# Bothin Marsh Geomorphology, Ecology, and Conservation Options

## Chapter 2:
## Overview of Sea Level Rise and Land Management Response


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# Chapter 2: Overview of Sea Level Rise and Land Management Response

## 2.0 Introduction

This Chapter is a critical review and synthesis of the readily available scientific and technical information about recent and likely future rates of sea level rise, plus general land management responses to sea level rise, pertaining to the protection and restoration of the Bothin Marsh Complex.

## 2.1 Tides

San Francisco Bay experiences a mixed diurnal tide, meaning there are two high tides and two low tides each lunar day, with the two low tides usually having different heights, and the two high tides also having different heights (Figure 2.1).

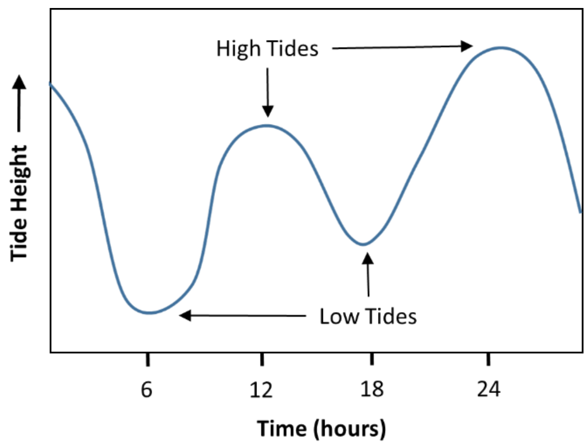


Figure 2.1. Diagram of the mixed semi-diurnal tide showing two high tides of different height and two low tides of different height each lunar day.

## 2.2 Mean Sea Level

Mean Sea Level (MSL) is the arithmetic mean of hourly tide heights observed over the National Tidal Datum Epoch (NTDE; NOAA 2000). MSL, as well as other average tidal heights, including the average of the high and low tides, are called vertical tidal datums, and are discussed further in section 2.4.1 below. NTDE is the specific 19-year period adopted by the National Ocean Service as the official time segment over which sea level observations are taken and reduced to obtain mean values for datum definition. The present NTDE is 1983 through 2001. It is reviewed annually for revision and must be actively considered for revision every 25 years.

The semi-diurnal range is the difference in height between consecutive high and low waters. It varies in approximately a two-week cycle. About twice a month, around the new moon and full moon, when the Sun, Moon, and Earth are aligned, the solar and lunar forces that cause the tide reinforce each other, and the semi-diurnal range achieves its monthly maximum. This is called spring tide, as if the high tide springs or jumps in height. When the Moon is at first or third quarter, the Sun and Moon are separated by 90° when viewed from the Earth, and the solar tidal force partially cancels the lunar tidal force. At these times, the semi-diurnal range is at its monthly minimum. This is called neap tide. In Middle English, neap means "without power" (https://www.etymonline.com/word/neap). Spring tides result in high waters that are higher than average, low waters that are lower than average, and stronger tidal currents than average. Neaps result in less-extreme tidal conditions. There is about a seven-day interval between springs and neaps.

## 2.3 Sea Level Rise

Absolute or eustatic sea level is the average height of the sea surface (Cazenave and Llovel 2010, Merrifield *et al*. 2014). Eustatic sea level rise is mainly due to thermal expansion of the sea and the addition of freshwater from melting of ice on land. Relative sea level is the average height of the sea relative to the land. It is affected by land rising or falling, as well as eustatic sea level. Understanding relative sea level is essential for coastal management (Morton 2003).

### 2.3.1 Long Terms Trends

Sea level has been rising globally since the end of the last ice age about 18,000 years ago. Global mean sea level rose about 400-450 feet during this period. Much of this rise took place between 18,000 and 8,000 years ago at average rates of about 45 inches per century, and then began to slow (Griggs *et al*. 2017). The global trend in sea level rise over past millennia is reflected in the record for San Francisco Bay (Atwater *et al*. 1977, IPPC 2014, Meyer 2014) (Figure 2.2).

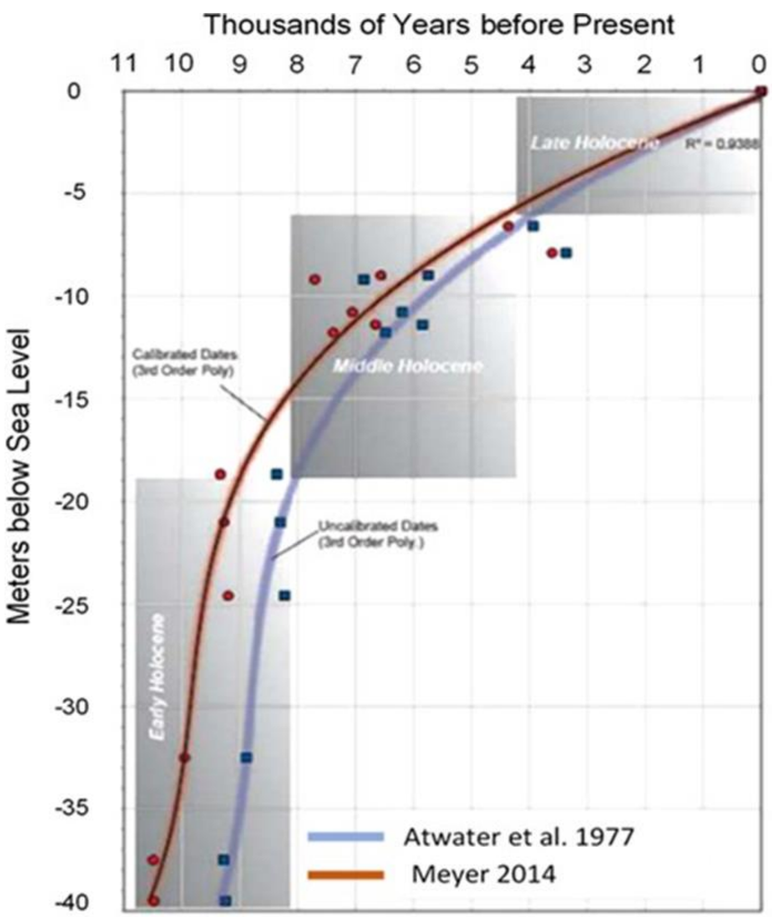


Figure 2.2. Two versions of the long-term trend in sea level for San Francisco Bay, from Meyer 2014.

Of particular interest is the fact that the oldest known tidal marshes in San Francisco Bay are less than 3,000 years old (Byrne et a.2001, Goman *et al*. 2008, Drexler *et al*. 2009, Watson and Byrne 2013), suggesting that they could not form until after the rate of sea level rise slowed to nearly its current rate about 6,000 years ago (Malamud-Roam *et al*. 2006). The implication is that long-term persistence of tidal marshes depends on a slow average rate of sea level rise, although this can be mediated by increases in the supply of inorganic sediment delivered to the marshes by the tides and from land, plus production of organic sediments within marshes (see Chapter 1).

### 2.3.2 Historical Trends

Rates of global sea level rise have ranged from about 0.05 inches per year to 0.06 inches per year (about 0.5 to 0.7 inches per decade) for the 20th century. However, since 1990, the rate has more than doubled, and the rise continues to accelerate (Church and White 2011, Ray and Douglas 2011, Hay *et al*. 2015). Since 1993, the measurement of eustatic sea level has been greatly improved with the use of satellites, especially since the advent of the U.S.-German Gravity Recovery and Climate Experiment (GRACE) beginning in 2002. These measurements reveal an average global rate of sea level rise of 1.3 inches per decade, which is more than twice the average rate over the 20th century (Leuliette and Nerem 2016).

The historical trend in sea level for San Francisco Bay is well documented, owing to the continuous record of tide height observations beginning in 1854 for the NOAA Tide Station at Fort Point (Figure 2.3). These data reveal an average rate of sea level rise just inside the Golden Gate of about 0.08 inches per year (about 8 inches per century). Short-term processes, including Pacific Basin climate fluctuations (e.g., El Niño Southern Oscillation), perigean high tides (i.e.; "King Tides"), and winter storms can produce significantly higher water levels than sea level rise alone (USGS 1999), and can cause actual sea levels to be significantly higher than predicted (Figure 2.4).

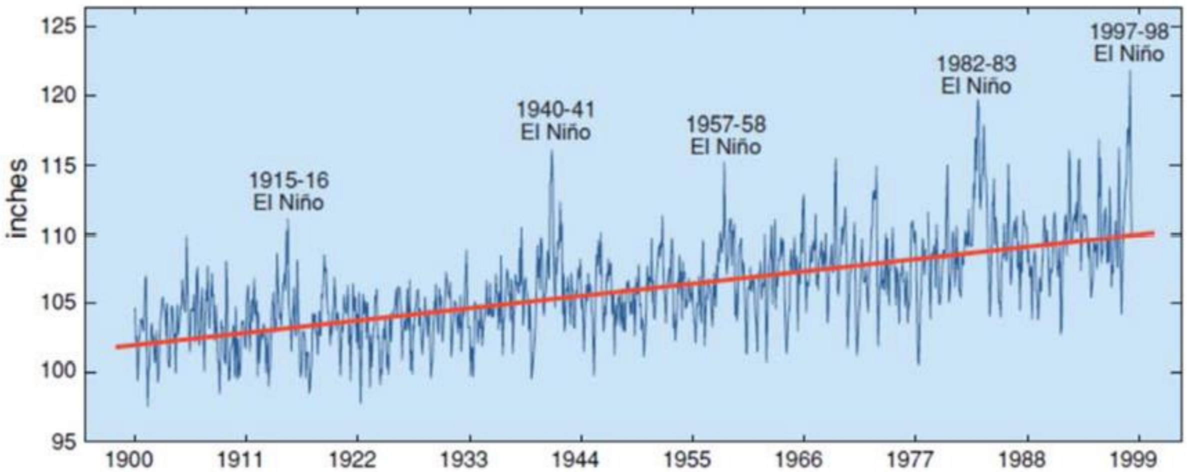


Figure 2.3. Sea level data from the Fort Point Tide Station 9414290 accounting for the historical shift in the local datum. Note the correspondence between extreme high tides and El Nino events (USGS 1999).

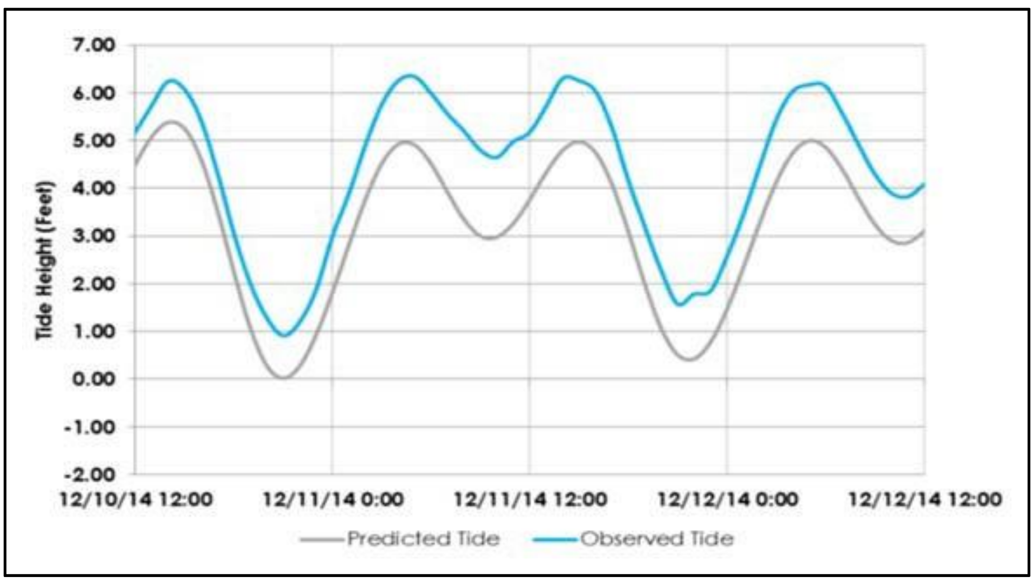


Figure 2.4. Predicted versus observed tide heights showing effect of storm surge on December 11, 2014 (BCDC 2016).

### 2.3.3. Extreme Events and Short-Term Variations

The sea level record provided by the Presidio Tide Station shows that extreme tides have become more frequent in recent decades. The annual maximum tide level has been rising at a rate of about 0.1 inches per year in recent decades, which is faster than the average rate of sea level rise (BCDC 2016). This has obvious implications for tidal flooding on lands adjacent to the Bay. Extreme high tides tend to have the greatest negative impacts (Goals Project 2015). If the maximum height of the tides is rising faster than the average tide height, then it represents a greater threat to life and property.

Sea level rise on the California coast is expressed as a trend of strongly fluctuating annual variations in sea level (Figure 2.5), rather than a smooth, idealized curve generated by numerical models. Short-term Pacific oceanographic events can result in ecologically significant, persistent pulses of sea level rise and falls that are similar in magnitude to average sea level rise over the eighteenth century. ENSO events (El Niño Southern Oscillation, alternating between warm Pacific with elevated sea level, and cool Pacific with lower sea level), Pacific Decadal Oscillations, the metonic tidal cycle (18.6 year, estimated as the NTDE, see Section 2.4.1), and Pacific sea surface temperature anomalies independent of El Niño events can cause both long-term and short-term responses by tidal marsh ecosystems (Kolker *et al*. 2009, Orson *et al*. 1998).

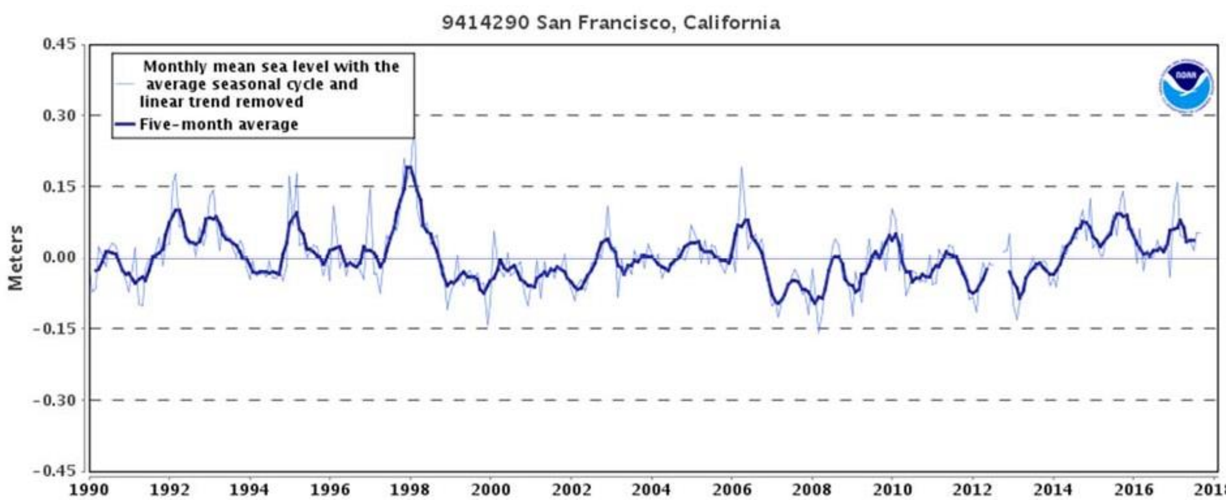


Figure 2.5. NOAA Sea Level Anomalies since 1990 – Central SF Bay and Golden Gate. Source:https://tidesandcurrents.noaa.gov/sltrends/anomalymapmonth.htm
https://tidesandcurrents.noaa.gov/sltrends/residual1980.htm?stnid=9414750

### 2.3.4 Forecasts

Scientific understanding of sea level rise is quickly advancing. Predictive models are incorporating new data for greenhouse gas emittance and ice sheet melting, and efforts to apply the models at the regional scale are increasing (Griggs *et al*. 2017). The models will continue to improve with gains in scientific understanding. The observed impacts of sea level rise at local, state, national, and global scales will be used to help calibrate the models. Monitoring of regional and local sea level rise will be essential to manage its social and ecological impacts.

The Intergovernmental Panel on Climate Change (IPCC) has adopted a set of four emissions scenarios (i.e., Representative Concentration Pathways, or RCPs), based on the predicted global average capacity of the atmosphere to trap heat in 2100, relative to pre-industrial values. The trapped heat is largely responsible for thermal expansion of the oceans, which has been a major cause of sea level rise (Merrifield *et al*. 2013). The current statewide guidance provided by the Ocean Protection Council (OPC) notes that different RCPs generate minor differences in sea level before 2050, but thereafter the forecasts increasingly depend on greenhouse gas emissions (Griggs *et al*. 2017). Thermal expansion has been the main driver of global sea level rise since the start of the Industrial Revolution, but ice sheets may soon become the primary contributor to global sea level rise (Nichols and Cazenave 2010, Church and White 2011). This is a particular concern for the Bay Area. The global effect of ice loss from West Antarctica is expected to be less than the local effect in San Francisco Bay; for every 1.0 foot of global sea level rise there is expected to be 1.25 feet of rise along the California coast (Griggs *et al*. 2017).

The most recent OPC guidance (Griggs et al. 2017) is based on the current state of science for sea level rise along the California Coast. It employs a probabilistic approach to assign likelihoods to sea level rise forecast (Kopp *et al*. 2014) based on data from three representative Tide Stations: Crescent City in northern California, San Francisco Bay (NOAA Presidion Station 9414290), and La Jolla in southern California. The comprehensive probabilistic approach was determined to be most appropriate for informing public policy and coastal zone planning. To be more specific, the approach enables planners and decision-makers to select an RCP and the related sea level rise forecast that best balances the uncertainty of the forecast with the need and cost to protect society and ecosystems. For example, the public may decide to invest in expensive measures to protect essential resources from a very high sea level, although the probability of that level is low.

The probabilistic approach (Kopp *et al*. 2014) may underestimate the likelihood of extreme sea level rise, particularly under high-emissions RCPs. Therefore the current OPC guidance includes the extreme sea level rise RCP (termed the H++ scenario). Under this scenario, rapid ice sheet loss from Antarctica drives rates of sea level rise in California above 2 inches/year by 2100, resulting in sea levels above 10 feet, relative to the current level. This rate of sea level rise would be about 30-40 times faster than the sea level rise experienced over the last century. It is scientifically premature, however, to estimate the probability of the H++ scenario (Griggs *et al*. 2017). Although the probability of this scenario is currently unknown, its consideration may be important, especially for high-stakes, long-term decisions.

The time horizon for most published forecasts is 2100, although the current OPC guidance extends the forecast for the H++ scenario to 2150. However, it is important to consider that sea level rise is not expected to stop by 2100. The contribution of ocean thermal expansion is unlikely to wane until after 2150, and may continue past that time to increase slightly for at least a thousand years, due to melting land ice, assuming that atmospheric $CO_2$ concentrations and air temperature stabilize within 300 years (IPPC 2007, Bamber *et al*. 2009, BCDC 2011).

### 2.3.4.1 Adopted Forecasts

The state of California began issuing guidance about sea level rise for coastal planning and management purposes through OPC in 2010 (OPC 2010), with an update in 2013 (OPC 2013). In 2010, the Governors of Oregon and Washington plus a consortium of federal agencies requested the National Research Council (NRC) to provide estimates and projections of future sea level rise based on the state-of-the-science. The NRC completed its report in 2012 (NRC 2012), based on the most recent Intergovernmental Panel on Climate Change (IPCC) report at that time (IPCC 2007). That NRC report has informed a number of important guidance documents and other materials specific to San Francisco Bay (OPC 2013, Goals Project 2015, BCDC 2016), including the BayWAVE report produced for the Marin County Planning

Department (Marin County 2017b). Since then, a new IPCC report was published containing updated sea level rise projections based on new scenarios, model simulations, and scientific advances (IPCC 2014), including new findings about the melting ice sheets of Antarctica (Kopp *et al*. 2014). Therefore, the California guidance provided by OPC has also been updated (Griggs *et al*. 2017), and is expected to be adopted by the OPC in 2018.

| Source | Timeframe | Sea Level Rise Relative to Present Level (in) | | | | | |
|---|---|---|---|---|---|---|---|
| OPC 2010 | | Average of Models | | | Range of Models | | |
| | 2030 | 7 | | | 5-8 | | |
| | 2050 | 14 | | | 10-17 | | |
| | | Low | Med | High | Low | Med | High |
| | 2070 | 23 | 24 | 27 | 17-27 | 18-29 | 20-32 |
| | 2100 | 40 | 47 | 55 | 31-50 | 37-60 | 40-69 |
| NRC 2012 | | Most Likely | | | Upper Range | | |
| | 2030 | 6 ± 2 | | | 12 | | |
| | 2050 | 11 ± 4 | | | 24 | | |
| | 2100 | 36 ± 10 | | | 66 | | |
| OPC 2013 | | Range | | | Mid-Range | | |
| | 2030 | 1.6 – 11.8 | | | 6.6 | | |
| | 2050 | 4.7 – 24.0 | | | 14.4 | | |
| | 2100 | 16.6 – 65.8 | | | 41.0 | | |
| Goals Project 2015 | | Low Value | | | High Value | | |
| | 2100 | 20.4 | | | 64.8 | | |
| Leventhal 2015 | 2030 | 12 | | | | | |
| | 2070 | 36 | | | | | |
| | 2100 | 60 | | | | | |
| Marin Co. 2017a (Bothin Marsh Bridge) | | 50-year Storm + Max. King Tide + Max. Sea Level | | | | | |
| | 2030 | 12 | | | | | |
| | 2050 | 24 | | | | | |
| | 2100 | 66 | | | | | |
| Griggs et al. 2017 | | 50% chance SLR is ≥ | 67% chance SLR is between | 5% chance SLR meets or exceeds | 0.5% chance SLR meets or exceeds | | |
| | 2030 | 12 | 4 - 6 | 8 | 11 | | |
| | 2050 | 11 | 7 - 13 | 17 | 24 | | |
| | 2100 | 20 | 12 - 29 | 40 | 70 | | |
| | | 24 | 14 - 32 | 43 | 72 | | |
| | | 31 | 19 - 41 | 55 | 85 | | |
| | | 120 | | | | | |
| | 2150 | 30 | 18 – 47 | 68 | 133 | | |
| | | 37 | 23 – 58 | 78 | 142 | | |
| | | 52 | 36 - 73 | 95 | 160 | | |
| | | 264 | | | | | |

Table 2.1. Forecasts of sea level rise from government guidance for shoreline planning in San Francisco Bay. Red circles mark the higher values reported for the year 2100.

The various forecasts of sea level rise that have been incorporated into public guidance documents relevant to Richardson Bay and Bothin Marsh are compiled in Table 2.1. It may be important that two of the seven adopted forecasts reported here for 2100 are 55 inches, and the five others range from 60 – to about 66 inches, excluding the relatively unlikely forecast of 85 inches provided by the current OPC guidance for its H++ (extreme) scenario (Griggs 2017). The similarity of these adopted forecasts reflects a common dependency on the NRC guidance. The adoption of 55 inches by the 2010 OPC document pre-dates the NRC report. The Goals Project adopted the 55-inch forecast by modifying the NRC forecast based on regional considerations, whereas the current OPC guidance adopted the 66-inch forecast without direct reference to the NRC report. At this stage in the development of sea level rise science, a forecast of 55 to 66 inches for 2100 seems justified. Less likely forecasts, including the 2100 value of 85 inches provided by the current OPC guidance, should not be ignored, however. Revised forecasts of sea level rise will be warranted through improved scientific understanding and the needs of coastal managers, and forecasts of sea level rise are likely to be adjusted upward (DeConto and Pollard 2016, Thompson *et al*. 2016, AMAP 2017).

## 2.4 Marsh Migration or Transgression

Marine or estuarine migration is the process by which sea level rises relative to the land, such that the extreme and average excursions of flood tide move upstream and inland. As used here, migration is synonymous with estuarine transgression. Migration can be caused by land sinking or the ocean surface rising, since either process can lead to increased inland tidal flooding. Estimates of migration heights and distances depend on knowing the elevation of the lands relative to the tides, and this requires knowing local vertical datums, as explained below.

### 2.4.1 Vertical Datums

A vertical datum is a fixed surface designated to have a certain numerical value of elevation to which the heights of other surfaces can be referred, such that their elevations can be compared. There are two primary kinds of vertical datums. Those based on a form of Mean Sea Level (MSL), are called orthometric datums, and those based on local measures of high or low tides are called tidal datums. In other words, a tidal datum is an average level of the tides for a selected tide phase, such as high tide or low tide. Tidal datums are used to determine the heights of the tides, and the heights of land surfaces, vegetation, and built structures relative to the tides.

Any effort to forecast the future extent of inland tidal flooding due to sea level rise at any location requires knowing the tidal elevation of the local lands currently above the tides, and this requires knowing the local relationship between orthometric and tidal datums. Federal standards and methods for determining tidal datums and tidal elevations are the responsibility of the Center for Operational Oceanographic Products and Services (CO-OPS) of the NOAA. Federal standards and methods for determining orthometric datums and elevations are the responsibility of the U.S. National Geodetic Survey (NGS). The NGS develops and maintains the current national orthometric vertical datum, called the North American Vertical Datum of 1988 (NAVD 88).

The tidal datums of greatest importance to tidal marsh restoration and protection are Mean Low Water (MLW), the average of all low tides during the National Tidal Datum Epoch (NTDE; see Section 2.1 above); Mean Lower Low Water (MLLW), the average of the lower of the two daily low tides during the NTDE; Mean High Water (MHW), the average of all high tides during the NTDE; and Mean Higher High Water (MHHW), the average of the higher of the two daily high tides during the NTDE. The tidal datums of San Francisco Bay, or Richardson Bay, are not flat, but vary between locations. For example, MHHW observed in San Francisco is lower than MHHW observed across the Bay in Alameda. The CO-OPS of NOAA publishes the relationship between NAVD88 and various tidal datums, such as MLLW and MHHW, as well as other tidal statistics, for each of its currently operating Control Tide Stations, where tide height measurement are ongoing, and some of its historical subordinate stations, where tidal datums have been determined in the past but are not necessarily updated for the current NTDE.

Subordinate Tide Stations located two historical CO-OPS within Richardson Bay. Both are in Sausalito. Station 9414819 is located at the dock used by the U.S. Army Corps of Engineers (COE), and Station 9414806 is located at Alexander Avenue. These were subordinate stations operated in the late 1970s to reference local tidal benchmarks to the 1960-1978 tidal epoch, based on corresponding tide height observations at the primary Tide Station 9414290, located inside the Golden Gate, near Fort Point at the Presidio in San Francisco. Tide Station 9414290 has a period of continuous record beginning in 1854. Of the two subordinate station in Sausalito, Station 9414819, the COE Dock Station, is nearer Bothin Marsh. Its tidal statistics have been updated by CO-OPS for the current tidal epoch (1983- 2001). The tidal datum sheet for COE Dock Station states that NAVD88 is 0.17 feet (2.04 inches) lower than local MLLW, the conventional zero tide datum for the U.S. West Coast (Figure 2.6). MHHW is 5.74 feet above MLLW, and 5.91 feet above NAVD88. For general purposes, tidal elevations at the COE Dock Station relative to NAVD88 are roughly the same elevation relative to MLLW. It is assumed that the correspondence between NAVD88 and MLLW observed for the COE Dock Station in Sausalito also exists for the foreshore (bayward margin) of Bothin Marsh. There are no long-term tide height data for Bothin Marsh or any other location near the upstream terminus of Richardson Bay.

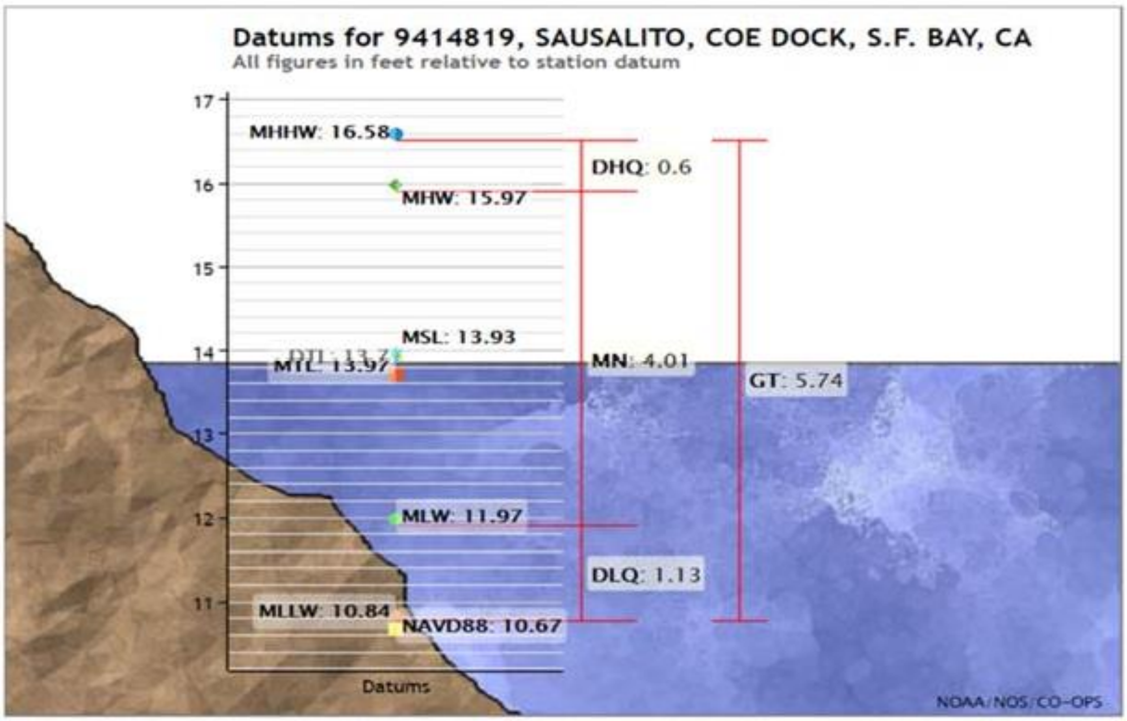


Figure 2.6. Tidal datums and other tidal statistics for the NOAA tidal station closest to the Bothin Marsh Complex, Station 9414819.

Short-term records of tide heights produced near Bothin Marsh for various engineering or other studies were not long enough to reckon tidal datums (e.g., Wetland Research Associates and Hydroikos Associates 2004, ESA PWA and Wetlands Research Associates 2006). However, the distance of tidal excursion between the COE Dock Station and Bothin Marsh is less than 2.0 miles, without obstructions. Furthermore, because of its location close to the Golden Gate, and with very little attenuation of the tidal range through Richardson Bay (Philip Williams & Associates 1983), the tidal statistics for the upstream terminus of Richardson Bay are likely to be very similar to those determined for the Presidio (see Table 2.2 below). Based on this assumption, local MHHW at the foreshore of Bothin Marsh is 5.91 feet NGVD [i.e., 16.58 (MHHW) – 10.84 (MLLW) + 0.17 = 5.91].

A recent regional modeling effort has generated estimates of tidal datums relative to NAVD88 for 900 study locations along the San Francisco bayshore, including locations within Richardson Bay (BCDC 2016). One study location is within 0.25 miles of South Bothin Marsh. While the model estimates agree well with datums determined empirically at NOAA control Tide Stations, their accuracy for subordinate stations and remote locations lacking empirical observations of tide heights remains uncertain. For the study station nearest South Bothin Marsh, the estimate of MHHW is 6.03 ft NGVD88, which is 0.12 feet higher than the estimate derived from the data for the COE Dock Station (6.03 – 5.91 = 0.12). Without knowing which value is truly better, their average might be used. Based on this approach, Local MHHW corresponds to elevations of about 6.0 feet (5.97 ft) NGVD88 on the Lidar DEM of Bothin Marsh provided by Marin County.

For the Bothin Marsh Complex and its immediate environs, the vertical datum used by Google Earth closely approximates NAVD88, such that tidal elevations can be reasonably estimated to the nearest foot using Google Earth. This was determined by overlaying the LiDAR DEM (digital elevation map) on Google Earth and comparing elevations from the two maps for a variety of common locations.

| Datum | Sausalito Station: 9414806 | Sausalito NAVD88 | Presidio Station: 9414290 | Presidio NAVD88 | Presidio minus Sausalito |
|---|---|---|---|---|---|
| MHHW | 8.82 | 5.86 | 11.82 | 5.9 | 0.04 |
| MHW | 8.23 | 5.27 | 11.21 | 5.29 | 0.02 |
| MTL | 6.25 | 3.29 | 9.16 | 3.24 | -0.05 |
| MSL | 6.2 | 3.24 | 9.1 | 3.18 | -0.06 |
| DTL | 5.98 | 3.02 | 8.9 | 2.98 | -0.04 |
| MLW | 4.28 | 1.32 | 7.11 | 1.19 | -0.13 |
| MLLW | 3.13 | 0.17 | 5.98 | 0.06 | -0.11 |
| NAVD88 | 2.96 | 0 | 5.92 | 0 | 0 |

Table 2.2. Correspondence between tidal datums for the NOAA Control Tide Station 9414290 at the Presidio in San Francisco and for the NOAA subordinate station 9414806 in Sausalito (NOAA 2017).

### 2.4.2 Migration Models

The simplest migration models fill Richardson Bay to a designated orthometric or tidal elevation, as if sea level rise were uniform throughout the Bay. For that reason, these models are sometimes referred to as "bathtub models." They assume that the existing topography will persist, and all structures, such as roadways and levees that might prevent migration are ignored. They do not account for any natural landscape change due to migration, such as the landward migration of dunes, beaches, or overwash berms.

Migration models are gaining sophistication, not only because of their ability to incorporate multiple local phenomena affecting migration distance and rates, but because they are being developed for specific audiences and applications. The status of migration models and visualization tools has recently been summarized for California by Climate Central (The Nature Conservancy et *et al*., 2017). In San Francisco Bay, migration models are beginning to incorporate the concept of a terrestrial-estuarine transition zone (Goals Project 2015), which encompasses the bayward extent of terrestrial and fluvial effects, and the landward extent of tidal effects on ecosystem form, composition, and function.

The most sophisticated modeling product generally applicable to Richardson Bay is the Coastal Storm Modeling System (CoSMoS). It is a dynamic 2-D wave modeling approach developed by USGS for predicting coastal flooding due to both future sea level rise and storms integrated with long-term coastal evolution (i.e., beach changes and cliff or bluff retreat). CoSMoS models all the relevant physics of a coastal storm (e.g., tides, waves, and storm surge), which are then scaled down to local tidal flood projections for use in community-based coastal planning and decision-making. Rather than relying on historical storm records, CoSMoS uses wind and pressure from global climate models to project coastal storms under changing climatic conditions. Projections of multiple storm scenarios (daily conditions, annual storm, 20-year- and 100-year-return intervals) are provided under a suite of sea level rise scenarios ranging from 0 to 2 meters (0 to 6.6 feet), along with an extreme 5-meter (16-foot) scenario. This is intended to enable users to manage future risks within their chosen planning horizons. The current version of CoSMoS for San Francisco Bay incorporates the effect of ocean swell penetration through the Golden Gate, vertical land motion (lifeet or subsidence), marsh accretion or erosion, vegetation-related LiDAR error, DEM uncertainty, and flood model uncertainty. Future integration of the modeled local tidal datums into CoSMoS can be anticipated. All migration models will need to be adjusted for revised estimates of sea level rise rates.

Wave run-up can be a significant factor in local tidal flooding. Waves dissipate upslope to higher elevations than predicted by sea level rise. Run-up can cause levees to be overtopped and significantly increase the risk of shoreline erosion. Wave heights increase with water depth, and the erosive power of waves might increase as sea level rises. Run-up heights and associated risks are greater along shorelines downwind of long fetches. CoSMoS 2.1 incorporates wave run-up inundation estimates in 0.8 feet increments for a variety of storm and tides scenarios.

In upper Richardson Bay, the usual fetch is northwesterly and attacks the levee of the Bay Trail along the northwestern side of South Bothin Marsh. The strongest winds tend to occur during the onset of major storms, however, when winds are southeasterly, and waves attack the foreshore of North Bothin Marsh. This helps explain the overwash berm and associated pannes that characterized the historical southeastern foreshore of historical Almonte Marsh (see Chapter 3)

Public access to output from CoSMoS is provided by Our Coast Our Future (OCOF). OCOF is a collaborative, user-driven web-based information delivery system that provide coastal resource managers in California locally relevant, online maps and tools to help understand, visualize, and anticipate vulnerabilities to sea level rise (http://data.pointblue.org/apps/ocof/cms/uploads/documents/OCOF_two%20pager_Jul2016.pdf). Some important features of OCOF include:

- Seamless Digital Elevation Model (DEM) at 2 meter horizontal resolution;
- Combination of 40 different sea level rise and storm scenarios, plus a King Tide scenario for San Francisco Bay, using the USGS CoSMoS;
- Interactive flood map including tidal flood extent, depth, duration, wave heights, current velocity, minimum and maximum flood potential, as well as the option to compare scenarios;
- Online and downloadable data access tailored to users information needs;
- Information on how and where products have been used, as well as links to end-users to promote sharing of lessons learned;
- New features and products will be available as they become needed and funding is available.

### 2.4.3 Regional Variability

The likely variability in sea level rise throughout San Francisco Bay is starting to be investigated. This includes modeling sea level rise with respect to spatial differences in tidal datums (Knowles 2010, BCDC 2016), and the effect of the Bay's bathymetry and planform on sea level, including relationships between shoreline modification at one location and sea level in other locations. Hardening the shoreline with levees and sea walls in one area of the bay transfers the risk of flooding to other areas (Holleman and Stacey 2014). Understanding the relationships among shoreline management, sea level rise, and tidal flooding will improve local shoreline planning (see Figure 2.7 below).

Studies to date indicate that future migration can mitigate sea level rise by decreasing tidal amplification, although this is likely to vary among the major basins of the Bay. It is important to emphasize the fact that reinforcing and hardening impacted shorelines can increase flood risks elsewhere. The distance over which these effects can be transmitted depends on the amount of total length of hardened shoreline, and basin bathymetry, as well as where in the bay the hardening occurs. Restoration of tidal marshland and construction of new low-lying tidal areas offer significant protection from rising tides by dissipating tidal energy, and these benefits may extend well beyond the areas directly sheltered by marshland (Holleman and Stacey 2014).

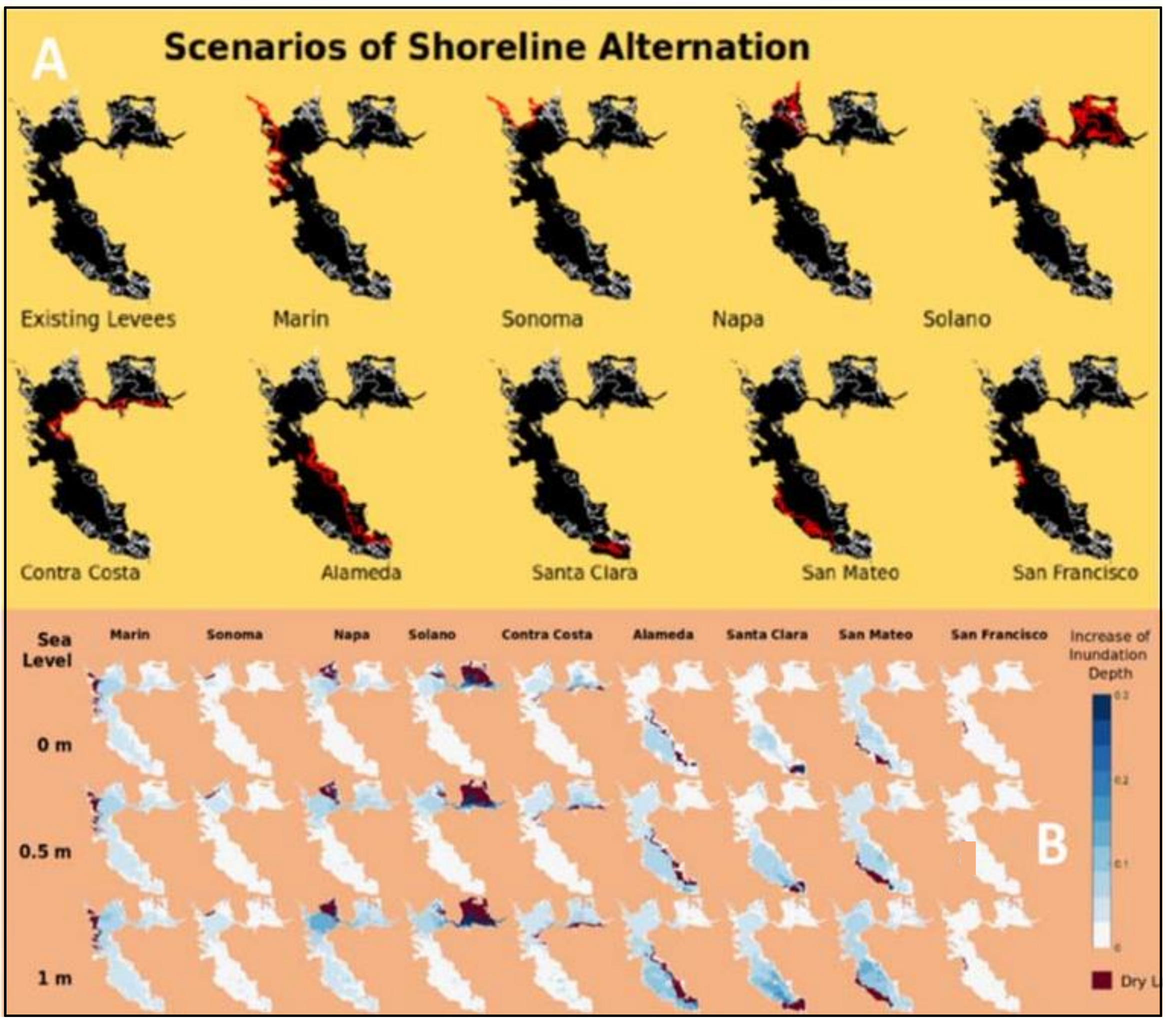


Figure 2.7. (A) Summary of hypothetical, future, county-based shoreline hardening scenarios (colored red) and (B) their regional effects on sea level, with darker areas indicating increased depth. Figure courtesy of Mark Stacey (Stacey 2017)

Studies of the possible effects of sea level rise on local transportation and the economic and overall social well-being of the Bay Area are also underway. The strong indication is that a Bay Area regional approach is needed to coordinate sea level planning and response. The dynamic interactions between shoreline modification in one area and sea level rise and tidal flooding elsewhere (Holleman and Stacey 2014) are matched by the effects on commerce and economy (Stacey 21078) (Figure 2.8).

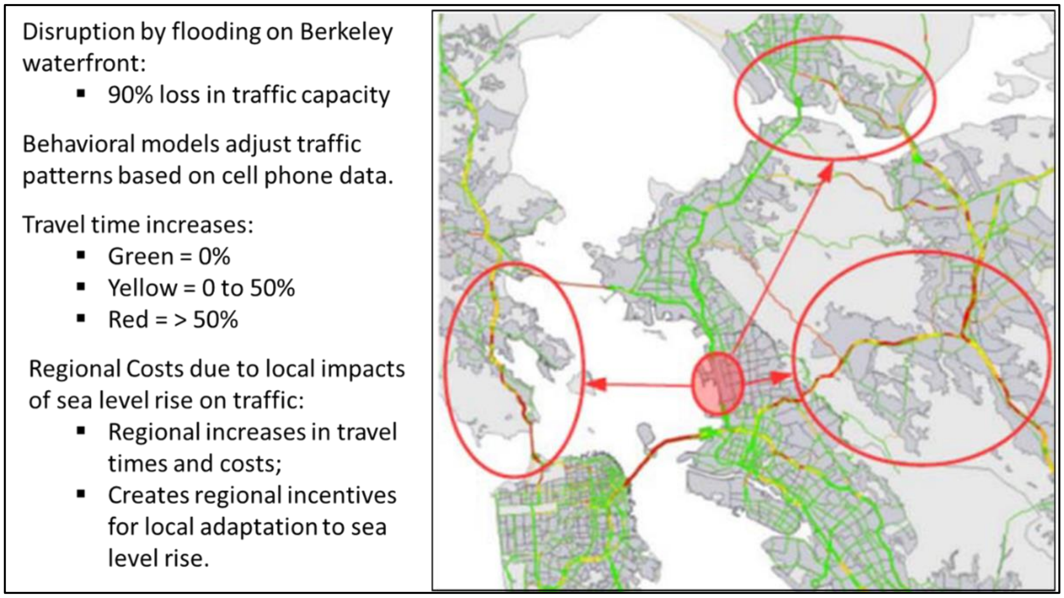


Figure 2.8: The expected effects of tidal flooding in Berkeley on travel times at major highways elsewhere in the region, illustrating the regional scope of inter-relations among local vulnerabilities. Figure courtesy of Mark Stacey (Stacey 2017).

### 2.4.4 Application of Sea Level Rise Forecasts to Bothin Marsh

Ongoing engineering and planning studies for bridges at Bothin Marsh provide the most current insights into local application of sea level rise forecasts and related tidal statistics. These studies are exploring new hydraulic criterion for the bridges to clear the 50-year storm, plus the highest King Tide on record for the past 20 years, plus the projected maximum sea level rise for 2030 (Figure 2.9 and Table 2.3). While there are uncertainties in the determination of local tidal datums and application of sea level rise forecasts, the studies nevertheless provide an example of incorporating this important information into local coastal engineering analysis and plans.

For the purpose of illustration, OCOF was used to estimate the extent of future tidal flooding at Bothin Marsh (Figure 2.10). OCOF enables the user to choose among a fixed set of sea level rise scenarios, and to choose whether to address King Tides or wave run-up. A sea level rise forecast of 66 inches for 2100 is not available. The 68.4-inch (5.7 feet) scenario was selected instead, plus the maximum expected King Tide. The forecasts for the ongoing Bothin Marsh bridge study and the OCOF illustration therefore differ by a few inches (68.4 inches versus 66 inches). However, the OCOF provides a reasonable approximation of the extent of flooding for the 2100 conditions being considered in the bridge study. It should be noted that the OCOF illustration does not reflect any changes in landform or land use related to migration that might affect the future extent of flooding.


| Bothin Marsh Bridge No. | Highest Observed King Tide | 50-yr Storm Plus Highest King Tide | 50-yr Storm Plus Highest King Tide + Maximum Sea Level | | |
|---|---|---|---|---|---|
| | | | 2030 | 2050 | 2100 |
| 1 | 8.7 | 8.8 | 9.7 | 10.7 | 14.2 |
| 2 | 8.7 | 8.7 | 9.7 | 10.7 | 14.2 |
| 3 | 8.7 | 9.2 | 10.2 | 11.2 | 14.2 |
| 4 | 8.7 | 8.7 | 9.7 | 10.7 | 14.2 |

Figure 2.9 and Table 2.3. Locations of four bridges near Bothin Marsh and the associated preliminary forecasts of water surface elevation in feet relative to NAVD88, due to the combined effects of sea level rise, rainstorm discharge, and King Tide. The 50-year storm values were provided by FEMA. King Tide values were evidently taken from the nearest NOAA Tide Station (COE Dock Station 9414819 in Sausalito). The forecasts for seal level rise were provided by NRC (NRC 2012), using the 66-inch value for 2100. Wave run-up was disregarded. All elevations are relative to NAVD88, which equals MLLW minus 0.17 feet.

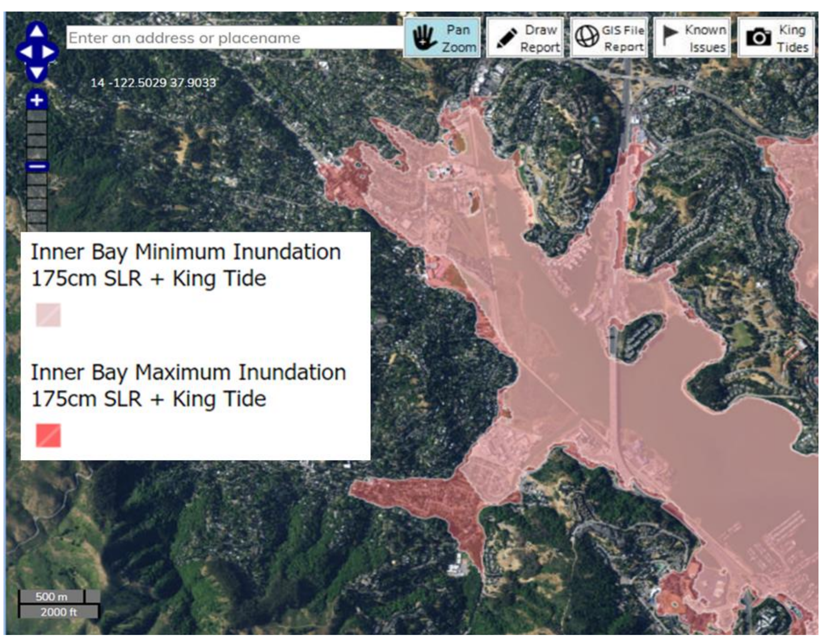


Figure 2.10. Screenshot from the OCOF website showing estimated future inland extend of tidal flooding due to about 69 inches of sea level rise plus maximum predicted King Tide. Stream flow and wave run-up are disregarded. Note that the minimum predicted tidal inundation extends inland and upstream beyond the

## 2.5 General Adaptation Strategies

Understanding the short and long-term costs and benefits of different adaptation strategies, as well as the costs of not taking action, is critical to choosing a strategy that is optimal. The choice is not based solely on economics. Other factors to consider include community culture, ecological benefits, and administrative and legal aspects. The unique conditions, history, and desired vision of each community will influence decisions about how it should best adapt to sea level rise. The optimal adaption strategy will have multiple benefits across a range of social and environmental considerations.

Sea level rise can negatively impact values of properties and industries within the expected areas of migration (Pew Center 2000, California Climate Change Center 2009). Disadvantaged communities may be especially threatened due to their relative lack of access to financial resources necessary to mitigate the threat through structural or landscape engineering (Martinich *et al*. 2013, Stutz 2017). Furthermore, the depressed equity of properties within disadvantaged communities limits opportunities to retreat to safer areas through real estate transaction. The possibility exists that these communities will be sacrificed as residential or industrial areas to create migration space that mediates the threat of sea level rise for other areas having more highly valued properties and industries. One consideration is that the lands owned by disadvantage communities have value as migration space that can be monetized. Part of this value is the equity of other lands that is protected by the sacrifices of the disadvantaged communities, which can be figured into the purchase of developmental rights (Eastern Research Group, Inc. 2013). These situations raise serious issues about environmental justice that might only be resolved through regional investments in local sea level rise planning (Kerlin 2017, Stacey 2017).

There is a variety of actions that can be incorporated into an adaptation strategy. All strategies involve engineering and economic analyses, as well as public outreach and education. The other actions that distinguish one strategy from another and that might be suitable for Bothin Marsh are outlined below. They generally can be aggregated into two groups: containment and accommodation.

### 2.5.1 Containment

Containment is the use of engineered structures, such as levees, dikes, and seawalls, to prevent sea level migration. Containment has been the conventional approach to defending lands against gradual rates of sea level rise (Spalding *et al*. 2014), since the advent of long-term, intransient agrarian societies (Needham 1971). The first known coastal dikes or levees are perhaps 5,000 years old (Lander 2014), and their development thus corresponds to the period of marked decrease in the rate of sea level rise (see section 2.1 above). Given the accelerated rates of sea level rise predicted for the future, structures built to prevent migration may have to be raised repeatedly. There are structural limits, of course, to their maximum heights. Large costs are associated with pumping or siphoning floodwaters from behind containments.

### 2.5.2 Seawalls

Seawalls are vertical or near-vertical structures built along the coast and designed to prevent erosion and coastal flooding of the areas behind them. Seawalls form a protective wall in front of coastal structures and may be constructed from a variety of materials, including concrete, steel, wood, and boulders.

### 2.5.3 Levees and dikes

Levees and dikes are constructed embankments designed to reduce the risk of flooding to the areas behind them. Levees typically are built parallel to the course of a river or coastline in order to contain, control, or divert the flow of water. Levees are constructed from compacted soil or artificial materials such as concrete or steel. To protect against erosion and scouring, earthen levees can be covered with grass, or a hard surface such as rock rip-rap or concrete.

### 2.5.4 Horizontal Levees

The horizontal levee is a recent addition to the array of levee types that have been constructed in the Bay Area (ESA PWA 2013, Myers 2017). The version most commonly discussed around San Francisco Bay consists of a levee with adjoining supra-tidal lands (i.e., lands above MHHW) on the outboard or bayward side that are gently graded to provide habitat and perhaps passive outdoor recreation compatible with sea level migration (see Figures 2.11 and 2.12 below). Similar concepts are referred to as “laid back Levees” or “habitat levees’, and can be collectively described as hybrid combinations of natural and built infrastructure that enhance coastal resilience to storm and coastal flooding protection, while also providing other benefits (Sutton *et al*. 2015).

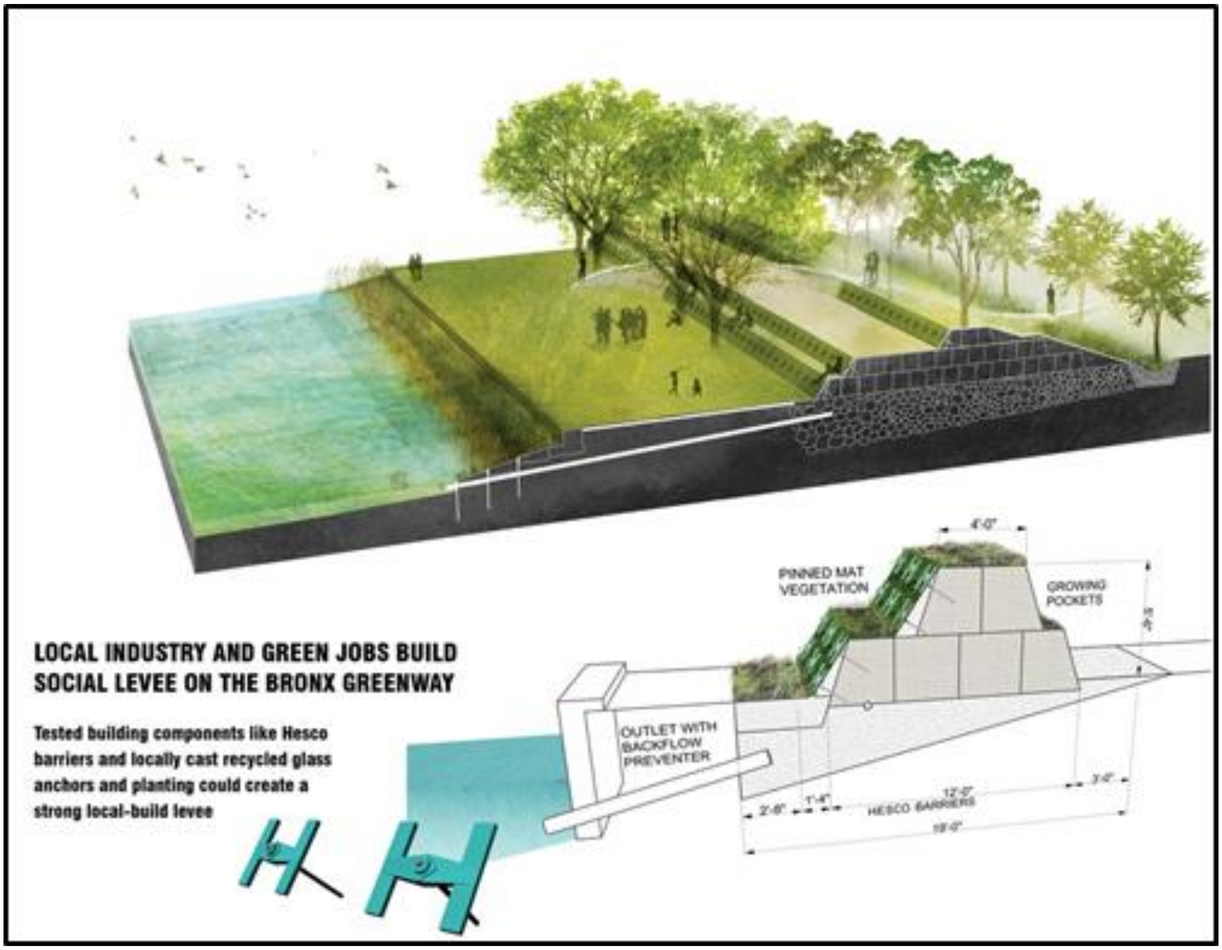


Figure 2.11. Conceptual multi-benefit horizontal levee, featuring social amenities including pedestrian and bicycle pathways. (http://www.loversiq.com/o/214876113/landscape/214876/).

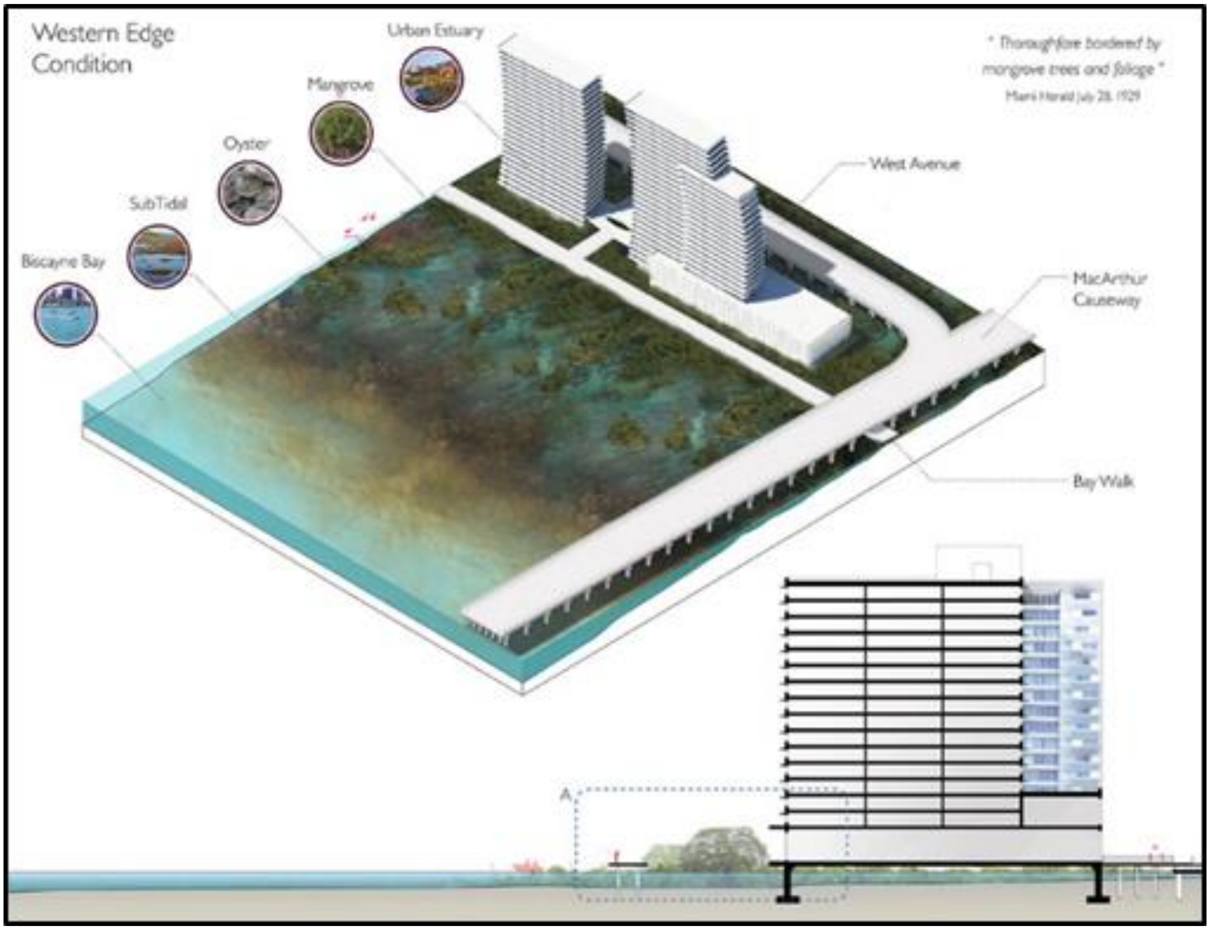


Figure 2.12. Conceptual multi-benefit horizontal levee, featuring a living shoreline of natural wildlife habitat plus social amenities including pedestrian and bicycle pathways for Miami Beach FL (https://www.vanityfair.com/news/photos/2015/11/miami-beach-rising-sea-levels-plan).

A local example of the multi-benefit potential of horizontal levees is the Ora Loma Project in Hayward (Ora Loma Sanitary District 2015). The project is based on a concept generated for San Francisco Bay (see Figure 2.13 below). The Project is designed to filter wastewater, provide habitat, and increase the resilience of the local shoreline to sea level rise. The project involves a basin that removes nutrients from wastewater while providing increased capacity to store stormwater during heavy rains. Wastewater that has undergone secondary treatment passes through the wetland and then through the levee to create habitat on the broad outboard levee slope. The surface and sub-surface filtering processes of the levee are expected to support native plants and purify the water enough to permit its safe discharge directly into San Francesco Bay. In the first year since its construction, the native vegetation planted in the treatment wetland and on the levee is meeting performance measures. Over the next 3-5 years, a UC Berkeley research team will evaluate the effectiveness of the project to treat wastewater as well as provide habitat. While horizontal levees provide resistance to sea level rise, they also adapt to it by creating migration space. Therefore, they can be regarded as a type of landscape adaptation.

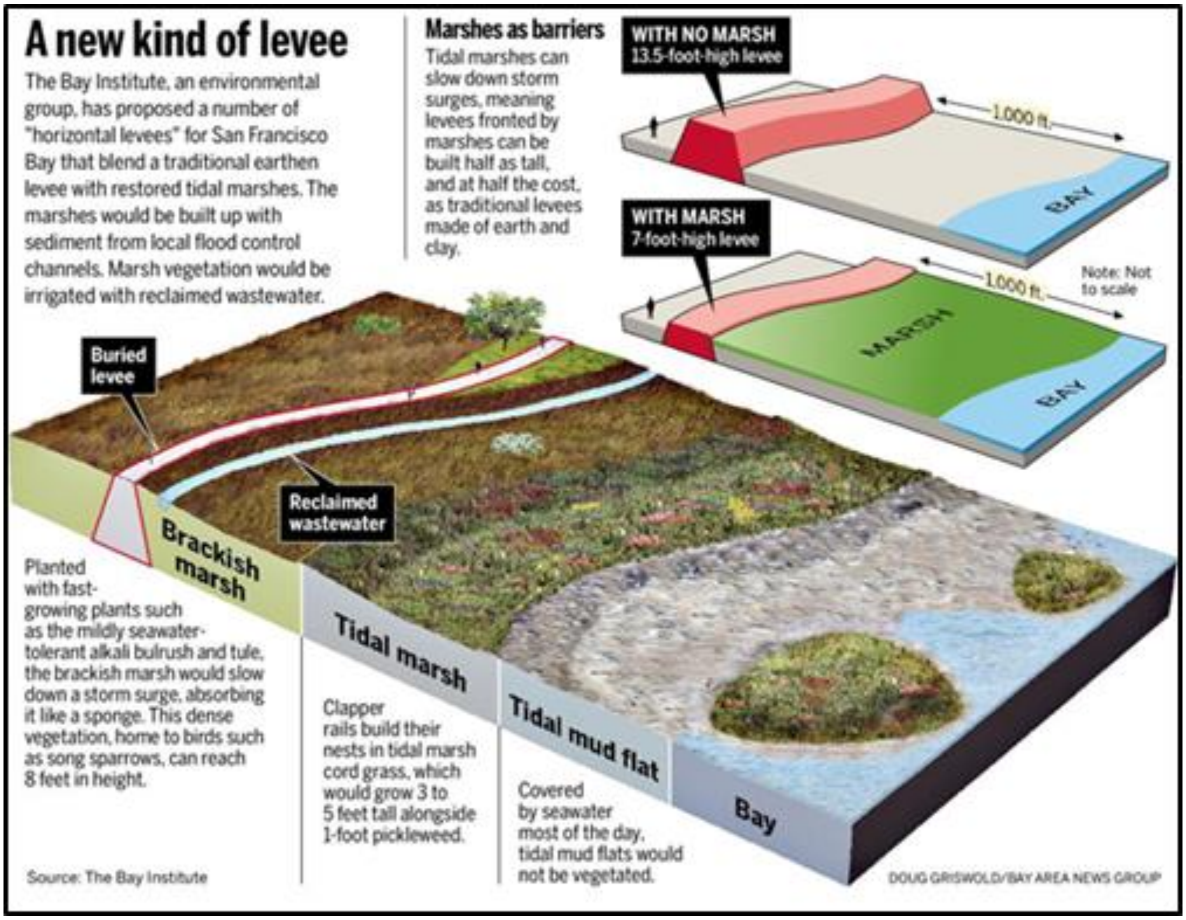


Figure 2.13. Multi-benefit horizontal levee conceptualized for San Francisco Bay, featuring a living shoreline of natural intertidal wildlife habitat plus a pedestrian and bicycle pathway (ESA PWA 2013, https://issuu.com/thebayinstitute/docs/slr_executive_summary-oro_loma_fina).

### 2.5.5 Containment at Bothin Marsh

There are various levees and dikes that historically have constrained tidal flooding at the Bothin Marsh Complex and its immediate environs (see Figure 2.14, below). They were constructed to support railroading, reclaim tidal marsh, contain dredged sediment, and provide flood control. The history of these features is provided elsewhere in this report (see Chapter 3). In addition to the levees, there are areas of artificial fill that provide some containment.

All of the exterior levees and dikes, except for the flood-control levees along the creeks draining to the Bothin Marsh (see levees shaded pink in Figure 2.14 below) are breached and can be overtopped by King Tides, due in part to wave run-up (personal observations of the authors). Even if their breaches were eliminated, none of these levees and dikes are high enough to resist tidal flooding beyond 2030, especially during King Tides or major storm events, when creek discharges and wave run-up are high.

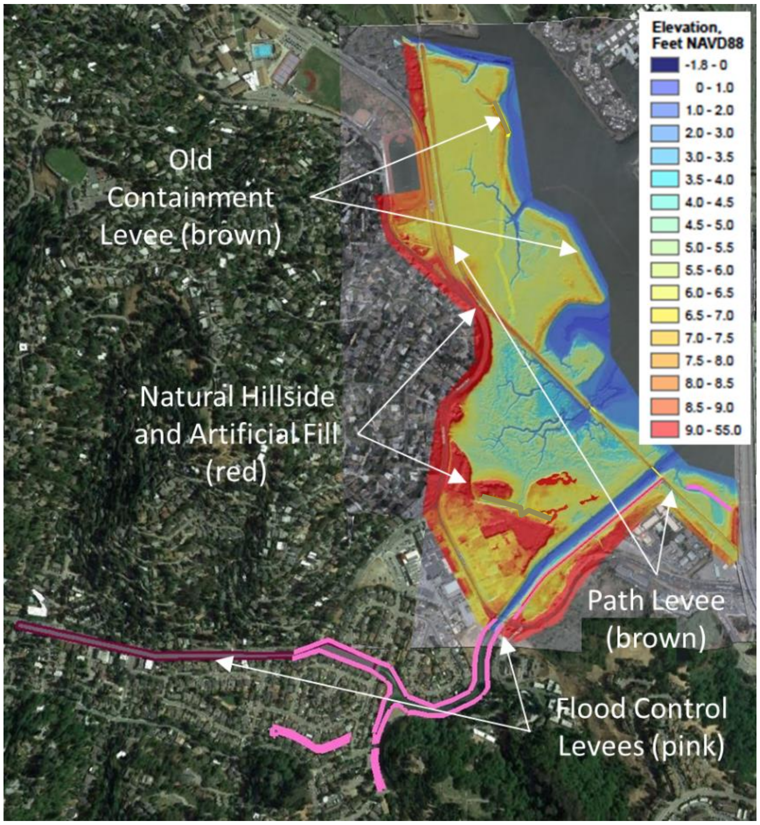


Figure 2.14. Example containment levees of varying age and purpose at the Bothin Marsh Complex, as evidenced by elevation and analysis of land use history (see Chapter 3).

### 2.5.6 Accommodation

Accommodation of sea level rise can be defined as the dedication of lands to the inland migration of tidal waters, as a well as the policies and financial mechanisms to achieve the dedication. The dedicated land is commonly called migration space.

There are many possible approaches to accommodation, or the provision of migration space, some of which are potentially suitable for the Bothin Marsh Complex.

The resources listed below provide national and statewide guidance on adaptation to sea level rise, including accommodation. Most of the national guidance is general and would need to be adapted to the local physical and social landscape. However, the general guidance provides many useful and creative ideas that can benefit local accommodation planning.

- NOAA: Adapting to Climate Change: A Planning Guide for State Coastal Managers (https://coast.noaa.gov/czm/media/adaptationguide.pdf).
- USEPA Adapting to Climate Change (https://archive.epa.gov/epa/climatechange/adapting-climate-change.html).
- Georgetown Climate Center: Adaptation Tool Kit: Sea-Level Rise and Coastal Land Use How Governments Can Use Land-Use Practices to Adapt to Sea-Level Rise (http://www.georgetownclimate.org/files/report/Adaptation_Tool_Kit_SLR.pdf).
- California Coastal Commission: Sea Level Rise Policy Guidance: Interpretive Guidelines. (https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0_Full_Adopted_Sea_Level_Rise_Policy_Guidance.pdf).
- Coastal and Ocean Working Group, California Climate Action Team: State of California Sea Level Rise Guidance Document (2018 update forthcoming) (http://www.opc.ca.gov/webmaster/ftp/pdf/docs/2013_SLR_Guidance_Update_FINAL1.pdf
- California Energy Commission, Adapting to Sea Level Rise: A Guide for Coastal Communities.

(https://seymourcenter.ucsc.edu/OOB/Adapting%20to%20Sea%20Level%20Rise.pdf).

Managed retreat (USACE 2012) or managed realignment (Esteves 2014) is often cited as means of accommodation. These are broad ideas that require one or more of the following activities to achieve. The land use activities and their legal or economic instruments of achievement are grouped separately. This is not an exhaustive list. The very broad range of activities were filtered by their applicability to the Bothin Marsh Complex.

### 2.5.7 Legal or Economic Instruments

#### 2.5.7.1 Transfer of Development Rights

A transfer of development rights (TDR) is a way for property owners to transfer development rights to one another. In the context of migration or tidal flooding, TDR can be used to move future development from migration spaces. TDR can also be used to preserve open space, thereby facilitating the implementation of other mitigation measures, such as wetlands development or other green infrastructure to further increase a community's resilience to coastal flooding. TDRs are usually administered through a local government zoning ordinance, with specific districts zoned to either give or receive development rights (American Planning Association 2006).

#### 2.5.7.2 Purchase of Development Rights

Purchase of development rights (PDR) involves a local government or nonprofit purchasing development rights while the land remains privately owned. This restricts the future use of a property from certain types of development and is often used to preserve open space or farmland. In the context of coastal flooding, this can be used as a measure to prevent future development from occurring in migration spaces (American Planning Association 2006).

#### 2.5.7.3 Rolling Easements

Rolling easements prohibit engineered barriers or other types of containment and involve removal of structures seaward of a migrating shoreline (EPA 2011). Rolling easements ensure existing migration space into the future. Structures that become threatened by tidal flooding are removed. Rolling easements can discourage future development in anticipated future migration spaces. As the shoreline continues to recede, the easement "rolls" farther inland. The intent of rolling easements is to allow natural migration to take place.

#### 2.5.7.4 Fee-Simple Acquisition

Fee-simple acquisition involves the outright purchase of property and all associated development rights (Berger 2012). Fee-simple acquisition is often used when local governments purchase waterfront properties that are vulnerable to erosion and flooding. In the context of coastal flooding, the purpose of the acquisition is to remove or prevent future development in vulnerable areas and to reduce future damage from coastal flooding. Fee-simple acquisitions can be used in conjunction with other managed retreat policies to preserve open space, which in turn can be used to implement other mitigation measures, such as wetlands development or green infrastructure, to increase a community's resilience to coastal flooding.

#### 2.5.7.5 Zoning in Migration Spaces

Zoning ordinances restrict allowable land uses for a defined area. Zoning may regulate land use kind, intensity, and density, and can regulate architectural design and other aspects of development. In the context of sea level rise and tidal flooding, zoning can prevent or limit development in migration spaces, ensure that new development does not increase the severity of flooding, and require that new and renovated structures incorporate flood-resilient designs and features. Local ordinances must, at a minimum, comply with federal requirements for developing within floodplains, and many zoning ordinances already include measures related to flood-hazard areas.

#### 2.5.7.6 Development Fees in Migration Spaces

Development fees are one-time charges imposed by local governments on new development projects to cover costs for infrastructure outside the developed area. In the context of sea level rise, development fees can be used to remove containment structures in areas otherwise suitable for migration.

### 2.5.8 Land Use Activities

#### 2.5.8.1 Infrastructure Relocation

Infrastructure relocation involves moving vulnerable infrastructure away from known or anticipated migration spaces. Relocation can be a viable option for many types of infrastructure, including roads, bridges, buildings, overhead utilities, and containment features such as levees and dikes. Moving infrastructure may involve physically relocating the existing infrastructure, constructing new replacement infrastructure, or otherwise shifting the function of the infrastructure to a different location.

#### 2.5.8.2 Elevated Development

Elevated development involves physically raising infrastructure (e.g., on stilts/pilings or raised land) so that tidal waters can temporarily and harmlessly flow underneath or around (UNESCO 2002) without harming the structure. Elevated development can be included in the original design or added as a retrofit. Traditionally, only buildings are elevated, while the surrounding infrastructure (e.g., roads, walkways) is not. While a building may be protected from flood damage, access to it may be limited during a coastal flood. It is possible to raise surrounding infrastructure, including roads, bridges, walkways, and utility lines. A common example of elevated development is beach homes built on stilts, often with the first floor at a height of 10 feet or more above ground level. Elevating structures is a relatively easy feature to incorporate into the design of a facility or infrastructure during initial construction, but it is more challenging to incorporate as a retrofit. Physically raising a structure that is already elevated slightly (e.g. with a crawlspace) is more feasible than elevating “slab-on-grade” construction.

#### 2.5.8.3 Floating and Floodable Development

Floating structures rise vertically on top of floodwaters instead of being inundated. The structures are prevented from moving horizontally by pilings or similar anchors that keep them in the same location and prevents them from floating away (UNESCO 2002). Only individual buildings are constructed on floating foundations. Floodable buildings experience minimal structural damage to being flooded. On a larger scale, floodable development can include structures and green infrastructure designed to capture, retain, and gradually release tidal water during ebb tide.

#### 2.5.8.4 Movable Buildings

Movable buildings are designed to be easily relocated in advance of sea level migration. The most common movable buildings are trailers and modular buildings, which are moved by truck or train. These buildings are usually left on trailers or set on a concrete slab foundation.

#### 2.5.8.5 Tidal Wetland Creation, Restoration, and Enhancement

Coastal wetlands provide more than $23 billion annually in storm protection (Anderson and Mulder 2008). They have significant value in protecting shores from erosion by anchoring sediments and dissipating the erosive energy of tidal currents, storm surges, wind waves (e.g., Shephard *et al*. 2011, Goals Project 2015). Communities can take steps to conserve, enhance, restore, or create wetlands in suitable intertidal areas. The conservation of tidal marshes can involve many scientific and engineering disciplines.

There is increasing concern that tidal marshes may drown due to rates of sea level rise that exceed rates of sediment accumulation and marsh accretion (Nuttle *et al*. 1997, Orr *et al*. 2003, Stralberg et al *et al*. 2011, Kirwan and Megonigal 2013, Mercury News 2016). There is a concomitant interest in developing methods to supplement natural tidal marsh accretion processes with suitable imported sediment (Roman and Burdick 2012), most commonly by the direct application of dredged sediment to the marsh surface (e.g., Marcus 2000, Schrift *et al*. 2008), or by redirecting fluvial sediment from nearby rivers and streams (e.g., SFEI 2015). The need to restore and sustain tidal marshes in San Francisco Bay as part of sea level rise accommodation and adaptation is well recognized (Goals Project 2015, San Francisco Bay Restoration Authority 2015), and is reflected in past efforts to conserve Bothin Marsh (e.g., Leventhal and Baye 2015).

### 2.5.9 Regional Initiatives

There are a number of regional projects converging on innovative designs for increasing the resilience of the natural and built shoreline landscapes of San Francisco Bay to climate change, especially sea level rise. Each effort intends to integrate landscape architecture, social science, and environmental science into model approaches and operational examples of sea level rise adaptation. The response of the regulatory and management agencies is uncertain, given that there is no legal obligation to adopt any of the findings or recommendations. However, it is likely that the projects will widen the field of view to recognize new opportunities and possibilities, while improving collaboration across disciplines and public agencies.

#### 2.5.9.1 Flood Control 2.0 (http://www.sfei.org/flood-control-20)

Flood Control 2.0 is an innovative regional project that seeks to integrate habitat improvement and flood risk management at the Bay interface (SFEI 2017). The project focuses on helping flood control agencies and their partners create landscape designs that promote improved sediment transport through flood control channels, improved flood conveyance, and the restoration and creation of resilient bayland habitats. The project findings have been synthesized into an online “toolbox” that includes channel classifications and relevant management concepts for reconnecting the tidal marshes to their watersheds and creating a marketplace for tidal marsh restoration sponsors to find available dredged sediment, regulatory guidance, and benefit-cost analyses of current and alternative flood management practices.

#### 2.5.9.2 Adapting to Rising Tides (ART) (http://www.adaptingtorisingtides.org/)

In 2010, the San Francisco Bay Conservation and Development Commission (BCDC) and the NOAA Office for Coastal Management (NOAA OCM) brought together local, regional, state and federal agencies and organizations, as well as non-profit and private associations for a collaborative planning project to identify how current and future flooding will affect communities, infrastructure, ecosystems and economy. Since then, the ART Program has continued to both lead and support multi-sector, cross- jurisdictional projects that build local and regional capacity in the San Francisco Bay Area to plan for and implement adaptation responses to sea level rise. The ART Program is integrating adaptation into local and regional planning and decision-making in multiple ways:

- Leading collaborative adaptation planning projects that build a comprehensive understanding of climate vulnerability and risk;
- Building regional capacity for adaptation by working with local, regional, state and federal agencies to find funding;
- Advocating for adaptation by communicating findings, issues, processes and needs to state and federal agencies.

#### 2.5.9.3 Resilient by Design (RbD) (http://www.resilientbayarea.org/about/)

RbD is a collaborative research and design project that brings together local residents, public officials and local, national and international experts to develop innovative solutions to the issues relating to climate change. In a yearlong challenge, teams of engineers, architects, designers and other experts will work alongside community members to identify critical areas throughout the Bay Area and propose innovative, community-based solutions that strengthen the region's resilience to sea level rise, severe storms, flooding, and earthquakes. The result will be 10 implementable projects that offer an imaginative and collaborative approach to resilience.

### 2.5.10 Previous Adaptation Plans for Bothin Marsh

Multiple recent studies provide evidence of efforts to incorporate sea level rise forecasts into plans and management of Bothin Marsh or its associated infrastructure (ESA PWA and Wetlands Research Associates 2006, Leventhal 2015, Leventhal and Baye 2015, Marin County Public Works 2017, WRA Environmental Consultants 2017, WRECO 2017). In addition, OCOF can be used to visualize sea level rise at Bothin Marsh. No studies have been conducted regarding the possible effects of local shoreline modification on variations in tidal energy or sea level rise within Richardson Bay.

#### 2.5.10.1 ESA PWA and Wetlands Research Associates 2006

The following italicized project description was excerpted from the public document. The terminology was edited to maintain consistency with the rest of this report.

> *The purpose of this study is to evaluate options for combining wetlands enhancement with flood management in Coyote Creek Lower Reach (i.e., the Coyote Creek Canal or tidal reach of the creek bayward of Highway 1), improving both flood management and habitat restoration. The project area includes Coyote Creek Lower Reach (between Highway 1 and the Bay Trail) and the north and south basins of Bothin Marsh. The main project goals were:*
>
> - *Reduce the need for ongoing maintenance dredging in Lower Coyote Creek;*
> - *Improve the habitat value of wetland and upland areas in the project area.*

There was no objective to address explicitly sea level rise, although that was a background consideration (Phil Williams, personal communication). Based on the constraints and opportunities identified in the study, it provides four conceptual alternatives (see Figure 2.15 below). All alternatives seek to increase tidal prism in the lower reach of Coyote Creek (i.e., the Coyote Creek Canal) to reduce the need for future dredging. Note that each alternative plan involves breaching the northern levee of the Coyote Creek Canal near its intersection with an earlier route of Coyote Creek (See Chapter 3 of this report), with the intent of draining Bothin Marsh into the Canal. This would reverse the natural drainage direction. The plans depend on the marsh being flooded by the tides through the existing inlet at the Bay Trail, northwest of the Canal, and draining during ebb tide through the proposed breach of the Canal levee.

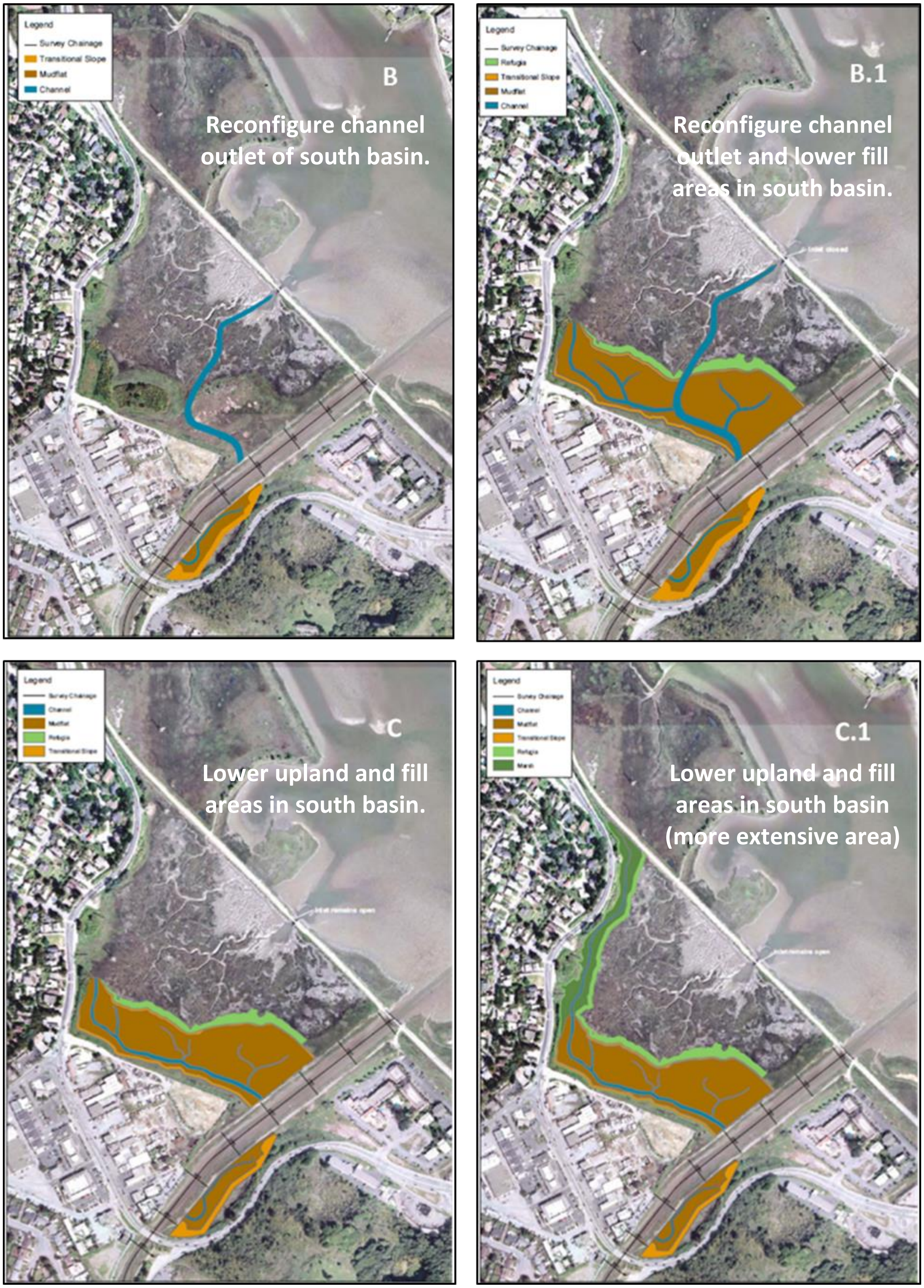


Figure 2.15. Four diagrams of conceptual plans to reduce the need for maintenance dredging of the Coyote Creek Canal by increasing its tidal prism while also improving aquatic habitats (PWA and Wetlands Research Associates 2006). Plans are described in text above.

#### 2.5.10.2 Leventhal 2015

The following italicized project description was excerpted from the public document. The terminology was edited to maintain consistency with the rest of this report.

> *The primary purpose of this study was to assess the impacts of sea level rise along parts of the Richardson Bay shoreline and to discuss a range of potential engineering and planning alternatives to increase the level of flood protection under selected scenarios of sea level rise. Adaptation options include a number of possible alignment alternatives for containment structures along the shoreline edge. In each case, alternatives were developed to inhibit direct coastal flooding and protect the built infrastructure along the urbanized shoreline edge. Therefore, no alternatives were developed that involved retreating or relocating buildings or existing infrastructure. However, the costs developed for protection in-place can be used as a baseline to compare against other adaptation approaches, such as planned retreat and removal of structures or utilities and use of larger, landscape-scale, natural approaches. Several nature-based solutions (horizontal levees and engineered beaches) have been included where they fit the landscape. For the sea level rise impact projections in this study, values for years 2030, 2050, and 2100 were taken from the NRC guidelines (NRC 2012). It was assumed that planning on a 30 to 100 year period is appropriate for major sea level rise adaptation strategies, given the potential expenditure of funds and the lifecycle of most infrastructure improvements. The project noted that any dates are subject to significant uncertainty and should only be read as a very approximate guide to the future to allow for long-term planning horizons.*

One of the interesting analyses of the report is the assessment of minimum elevations of containment structures to prevent their overtopping by King Tides and to meet FEMA flood protection standards under different sea level rise forecasts (Table 2.4). As stated in the report, how high to build a barrier depends on several factors including the level of protection desired, costs, impacts of overtopping, and the critical importance of the assets being protected. The significant differences in barrier elevations (Table 2.4) can translate to large cost differences.

| Year | Sea Level Rise Scenario (inches NAVD88) | Minimum Design Elevation (ft NAVD88) to Contain Annual King Tide | Minimum Design Elevation (ft NAVD88) to Achieve FEMA Certification |
|---|---|---|---|
| 2030 | 12 | 9 - 10 | 13 |
| 2070 | 36 | 11 - 12 | 15 |
| 2100 | 60 | 13 -14 | 17 |

Table 2.4. Design elevations for containment features having different performance objectives, such King Tide containment of FEMA certification. (Leventhal 2015).

A variety of possible alignments of containment features were developed based on sets of reasonable assumptions about flood control needs (Figure 2.16). The alignments serve to illustrate an approach to land use planning and do not represent the findings of final engineering studies. It should be noted that the alternative alignments were developed without the benefit of more recent studies showing how containment in one area of an embayment can affect flood risks elsewhere in the same embayment (Holleman and Stacey 2014, Stacey 2017). The idea of preventing tidal excursion into upper Richardson Bay (see Figure 2.16D, and Kennedy 1957) probably has serious implications for flood risks in others parts of San Francisco Bay. Individual containment projects will need to be assessed in terms of their cumulative effects on sea level rise and tidal flooding at a variety of spatial scales.

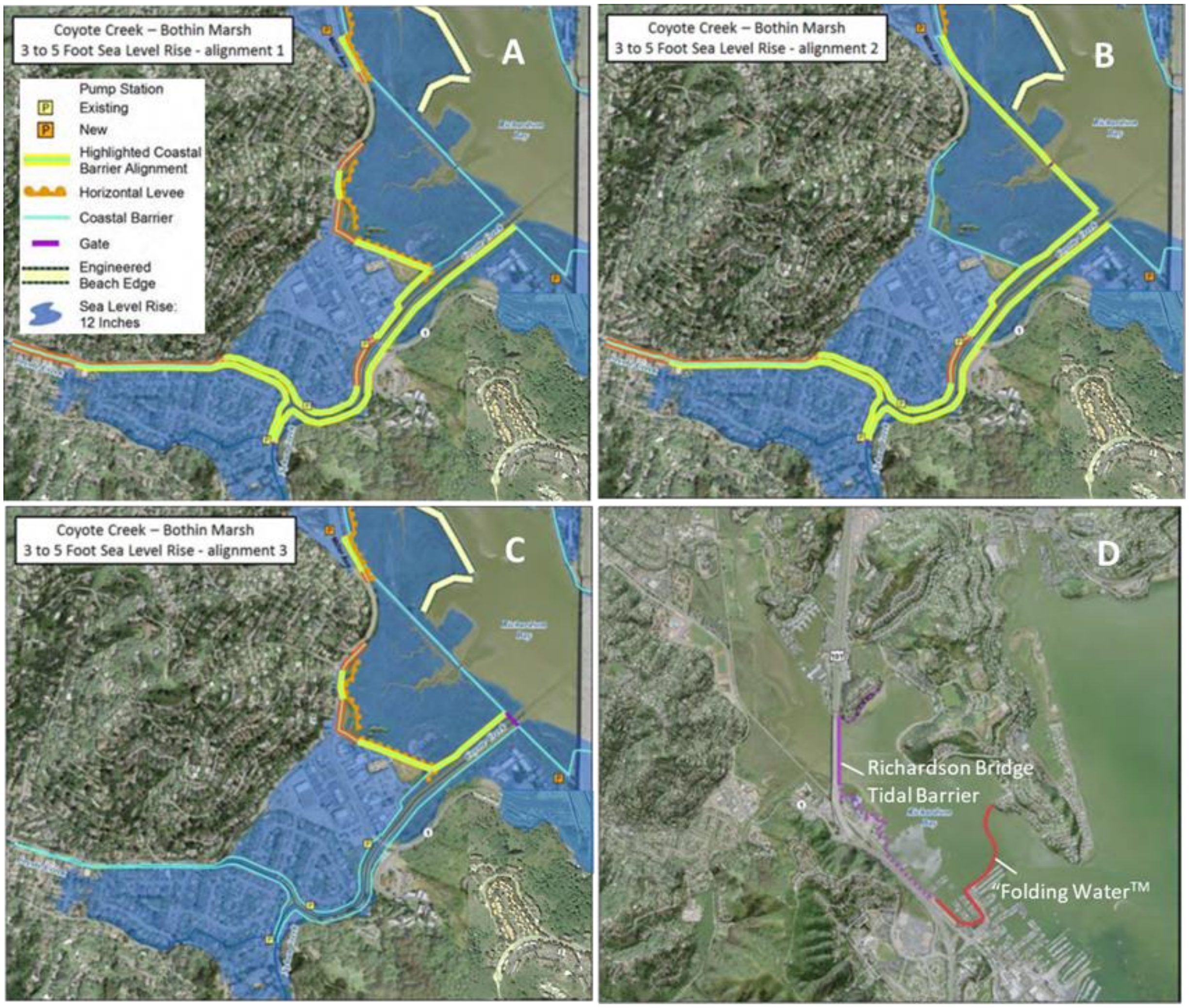


Figure 2.16. Example alternative alignments (A-C) for containment features at Bothin Marsh for a sea level rise of 3 - 5 feet NAVD88, plus (D) possible alignment of features affecting tidal containment throughout upper Richardson Bay (Leventhal 2015).

#### 2.5.10.3 Leventhal and Baye 2015

This study generated conceptual landscape plans for enhancing the ecology of Bothin Marsh and its resilience to sea level rise using naturalistic adaptation features. The value of the plans is their innovation, building on experience with horizontal levees and overwash berms, both of which have historical, natural analogues at Bothin Marsh. In many ways, these conceptual plans build on the previous site-specific studies of Bothin Marsh while incorporating concerns about sea level rise. The design elevations of the features would be based on the best available local information on tidal elevations and sea level rise relative to NAVD88 (Roger Leventhal, personal communication). In the context of recent forecasts of sea level rise for San Francisco Bay (Griggs *et al*. 2017), these conceptual plans are probably viable for a timeframe of 50-75 years, although some significant shifts in relative amounts of low and high intertidal habitats can be expected, with lower habitat types becoming more dominant. When combined with containment features designed to protect the adjoining built environment, these naturalistic features could provide adequate flood control and conserve local habitats for decades. Addressing sea level rise in the longer term will likely involve more difficult landscape activities, such as managed retreat.

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