2018, “Adaptive Management Plan: Cardiff Beach Living Shoreline Project”, submitted to the City of Encinitas August 2018, 16 pp.
- Moffatt & Nichol, 2018, “Final Dune Creation and Management Plan: Cardiff State Beach Living Shoreline Project”, submitted to the California Coastal Commission, September 2018, 28 pp.
- National Research Council (NRC). 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Report by the Committee on Sea Level Rise in California, Oregon, and Washington. National Academies Press, Washington, DC. 250 pp. <http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington>.
- O’Neil, A., Erikson, L., and P. Barnard, (2017), “Downscaling wind and wavefields for 21st century coastal flood hazard projections in a region of complex terrain”, *Earth Space Science*, American Geophysical Union, vol. 4, pp. 314–334, doi:10.1002/2016EA000193.
- OPC, 2018. Ocean Protection Council State of California Sea-Level Rise Guidance: 2018 Update. http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf
- SCE, 2005, “ San Dieguito Wetlands Restoration Project, Final Restoration Plan” submitted to California Coastal Commission, prepared by Southern California Edison Company, November, 2005, 265 pp.
- Sweet, W., Kopp, R., Weaver, C., Obeysekera, J., Horton, R., Thieler, E., and C. Zervas, 2017, “Global and Regional Sea Level Rise Scenarios for the United States”, NOAA Tech. Rpt. CO-OPS 083, 75 pp.



USACE, 2011, “Coastal Engineering Manual. Engineer Manual- Part VI” No. 1110-2-1100P6, 771 pp.

USGS, 2021, “DEM data base for the San Francisco Bay Estuary”, available at:<https://apps.nationalmap.gov/downloader/#1/>

USGS, 2021, “Coastal Storm Modeling System CoSMoS 2.1: San Francisco Bay”,https://www.usgs.gov/centers/pcmssc/science/cosmos-21-san-francisco-bay?qt-science_center_objects=0#qt-science_center_objects

WDCSF, 2021, wave Data Centers San Francisco