CORTE MADERA BAYLANDS

Conceptual Sea Level Rise Adaptation Strategy

PREPARED BY

The San Francisco Bay Conservation and Development Commission and ESA PWA

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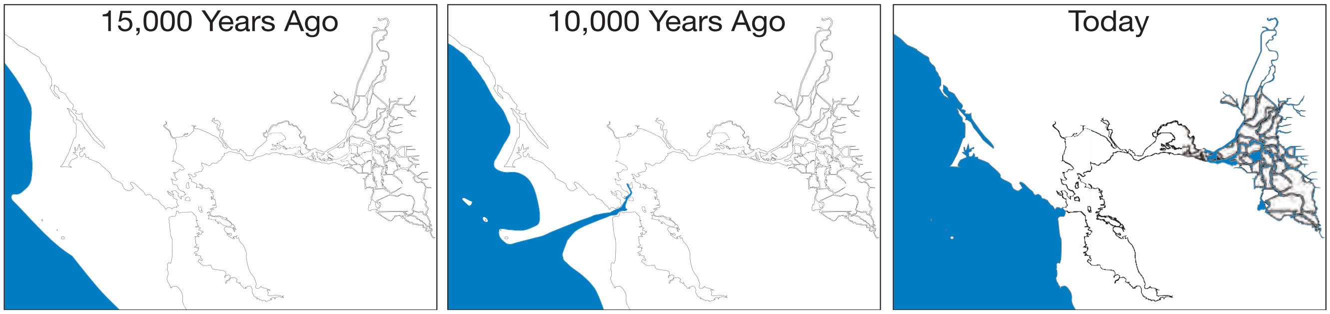

Cohen and Laws (2000)

Abstract

Baylands provide the first line of defense against coastal flooding along the San Francisco Bay shoreline. However they are vulnerable to sea level rise, and measures will be needed to proactively manage them to improve their resilience. This study sheds new light on the flood risk reduction benefits baylands provide, and the specific measures that could be used to help maintain this and other key ecosystem services.

Intertidal mudflats and tidal marshes around San Francisco Bay (referred to as baylands) serve as a buffer between the Bay and shoreline development. As waves propagate across these relatively flat areas of shallow water, baylands reduce wave height and energy. This wave attenuation protects inland coastal areas from flooding that could result from overtopping or failure of structural shorelines such as levees, berms and revetments.

As sea level rises, the depth, duration, and frequency that baylands are inundated will increase, stressing marsh vegetation. Marsh elevation is maintained by accretion, that is the accumulation of sediment on the surface and the input of organic matter from local plant production. Stressed marsh vegetation will lead to decreased accretion and a loss in marsh elevation, which in turn will lead to more inundation and further plant stress. With this feedback loop tidal marshes might "downshift" from high to mid marsh, from mid marsh to low marsh, and eventually to mudflat.

The resilience of baylands to sea level rise depends on whether they are able to build upward or move landward. The capacity to build upward depends on the amount of available mineral sediment, and in the Bay suspended-sediment concentrations appear to be decreasing. Furthermore, there is limited room to move landward as many baylands are bordered by levees or are adjacent to development. If baylands cannot keep pace with sea level rise, water depths will increase and the flood risk benefits will diminish since waves propagating across deeper water experience less attenuation.

To investigate wave attenuation and its sensitivity to sea level rise, field measurements and 1-D and 2-D modeling were conducted at the Corte Madera Baylands in San Francisco Bay. Currently, waves crossing Corte Madera Bay can be attenuated by as much as 80% before they reached the marsh edge. At water depths and wave heights large enough that waves reach the marsh, there is a sudden deceleration of wave energy as water depth changes abruptly. This loss of wave energy

at the marsh can cause a considerable amount of marsh edge erosion. As wave cross the marsh plain vegetation furthers the attenuation regardless of species (i.e., cordgrass or pickleweed). As water depths increase, for example with sea level rise, wider marshes will be needed to maintain comparable flood risk reduction benefits.

Field measurements suggest that the Corte Madera Baylands are currently keeping pace with sea level rise; however, there are several lines of geomorphic evidence that suggest these baylands are sediment-limited. Regional marsh sustainability modeling predict that the Corte Madera tidal marshes will convert to mudflat as sea level rise rates accelerate towards the end of century. Measures will therefore be needed to proactively manage baylands to improve their resilience.

To demonstrate the kind of information and process that can be used to select management measures, a conceptual sea level rise adaptation strategy was developed for the three distinct tidal marshes within the Corte Madera Baylands. The objective of the conceptual strategy was to preserve flood risk reduction benefits by maintaining high, wide marshes over time. The conceptual strategy consists of multiple management measures to be implemented in phases. In the first phase, existing marsh features are enhanced to maximize resilience through mid-century, while the second phase prepares a landward area into which the marsh can migrate when sea level rise begins to outpace vertical accretion. Seven management measures were considered, and using a geomorphic conceptual model as a decision-support tool, four were selected for the Corte Madera Baylands. These include: stabilize with a coarse beach, recharge the mudflat and marsh, improve sediment pathways, and increase the transition zone.

The challenges of accelerating sea level rise rates and declining sediment supply are generally similar across the Bay, and much of the research and information developed by this project can be applied throughout the region. To develop a site-specific sea level rise adaptation strategy, it is important to identify the ecosystem services to be protected, and have a good understanding of the local geomorphic context, sediment availability, and status of shoreline change. Additionally, depending on the project scope, field observations and wave attenuation modeling may be necessary or desirable. Lastly, the different management measures are understood to varying degrees. Some have been used successfully in Bay restorations, while others are untested and need further appraisal.

Baylands can play a significant role in reducing coastal flooding and future capital investments in structural shoreline protection. To ensure they achieve and maintain this potential as sea level rises, the region needs a better understanding of sediment transport processes in mudflats and marshes, further field studies to calibrate and validate marsh wave attenuation models, and the integration of baylands management into coastal zone hazard mitigation planning.

Preface

The *Innovative Wetland Adaptation Techniques in Lower Corte Madera Creek Watershed* project is one of the first efforts in San Francisco Bay to examine the resilience of tidal marshes and mudflats to accelerating sea level rise, and to contemplate how the wave attenuation benefits and other ecosystem services they provide can be preserved. Led by the San Francisco Bay Conservation and Development Commission (BCDC), the project was conceived in recognition of the significant gap in understanding of the role Bay wetlands play as the first line of defense against coastal flooding, and how that role may change in the future. The project was supported with funding from the San Francisco Estuary Partnership (SFEP) through a *Resilient Watersheds for a Changing Climate* grant of the San Francisco Bay Water Quality Improvement Fund from the U.S. Environmental Protection Agency, and by the generous contributions of research partners including the U.S. Geological Survey, UNESCO-IHE, and Marin County.

The results of the project are presented in the *Corte Madera Baylands Conceptual Sea Level Rise Adaptation* Strategy report that follows. This report is built on the foundation of a number of scientific studies conducted by the project research team and others. A great deal of gratitude goes to the project Technical Lead, Science Team, and Technical Advisory Committee in addition to many other informal advisors and contributors. The staff at SFEP was instrumental in facilitating project contracting and efficient management. Lastly, a number of former and present BCDC staff should be acknowledged for their vision and foresight in conceiving and obtaining funding for the project, and in ultimately communicating the project to a wide audience of Bay Area coastal managers. In particular Adam Parris, Steve Goldbeck and Joe LaClair deserve great credit for their tireless efforts, and Sarah Richmond and Wendy Goodfriend for their commitment and fortitude in guiding the project to a successful completion. Javier del Castillo provided critical GIS and graphics assistance throughout the project.

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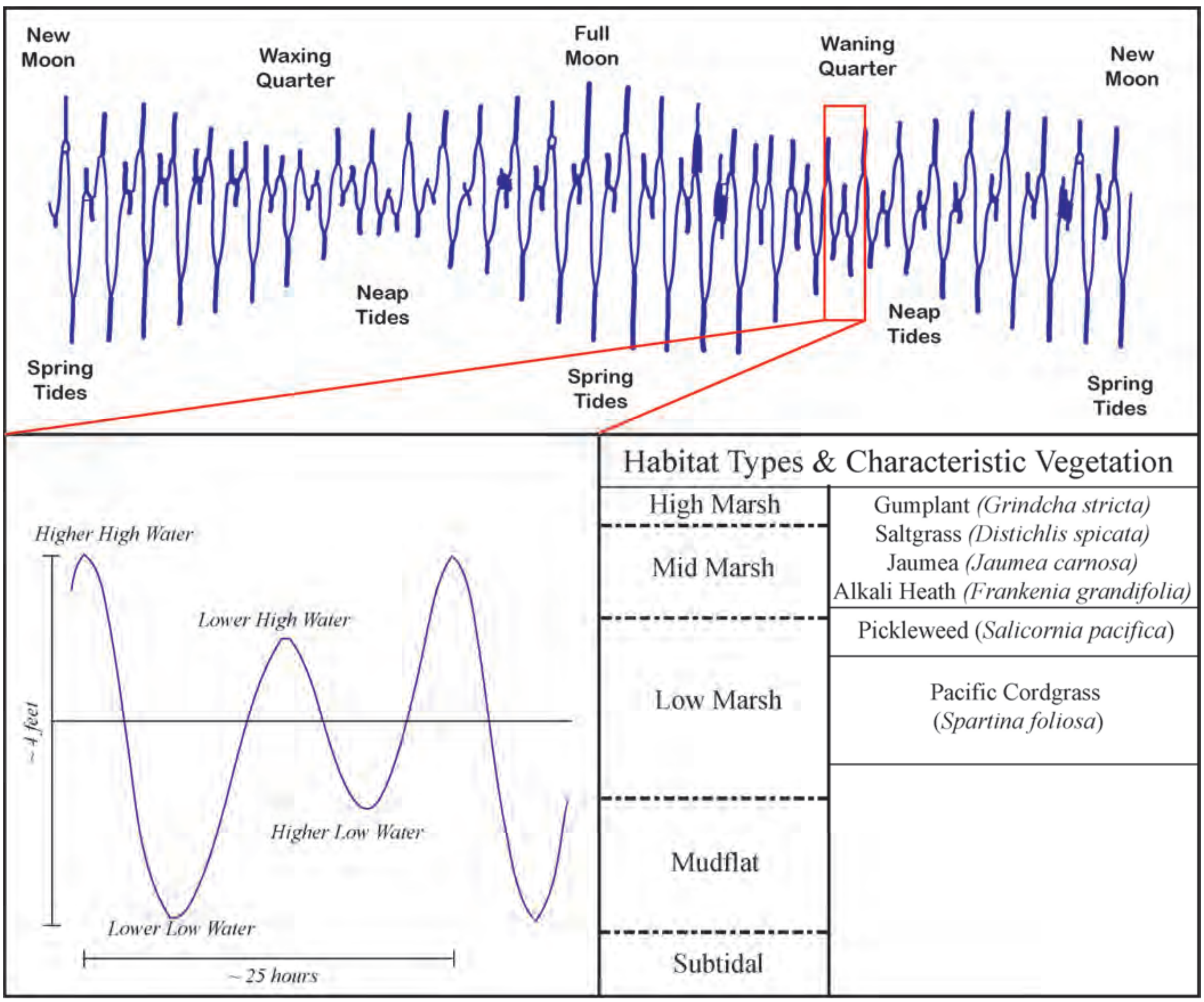
Contents

Tides regularly flood and drain marshes, resulting in distinct groups of plants that grow at different elevations (adapted from Cohen and Laws 2000).

Tides in the Bay are of the mixed semi-diurnal type, meaning there are two unequal high tides and two low unequal tides almost every day. Mudflats are inundated twice daily, while the high marsh may only be inundated once or twice a month by high spring tides, resulting in marsh sediment salinity concentrations many times that of seawater (Watson and Byrne 2009). Physical factors such as the frequency and duration of inundation and the saltiness of the soil tend to set the lower limits of marsh plant establishment, while competition from other plants usually set the upper limits. The boundaries between the habitats are fuzzy, with plant species integrating across boundaries and occurring outside of their nominal zone in response to subtle differences in elevation, soils, and drainage.



Glossary

Terms included herein are in **bold** when first presented in the report.

Note that English units are used in much of this report. The following factors may be used to convert English to Metric units: 1 inch = 2.54 centimeters and 1 foot = 0.30 meters.

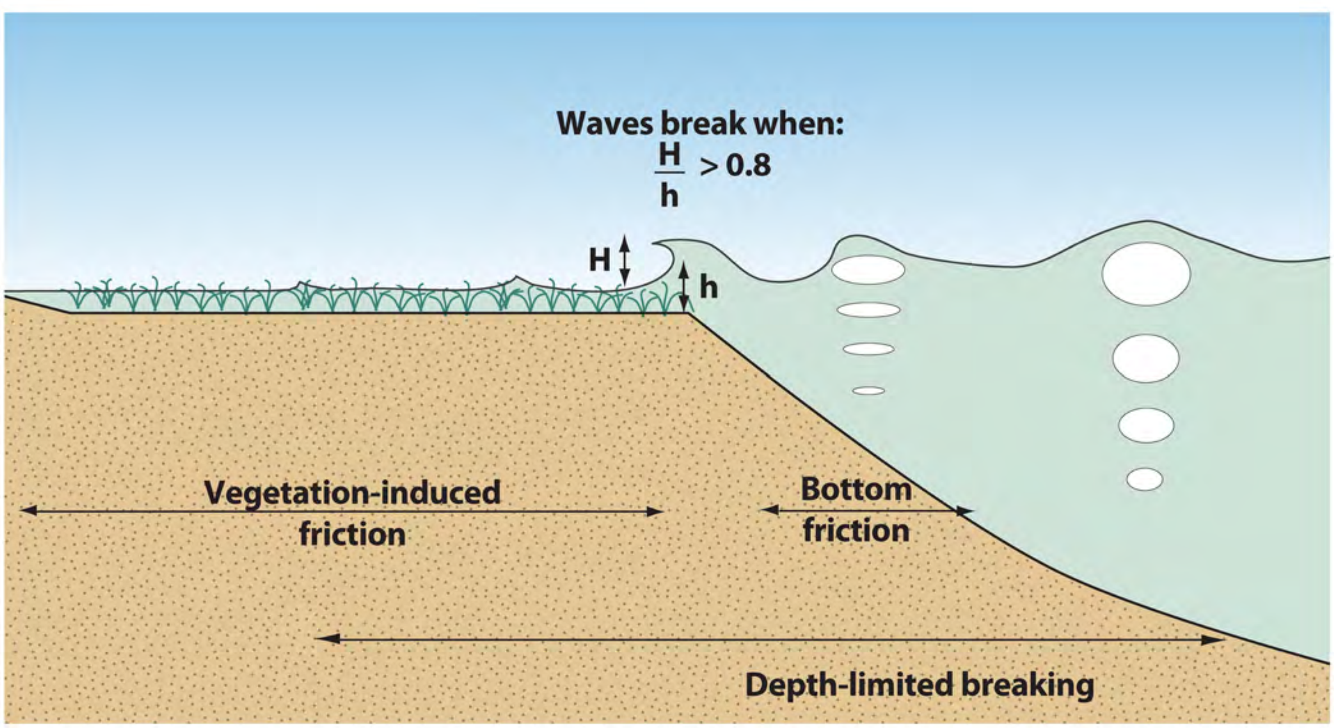
Baylands	The lands around the Bay subject to the daily action of the tides, plus historical tidal marshes that have been isolated from the tides by dikes (levees), tide gates or other water control structures.
Bed shear stress	The ability of flow to erode sediment from the bed, which varies with the square of bottom orbital velocity.
Bottom friction	Friction between the water moving under a wave and the sediment at the bottom of the water column, which serves to dissipate the kinetic energy of a wave, reducing its height.
Bottom orbital velocity	Maximum near-bed wave velocity, which according to linear wave theory, is inversely related to water depth.
Depth-limited breaking	An upper bound on wave height as a function of water depth. Waves are prevented from exceeding this height by breaking. Waves break when their wave height H is larger than 0.8 times the water depth h, or when $H > 0.8\ h$ (Dean and Dalrymple 2002).
Extreme High Water (EHW)	The highest elevation reached by the sea as recorded by a tide gage during a given period. Extreme high waters are recorded monthly and yearly by the National Ocean Service for its control stations.
Incident wave height	The height of a wave approaching a surface such as a marsh plain, e.g., the wave height immediately before encountering the marsh edge.
Mean Higher High Water (MHHW)	The average of the higher-high water elevations of each tidal day observed over the National Tidal Datum Epoch (NTDE).
Mean High Water (MHW)	The average of all the high water elevations observed over the NTDE.
Mean Tide Level (MTL)	The average of mean high water and mean low water.
Mean Sea Level (MSL)	The average of all tide stages over the NTDE.

Mean Low Water (MLW)	The average of all the low water elevations observed over the NTDE.
Mean Lower Low Water (MLLW)	The average of the lower-low water elevations of each tidal day observed over the NTDE.
National Tidal Datum Epoch (NTDE)	The specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. The present NTDE is 1983 through 2001 and is actively considered for revision every 20-25 years.
Neap tide	Tides with the smallest range of the lunar cycle, which occur during the first and third quarters of the moon.
Resilience	The amount of change or disturbance that can be absorbed by a system (e.g., organism, population, community, or ecosystem) *before* the system is redefined by a different set of processes and structures (i.e., the ecosystem recovers from the change or disturbance without a major phase shift) (U.S. CCSP 2008).
Return period	An estimate of the likelihood of an event, also known as a recurrence interval. It is the inverse of the probability that the event will be equaled or exceeded in any given year, e.g., a 100-year return period water level has the probability of occurring once every 100 years (1% chance).
Spring tides	Tides with the greatest range of the lunar cycle, which occur at the new and full quarters of the moon.
Storm surge	Increase in water level due to low atmospheric pressure and/or wind set-up due to storms.
Simulating WAves Nearshore (SWAN)	The two-dimensional SWAN model simulates wave propagation in time and space. It accounts for bottom friction, depth-limiting breaking, and vegetation-induced friction.
Sweep zone	Vertical and lateral extent of the mudflats and shallows (subtidal zone between 6.6 feet below MLLW and MLLW based on work in the South Bay; Brew and Williams 2010), where shallow water depths allow for waves to interact with the bottom, which dissipates wave energy and induces wind-wave re-suspension and reworking of sediment, e.g., erosion and deposition.
Vegetation-induced friction	Friction between a moving wave and the vegetation on the marsh plain, which serves to dissipate the kinetic energy of a wave, reducing its height.

Wave attenuation	Wave height and energy reduction with increasing distance traveled across relatively flat areas of shallow water (i.e., mudflats and marshes). Processes that attenuate waves include depth-limited breaking, bottom friction, and vegetation-induced friction.
Wave crest elevation	The elevation of the highest point of the water surface deflected by a wave. This water surface elevation is also referred to as total water level because it includes waves on top of a given still water level in reference to some arbitrary elevation datum. In this report, the North American Vertical Datum of 1988 (NAVD88) is used.
Wave height	The distance between the highest (crest) and lowest (trough) points of a wave.
Wave Height Analysis for Flood Insurance Studies (WHAFIS)	The one-dimensional, transect model was developed to predict wave conditions associated with storm surge (FEMA, 1988). It accounts for depth-limiting breaking and vegetation-induced friction.

Wave attenuation refers to reducing or attenuating wave height and energy through wave breaking and energy dissipation.

As waves propagate across relatively flat areas in shallow water, they break when they reach a limiting depth, i.e., when wave height *(H)* over water depth *(h)* is greater than 0.8. In other words, when wave height is larger than approximately 0.8 times the water depth *(H > 0.8 x h)*. Wave energy is also dissipated due to bottom friction and vegetation-induced friction. These dissipation mechanisms can result in smaller wave heights than predicted by depth-limited breaking.



Ward (2012)

1 Introduction

Over the past century, mean sea level along the California coast has risen nearly 8 inches[1], and by 2100, it is projected to rise as much as 66 inches relative to 2000 levels (National Research Council 2012). Many shoreline communities and ecosystems around the San Francisco Bay (Bay or Estuary) are *already* vulnerable to coastal flooding, especially when high tides coincide with storms and strong winds. For example, coastal flooding during the El Nino winter of 1982 – 1983 caused $500 million in damage (Association of Bay Area Governments 2010). Accelerating rates of sea level rise will exacerbate flooding and other impacts in vulnerable coastal areas (BCDC 2011).

Coastal flooding along the Bay shoreline is mitigated by **baylands**, that is, the intertidal mudflats and tidal marshes that sit between the minimum and maximum elevations of the tides (Goals Project 1999). Baylands mitigate flood risk by reducing, or attenuating, **wave height** and energy that reach the shoreline. As waves propagate across relatively flat areas of shallow water (i.e., mudflats and marshes), they break when they reach a limiting depth and lose energy to friction between the water and the sediment along the bottom, and at high water levels, to friction between the water and the vegetation on the marsh plain. Baylands, and the coastal flood protection they provide, are however vulnerable to sea level rise. Sea level rise will increase the depth, duration, and frequency that baylands are inundated, and will magnify erosion caused by storm surges and wave energy.

The **resilience** of baylands to sea level rise depends on whether they are able to counteract these increases in inundation by building upward or moving landward. Building upward involves both mineral and organic matter accumulation and is affected by the supply of available mineral sediment. Suspended-sediment concentrations in the Bay appear to be decreasing (Schoellhamer 2011), which limits the amount of available mineral sediment for building upward and increases the risk of tidal marsh ‘drowning’. Furthermore, many baylands are bounded by steep slopes, e.g., inboard levees, which reduce the width of the transition zone across which they can move landward to avoid being ‘squeezed’ between a rising Bay and adjacent land uses. If baylands are not resilient to sea level rise, the ecosystem services they provide such as flood risk reduction will be lost, and the resilience of surrounding shoreline communities will be diminished.

1 San Francisco gage (CA Station ID: 9414290): http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

1.1 Purpose

The purpose of this project is to increase the region's understanding of how to improve the resilience of baylands to sea level rise, thereby protecting the ecosystem service benefit of flood risk reduction through **wave attenuation**. To achieve this purpose, the Corte Madera Baylands in Marin County were selected as the study site to examine two overarching questions:

1. How is wave attenuation at the Corte Madera Baylands sensitive to sea level rise?
2. What management measures would improve the resilience of the Corte Madera Baylands to sea level rise and thereby maintain their ability to attenuate waves and reduce flood risk?

The Corte Madera Baylands were selected as the study site because they contain tidal marsh that was not diked or filled in the last 150 years (referred to as 'historic' or 'natural') and tidal marsh that was diked and filled and subsequently restored, therefore providing the opportunity to investigate the sensitivity of both types of systems to sea level rise. In addition, the Marin Countywide Plan (updated in November 2007) specifically calls for incorporating sea level rise into planning processes and adopting policies and programs to adapt to climate change. This includes the identification of baylands that could provide shoreline communities protection from sea level rise. As a result, local resource managers were engaged in the project and interested in its applications.

To examine the two questions above, this project quantifies wave attenuation at the Corte Madera Baylands, demonstrating "proof of concept" that baylands provide flood risk reduction benefits. These results contribute foundational information to the discussion of how preserving, enhancing, and restoring baylands can reduce future needed investment in repairing or raising levees to protect shoreline communities from sea level rise (ESA PWA 2013). In addition, the project demonstrates the importance of understanding and considering the spatial, temporal, and social context of individual baylands in the selection of management measures to improve resilience to sea level rise. The conceptual sea level rise adaptation strategy presented in this report to maintain wave attenuation at the Corte Madera Baylands exemplifies this selection process.

The conceptual sea level rise adaptation strategy is not intended for implementation. More detailed information is needed to conduct feasibility studies and develop design alternatives, plan sets, and costs estimates. Similarly, it will be important to decide which ecosystem services are protected, and to what degree, and to coordinate agency roles, responsibilities, and resources during environmental review and future monitoring and maintenance.

The report that follows summarizes the findings of the *Innovative Wetland Adaptation Techniques in Lower Corte Madera Creek Watershed* project. Additional information can be found in the report appendices and on the project webpage. Here is a guide to the information:

- **Chapter 1** introduces the most significant baylands ecosystem services, describes the study site, and states the technical approach to the work.
- **Chapter 2** presents the geomorphic conceptual model used to organize the study and highlight relationships between accelerating rates of sea level rise and declining sediment supply, factors that affect key processes of baylands evolution, and ultimately how changes in the baylands ecosystem can lead to changes in ecosystem services provided (**Figure 2-1**).
- **Chapter 3** synthesizes historical records and field measurements to explain the geomorphic context and key processes of evolution at the Corte Madera Baylands.
- **Chapter 4** describes the observations and sensitivity of **wave attenuation** at the Corte Madera Baylands to current and projected conditions, e.g., sea level rise based on modeling results. In addition to this investigation of flood risk reduction benefits, the chapter also explores, though in lesser detail, carbon sequestration benefits and how they may change in the future.
- **Chapter 5** lays out a conceptual sea level rise adaptation strategy that exemplifies how a sequence of management measures could be selected to improve the resilience of the Corte Madera Baylands.
- **Chapter 6** summarizes the main findings of the project and implications for planning and research related to coastal flood management around the Bay.

1.2 Baylands ecosystem services

Ecosystem services are defined as the goods and services produced by ecosystems that benefit humankind (Millennium Ecosystem Assessment 2005). The concept of ecosystem services has emerged in recent years as a way to value key physical and ecological functions that benefit society. These services are traditionally undervalued, however, because they often fall outside of conventional markets and pricing (National Research Council 2005). Four of the most significant baylands ecosystem services are flood risk reduction, carbon sequestration, water quality improvement, and biodiversity. We focused on flood risk reduction because the purpose of the project was to evaluate how baylands protect shoreline communities from coastal flooding by attenuating waves. A general description of all four ecosystem services is presented in the sections below; however, only findings regarding the flood risk reduction and carbon sequestration benefits provided by the Corte Madera Baylands are presented later in the report (see Chapter 4).

1.2.1 Flood risk reduction

Baylands serve as a buffer between the Bay and shoreline development. They reduce flood risk by attenuating wave height and energy, protecting inland coastal areas from flooding that could result from the overtopping or failure of structural shoreline protection such as levees, berms, and revetments. The behavior of waves traveling across subtidal shallows, intertidal mudflats, and tidal marshes is fundamentally controlled by water depth, thus tidal elevations. Waves break when wave height (H) is larger than approximately 0.8 times the water depth (h), i.e., $H > 0.8 \times h$. Generally, at low tides, waves break on mudflats, dissipating much of their energy due to **bottom friction** before reaching either the tidal marsh or shoreline. At mid-tide levels, waves break near marsh edges, sometimes undercutting them below the root zone of marsh plain vegetation. At high tides, waves break at the transition between the mudflat and marsh, either against a vertical scarp or along a gradual slope depending on the marsh edge geometry. Beyond the marsh edge, marsh vegetation exerts a drag force, which slows the flow of water due to **vegetation-induced friction** (Gedan et al. 2011). These energy dissipation mechanisms result in smaller wave heights than predicted by **depth-limited breaking** alone. Therefore, the overall flood risk reduction benefit provided by baylands depends on the bathymetry and bed roughness of the shallows and mudflats that compose the **sweep zone**, as well as the morphology and vegetation of the tidal marsh.

1.2.2 Water quality improvement

Tidal marshes improve water quality by trapping sediments and filtering pollutants, such as nutrients and heavy metals. Pollutants enter tidal marshes when creeks and streams draining into the Bay flow overbank directly into them, or when pollutants deposited in the Bay are remobilized and transported onto them by wave and tidal action. The San Francisco Estuary Institute Regional Monitoring Program demonstrated that sediment is the main transport mechanism for pollutants entering the Bay (e.g., McKee et al. 2006; Davis et al. 2007; Oram et al. 2008; David et al. 2009; Gilbreath et al. 2012). Since marsh vegetation slows the flow of water, larger sediment particles and the pollutants adsorbed to them settle out and are buried in accreting marsh sediment. Tidal marshes can also remove pollutants including pathogens and pesticides through vegetation uptake, and through the uptake and transformation by microbial activity in shallow soil layers (e.g., denitrification).

1.2.3 Carbon sequestration

During photosynthesis, tidal marsh plants capture carbon dioxide from the atmosphere and convert this carbon into the production of aboveground and belowground biomass. The lack of oxygen in saturated soils substantially slows down decomposition of belowground biomass, leading to the sequestration of carbon and development of organic rich soils. Tidal marsh soils can store carbon for thousands of years, as long as they are not drained. Consequently, tidal marshes are important carbon sinks due to their high rates of plant productivity and tendency to retain much of their autochthonous plant material in the form of highly organic soils.[2]

1.2.4 Biodiversity

Baylands include a diversity of habitat types that host an array of plant, invertebrate, fish, shorebirds, waterfowl, and mammal species, many of which are listed as threatened or endangered under state and federal law. Some species primarily use one habitat type, while other species move back and forth between habitat types. For example, the Salt Marsh Harvest Mouse (*Reithrodontomys raviventris)* is found in the mid marsh, while the California Clapper Rail (*Rallus longirostris obsoletus*) forages in cordgrass (*Spartina foliosa*) stands in the low marsh at low tide and takes refuge in gumplant (*Grindelia hirsutula*; syn. *G. stricta* var. *angustifolia)* in the high marsh at high tide. Since small changes in topography can result in considerable changes in tidal inundation, the more varied the microtopography is within a marsh, the more habitat types available for species to use and thus the higher the level of biodiversity (Baye 2012).

1.3 The Corte Madera Baylands

The Corte Madera Baylands are located in Corte Madera Bay, just north of the Tiburon peninsula in the Central San Francisco Bay (Central Bay) (**Figure 1-1**). Corte Madera Creek flows into the northwest corner of

2 Unlike freshwater wetlands, tidal marshes emit very little methane because of relatively high inputs of sulfate from seawater. Methane has 25 times the greenhouse gas potential as carbon dioxide and could negate the benefits of belowground carbon storage (Bartlett and Harriss 1993; Megenheimer et al. 1996).

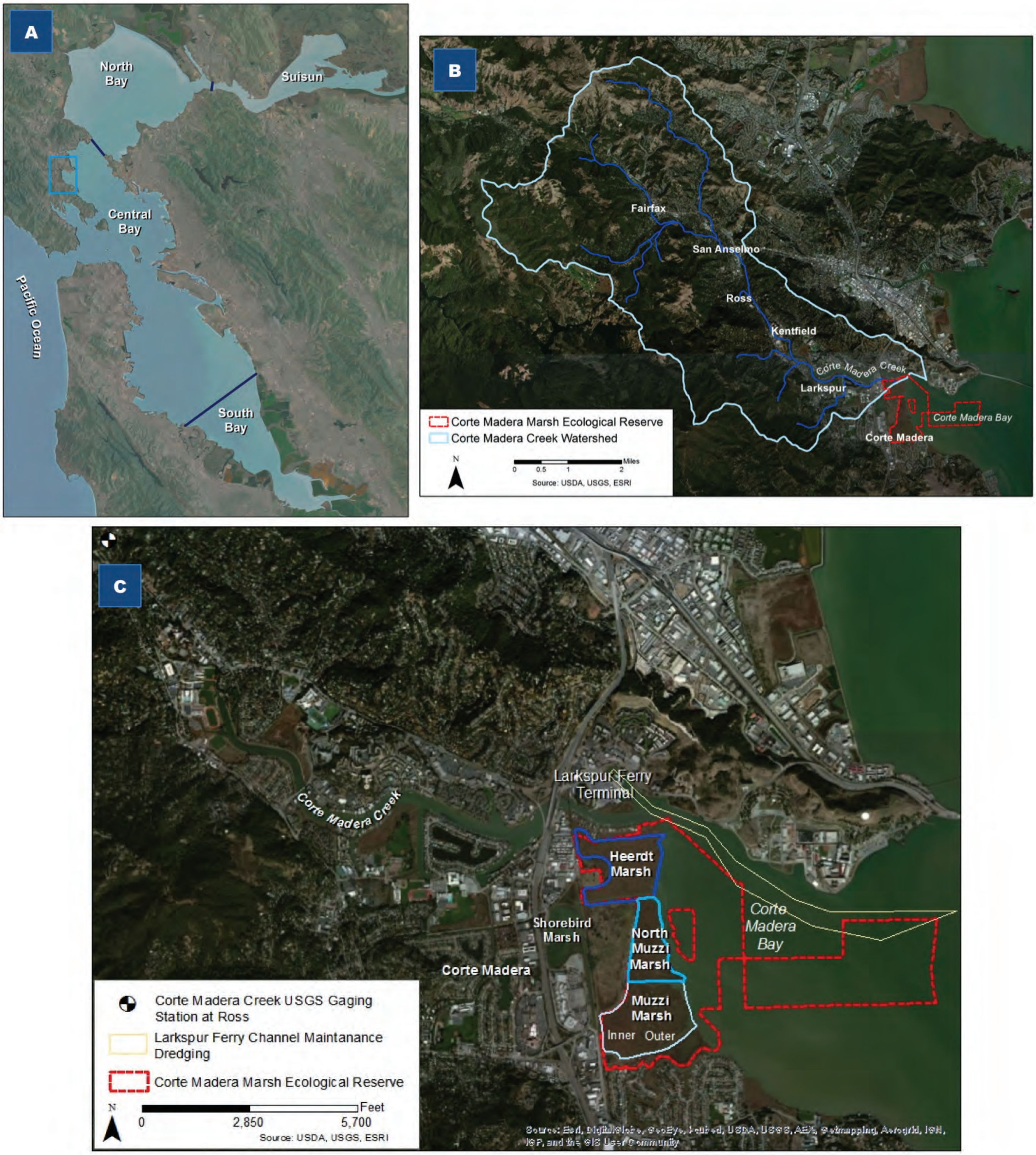


Figure 1-1 Study Site Maps

A) Corte Madera Bay is located in Central San Francisco Bay. B) The Corte Madera Creek Watershed drains into Corte Madera Bay north of the study site. C) The Corte Madera Baylands consist of three tidal marshes: Heerdt Marsh, North Muzzi Marsh, and Muzzi Marsh.

Corte Madera Bay draining a 28-square-mile watershed that has had numerous flood events in the past 70 years and is home to communities including Kentfield, Ross, San Anselmo, and Fairfax and. Approximately two miles upstream of the mouth of Corte Madera Creek, there is a 2,000-feet long reach of flood control channel constructed by the U.S. Army Corps of Engineers (USACE) in the late 1960s and early 1970s that currently has limited conveyance capacity. Sediment from the watershed continually deposits in the channel and there are ongoing efforts to improve flood control in the area (PBS&J 2010; Stetson 2011). At the mouth of Corte Madera Creek sits the Larkspur Ferry Terminal, which began operations in 1976. Ferries regularly travel through a dredged channel that runs along the north side of Corte Madera Bay. San Clemente Creek flows into the southwest portion of Corte Madera Bay, and industrial, commercial, and residential development border the west and south sides of the Corte Madera Baylands.

The Corte Madera Ecological Reserve (CMER) managed by the California Department of Fish and Wildlife is a specific portion of the Corte Madera Baylands. The reserve supports long-term populations of California Clapper Rail, which is a sensitive indicator of tidal marsh health, as well as San Pablo song sparrows (*Melospiza melodia samuelis*) and California black rails (*Laterallus jamaicensis coturniculus*). All three are California species of concern. The study site is within CMER and consists of three tidal marshes (in order from north to south): a historic marsh adjacent to Corte Madera Creek (Heerdt Marsh), a formerly diked marsh with a wave-eroded remnant levee (North Muzzi Marsh), and a formerly diked marsh restored to tidal action in 1976 (Muzzi Marsh). Hereafter, these three tidal marshes and the adjoining mudflats are referred to as the Corte Madera Baylands. The following sections describe key features of the three marshes within the study site.

1.3.1 Heerdt Marsh

Heerdt Marsh is one of the few historic tidal marshes in the Bay that has never been diked or filled (**Figure 1-2**). As a result, it is possible to obtain an intact record of past mineral and organic matter accumulation rates for the marsh. The marsh edge is marked by a vertical scarp and the marsh has a dendritic tidal channel network.[3] The natural levees that form along these channels provide local topographic variation within the marsh plain and support linear stands of gumplant, a tall evergreen scrub that provides critical high tide cover for

3 These networks are generally only found in tidal marshes that have not been diked or filled, as their long, branching morphology was formed by the gradual stabilization of sea level during the last several thousand years (Baye 2012). Recent restorations have not developed this topographic complexity.

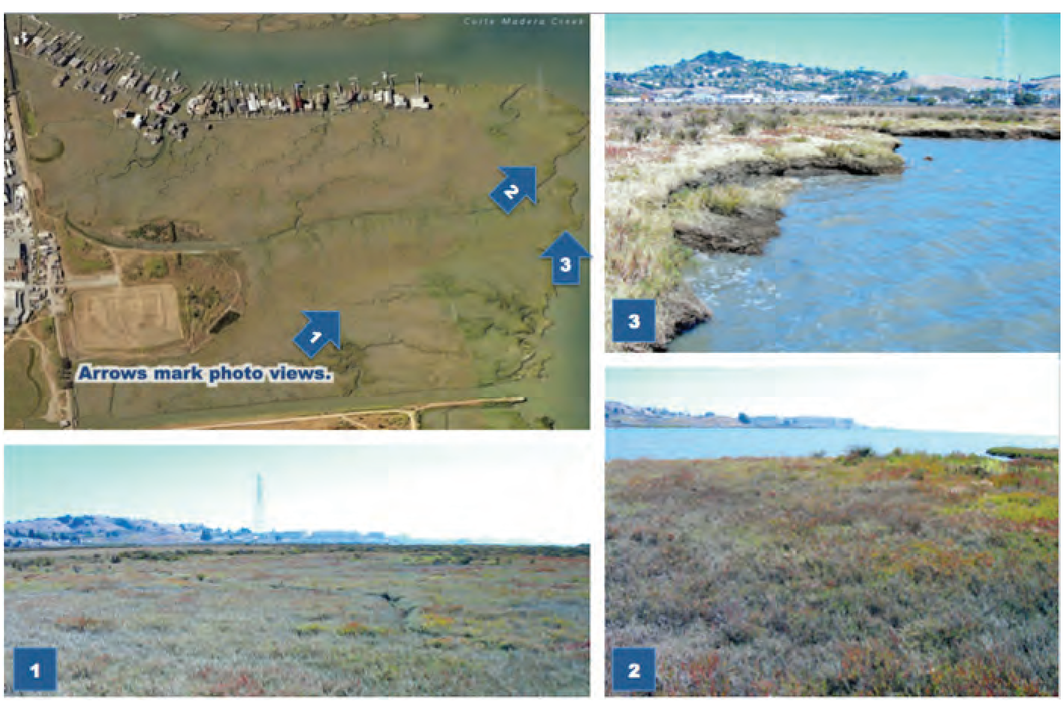


Figure 1-2 Heerdt Marsh

Bird's eye view showing the dendritic tidal channel network that is characteristic of a natural marsh. The marsh edge is a vertical scarp and the marsh plain has significant plant species diversity (aerial imagery courtesy of Bing Maps; photographs courtesy of John Callaway).

rare marsh wildlife. In addition, the marsh has significant native plant species diversity, including the northern ("Point Reyes") salt marsh bird's-beak (*Chloropyron maritimus* ssp. *palustre*) and a number of species that are widespread *outside* of tidal marshes but make important ecological contributions to tidal marshes when found within them – clustered field sedge (*Carex praegracilis*), basket sedge (*C. barbarae*), centaury (*Zeltnera trichantha*), and western ragweed (*Ambrosia psilostachya*) (Baye et al. 2000).

1.3.2 North Muzzi Marsh

North Muzzi Marsh has a wave-eroded remnant levee along the bayward edge (**Figure 1-3**). Wave-cut cliffs in the compacted bay mud core of the levee are eroding progressively at variable rates along the marsh edge. There are relatively few channels and little microtopography within the marsh due to placement of terrestrial fill at the back of the marsh in the 1970s (dredge materials from the Larkspur Ferry Terminal that could not be disposed of in-Bay; Marin Conservation League 2010). This large undeveloped and partly filled, but subsided, diked bayland owned by the Golden Gate Bridge, Highway and Transportation District supports a mix of non-native terrestrial vegetation and seasonal wetlands.

1.3.3 Muzzi Marsh

Muzzi Marsh is one of the oldest and best-monitored restoration projects in the Bay (**Figure 1-4**; PWA and Farber 2004). After decades of use as pastureland, the marsh was restored to tidal action in 1976 to mitigate for dredging the Larkspur Ferry Terminal. The outboard levees were breached, but left partially intact to combat erosion from east-southeast wind-waves and the

Figure 1-3. North Muzzi Marsh

Bird's eye view showing the relatively few channels due to fill placement. The marsh edge is a wave-eroded levee. Landward of the marsh plain, there is a narrow band of high marsh, and within the fill area there are seasonal wetlands (aerial imagery courtesy of Bing Maps).

restoration has been the subject of observation for over 30 years. The marsh is divided into two distinct zones based on elevation – a lower “Outer Muzzi Marsh” and a higher “Inner Muzzi Marsh.” Outer Muzzi Marsh accreted to elevations between **MTL** and **MHW** through natural sedimentation, while Inner Muzzi Marsh was filled with dredge material placed above **MHHW.** As a result of a greater tidal prism, Outer Muzzi Marsh has a high density of channels and a relatively complex marsh topography given its young age, while Inner Muzzi Marsh has a lower density of channels in the higher elevation fill area. This restoration was the first project in the Bay to rely on the natural establishment of salt marsh plants. Native cordgrass established in Outer Muzzi Marsh within three or four years (and there has been insignificant *Spartina* invasion), while pickleweed (*Sarcocornia pacifica*) colonized Inner Muzzi Marsh within a year.

1.4 Technical approach

Our analysis of the Corte Madera Baylands and their sensitivity to sea level rise is based on a review of existing literature, field measurements, one- and two-dimensional modeling, and collaboration among local, state, and federal agencies, institutions, and the private sector (**Figure 1-5, Table 1-1**). By reviewing historical records (e.g., aerial imagery and topography-bathymetry), we learned how the Corte Madera Baylands responded to past changes, which improves our understanding of how they may respond to future changes and how to improve

Figure 1-4. Muzzi Marsh

Bird’s eye view showing Outer Muzzi Marsh with a higher density of channels than Inner Muzzi Marsh. Vegetation transitions from cordgrass to pickleweed as elevations increase from Outer to Inner Muzzi Marsh (aerial imagery courtesy of Bing Maps; photographs courtesy of John Callaway).

their resilience. We measured sediment erosion in the shallows and mudflats (Jones 2011) and sediment accumulation on the tidal marshes (Callaway et al. 2012a). Because baylands must build upward to be resilient to sea level rise, measuring short-term sediment accumulation rates from the spring of 2011 through the summer of 2012 was particularly important. Long-term sediment accumulation and carbon sequestration rates were also determined in historic Heerdt Marsh.

Fundamental to the analysis of the flood risk reduction benefits was the development of a digital elevation model (DEM) extending from the subtidal area through the tidal marsh, including the adjacent upland area.

Foxgrover et al. (2011) collected bathymetric data in the winter of 2010 and merged the bathymetry with aerial LiDAR data collected by the National Oceanic and Atmospheric Administration in the spring of 2010 as part of the California Coastal Mapping Project[4] to create a seamless DEM. Lacy and Hoover (2011) deployed instrumentation during the winter of 2010 in Corte Madera Bay to measure wave attenuation. ESA PWA (2012) and van der Wegen and Jaffe (2012) conducted wave modeling to provide a broader perspective of wave attenuation at the site by simulating wave attenuation over the marsh plain and forcing conditions not observed during the study period, e.g., high water levels associated with **storm surge** and sea level rise.

4 http://www.opc.ca.gov/2010/01/mapping-californias-coastal-areas/

Figure 1-5. Field measurement locations

Showing where bathymetric, topographic, wave, sediment erosion, and sediment accumulation data were collected.

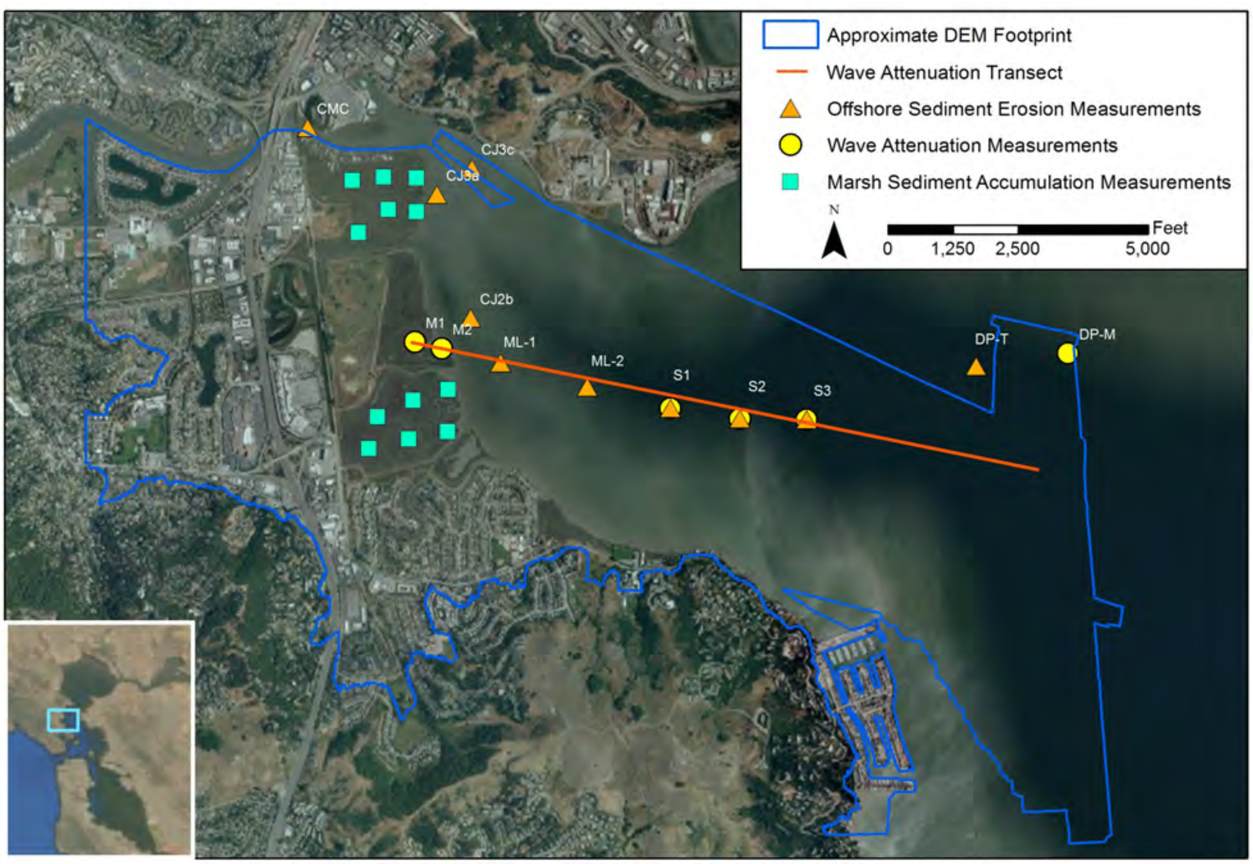


Table 1-1.
Summary of results from field measurements and modeling.

Study	Objectives	Results
DEM (Foxgrover et al. 2011)	Develop DEM for subtidal through tidal marsh based on bathymetric survey (winter 2010) and aerial topographic LiDAR (spring 2010)	Merged DEM available at 1 m and 10 m resolution
Wave attenuation (Lacy and Hoover 2011)	Determine whether, and to what degree, waves are attenuated across Corte Madera Baylands based on transect wave measurements (winter 2010)	Wave height decreased by as much as 80% across Corte Madera Bay; most waves break against the marsh edge; lower part of the marsh was inundated 15% of the study period, only during storms coinciding with high tide
Offshore Sediment Erosion Rates (Jones 2011)	Characterize physical properties and erosion rates of sediments from 10 stations offshore the marsh using Sedflume analysis	Sedflume results generally illustrate increasing erosion rates with increasing water depths (i.e., distance offshore), where there is relatively less bed shear stress such that sediment is more easily eroded and less consolidated; signals from Corte Madera Creek, Larkspur Ferry dredged channel, and deep San Francisco Bay also evident
Marsh Sediment Accumulation Rates (Callaway et al. 2012a)	Measure short- and long-term sediment accumulation and carbon sequestration rates across Heerdt and Muzzi Marshes using marker horizons/SETs and isotopic methods	Marshes are keeping up with sea level rise; no short-term sediment accumulation at marsh edge; unusual pattern where short-term vertical accretion rates lower than long-term rates across Heerdt Marsh; carbon sequestration rates similar to other baylands
Wave Attenuation - WHAFIS (ESA PWA 2012)	Evaluate sensitivity of tidal marsh wave attenuation to present and future conditions, e.g., sea level rise	Waves over tidal marshes are largely depth-limited but also influenced by vegetation-induced friction; rate of wave attenuation increases with larger waves; wide marsh provides additional attenuation for high water levels
Wave Attenuation - Delft3D (van der Wegen and Jaffe 2012)	Evaluate sensitivity of mudflat and tidal marsh wave attenuation to present and future conditions, e.g., sea level rise	Demonstrated good agreement with WHAFIS over the tidal marsh, with decreased attenuation with increased water levels and rapid attenuation over the scarp edge; decreases in the elevation and extent of mudflats and marshes would result in decreased wave attenuation

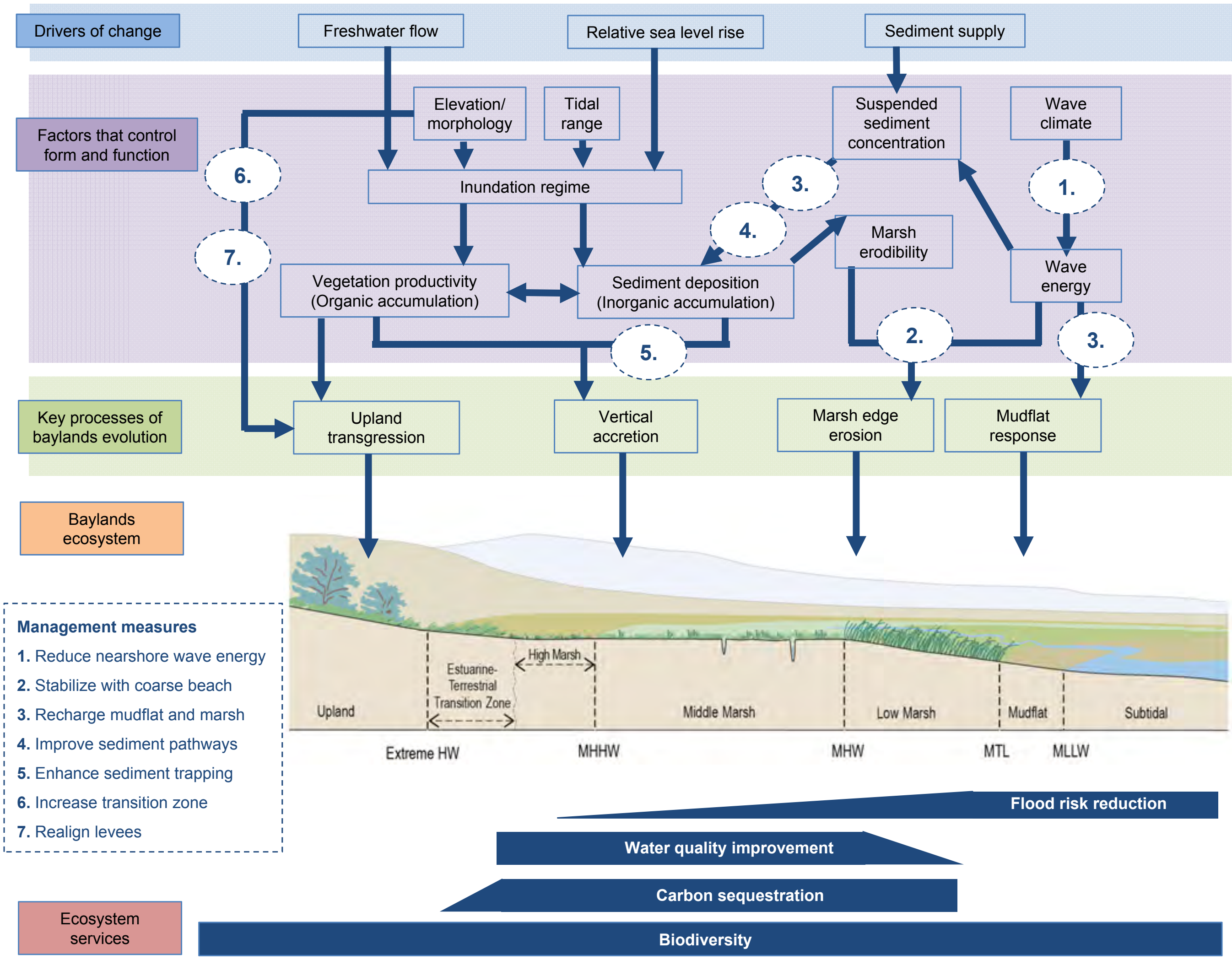


Figure 2-1. Geomorphic conceptual model of baylands evolution.

Dashed circles indicate management measures that can influence the key processes and thereby improve baylands resilience.

2 Geomorphic Conceptual Model

The ecosystem services provided by baylands, as described in Chapter 1, are the result of many physical, chemical, and biological interactions. This chapter reviews the geomorphic conceptual model that serves as a framework to understand the baylands – how they evolve and how accelerating rates of rates of sea level rise and decreasing sediment supply may drive changes to the ecosystem that will lead to changes in the ecosystem services provided (**Figure 2-1**). Conceptual models are “abstractions” of reality created to express a general understanding of a more complex process or system (Fischenich 2008). The geomorphic conceptual model is based on the Ecosystem Restoration Program’s Delta Regional Ecosystem Restoration Implementation Plan (DiGennaro et al. 2012) that distinguishes between drivers, linkages, and outcomes:

- Drivers of change are natural or human-created forces that have a large influence on the system, e.g., sea level rise and sediment supply[1];
- Factors that control form and function are linkages among system elements, e.g., wave climate and wave energy, or inundation regime and sediment deposition; and
- Key processes of baylands evolution are outcomes that the conceptual model is attempting to explain, e.g., vertical accretion.

The geomorphic conceptual model was particularly useful in identifying alternative management measures that would act on the key processes of baylands evolution and improve baylands resilience (see Chapter 5).

2.1 The baylands ecosystem

The baylands ecosystem is defined as the baylands, adjacent habitats, and their associated plants and animals (**Figure 2-2**; Goals Project 1999). The characteristics of a specific baylands ecosystem have a significant bearing on its overall health and ability to provide ecosystem services (**Figure 2-3**). For example, subtidal and mudflat habitats support invertebrates, fish and shorebirds. They also support the marsh in that sediment deposited in the sweep zone can be re-suspended into the water column by wave action, transported into marshes via tidal channels during flood tides, and deposited during the slack waters. The overbank deposition of suspended sediment that occurs a short distance from channel banks can form natural levees slightly higher than the surrounding marsh plain in mature tidal marshes. This creates microtopography, which support habitat and species diversity

1 Freshwater flow is an important driver, though not explored in this report. Reductions in Sacramento-San Joaquin River Delta snowmelt and shifts in the timing of local watershed runoff are expected to increase salinity. Increased inundation and salinity will promote conversion of brackish marshes to salt marshes and intrusion of brackish waters into areas that are currently fresh. As salinity increases, plant productivity decreases, such that greater rates of mineral sediment supply are required for baylands to keep pace with sea level rise (e.g., Parker et al. 2011, Callaway et al. 2011).

in tidal marshes. Away from channels, the marsh plain is dominated by dense salt-tolerant vegetation, although pannes can form from differential rates of peat production (Collins and Grossinger 2004). Lastly, the estuarine-terrestrial transition zone ('transition zone') sits above the reach of regular tidal inundation, providing a buffer to the tidal marsh and serving as high tide refugia for many species. This zone is characterized by physical and ecological gradients of salinity and vegetation, and serves an important role in overall baylands resilience by providing space for landward migration as sea level rises.

2.2 Baylands evolution

Baylands evolution is closely related to the history of changing sea level. As a whole, baylands respond to sea level rise by building upward and migrating landward through four distinct, yet interrelated evolution processes (**Figure 2-4**):

1. Mudflat response influences marsh width and is primarily a function of the rate of sea level rise, wave energy, and sediment supply;
2. Marsh edge erosion also influences marsh width and is primarily a function of the rate of sea level rise, wave energy, and marsh scarp erodibility (e.g., soil strength);

Figure 2-2. Schematic plan and profile views of a bayland identifying the habitat types within the ecosystem.
The extent of the habitats varies with the physical configuration of the site, and the boundaries between the habitats are fuzzy (indicated by dashed lines).

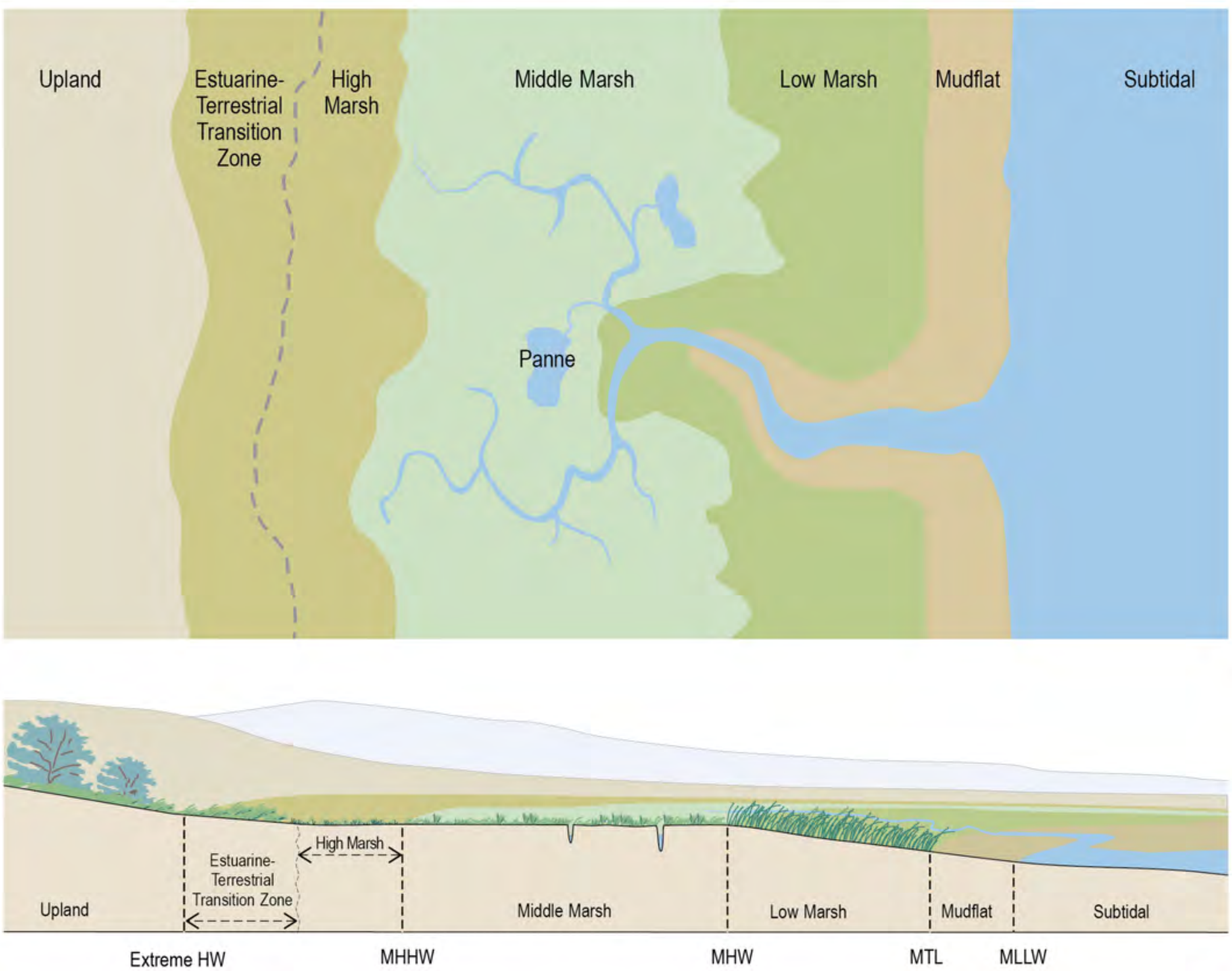


Figure 2-3. Summary of characteristics of the habitats that together comprise the baylands ecosystem.

These characteristics can vary markedly from one part of the Bay to another. Photographs of China Camp are shown because it serves as a reference site for many restoration projects, as it contains dendritic tidal channel networks and rare examples of the estuarine-terrestrial transition zone (courtesy of Peter Baye).

Subtidal

- Deep water (> 18 feet below MLLW) sediment varies from clays and silts to coarse sand (where currents are strong)
- Shallow water (between 18 feet below MLLW and MLLW) sediment is mostly mud; includes sweep zone that attenuates waves and supplies sediment
- Provides habitat for invertebrates, fish, and water birds

Mudflat

- Part of sweep zone that attenuates waves and acts as a local reservoir of sediment available to build up tidal marsh
- Provides foraging habitat for shorebirds

Tidal marsh

- Vegetation attenuates waves, sequesters carbon, promotes sediment deposition, and filters pollutants
- Channels transport nutrients and sediment (forming natural levees); pannes persist in backwater areas
- Includes low, mid and high marsh zones that provide breeding/foraging habitat

Estuarine-terrestrial transition zone

- Creates space for upland transgression
- Provides high tide refuge and species movement
- Buffers tidal marsh from upland disturbances

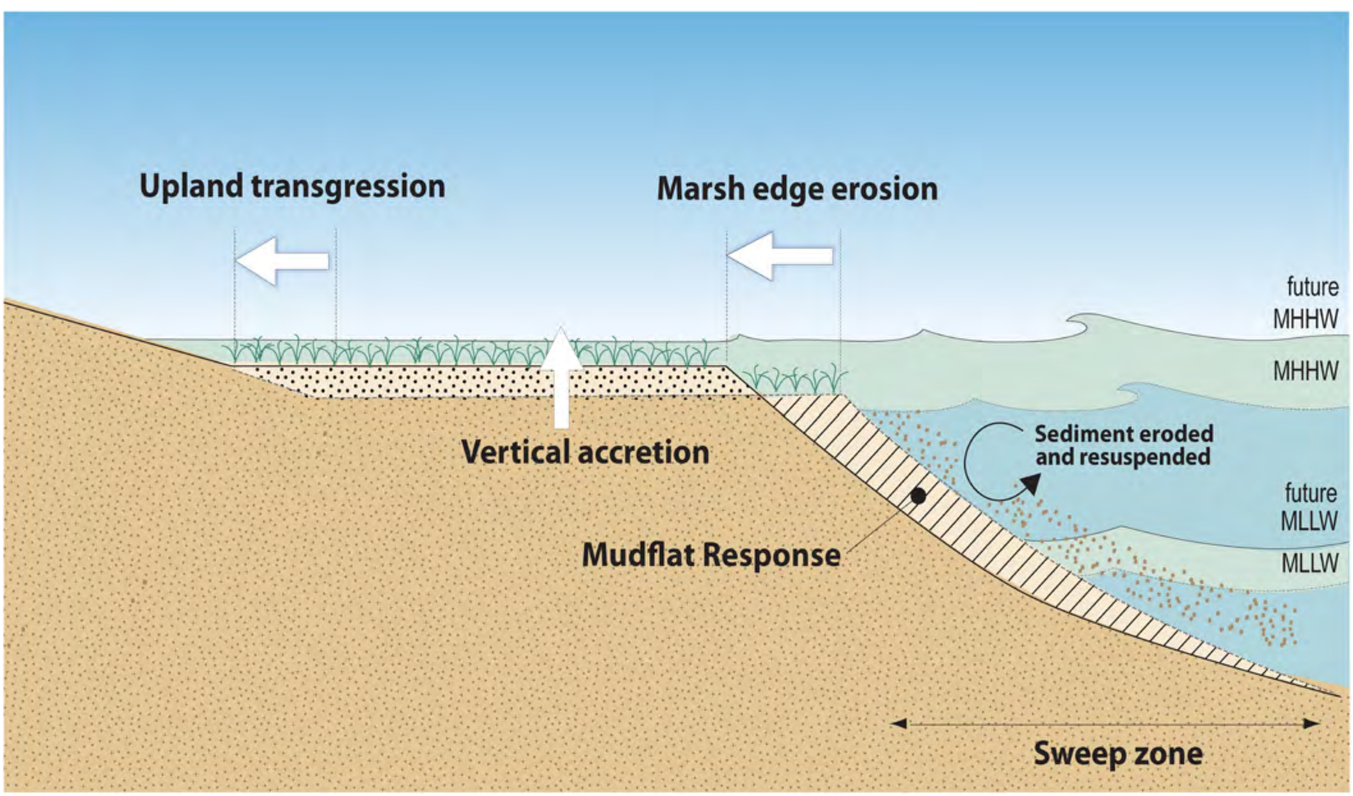
3. Vertical accretion influences marsh height and is primarily a function of the rate of sea level rise, sediment supply, and organic accumulation from marsh plant production; and
4. Upland transgression influences both marsh width and height and is primarily a function of the rate of sea level rise and the elevation/topography (e.g., slope) of the space landward of the baylands.

As sea level rises, waves propagating across deeper water experience less wave attenuation (see Section 4.1). Since water depth determines the extent and location of the sweep zone, the sweep zone migrates landward and the mudflat lowers to dissipate the additional wave energy. This lowering causes the marsh edge to erode until a new equilibrium profile is reached. Eroded and resuspended sediment can be captured in sediment sinks such as deep channels or tidal marshes, or redistributed within the Bay. However, if the sweep zone cannot migrate landward, e.g., the marsh edge cannot erode due to shoreline armoring, the sweep zone would narrow, resulting in even deeper water, less wave attenuation, and potentially more wave erosion along the shoreline.

Vertical accretion depends on elevation, where rates of vertical accretion tend to be higher in areas that are more frequently inundated, i.e., areas closer to tidal channels and at lower elevations. Salt-tolerant marsh plants begin to colonize areas above MTL and vertical accretion rates begin to slow around MHW to MHHW, as there is less tidal inundation and input of mineral sediment (Collins et al. 1987; Culberson 2001; Eisma and Dilkema 1997). At these higher elevations, the marsh gradient flattens and vertical accretion is mostly due to organic matter accumulation. Tidal marshes can accumulate substantial amounts of organic matter due to high rates of belowground production and relatively low rates of anaerobic decomposition in saturated soils.

Figure 2-4. Key processes of baylands evolution in response to sea level rise (marked with arrows).

As sea level rises, the mudflat lowers and the marsh edge retreats, while the marsh plain accretes and transgresses upland to a lower energy location.



The rates of vertical accretion need to be higher than the rates of sea level rise for baylands to keep pace. Vertical accretion rates may increase with sea level rise due to increased depth, duration, and frequency of tidal inundation over marshes, e.g., more sediment-laden water flooding the marsh and longer time periods for suspended sediment to drop out of the water column. However, this potential increase in vertical accretion greatly depends on the suspended sediment concentration and velocity of the water inundating the marsh. At some point, sea level rise rates may outpace vertical accretion rates and the marsh would need to migrate landward. The ability to do so depends on the slope of the transition zone across which upland transgression can occur. The transition zone would migrate landward if slopes were suitable, with the leading edge marked by new tidal marsh.

2.3 Drivers of change

The future of the Bay appears to be one of accelerating rates of sea level rise and declining sediment supply. During the early Holocene between 10,000 and 6,000 years ago, the rate of sea level rise, around 0.8 inches per year, was too fast for large areas of tidal marshes to establish in the Bay (Atwater 1977, Atwater 1979, Goman et al. 2008). Approximately 6,000 years ago, the rate of sea level rise slowed to around 0.1 inches per year, with most baylands forming within the last 5,000 years. Tidal marsh formation and evolution are also affected by sediment supply. Elevated sediment supply associated with hydraulic mining debris in the late 1800s (Gilbert, 1917) increased sediment transport to the Bay by an order of magnitude and led, in some instances, to rapid progradation of marshes. If sediment supply had been sufficient between 10,000 and 6,000 years ago, marshes could have developed even at the high rates of sea level rise (e.g., Palaima 2012). For example, during the early 1900s, groundwater pumping in the South Bay caused rapid subsidence and initiated a natural experiment in how baylands may evolve given high rates of relative sea level rise. While the subsidence was rapid, the baylands remained within the tidal range and there was sufficient sediment supply to support increased vertical accretion rates that kept up with the increased rate of relative sea level rise (Patrick and DeLaune 1990; Watson 2004).[2]

2 For example, Triangle Marsh subsided over 3 feet and accreted a similar amount over the post-subsidence period. Sediment accretion was so rapid that it was *not* the result of increased sediment supply. In response to increased sediment supply, data from the North Bay and coastal California shows that marshes tend to prograde and experience modest increases in sediment accretion. The South Bay maintains some degree of autonomy with regard to sediment dynamics.

Although there remains uncertainty in the future rate of sea level rise, there has been recent updates to global sea level rise projections, and the National Research Council (2012) has used these to develop projected sea level rise rates for the west coast of the United States that incorporate regional variability. Relative sea level rise projected for California south of Cape Mendocino is 6 inches by 2030 (with a range of 2 to 12 inches), 11 inches by 2050 (with a range of 5 to 24 inches), and 36 inches by 2100 (with a range of 17 to 66 inches) (**Figure 2-5**), relative to 2000 levels. These projections for California south of Cape Mendocino translate to rates of sea level rise between 0.1 and 0.8 inches per year between 2000 and 2100, with higher rates occurring in the second half of the century.

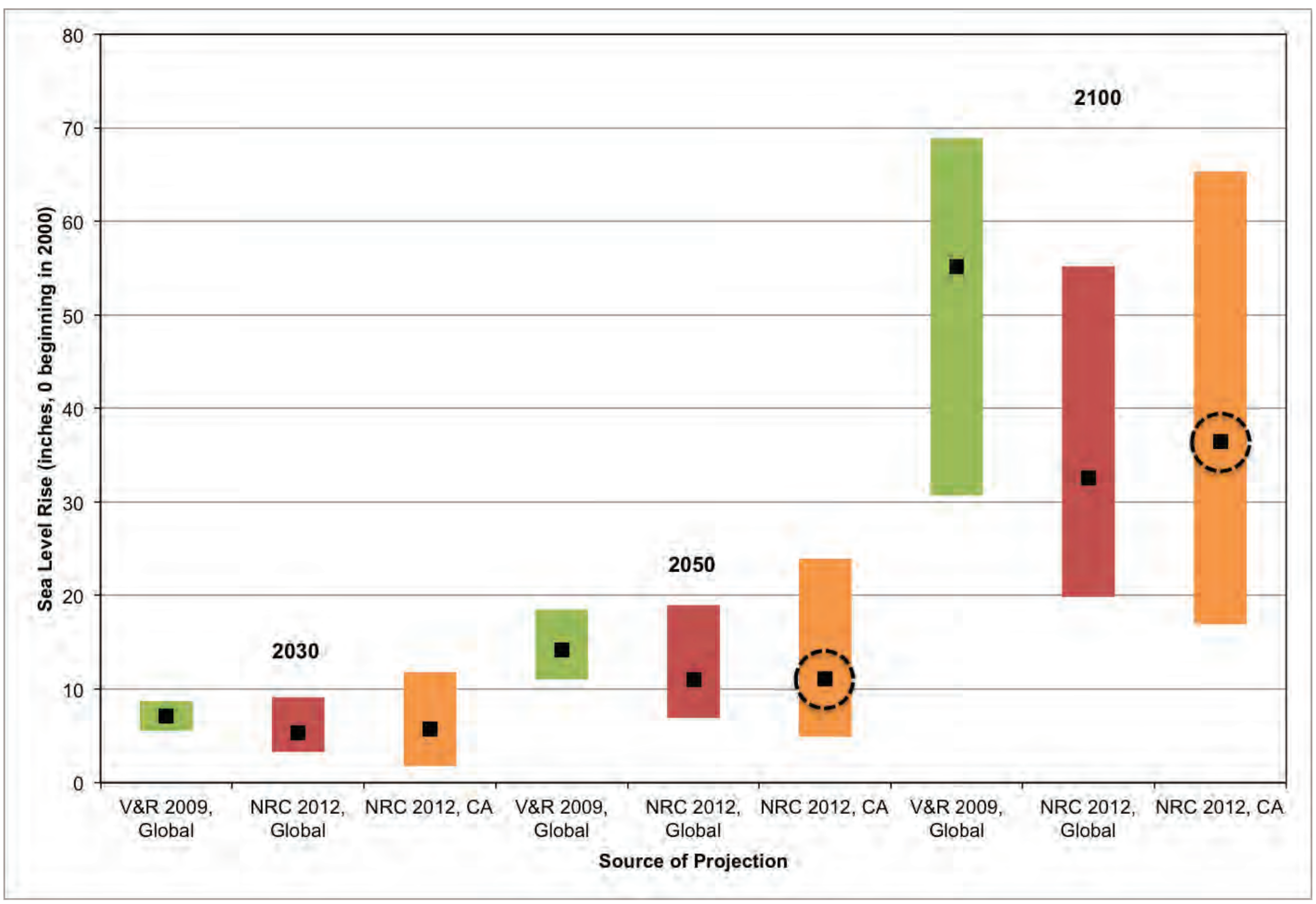
In addition to sea level rise, suspended sediment concentrations in the Bay have dropped by a precipitous 36% over the last 10 years, and Schoellhamer (2011) hypothesized that the Bay has crossed the threshold from a transport-limited to a supply-limited sediment regime (see Chapter 3). Changes in the Bay ecosystem in the 2000s have been symptomatic of this sharp decline in suspended sediment. For example, there has been an observed increase in phytoplankton due to increased light in the water column associated with this sudden clearing (Cloern et al. 2007).

As a result of these drivers of change, the current paradigm of baylands evolving in a manner that keeps pace with sea level rise, as described in Section 2.2 above, is not likely to continue. Alternatively, there will likely be “downshifting” of bayland habitats, i.e., high marsh to mid marsh, mid marsh to low marsh, low marsh to mudflat, and mudflat to shallows driven by both increased depth, duration, and frequency of inundation and decreased sediment supply. Increased inundation will cause waterlogging that will stress marsh vegetation, reducing their primary production and sediment trapping potential. Since marsh elevation is increased by accumulation of sediment on the surface and input of organic matter from local plant production, stressed marsh vegetation will lead to loss in marsh elevation, which in turn will lead to more inundation and further plant stress (DeLaune et al. 1983). Without a significant increase in local suspended sediment concentrations, this positive feedback loop will continue until there is total vegetative die off. Tidal marsh pannes will expand and tidal channels will enlarge as a result of the increased tidal prism.

The critical issue is the rate of sea level rise. For example, if sea level rises 12 inches over 100 years, baylands will likely be able to keep up. However, the picture will be very different if sea level rises 12 inches over a short-time period because baylands will have to accumulate a lot of sediment to avoid losing elevation. Because the rate of sea level rise is projected to slowly increase until approximately mid-century, the greatest threat in the near term to baylands is extreme inundation events (**Figure 2-6**). **Mean sea level** projections for the Bay region do not consider significant annual fluctuations that are caused by thermal expansion of warm Pacific waters, which may cause water levels approximately 8 inches above average levels during strong El Niño events. Storms that occur in tandem with high tides during El Nino events may result in water levels overstepping the marsh edge and wholesale drowning of the marsh plain. Thus, near-term changes in tidal marshes may not occur in either an incremental or linear fashion, and rapid changes are likely beyond mid-century when the rates of sea level rise are predicted to accelerate greatly.

Figure 2-5. Sea level rise projections for California (south of Cape Mendocino) compared with global projections.

The colored bars are the ranges and the solid squares within them are the averages based on different emissions scenarios and geographies. The sea level rise projection for California in 2050 is 11 inches and in 2100 is 36 inches. The dashed circles indicate the projections used for wave attenuation modeling (rounded to the nearest foot): one foot by mid-century and three feet by the end of century, relative to 2000 levels (see Chapter 4).



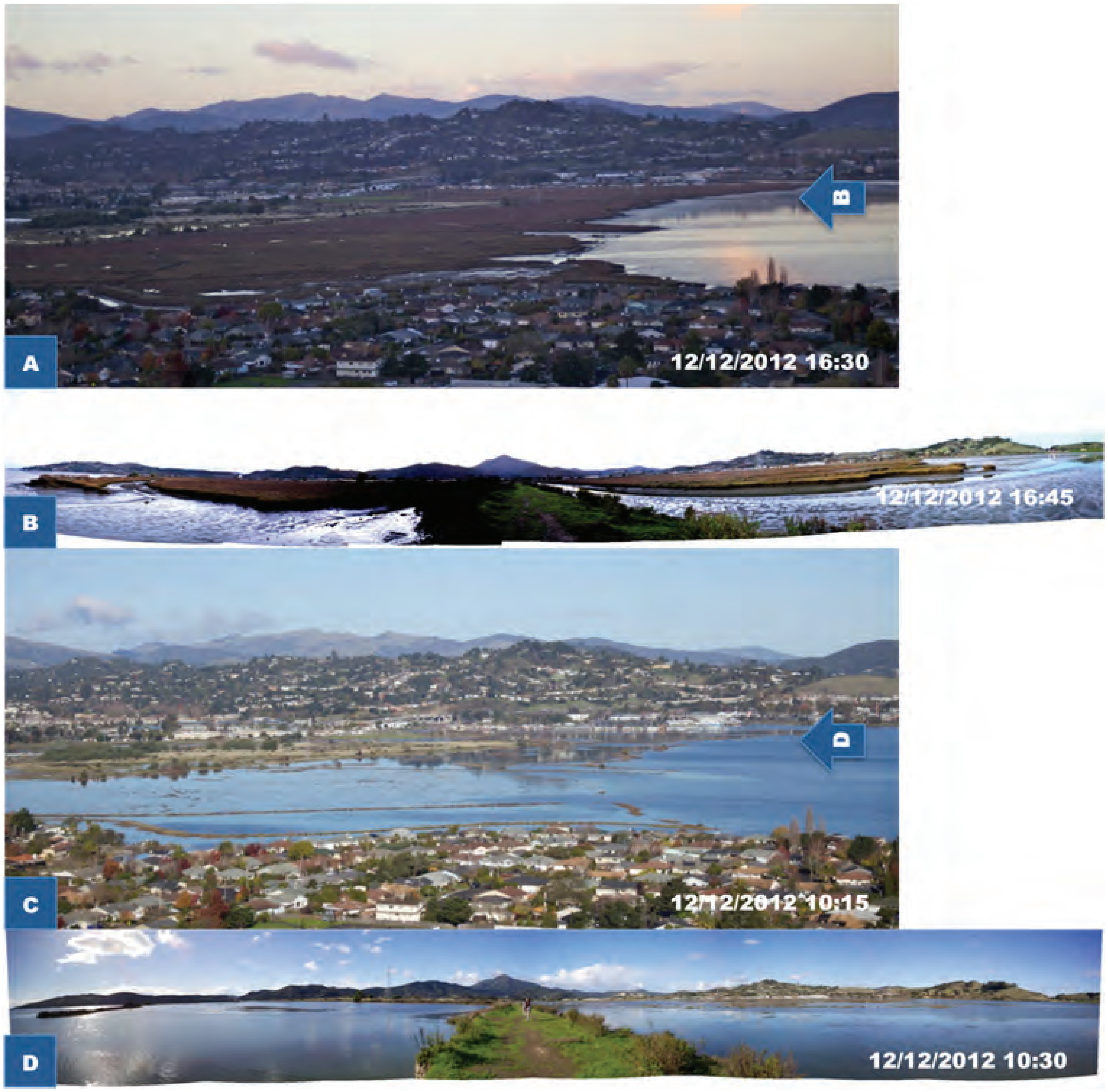


Figure 2-6. Photographs of the Corte Madera Baylands showing extreme low and high water levels.
The high tide at 10:21 a.m. was 7.06 feet relative to MLLW (C and D) and the low tide at 5:25 p.m. was -1.57 feet relative to MLLW (A and B). December 12, 2012 was a 'King Tide,' which refers to especially high tide conditions that happen only a few times a year when the moon is closest to the Earth (perigee) during the spring tide (therefore scientifically known as a 'perigean spring tide'). In San Francisco Bay, King Tides are typically most dramatic during the winter months. King Tides can be 10 – 16 inches higher than MHHW (i.e., 5.80 feet relative to MLLW datum). Therefore, the inundation of low-lying areas around the Bay during a King Tide is often used as a real-world illustration of what future, more regular inundation could look like with sea level rise. Since baylands can respond to some increases in the rate of sea level rise by adjusting their horizontal and vertical position, inundation by King Tide conditions today could be comparable to rapid increases in the rate of sea level rise. For Corte Madera Baylands tide data, see: http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=9414874.

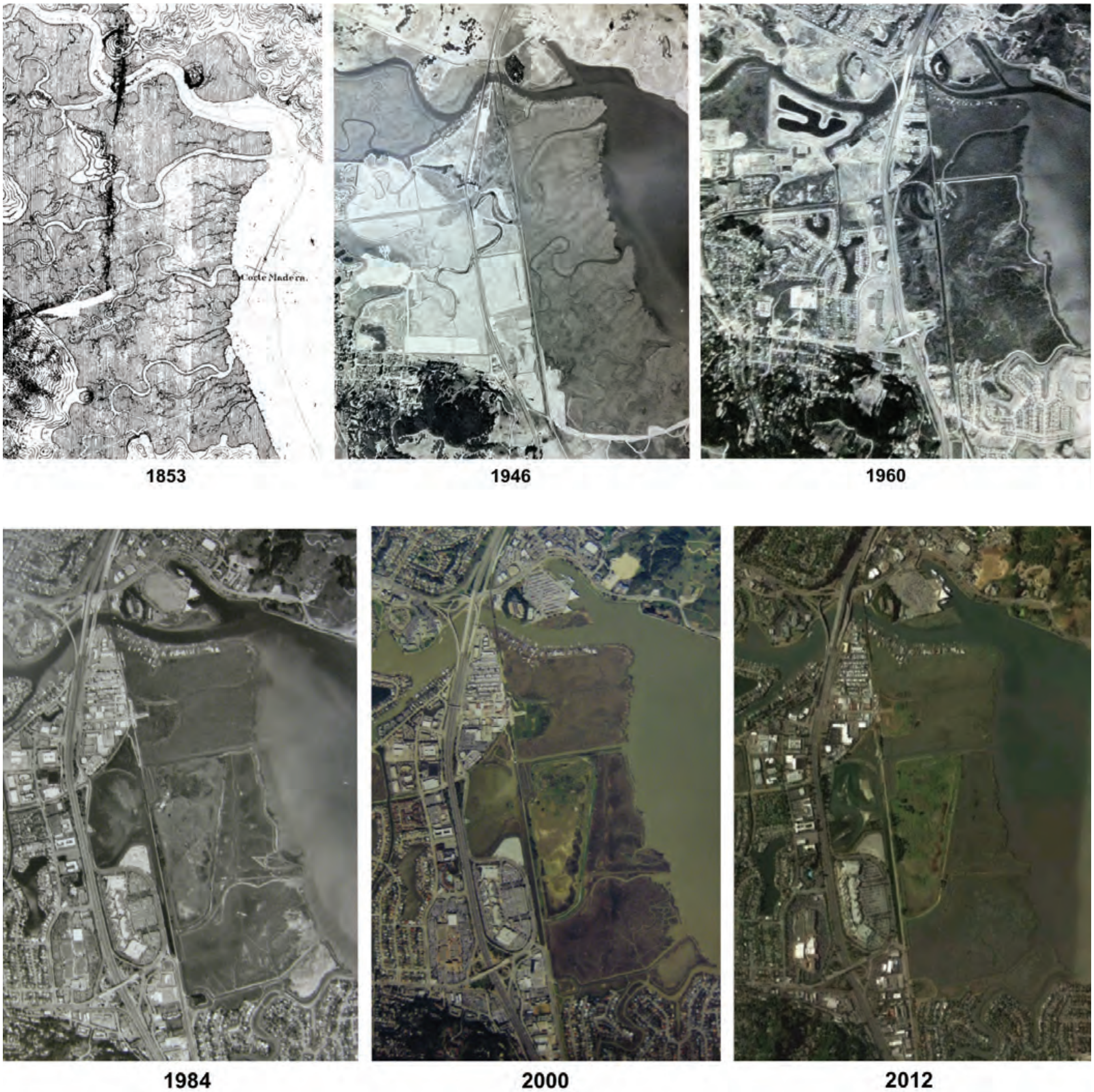


Figure 3-1. Historical imagery of the Corte Madera Baylands (courtesy of UC Berkeley Earth Sciences and Maps Library).

The 1853 image shows large tidal channels spreading into dendritic networks of smaller channels distributed through the marsh and valley bottom. Diking and filling severed the connection to the watershed and squeezed tidal marsh habitat between an urbanized landscape and the Bay.

Photograph courtesy of John Callaway

3 Corte Madera Baylands Evolution

As discussed in Chapter 2, baylands respond to sea level rise by building upward and migrating landward through four evolution processes – mudflat response, marsh edge erosion, vertical accretion, and upland transgression. This chapter reviews the geomorphic context of the Corte Madera Baylands and discusses physical data collected on these four evolution processes at the study site. While acknowledging that conditions change over time, an understanding of how the Corte Madera Baylands have evolved in the past improves the understanding of how they may evolve in the future, and how management measures can be used to protect and enhance natural features that support ecosystem service benefits.

3.1 Geomorphic context

Figure 3-1 shows how the Corte Madera Baylands have changed since 1853. The Marin Conservation League (2010) recounted the history of the Corte Madera Shoreline and much of the historical information below is based on their work. The Corte Madera Baylands were historically connected to the upper watershed by Corte Madera Creek (**Figure 1-1B**). The creek has a relatively high sediment yield due to continuing tectonic uplift and faulting, steep relief, and active hillslope processes in the upper watershed (Smeltzer et al. 2000). As the creek transitions from the upper watershed into its lower reaches that are influenced by the tides, the decreasing slope creates a naturally depositional environment. During large storm events of the past this depositional portion of the creek would flow overbank delivering watershed-sourced sediments directly to the adjacent tidal marsh. Meandering Corte Madera Creek used to be navigable to Ross Landing near the College of Marin, and tidal marshes and sloughs covered virtually all of the lower Ross Valley.

The North Pacific Coast Railroad set its tracks through the tidal marsh in 1875, and small communities began to form around the reclaimed tidal marsh by 1900. Houses along the Greenbrae Boardwalk that sit on pilings above the northern shoreline of Heerdt Marsh adjacent to Corte Madera Creek were built by the 1910s. Construction of the two-lane state highway (now U.S. 101) was completed in 1930. The 1946 image shows the tidal marsh was filled for development and dissected by railroad tracks and roadways. Comparison of the 1853 and 1946 images shows the substantial loss of tidal marsh habitat and disappearance of the estuarine-terrestrial transition zone. In the early 1950s during the post-war population boom, towns including Corte Madera were under intense pressure to allow tract development. Until then, Corte Madera had been mainly a hillside town, but filling tidal marsh to support development was a relatively inexpensive way to support local population growth. Around the same time, bayfront levees along North Muzzi and Muzzi

Marshes were put in place to create pastureland bayward of a steadily growing Corte Madera (see the 1960 image), and the once meandering creek was straightened, channelized, and essentially isolated from the Corte Madera Baylands.

The diking and filling of the baylands destroyed large amounts of historical floodplain, and the concomitant loss of tidal prism caused channels to narrow and shallow via sedimentation (Dedrick and Chu 1993). In 1976, the levee along Muzzi Marsh was breached, allowing the tidal marsh to evolve, while the levee along North Muzzi Marsh was allowed to remain in place and slowly erode by wave action.

3.2 Mudflat response

While land uses around the Corte Madera Baylands have changed over the last 150 years, so have the morphology and sedimentation in Corte Madera Bay. Corte Madera Bay is a shallow embayment less than 7 feet deep relative to **MLLW** (Lacy and Hoover 2011). At low tide, mudflats adjacent to the tidal marsh are typically exposed for several hundred feet, while at high tide, water runs up against the marsh edge. All of Corte Madera Bay is effectively within the sweep zone. The sweep zone is dynamic and responds to both natural and human caused changes to the environment, such as high winds or storm activity and large volumes of hydraulic mining-derived sediment, respectively. The shape and extent of the sweep zone can change within a single season or persist over many years.

Corte Madera Bay receives sediment both from the Corte Madera Creek Watershed and the Bay, which receives sediment from other local watersheds and the Sacramento-San Joaquin River Delta.[1] Net sedimentation in the Bay results from the difference between sediment delivery from rivers, primarily through episodic flood deposition (Wright and Schoellhamer 2005), and sediment loss from wind, wave, and tidal processes that erode the Bay (Krone, 1979). Jaffe et al. (2007) found human activities that changed sediment delivery from rivers were a primary control on the morphology and sedimentation of San Pablo Bay. For instance, hydraulic gold mining in the Sierra Nevada between 1853 and 1884 greatly increased the quantity of sediment delivered to rivers and streams flowing into the Bay, resulting in deposition in the shallows and an increase in mudflat area from 1856 to 1887. Around the same time, large-scale diking and draining of tidal marshes occurred around the Bay, which reduced the marsh area capturing sediment. Outboard of these diked marshes, the temporary sediment pulse formed extensive mudflats (Jaffe et al. 1998) and long, narrow tidal marshes ('fringing' marshes) grew out on these accreted sediments in some parts of the Bay (Doane 1999). Tidal marshes were prevented from prograding too far into the Bay by periods of high wind-wave action, especially during high tides and storms.

1 Historically, the primary source of sediment to the Bay has been large flood flows on the Sacramento River. Most of the coarse material is deposited at the head of the Bay, but large volumes of clays and silts are deposited in the shallows of San Pablo Bay. From there, this fine sediment is distributed throughout the rest of the Bay by tidal currents.

The rate of sediment delivery to Corte Madera Bay has changed over time and the area of mudflats and shallows have changed accordingly. The long-term sediment erosion and deposition trends in Corte Madera Bay are depicted in **Figure 3-2** (Fregoso et al. 2008; Foxgrover et al. 2011), where **Panel A** presents maps of bathymetry in 1855, 1895, 1947, 1979, and 2010, with a red line showing the profile transect where wave measurements were made (Lacy and Hoover 2011, see Chapter 4); **Panel B** presents profiles of bathymetry along the transect, noting the location of wave measurement stations; and **Panel C** presents maps of bathymetric change, again with reference to the profile transect and wave measurement stations.

It appears that sweep zone elevations in Corte Madera Bay have generally been decreasing, except during the early 1900s when a large volume of sediment was deposited. Each panel in **Figure 3-2** illustrates the same overall patterns:

> **1855 – 1895**: The sweep zone was erosional, suggesting more sediment was eroded than deposited.
>
> **1895 – 1949**: The sweep zone was depositional and prograded beyond 1855 conditions, most likely in response to hydraulic mining-derived sediment deposited earlier in San Pablo Bay. There are a few erosional traces indicated by straight paths on the north side of Corte Madera Bay and near S2 along the profile transect that are probably dredge channels.
>
> **1949 – 1979**: The sweep zone was mostly erosional, perhaps due to decreasing sediment supply to the Bay caused by, for example, the construction of dams on many Central Valley rivers, which trapped sediment and decreased peak flows, thereby diminishing the capacity of rivers to transport sediment (Wright and Schoellhamer 2004).[2] There is some deposition on the mudflat just south of Corte Madera Creek. Erosion associated with the first dredging of the Larkspur Ferry channel in 1976 is also evident.

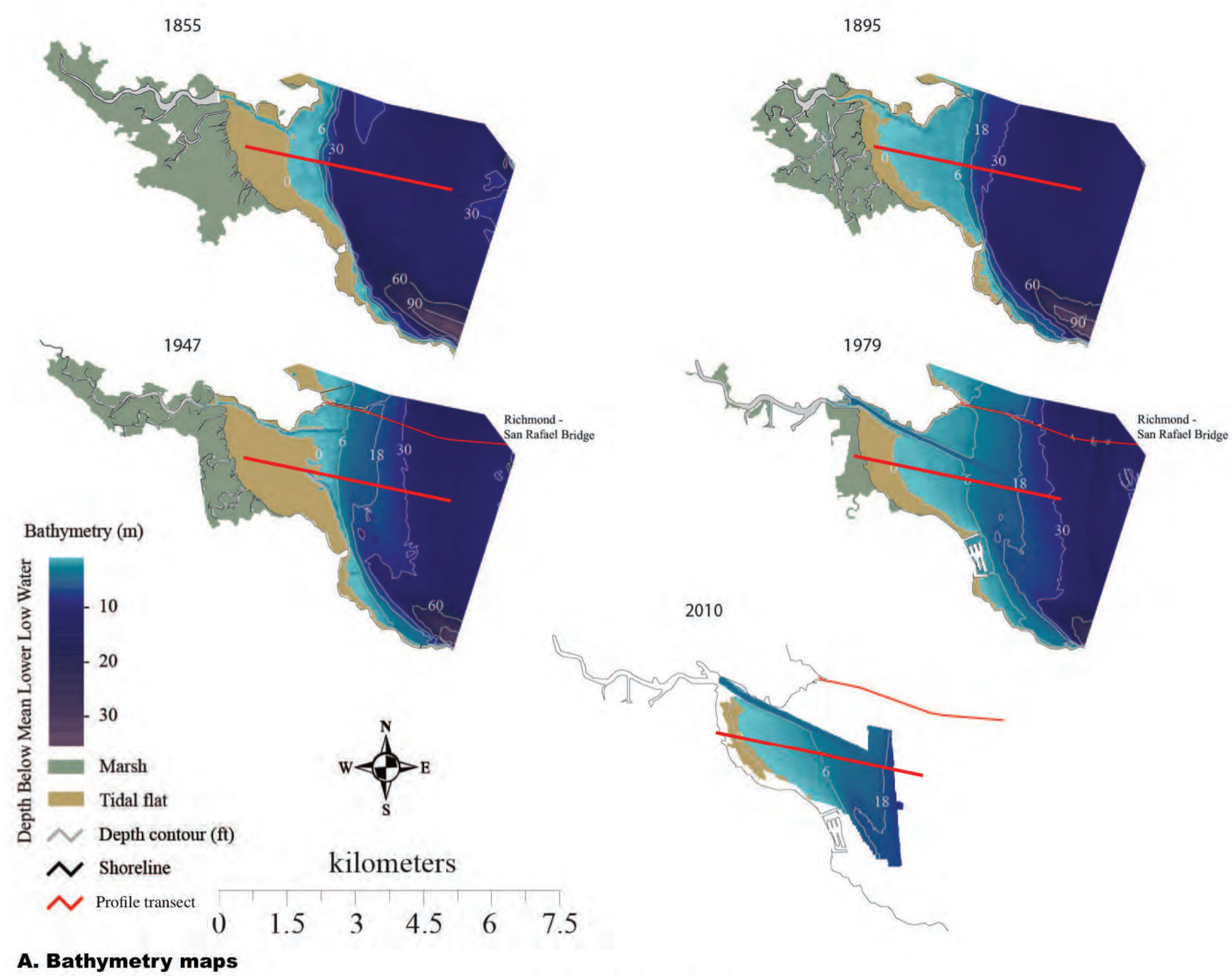
2 Sacramento River suspended-sediment concentrations have decreased about 50% since 1957.

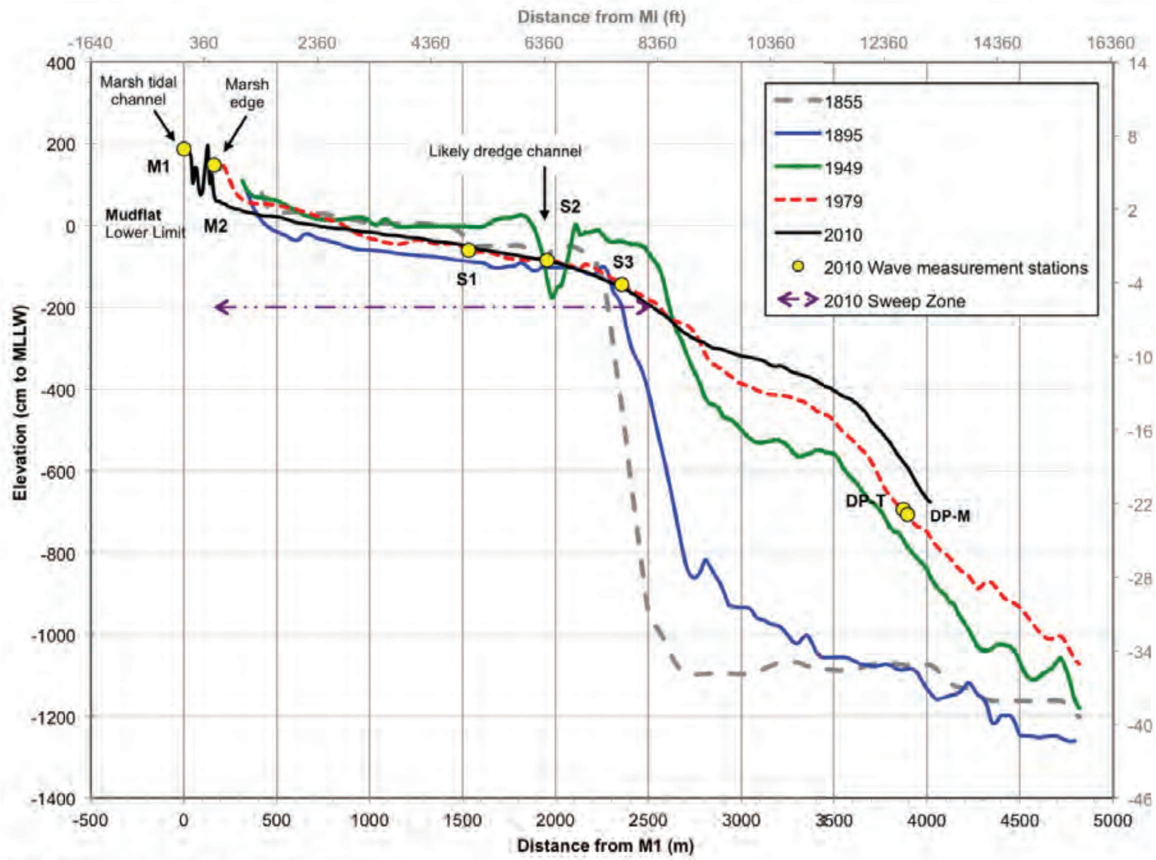
1979 – 2010: Most recently, the mudflat has continued to erode, while the shallows have remained relatively stable. This represents a slight deviation from past sedimentation patterns where the response of mudflats reflected erosion and deposition trends in the shallows. Sediment regularly deposits in the Larkspur Ferry channel, and since most of Corte Madera Bay either shows erosion or no change, this deposition suggests that this dredged channel is a sediment trap. Interestingly, Downing-Kunz and Schoellhamer (in press) analyzed suspended-sediment dynamics through the tidal reach of Corte Madera Creek to determine watershed sediment supply to Corte Madera Bay. During their research, they observed noticeably more turbid conditions in the Larkspur Ferry channel than the surrounding Corte Madera Bay, suggesting that the dredged channel could also be a pathway for sediment to bypass Corte Madera Bay and enter the Bay directly (Downing-Kunz, personal communication, March 29, 2013).

To better understand mudflat response, Jones (2011) conducted Sedflume analysis on 10 cores in Corte Madera Bay (refer to **Figure 1-5** for core locations). The cores were eroded using Sedflume to determine

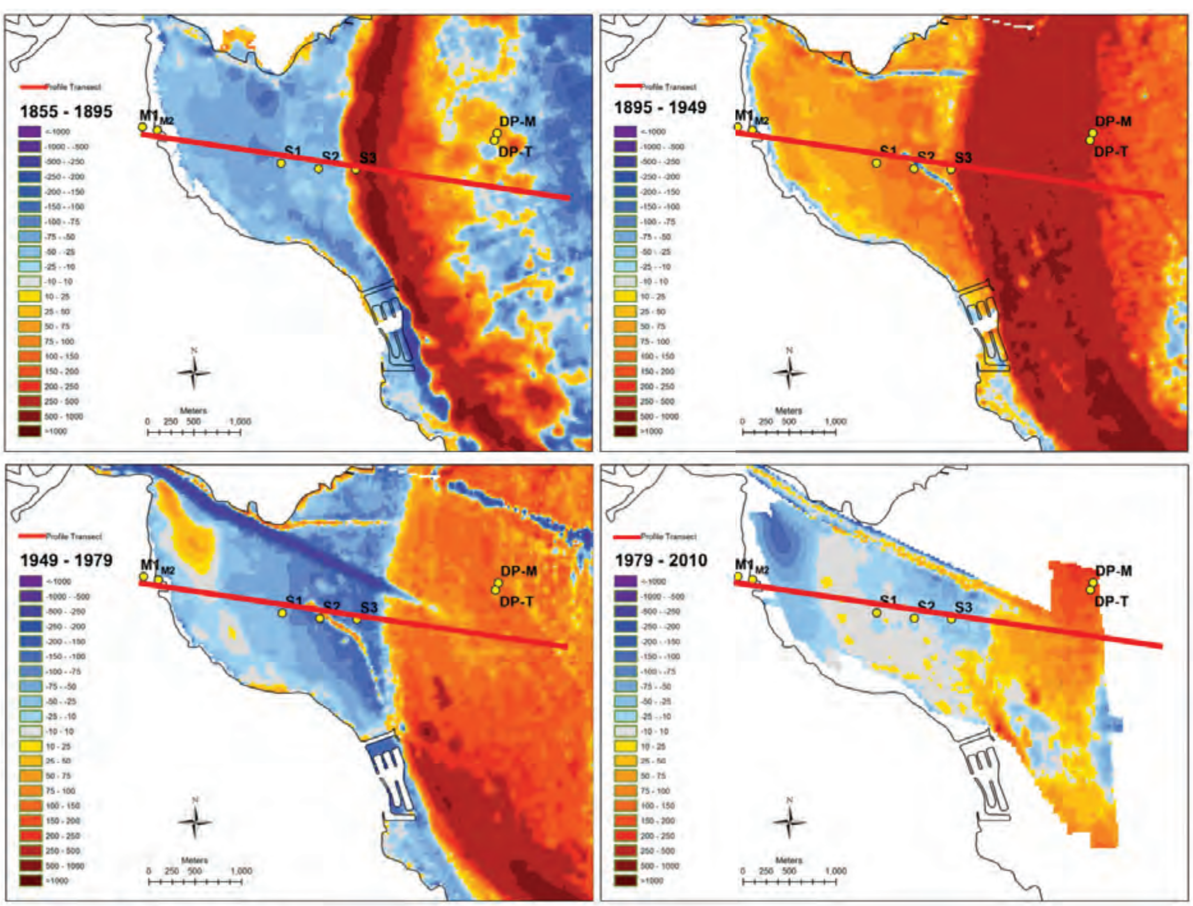
Figure 3-2. Corte Madera Bay bathymetry (1855 – 2010).

A) presents maps of bathymetry in 1855, 1895, 1947, 1979, and 2010, with a red line showing the profile transect where wave measurements were made (Lacy and Hoover 2011); B) presents profiles of bathymetry along the transect, noting the location of wave measurement stations; and C) presents maps of bathymetric change (in centimeters) between surveys, again with reference to the profile transect and wave measurement stations. Stations M1 and M2 are in the tidal marsh, while stations S1, S2, and S3 are in the shallows. S3 approximates the boundary between the shallows and the deeper San Francisco Bay instrumented with stations DP-T and DP-M. A decrease in water depth between surveys in interpreted as deposition, whereas an increase in water depth is interpreted as erosion that has removed previously deposited sediments. Corte Madera Bay was erosional in late 1800s, depositional in early 1900s, and erosional in late 1900s. While the mudflat has continued to erode from the late 1900s to the present, the shallows show little change (Fregoso et al. 2008, Foxgrover et al. 2011).





B. Bathymetry along profile transect



C. Change in bathymetry

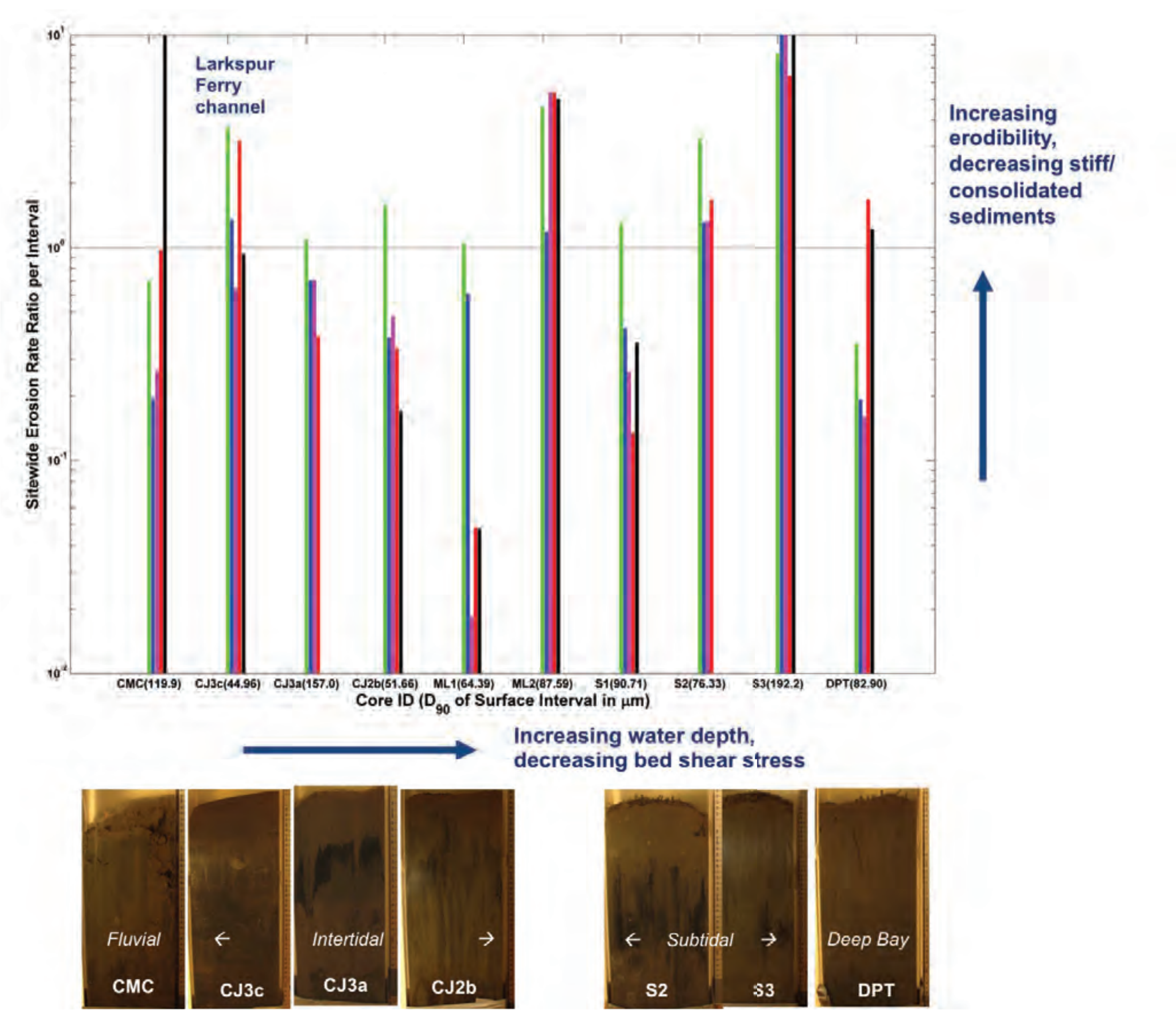
erosion rates as a function of depth and shear stress. This technique provides insights into historic sediment erosion and deposition patterns as well as current cross- and along-shore variations in sediment properties due to depth, energy gradient (e.g., waves and currents), and geomorphic differences (e.g., grain sizes and biological activity).

Sediment age profiles were reconstructed based on the Sedflume results and the sequence of historical bathymetric changes (**Appendix A**). For example, the age of the near-surface sediment on the mudflat (e.g., ML1) dates back to the turn of the century. This suggests that the hydraulic-mining derived sediment was eroded between 1949 and 2010, exposing older sediments. Reconstructions in the shallows (e.g., ML2, S1, and S2) show recent deposition between 1979 and 2010 on top of sediment dating around 1900, exposed as a result of erosion of the hydraulic-mining derived sediment.

Sedflume erosion rates indicate the erodibility of sediment in Corte Madera Bay. **Figure 3-3** presents sediment erosion rates by core interval, where higher erosion rates indicate more easily eroded sediment, and representative photographs of cores that highlight stratigraphic differences in fluvial, intertidal, and subtidal sedi-

Figure 3-3. Sediment erosion rates by core interval and representative photographs showing stratigraphic differences in fluvial, intertidal, and subtidal cores.

Dashed line represents site-wide average erosion rate (Jones 2011).



ment. While Corte Madera Bay is mostly fine silt (bay mud), the coarsest sediment size at the surface of each core is also shown (D_{90}) to convey the textural variability of the bed surface. The combined wave-current stresses along the bed erode sediment, but the response of the sediment to these combined stresses varies with texture (mud-sand mixture), cohesion (mud-organic content), compaction (often related to deposition patterns), and roughness (biological features such as mounds). Because sediment erosion is related to many variables, it is complex. The Sedflume results generally illustrate increasing erosion rates with increasing distance offshore. **Bed shear stress** decreases as water depth increases, meaning bed sediment in deeper water experience relatively less wave-current stresses along the bed, resulting in less consolidated and more erodible sediment. A summary of the Sedflume findings is outlined below:

Corte Madera Creek (CMC): Based on erosion rates, this core has stiff sediment at the surface, perhaps due to more erodible sediment regularly scoured or dredged out. The photograph also shows bedforms at the surface, characteristic of fluvial fine- and coarse-grain sorting processes.

Larkspur Ferry channel (CJ3c): This core from the navigation channel has relatively high erosion rates, characteristic of deep water, and the finest D_{90}, which supports the finding that that the dredged channel traps sediment. Frequent dredging, i.e., every 3 – 4 years, appears to remove distinct, historic layering (like CJ3a, see below).

Mudflats (CJ3a, CJ2b, and ML1, with CJ3a closest to Corte Madera Creek and ML1 farthest south): The photograph of CJ3a shows a very black layer in the middle of the core, which represents historic deposition of a very different nature (probably higher organic content) at some point in the past. All of these cores have similar erosion rates. The area experiences relatively high bed shear stress and surface sediment dating back to the turn of the century is underlain by older, stiffer sediment.

Shallows (ML2, S1, S2, and S3): The relatively high erosion rates at ML2 imply natural heterogeneity in the system, while S1, S2, and S3 show increasing erosion rates with increasing distance offshore. Since deeper water experience relatively less wave-current stresses along the bed, worms and other benthic organisms appear to reside at the surface.

Central San Francisco Bay (DPT): This deep water site is outside of the sweep zone and shows marked differences in erosion rates compared to cores within Corte Madera Bay, suggesting that different sediment transport processes occur in Central San Francisco Bay.

3.3 Marsh edge erosion

As mudflats erode, so does their ability to attenuate waves, resulting in higher **incident wave heights** at the marsh edge (see Section 4.1). The marsh edge along the Corte Madera Baylands has variable geometry, ranging from steep vertical and undercut banks topped with pickleweed (common along Heerdt and North Muzzi Marshes) to gradual slopes covered by cordgrass (common along restored Muzzi Marsh). Vertical banks, with as much as a 4-foot difference between the top and toe of the bank, indicate that erosion has removed the gradual slope and cut back into the marsh plain, whereas gradual slopes indicate ongoing deposition in the transition zone between the mudflat and marsh plain. However, observations by the San Francisco Estuary Institute (SFEI in preparation) suggest that the marsh edge profile (scarp or slope) is not necessarily an indicator of shoreline change (retreat/progradation). SFEI has found scarps on prograding marshes and developed the following working hypothesis describing the cycle of shoreline change:

1. A given marsh scarp with incipient fractures near the marsh edge fails under pressure from wind wave energy, depositing slump blocks of eroded marsh plain in front of the marsh scarp.
2. These blocks dissipate wave energy, and if they are large enough, allow deposition between the block and failed scarp. This deposition builds a gradual profile, creating a ‘ramp’ of new low marsh.
3. This low marsh traps sediment and builds to mid marsh elevation, when its profile flattens. Wave energy begins to erode the new mid marsh, creating another scarp. While this scarp is an erosional feature, net shoreline movement is bayward, resulting in marsh progradation.
4. When the new marsh scarp fails, the deposited slump block is, however, small this time and the eroded sediment is resuspended and redistributed in the Bay. In absence of a protective slump block, wave activity may continue to erode the marsh, resulting in net movement landward, resulting in marsh retreat.

The timing of this complex cycle of shoreline change has yet to be determined – it may be yearly or on a decadal scale. There may also be significant spatial variation. For example, at the Corte Madera Baylands erosion and deposition occur in different places, such that there may be a marsh scarp a short distance away from a slump block of eroded marsh sediment being actively colonized by cordgrass (PWA 1993).

Zoulas (unpublished) estimated long-term shoreline change rates at the Corte Madera Baylands from 1853 to 2006 based on georeferenced T-Sheets, USGS Digital Orthophoto Quadrangles, and aerial photographs. Based on this analysis, the shoreline has retreated inland by an average of 485 feet over the 153-year period, with less erosion along the northern edge than the southern edge. Mean erosion rates decreased from approximately 3.5 feet per year during the period spanning 1853 to 1930 to around 1 foot per year from 1930 to 1978, and then increased back to around 3.5 feet per year after 1978. Given the error implicit in shoreline change analysis[3], the relative erosion rates are more significant than the absolute rates. The sequence of erosion rates suggests that the shoreline was relatively stable when levees were in place along the southern marsh edge. The beginning of this stable period also coincided with the 1895 to 1949 period when a large volume of sediment was deposited in Corte Madera Bay (**Figure 3-2C**). During this time, the higher, wider sweep zone likely dissipated more wave energy and reduced incident wave heights and associated erosion at the marsh edge. **Figure 3-4** presents aerial images of Muzzi Marsh showing how the levees constructed in the early 1900s prevented edge erosion, and how after they were breached in 1976, edge erosion accelerated due to exposure to tidal and wave action.

3 Several sources of error compound to affect the accuracy and precision of historical shoreline positions and final erosion rates. Positional uncertainty refers to the error in defining a historical shoreline due to tides, storms, and short-term changes. Measurement uncertainty refers to map resolution and shoreline digitization required for analysis.

The cause of marsh edge erosion at the Corte Madera Baylands is likely complex, with contributions from various processes and sources. Tidal and wave action, including boat wakes[4], sediment supply[5], eutrophication, and biological activity[6] all could affect marsh edge erosion. Regardless of the cause, sediment accumulation measurements collected for this study provide another line of evidence to support the finding from shoreline change analysis of active marsh edge erosion along the Corte Madera Baylands. Callaway et al. (2012a) measured short-term (two-week), mass-based sediment accumulation using sediment pads at Heerdt and Muzzi Marshes and found that no deposition occurred at the marsh edge/low marsh stations during almost all sampling periods. This finding was surprising, as low marsh stations typically have the highest sediment accumulation rates because lower elevations are flooded more frequently and these stations are closer to sediment sources from the Bay and adjacent mudflats (Hatton et al. 1983; French and Stoddart 1992; Callaway et al. 1997; Weis et al. 2001). Callaway et al. (2012a) hypoth-

4 When waves break against the marsh edge with energy levels that exceed the resistance to erosion, the marsh edge erodes and retreats landward. There was concern that the actively eroding scarp along Heerdt Marsh was correlated with increased wave energy due to ferry wakes. PWA (1993) monitored the marsh edge from 1989 to 1992 and failed to find a direct correlation between ferry operations and increased erosion rates, but estimated that the ferries contributed approximately 10% of the wave energy potentially affecting Heerdt Marsh.

5 Allan (1989) found lithology was the chief determinant of marsh edge erosion, whereby cohesive muddy sediments yielded relatively tall and strong marsh scarps, while sandy sediments build rather low and comparatively weak scarps susceptible at high tide to grain-to-grain wave attack below root systems.

6 Increased scarp erodibility may also be a result of biological activity (bioturbation/burrowing by invasive isopod *Sphaeroma quoyanum*) (Talley et al. 2001).

Figure 3-4. Historical imagery of the levee breach along Muzzi Marsh.

The sequence shows progressive marsh edge erosion. The 2003 image is a color infrared photograph, with blue areas indicating more moisture than red areas, e.g., Outer Muzzi Marsh is more frequently inundated than Inner Muzzi Marsh.

esized that the low accumulation rates at the lowest elevations at Heerdt and Muzzi Marshes were due to more significant wave exposure at these locations compared to others around the Bay, although additional data are needed to confirm this hypothesis.

3.4 Vertical accretion

Corte Madera tidal marshes are generally keeping pace with sea level rise, meaning the rate of vertical accretion is higher than the rate of sea level rise. **Table 3-1** presents a summary of measured rates of vertical accretion at different elevations within Heerdt Marsh using short-term marker-based and long-term isotope dating methods, and within Muzzi Marsh using short-term marker-based methods only (refer to **Figure 1-5** for core locations; Callaway et al. 2012a). Only short-term rates are provided for Muzzi Marsh because sediment cores from this restored marsh are too young to be dated using isotope methods. Long-term vertical accretion rates within Heerdt Marsh are similar to rates measured in other locations in San Francisco Bay (Callaway et al. 2012b). All long- and short-term rates are slightly higher than the current 0.1 inches per year rate of sea level rise, except short-term rates at mid and high stations in Heerdt Marsh.

Data collected at Heerdt Marsh indicates that long-term accretion rates are slightly higher than short-term rates. Accretion rates based on ^{210}Pb profiles (approximately 100 years) were slightly higher or similar to rates based on ^{137}Cs (approximately 47 years), and these were higher than the short-term rates based on feldspar marker horizons (15 months) (**Table 3-1**). This temporal pattern is consistent across all marsh stations (low, mid, and high) and is in stark contrast to the pattern found in most other tidal marshes. Typically, long-term rates are lower than short-term rates (e.g., ^{210}Pb-based rates < ^{137}Cs-based rates < markers-based rates) because compaction, decomposition, and other belowground processes lead to reduced rates of vertical accretion over longer timer periods. This unusual pattern at Heerdt Marsh could be due to a reduction in local sediment availability and/or increased wave erosion in recent decades.

The results in **Table 3-1** also suggest the spatial variability in vertical accretion rates across the marsh is different at the natural marsh compared to the restored marsh. Natural Heerdt Marsh has a very slight decrease in the average rate of vertical accretion from low to high stations, possibly due to the mature nature of the marsh and the relatively uniform high elevation across the entire marsh. In contrast, restored Muzzi Marsh show a more typical gradient in rates from low to high stations. At Muzzi Marsh, vertical accretion rates were greater at the low and mid stations, as expected, since these stations are at lower elevations and thus more frequently inundated by the tides. The accretion rate at the Muzzi Marsh high station, which is at a similar elevation as Heerdt Marsh, was slightly higher but comparable to rates measured in Heerdt Marsh. At both Heerdt and Muzzi Marshes, there was little indication of higher sedimentation rates in winter, as most stations showed a constant gradual increase in vertical accretion rather than a strongly seasonal pattern.

Since vertical accretion occurs through the accumulation of mineral sediment on the surface of the marsh and through the input of organic matter from local plant production, Callaway et al. (2012a) also measured organic matter content. They detected slight differences between Heerdt and Muzzi Marshes, with organic matter content at natural Heerdt Marsh ranging from approximately 10

Table 3-1.

Average rates of vertical accretion (inches per year) from low, mid, and high stations at Heerdt using long- and short-term methods, and at Muzzi Marshes using short-term methods. Rates based on 210Pb are relative to approximately 100 years, though sometimes less to preserve an undisturbed core and avoid mixing issues; rates based on 137Cs are relative to 47 years (1963 to the collection date); rates based on feldspar marker horizons convert cumulative accretion over about a 15-month sampling period into an annual rate.

	Heerdt Marsh	Muzzi Marsh		
Station	Long-term rates based on 210Pb (in/yr)	Long-term rates based on 137Cs (in/yr)	Short-term rates based on markers (in/yr)	Short-term rates based on markers (in/yr)
Low	0.21	0.17	0.12	0.31
Mid	0.16	0.16	0.08	0.31
High	0.14	0.14	0.07	0.15

– 20% and at restored Muzzi Marsh from approximately 5 – 13%. Values from Heerdt Marsh are similar to values from other natural tidal marshes in the Bay (Callaway et al. 2012b). Lower values at Muzzi Marsh are expected as the input of organic matter in restored tidal marsh soils can take many decades (Craft et al. 1999; Zedler and Callaway 1999).

3.5 Upland transgression

Since the Corte Madera Baylands are squeezed against a flood risk management levee along the historic railroad alignment and are vertically accreting at a pace that is keeping up with the current rate of sea level rise, there is little indication of recent upland transgression. More importantly, there is no natural transition zone across which upland transgression could occur in response to accelerating rates of sea level rise in the future. Terrestrial fill along the backshore of Heerdt, North Muzzi, and Muzzi Marshes is at relatively high elevations and would require intervention (e.g., grading) if this area were to support landward and upward migration of the baylands profile.

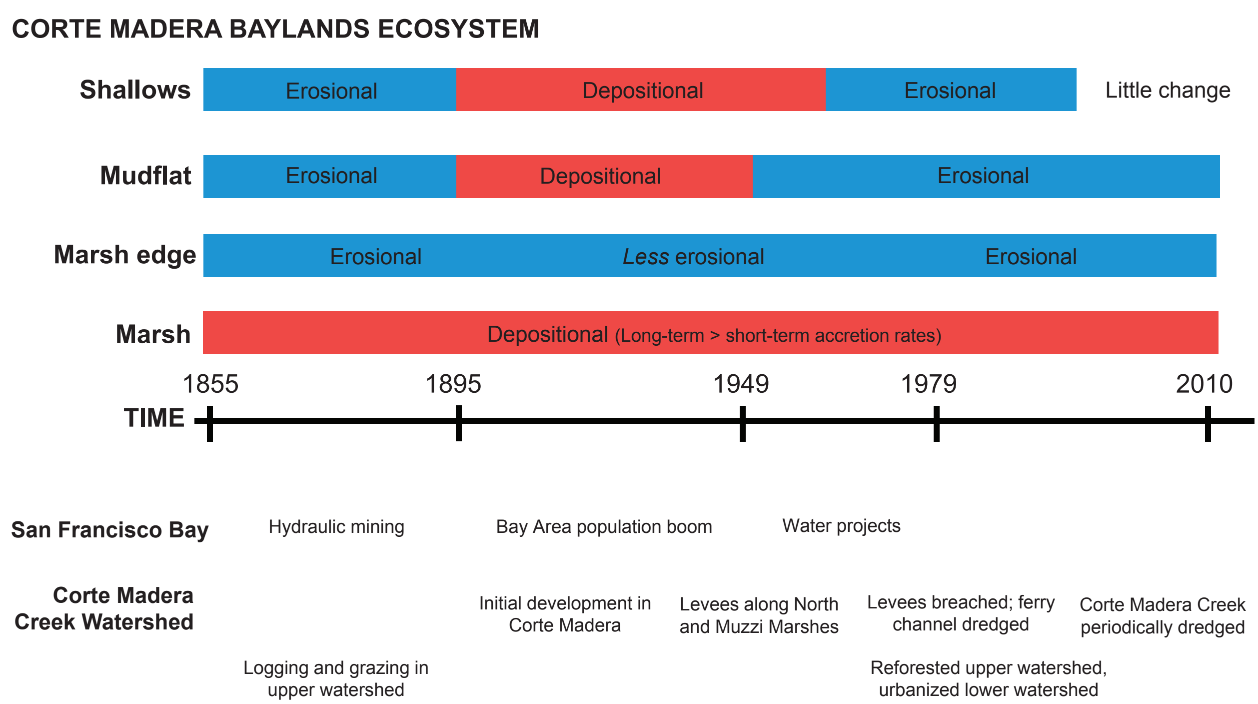
3.6 Recap: A sediment-limited system

The available geomorphic evidence suggests that the Corte Madera Baylands are sediment-limited (**Figure 3-5**). Mudflat lowering, active marsh edge erosion, and decreasing vertical accretion over time indicate a reduction in local sediment availability. Sediment supply from the Central Valley appears to be declining.[7] Levees and development separate Corte Madera Creek and its watershed-derived sediment supply from the Corte Madera tidal marshes, while the Corte Madera Creek

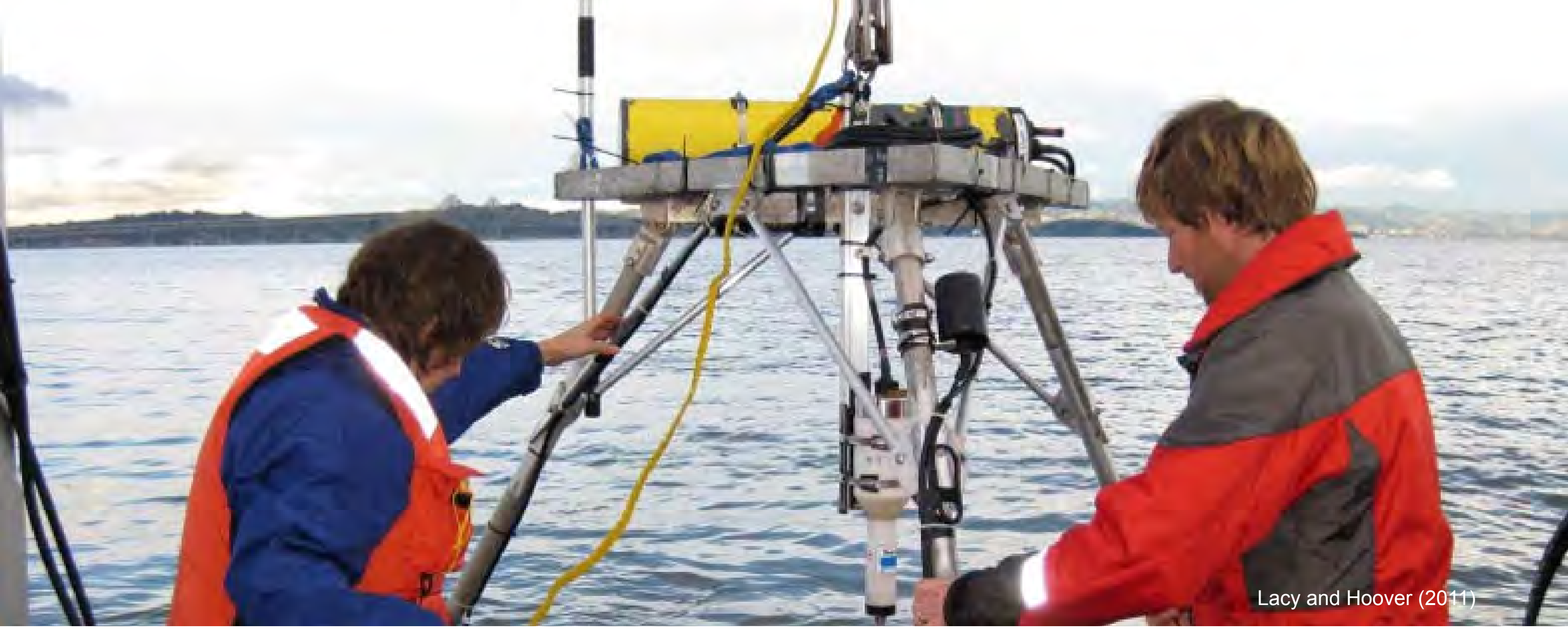
7 Schoellhamer et al. (2005) found that sediment supply from the Sacramento-San Joaquin River Delta (as opposed to local watersheds) accounted for 50% of the sediment supply to the Bay at the end of the 1900s, whereas its contribution used to be estimated at about 85% (Porterfield 1980). Some of this change is due to a real trend in loads entering the Bay from the Central Valley and some of it is an artifact of improved measurement and computation techniques. In the most recent contribution on the topic, the supply from the Central Valley is computed to be 39% for the period Water Year 1995-2010 (McKee et al. in press).

Figure 3-5. Conceptual timeline showing sediment deposition and erosion trends in Corte Madera shallows, mudflats, and tidal marshes

based on review and analysis of bathymetric surveys, topographic maps and aerial photographs, and sediment accumulation measurements. Major events in San Francisco Bay and the Corte Madera Creek Watershed are provided below the timeline for reference.



Flood Control Channel, the tidal reach of Corte Madera Creek (Downing-Kunz and Schoellhamer in press) and the Larkspur Landing Ferry Channel all trap sediments, further reducing the local availability of sediment for baylands deposition. A quantitative sediment budget accounting for sediment fluxes through the Corte Madera Baylands would be helpful to estimate the net loss and gain of sediment within the system (e.g., Brew and Williams 2010). Research is underway to better understand the mechanisms of sediment transport in Corte Madera Bay and Corte Madera Creek (Downing-Kunz et al. in preparation) and how these relate to sedimentation in Corte Madera tidal marshes (Takesue and Jaffe, 2012).



4 Corte Madera Baylands Ecosystem Services

This chapter builds on our understanding of the key processes of evolution and discusses the ecosystem services provided by the Corte Madera Baylands. We describe how the Corte Madera Baylands attenuate waves and provide flood risk reduction to shoreline communities based on wave measurements and modeling. We also describe how tidal marshes sequester carbon dioxide that would otherwise enter the atmosphere based on analysis of the cores collected to measure long-term vertical accretion in Heerdt Marsh. The nature of these benefits, their sensitivity to sea level rise coupled with declining sediment supply, and management implications are also explored below.

4.1 Flood risk reduction

Coastal flooding is the combined result of tides, storm surge, and waves.[1] The short-period wind waves that occur in San Francisco Bay do not penetrate the full water depth, but do produce bed shear stress and sediment resuspension in the shallows. The Corte Madera shoreline is exposed to easterly and southeasterly wind-waves. Winter storms tend to produce southerly winds, whereas the summer tends to generate westerly winds, from which Corte Madera Bay is fairly protected.

Lacy and Hoover (2011) collected data on waves in shallow Corte Madera Bay during the winter of 2010 to determine whether, and to what degree, waves are attenuated as they transit Corte Madera Bay and North Muzzi Marsh (the location of the wave measurement transect; refer to **Figure 1-5** for wave measurement station locations). Wave events during the study period were moderate and therefore representative of conditions likely to occur each winter. However, waves only reach the marsh plain at high water levels. Since water levels and waves are random processes that are only partially correlated, the likelihood of both occurring simultaneously is *less* than the likelihood of each occurring individually. For example, the likelihood that both water levels and waves occur simultaneously at their individual 10-year **return period** (10% annual chance) is less than the 10% annual chance. This reduced likelihood of simultaneous events occurring was exemplified during the 2010 deployment, when the peak observed

1 The Preliminary Flood Insurance Study for Marin County cites a hydraulic study conducted by the USACE that indicates that a flood having a 1-percent annual chance recurrence interval in Corte Madera Creek will not create an inundation problem as severe as that created by the estimated 1-percent annual chance tide in [the] Bay (USACE, "Comprehensive Survey of San Francisco Bay and Tributaries (Tidal Stage Frequency and Tidal Reference Plans", FEMA 2012).

water level of approximately 7 feet NAVD88 coincided with wave heights less than 1 foot at the offshore DP station. At no time during the study period was significant wave energy observed on the tidal marsh. Thus, the only observational insight about wave attenuation over the tidal marsh is that waves were completely attenuated somewhere between the station at the edge of the marsh and the station within the marsh.

Modeling was used to expand the understanding of wave attenuation beyond the measurements at the Corte Madera Baylands. To explore the role of tidal marsh vegetation in attenuating waves at higher water levels associated with extreme events and sea level rise, the **WHAFIS** (Wave Height Analysis for Flood Insurance Studies) wave model was used (FEMA 2005). The model is one-dimensional (1-D), in that it predicts wave height and period along a transect perpendicular to the shoreline.[2] Waves attenuate due to depth-limited breaking across the Corte Madera Baylands. Waves also attenuate due to bottom friction in the shallows and mudflats and due to vegetation-induced friction in tidal marshes. The WHAFIS model does not include a bottom friction coefficient, so cannot be used to predict wave attenuation in the sweep zone. Nevertheless, the WHAFIS model enables characterization of present and future flood risk reduction benefits of the tidal marsh through the investigation of the sensitivity of wave attenuation to water levels (e.g., sea level rise), wave conditions, vegetative cover, and the profile of the marsh edge.

Ideally, the WHAFIS model would be calibrated[3] and validated[4] using wave measurements over marshes; however beyond the wave data collection conducted for this study, no known San Francisco Bay wave data within marshes is currently available.[5] Output from the WHAFIS model was verified in that the predicted wave attenuation is consistent with a general understanding of wave attenuation observed at other marshes and is consistent with the wave attenuation predicted by the **SWAN** (Simulating WAves Nearshore), a more sophisticated two-dimensional (2-D) shallow water wave model that was also applied to the Corte Madera Baylands (van der Wegen and Jaffe 2012; Delft University of Technology 2012). Key findings from the wave attenuation measurement and modeling efforts are summarized below.

4.1.1 Wave attenuation measurements

During the study period, **wave crest elevations** did not exceed 8 feet NAVD88 and wave heights decreased toward the shore (**Figure 4-1**). The largest waves were associated with strong, sustained south-southeasterly winds. At low water surface elevations, waves break on the mudflat or against the marsh edge before inundating the marsh plain. Waves only reach the tidal marsh station (M1) when the marsh plain bayward of the station is inundated, which occurred only 15% of the study period.

During the study period, there were three large wave events: February 5, 24, and 26. **Figure 4-2** shows wave statistics at all the stations for the 5-day period including the February 24 and 26 events. On February 24, the high tide wasn't high enough to inundate the marsh, so no waves were recorded at the M1 station. On February 26, the high tide was approximately 7-feet (close to the maximum recorded) and a 2-foot wave was measured at the DP station. This 2-foot wave was reduced to a 1-foot wave at the marsh edge station (M2) after traveling over more than 10,000 feet of shallows and mudflats. Since the elevation of North Muzzi Marsh is roughly 6 feet, water depth over the marsh was approximately 1 foot and the 1-foot wave at M2 was completely attenuated (to less than an inch) at M1, just 500 feet from M2 across the tidal marsh. With a water depth of 1 foot, waves with incident heights greater than 0.8 feet break simply due to depth-limitation, i.e., $H > 0.8 \times 1 = 0.8$. Thus, the low water depths over the marsh even at high tide cause all but the smallest waves to break. Only during storms that occur at high tide would the water depth over the marsh be deep enough to allow waves to reach beyond the marsh edge. Only when waves reach beyond the marsh edge and propagate across the marsh plain would vegetation play a role in wave attenuation by imparting resistance on incoming waves, thereby causing energy dissipation and potentially wave breaking.

The muddy bottom of Corte Madera Bay causes significant wave attenuation through bottom friction.[6] While wave heights decreased toward the shore, **bottom orbital velocities** were remarkably constant during large wave events (**Figure 4-2**). The near-constant bottom orbital velocities are the result of two opposing tendencies: a decrease associated with smaller wave height

2 The WHAFIS model was also used in FEMA flood hazard mapping for the San Francisco Bay Area Coastal Study. Vegetation was parameterized according to the same values in this project and the ongoing FEMA effort.

3 Calibration refers to the process of adjusting model parameters so the predicted output more closely matches observed values.

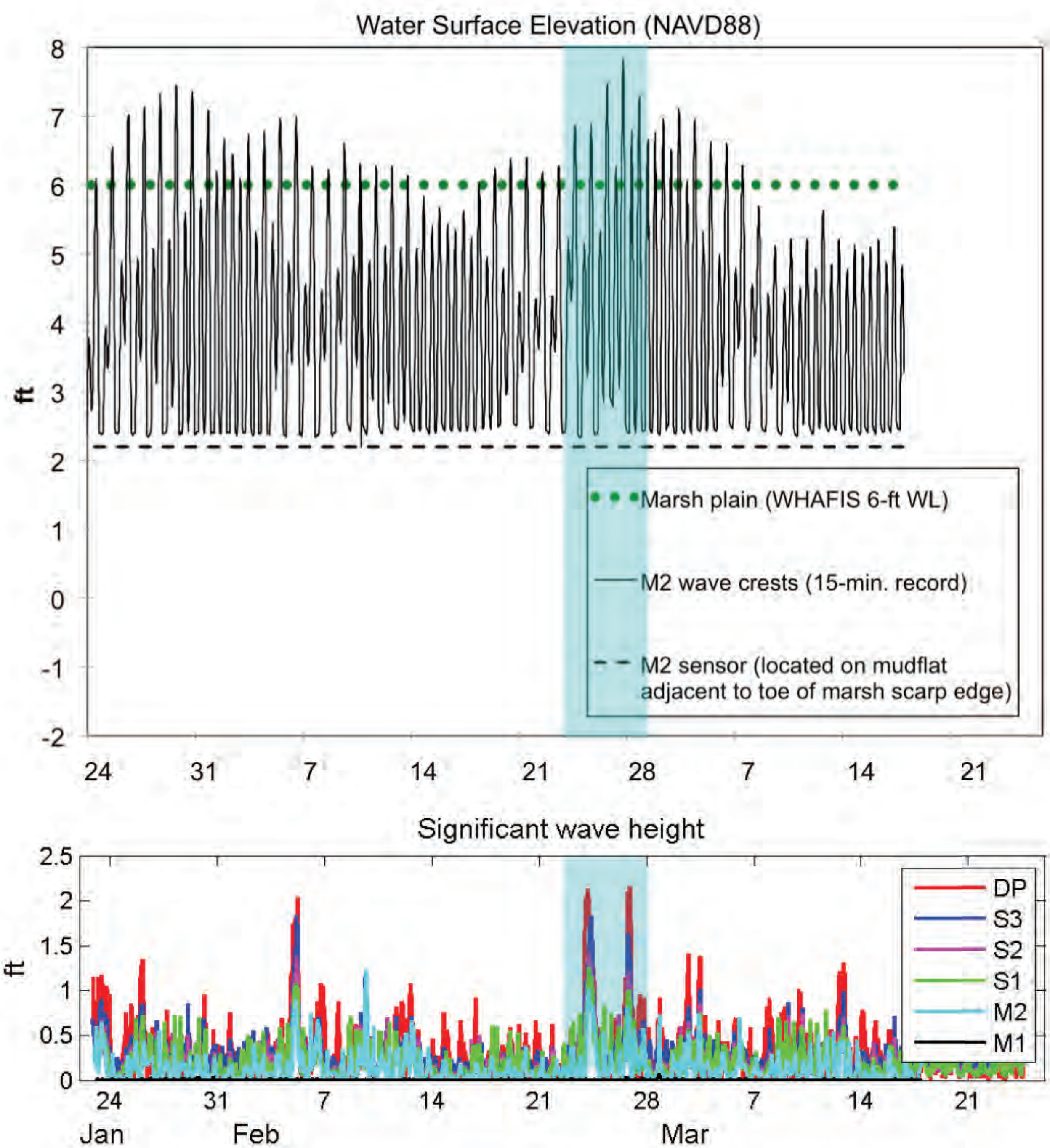
4 Validation refers to comparing the calibrated model to a different data set to quantify the parameterized model's skill at predicting observed vales over a broader range of conditions.

5 Data from Lacy and Hoover (2011) describe waves that attenuated before reaching the internal marsh station, so the precise rates of wave attenuation could not be measured. Data from Brand et al. 2010 (wave attenuation in South Bay) was across shallow subtidal shoals, not marshes, and as such is not applicable.

6 Depth limitation was insignificant at the other wave measurement stations located in the shallows (S1, S2, S3), where wave heights were less than 0.8 times the water depth.

Figure 4-1. Wave statistics during the study period.

The upper panel shows M2 water levels, which are representative of other stations, and helpful for evaluating water surface elevations relative to the marsh plain. The marsh was not inundated very often since the observed water surface elevations were seldom above the elevation of the marsh plain (green dots). Note: the tidal signal is often truncated at low tide when the M2 sensor was dry (black dashed line)). The lower panel shows wave attenuation in Corte Madera Bay, where at any given time, wave heights are largest at the offshore station (DP) and smallest adjacent to the marsh (M2). ***Figure 4-2*** zooms into the shaded blue area.



and an increase associated with shallower water depths. In other words, bottom orbital velocities vary directly with wave height and inversely with water depth, such that bigger waves occur in deeper water, while smaller waves occur in shallower water, and orbital velocities decay with distance below the water surface. This results in relatively constant bottom orbital velocity as wave height and water depths change towards shore. Bed shear stress varies with the square of bottom orbital velocity; therefore bed shear stress is relatively constant as is the potential for wave-driven sediment resuspension across Corte Madera Bay during large wave events.[7]

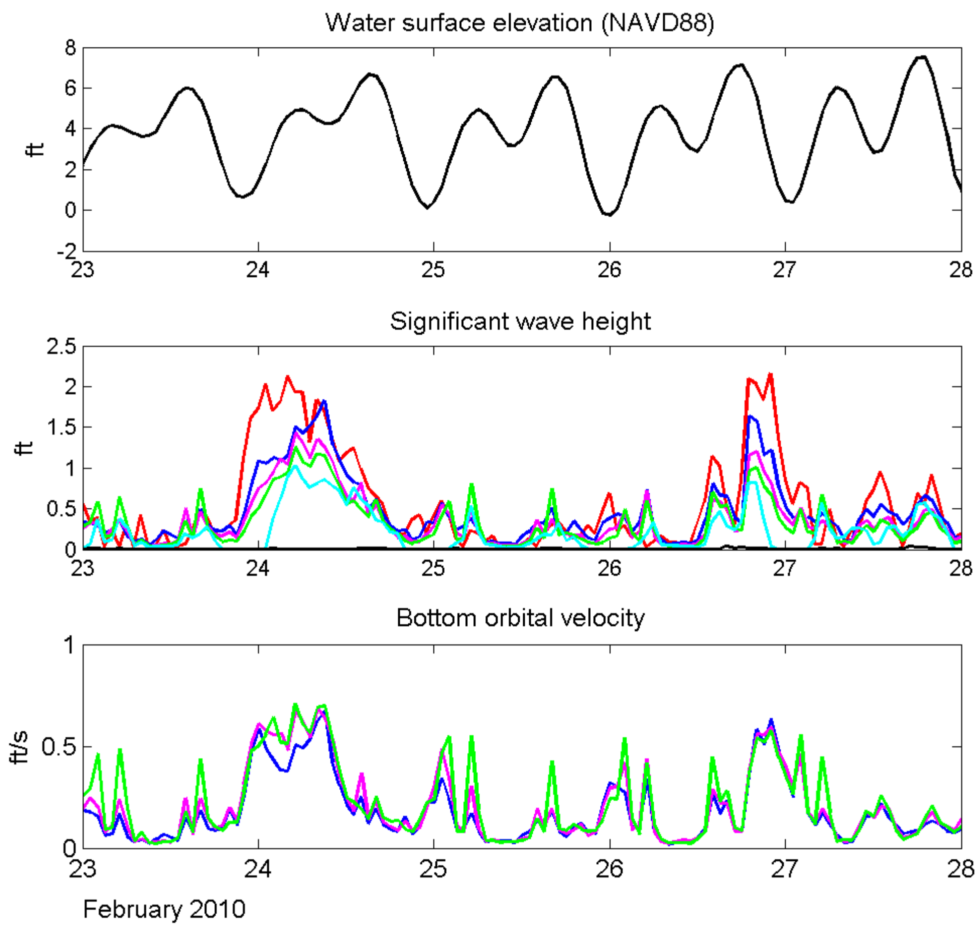
Bottom friction, bed shear stress, and wave attenuation were measured to be greater at low than high water levels. In addition, wave direction appeared to influence wave attenuation, while wave height did not.[8] **Figure 4-3** illustrates the influence of water level on wave attenuation, where wave heights in the mudflats and shallows are only a small fraction of the original wave height entering Corte Madera Bay (measured at station DP) at low water surface elevations when bottom friction affects more of the water column. Wave heights were as little as 20% of that at station DP as waves propagated across

7 This result is not to be confused with the variability in sediment erosion rates due to varying bed shear stress (Section 3.2). There are spatial and temporal considerations to shear stress. The bottom orbital velocities may be relatively constant during large events, but differences in sediment erosion rates reflect differences in exposure to wave action, e.g., bed shear during small, medium, and large events.

8 See Lacy and Hoover (2010) for a discussion of wave direction.

Figure 4-2. February 23 – 27 wave statistics (see legend from 4-1).

The marsh plain is at approximately 6 ft NAVD88. On February 24, the morning high tide wasn't high enough to inundate the marsh and a 2-foot wave at the furthest offshore station (DP) was reduced to a 1-foot wave at the marsh edge (M2) after traveling over more than 10,000 feet of shallows and mudflats. On February 26, the evening high tide was high enough to inundate the marsh, but within 500 feet of the marsh, the wave was completely attenuated (M1 wave heights were less than an inch) due to depth-limited breaking. The lower panel shows relatively constant bottom orbital velocities in the shallows, which indicate relatively constant bed shear stress (and sediment resuspension potential) during large wave events.



the shallows of Corte Madera Bay. The average wave height was 70% of that at station DP at S3, 53% at S2, 45% at S1, 34% at M2, and 0.7% at M1.

Although wave attenuation within North Muzzi Marsh can largely be attributed to depth-limited breaking, the entire marsh is nonetheless important in protecting the shoreline from waves energy. In absence of the marsh, the wave forces currently eroding the marsh edge would likely reach, and impact, the developed shoreline. Sea level rise will exacerbate this impact by causing the sweep zone to move toward the shore, with the potential for wave erosion to increase due to increased water levels (and decreased wave attenuation).

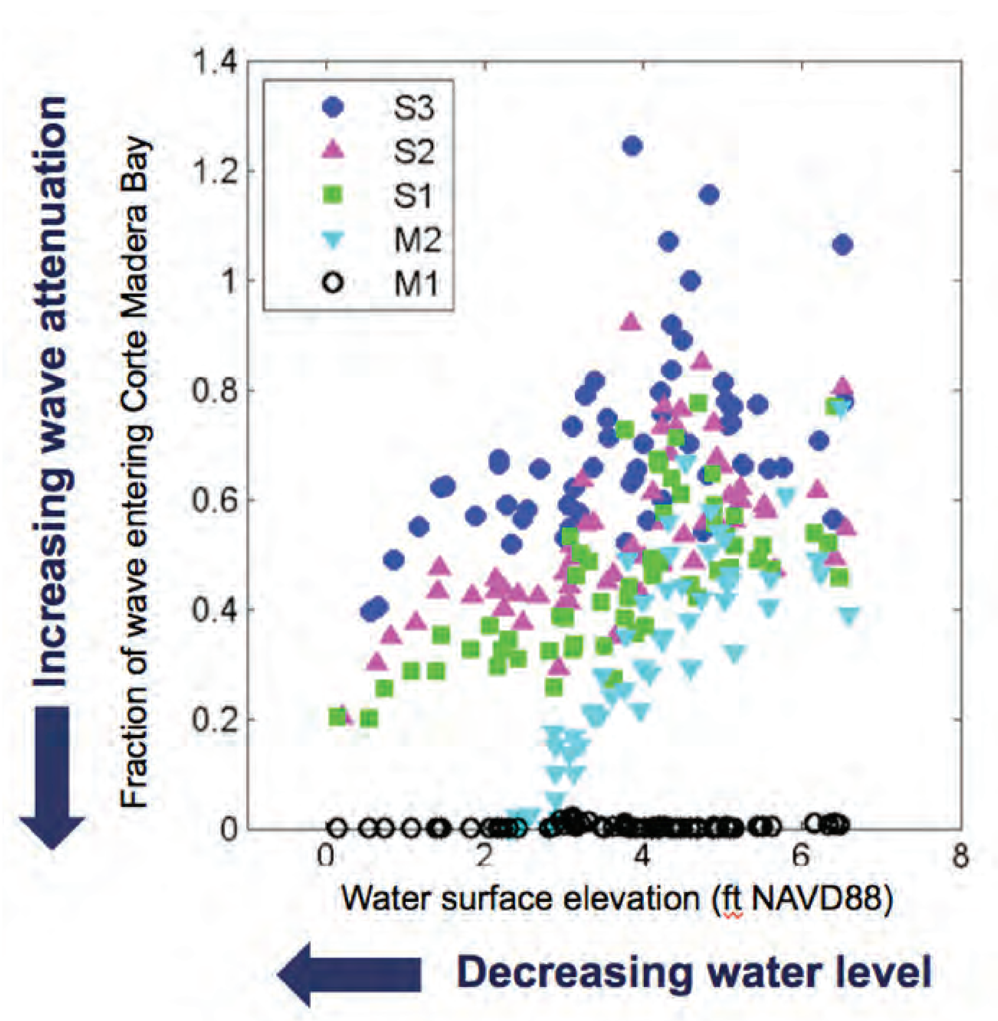
4.1.2 Wave attenuation modeling

The WHAFIS model was used to further quantify wave attenuation at the Corte Madera Baylands. Model results are summarized below and model parameterization is described in detail by ESA PWA (2012) (**Figure 4-4**).

Water level: To determine the sensitivity of the model to water level, the WHAFIS model runs considered five water levels that span current and projected conditions with sea level rise (rounded to the nearest foot, see Section 2.3): 6 feet, 7 feet, 8 feet, 9 feet, and 10 feet NAVD88. To assist in the interpretation of these water levels, **Table 4-1** presents each in terms of current and projected return periods. For example, the 9-foot water

Figure 4-3. Wave attenuation is greater at low water levels

at each station when wave height at station DP was greater than 1-foot. On average, wave heights at the marsh edge (M2) are 0.34 of what they were at DP (66% reduction). The black dots (M1) along the bottom of the plot show that no significant wave activity was measured on the marsh.



level can be interpreted as the upper end of present day extreme conditions (1% annual chance event), and with sea level rise, this water level is projected to occur more frequently, as a 50% annual chance event by 2050, a peak **spring tide** sometime between 2050 and 2100, and as MHHW by 2100. The modeling assumed a static bed elevation of roughly 6 feet for all water levels; while in reality there will likely be evolution of the marsh plain as sea level rises.

As discussed in Section 4.1.1, water depth largely determines wave attenuation. This is most dramatically illustrated at the marsh edge, where water depth decreases suddenly from the mudflat to the marsh plain and causes significant reduction in wave height and energy. As water levels increase, wave attenuation over the marsh edge decreases. **Figure 4-5** illustrates this phenomenon by showing representative WHAFIS model runs – wave attenuation for 7- and 9-foot water levels, each with a 2-foot incident wave. Since the WHAFIS model does not include bottom friction over the sweep zone, wave heights in Corte Madera Bay appear the same as incident wave heights at the marsh edge. SWAN results confirm the significant wave attenuation is at the marsh edge. At the 7-foot water level, a 2-foot wave decreases by more than 70% in the first 160 feet of marsh plain due to depth-limited breaking, i.e., 2 > 0.8 x 1 = 0.8. Conversely, at the 9-foot water level, a 2-foot

Figure 4-4. Representative WHAFIS model tidal marsh profile.

The profile transect is the same as that shown in Figures 1-5 and 3-2, with distance relative to Station M1. To represent characteristic conditions along the Corte Madera shoreline, the profile does not include an outboard levee. Modeled geometry is based on idealized bed elevations from the seamless USGS topographic/bathymetric data set, where topographic data was collected using airborne LiDAR. Airborne LiDAR reads the elevation of the top of vegetation instead of the ground surface, which resulted in an offset of approximately 9 inches at Corte Madera (Athearn et al. 2010, Foxgrover et al. 2011).

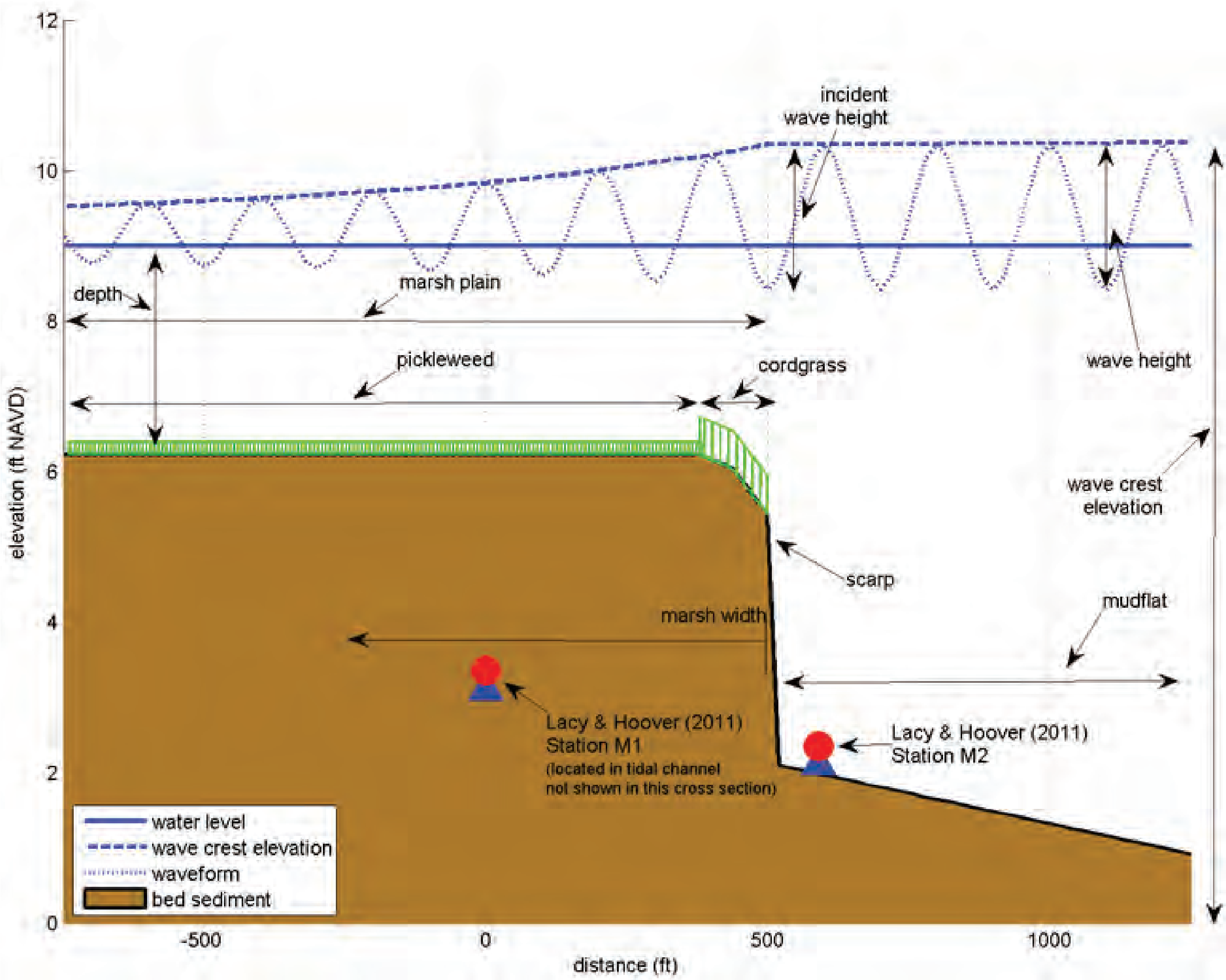
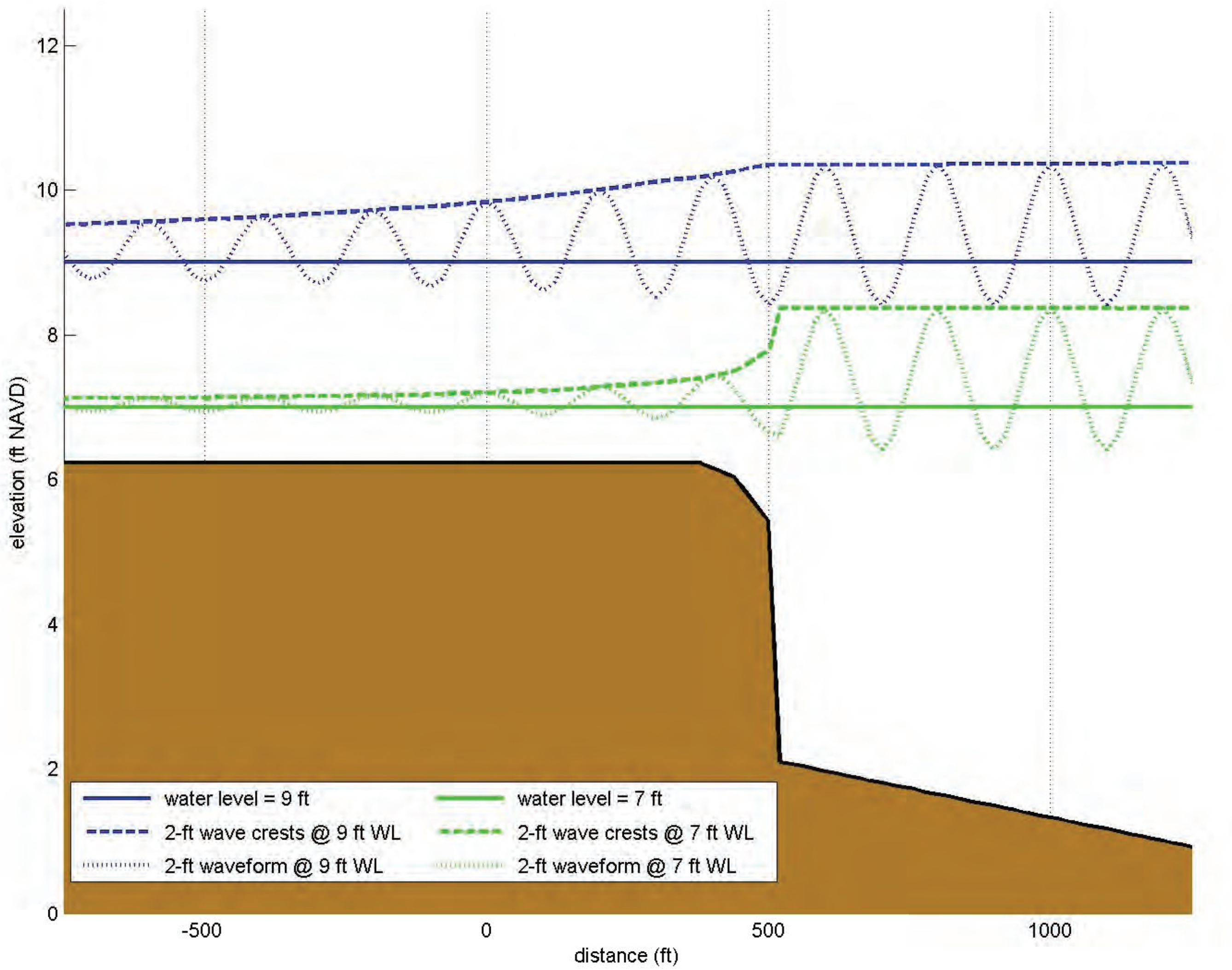


Table 4-1.
Modeled water levels interpreted as events.

	Modeled water levels (ft NAVD88)			
Event	Today	+1 ft SLR (2050)	+2 ft SLR	+3 ft SLR (2100)
MHHW	6	7	8	9
Peak spring tide	7	8	9	10
2-year (50% annual chance)	8	9	10	--
100-year (1% annual chance)	9	10	--	--

Figure 4-5. WHAFIS results for 7-foot and 9-foot NAVD88 water levels with 2-foot wave heights.
Higher water levels experience relatively less attenuation from depth-limited breaking and vegetation-induced friction.

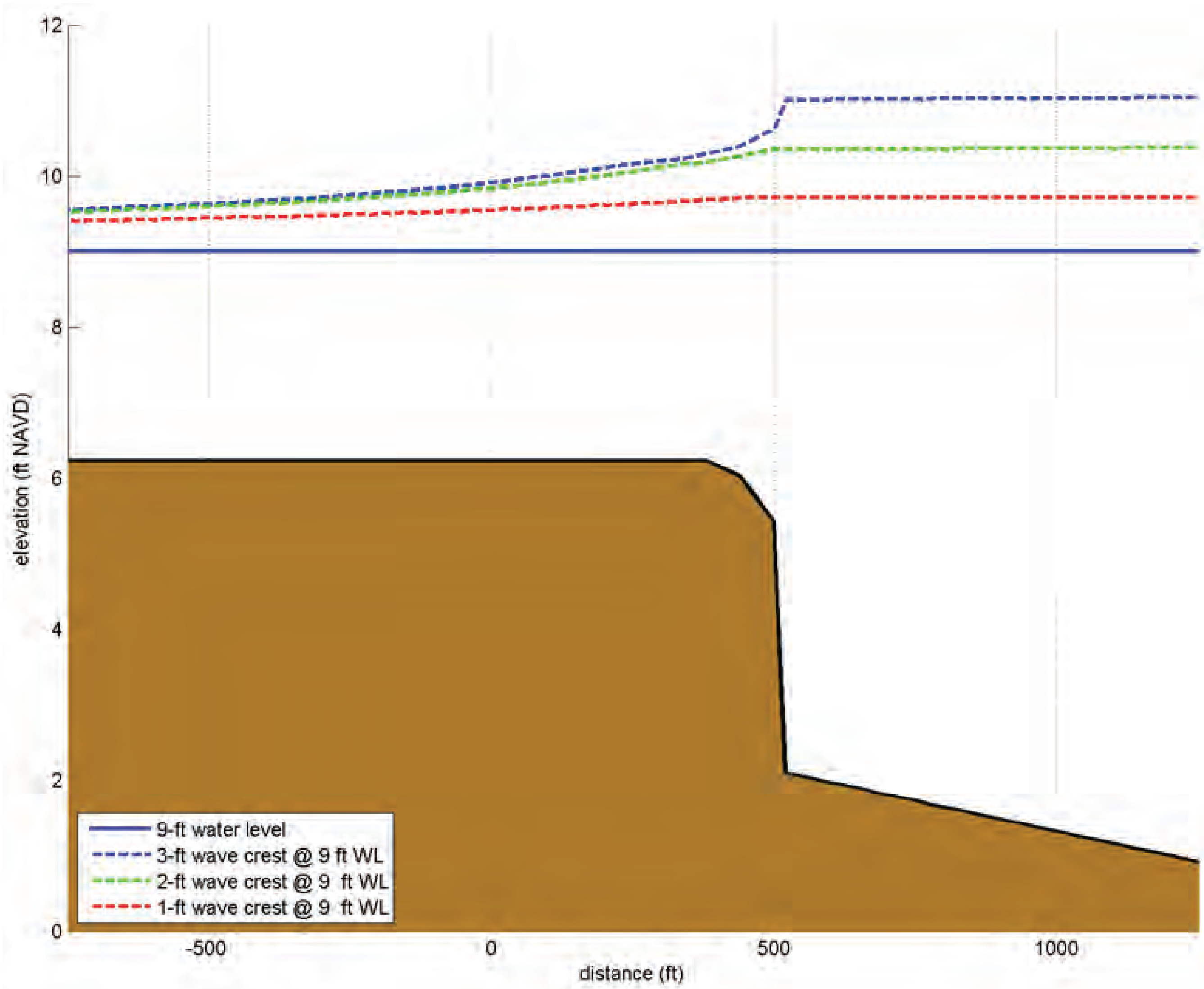


wave decreases by only 17% over the same 160 feet distance because the wave height is *not* greater than the depth-limited wave height (2 < 0.8 x 3 = 2.4). At the 7-foot water level, a 2-foot wave is attenuated by more than 60% over the next 500 feet of marsh, while at the 9-foot water level, a 2-foot wave is attenuated by less than 40% over the same distance. Shallow water over the marsh also means waves are closer to vegetation and therefore subject to more vegetation-induced friction.

Wave height: Wave height depends on local bathymetry, wind speed and duration, wind direction, and fetch. There are no long-term wave records for Corte Madera Bay, so a generalized set of wind and resulting wave conditions were derived to determine the sensitivity of the WHAFIS model to wave height (**Table 4-2**). **Figure 4-6** presents wave attenuation for 1-foot, 2-foot, and 3-foot waves at the 9-foot water level. Although a 3-foot wave at the 9-foot water level is not likely to occur, it helps to exemplify the potential importance of different parameters. Only the 3-foot wave is depth-limited over the marsh plain, i.e., 3 > 0.8 x 3 = 2.4. As a result, when the 3-foot wave reaches the scarp, it experiences rapid attenuation and is dissipated to almost the same height as the 2-foot wave. All three wave crests converge to within approximately 0.5 feet of each other at the back of the marsh.

Figure 4-6. WHAFIS results for 1-foot, 2-foot, and 3-foot wave heights with 9-foot NAVD88 water levels.

All three wave crests converge to within approximately 0.5 feet of each other at the back of the marsh.



Vegetation: The WHAFIS model was used to test the sensitivity of wave attenuation to vegetation parameters by modifying the extent of different vegetation species over the marsh. The starting point for this sensitivity analysis was the characteristic vegetation at Muzzi Marsh, which consists of cordgrass occupying the lower elevation outboard 120 feet of the marsh and pickleweed occupying the remainder of the marsh plain. Cordgrass grows as a tall, straight emergent plant, while pickleweed has a smaller shrub-like structure, forming a dense mat with many branching stems lying prostrate. The additional conditions modeled were:

- All pickleweed – Cordgrass on the outboard edge of the marsh was changed to pickleweed. This condition is representative of an eroding fringing marsh, e.g., North Muzzi Marsh without the wave-eroded levee.
- All cordgrass – Pickleweed on the inboard section of marsh was changed to cordgrass. This condition is representative of a downshift in vegetation from mid marsh to low marsh in response to sea level rise rates that outpace vertical accretion.
- No vegetation – Removal of all vegetation from the marsh plain. This condition is representative of a drowned tidal marsh that has converted to an unvegetated mudflat in response to sea level rise rates that significantly out-pace vertical accretion.

WHAFIS modeling suggested that wave attenuation is relatively insensitive to marsh vegetation species. Cordgrass attenuates waves slightly more than pickleweed, but the largest difference from characteristic conditions was when there was no vegetation. SWAN results are more informative to understand the no vegetation condition because, unlike WHAFIS, it accounts for bottom friction over an unvegetated surface. van der Wegen and Jaffe (2012) found that wave heights almost double at the 10-foot water level when there was no vegetation. Furthermore, vegetation indirectly contributes to wave attenuation by promoting sediment deposition, which determines marsh elevations and water depths, especially important to depth-limited breaking (Gedan et al. 2011).

Geometry: Changes in marsh plain elevation due to erosion or deposition are identical to modeled changes in water level. For example, waves propagating across an 8-foot water level over the existing 6-foot marsh plain would be equivalent to waves propagating on a 9-foot water level over the marsh plain that had accreted by 1 foot (to a 7-foot marsh plain). Thus, to determine the sensitivity of the model to geometry, the profile geometry was modified such that the transition from the mudflat to the marsh plain was a gentle slope instead of a steep scarp.

Whether the waves break gradually over a gentle slope, or suddenly at a steep scarp, depth limitation dictates the incident wave height. As the water becomes shallower, WHAFIS demonstrates that waves experience a corresponding reduction in height. It is important to recognize that this does not necessarily mean that the erosive power of the wave breaking over the slope and at the scarp is the same. The breaking and sudden deceleration of waves at the scarp exposes the scarp to a considerable amount of erosive energy, more so than if the wave was gradually depth-limited over a slope. This can lead to active erosion that maintains the scarp marsh edge. For these reasons, wave height is an imperfect surrogate for erosive wave energy.

After the initial and sometimes abrupt breaking that occurs at the scarp marsh edge, wave attenuation occurs gradually through vegetation-induced friction over the marsh plain. As such, the marsh width (distance from

Table 4-2.
Wind speed and estimated wave height and period for 100-year event (USACE, 2002).

Wind Speed	Nominal wave height	Wave period
10 mph	1 ft	2.1 s
20 mph	2 ft	2.5 s
30 mph	3 ft	2.9 s

the Bay towards the shore) affects wave height. **Figure 4-7** highlights the role of marsh width, where wave attenuation is shown by scaling the wave height across the marsh by its incident height at the marsh edge. For those water levels that result in depth-limited waves, the first parts of these curves typically show the steepest decrease associated with rapid wave attenuation. While a narrow strip of marsh can perform significant wave height reduction via breaking at lower water levels, the inland portion of the marsh provides significant additional attenuation in particular for extreme water levels. For example, the 9-foot water level is approximately today's 100-year water level and at this water level for both a 2- and 3-foot wave, 1,000 feet is an order of magnitude width needed to attenuate waves to a 1-foot target wave height (a measure based on FEMA flood mapping standards).

Table 4-3 shows that the minimum marsh width required to attenuate waves to a 1-foot target wave height is more sensitive to water level than incident wave height, and width increases nonlinearly with water level. This is consistent with wave attenuation being dominated by depth limitation for lower water levels and by vegetation-induced friction for higher water levels. A calibrated and validated wave model would improve the 1,000-feet minimum marsh width estimate required to attenuate waves to below a 1-foot target wave height. If the bed elevation relative to extreme water levels is lower, for instance, in the case that marshes cannot accrete sediment fast enough to keep pace with sea level rise, then the marsh width would need to be *greater* to accomplish the same reduction in wave height.

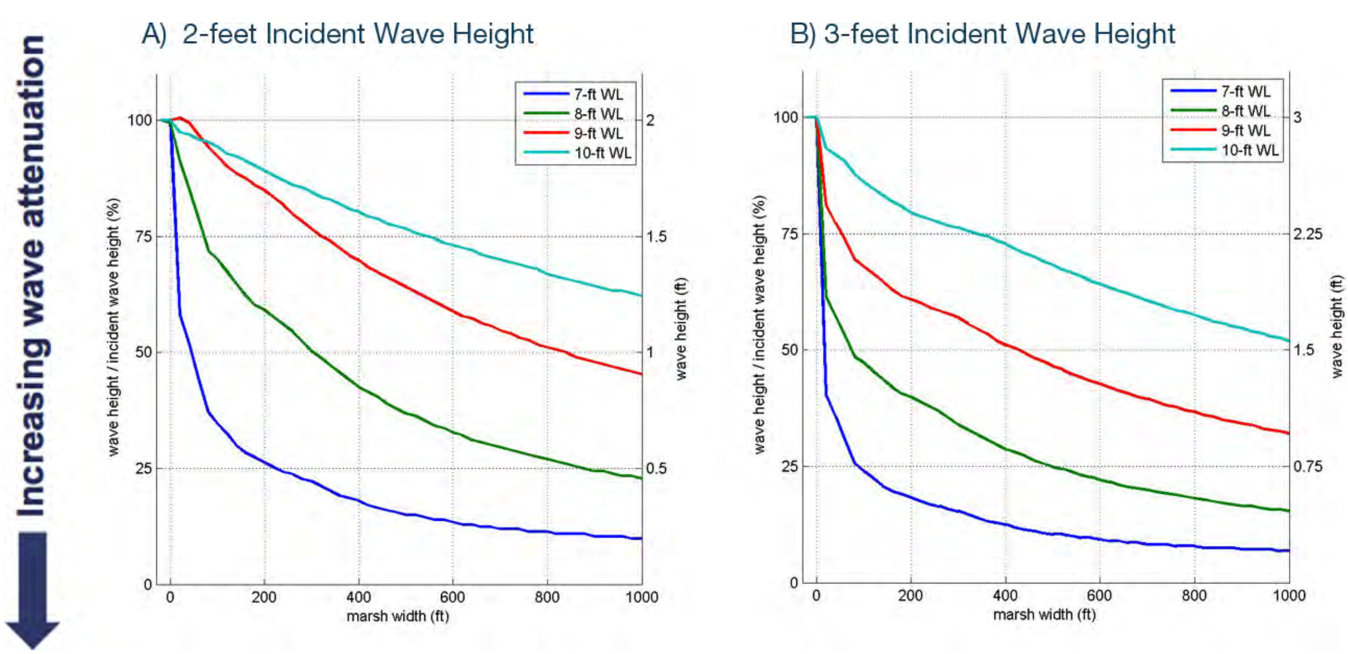
4.2 Carbon sequestration

Tidal marshes can play a role in mitigating climate change by sequestering carbon. Interest in carbon sequestration has increased significantly as federal and state governments consider the possibility of incorporating carbon credits for tidal wetland restoration into plans to reduce carbon dioxide emissions (Crooks et al. 2010).

Callaway et al. (2012a) measured the rates of carbon sequestration in natural Heerdt Marsh using long-term isotope dating methods (**Table 4-4**). Carbon sequestration rates based on ^{137}Cs across the site averaged 112

Figure 4-7. WHAFIS results for wave attenuation as a function of marsh width, where incident wave heights are A) 2 feet and B) 3 feet NAVD88.

Due to depth-limitation, a steep decrease is readily apparent for a 2-foot wave traveling across 7-foot and 8-foot water levels and for a 3-foot wave traveling across 7-foot, 8-foot, and 9-foot water levels. For reference, North Muzzi Marsh is approximately 1,000 feet wide.



g/m²/yr, which is similar to other tidal marshes around the Bay (Callaway et al. 2012b). Rates based on ^{210}Pb were not compared to other tidal marshes because of the varying time scales of the ^{210}Pb dating on the cores at Heerdt Marsh. Across Heerdt Marsh there were small differences in the rates of carbon sequestration; however, these are unlikely to be significant, especially given the small sample size. Rates of carbon sequestration were not measured at Muzzi Marsh because of the limitation in dating long-term cores there; however, we would expect that rates of carbon sequestration in the future would be similar to or slightly higher than rates measured at Heerdt Marsh, based on the similarities in accretion rates at stations that were located at similar elevations.

If the Corte Madera tidal marshes continue to keep pace with sea level rise, they will continue to sequester carbon into the future; however, if they cannot keep up with future sea level rise, their associated vegetation and carbon sequestration benefits will be lost. As tidal marsh converts to mudflat, overall rates of carbon sequestration across the entire marsh will likely decrease. While most of the carbon already sequestered will likely stay sequestered, no new sequestration benefits will be gained.

4.3 Management implications

Tidal marshes are particularly vulnerable to sea level rise because vegetation at each elevation is adapted to a specific tidal-inundation regime. For example, Baye (2012) reports conspicuous “gray marsh” patches of pickleweed die off at China Camp after prolonged waterlogging from high rainfall and frequent over-marsh flooding during El Nino winters. Prolonged saturated conditions in marshes will likely become more frequent as sea level rises.

Takekawa et al. (2012) modeled the response of the Corte Madera tidal marshes to projected rates of sea level rise and found that marsh habitats will downshift

Table 4-3.
Minimum marsh width in feet to reduce incident wave height to a 1-foot wave.

Incident wave height (ft)	Water level (ft NAVD88) 7	8	9
2	40	300	840
3	50	320	980

Table 4-4.
Average rates of carbon sequestration from low, mid, and high stations at Heerdt Marsh using long-term dating methods. Rates based on 210Pb are relative to approximately 100 years, though sometimes less to preserve an undisturbed core and avoid mixing issues; rates based on 137Cs are relative to 47 years (1963 to the collection date).

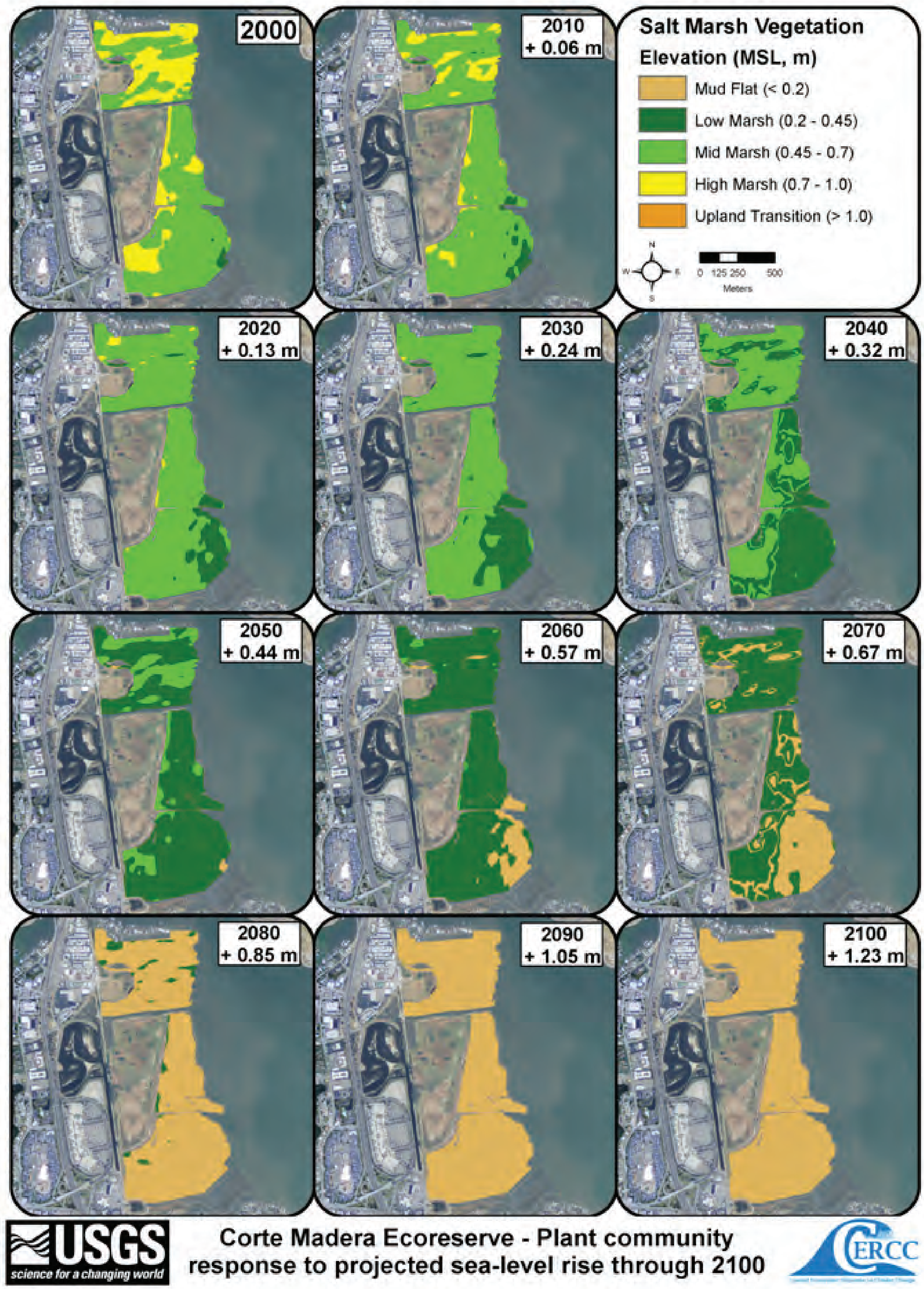
Station	Long-term rates based on 210Pb (g/m2/yr)	Long-term rates based on 137Cs (g/m2/yr)
Low	137.7	113.3
Mid	127.1	118.9
High	94.1	102.7

until they are eventually lost and convert to mudflat before the end of the century (**Figure 4-8**). These results were sensitive to the rate of sea level rise and sediment supply, which highlights the importance of these drivers of change. There is, however, limited data on suspended sediment concentrations and model inputs are often estimated from measurements collected within a large channel, river, or the Bay. More appropriate suspended sediment concentration data are needed from tidal channels within a marsh and the marsh plain, where sediment transport and deposition actually take place, to support these types of modeling efforts.

While all lines of evidence suggest that the Corte Madera tidal marshes will not keep pace with accelerated sea level rise, the threshold rate of sea level rise that leads to vegetation mortality, elevation loss, and irreversible conversion of marsh to mudflat is unknown. Low elevations in Muzzi Marsh are currently accreting around 0.3 inches per year, suggesting that the Corte Madera tidal marshes can keep up with *some* increase in the rate of sea level rise. The fundamental issue is *how much*. Furthermore, if sediment supply continues to decrease, it will be more difficult for the Corte Madera Baylands to keep pace with future increases in the rate of sea level rise. Decreases in the extent and/or elevation of mudflats and marshes effectively increase water levels and therefore decrease wave attenuation by depth-limited breaking, bottom friction, and vegetation-induced friction. The result would be less flood risk reduction benefits provided by the Corte Madera Baylands to shoreline communities. As such, understanding potential changes in this ecosystem service directly informs the need to more actively and adaptively manage the Corte Madera Baylands in light of both sea level rise and a changing Bay sediment regime.

Figure 4-8. Corte Madera WARMER model results.

Model inputs include constant vertical accretion rate of about 0.07 inches per year on the marsh plain and sea level rise projections of 1.6 feet by 2050 and 3.3 feet by 2100 (Takekawa et al. 2011). Currently, tidal marshes in the Corte Madera Baylands are mostly mid marsh dominated by pickleweed, with limited high marsh. By 2030 all high marsh is predicted to disappear, by 2060 nearly all mid marsh is predicted to disappear, and by 2080 all former marsh habitat is predicted to be primarily mudflat.




Photograph courtesy of Peter Baye

5 Corte Madera Baylands Conceptual Sea Level Rise Adaptation Strategy

As presented in the introduction to this report, the purpose of this project is to increase the region's understanding of how to improve the resilience of baylands to sea level rise, thereby protecting the ecosystem service benefit of flood risk reduction through wave attenuation. To achieve this purpose, the project measured and modeled wave attenuation at the Corte Madera Baylands and considered how this benefit was sensitive to sea level rise. The project also investigated the geomorphic context and evolutionary history of the study site to inform the selection of management measures for each marsh that together comprise the conceptual sea level rise adaptation strategy to maintain a high, wide bayland and its flood risk reduction benefits.

This strategy is not an implementable plan; rather, it demonstrates the process of evaluating the sensitivity of an ecosystem service to accelerating rates of sea level rise and declining sediment supply, and selecting management measures to preserve the service based on site-specific information. The selection of management measures for implementation would require additional consideration of trade-offs between competing uses, short- and long-term impacts, and different priorities regarding ecosystem services, i.e., which are protected and to what degree. Furthermore, more detailed information beyond the description of technical approach, costs, monitoring, and operations and maintenance presented in this chapter is needed for implementation of the selected management measures of the Corte Madera Baylands conceptual sea level rise adaptation strategy. Ultimately, successful implementation of a sea level rise adaptation strategy will involve adaptive management, defined as a rigorous process of learning by doing and using the results to improve management actions (**Figure 5-1**). Restoration practitioners have found that, because knowledge of natural and social systems is incomplete, systems can respond in unexpected ways (Trulio 2007). Given this, many data gaps can only be addressed by implementing management measures and conducting long-term monitoring to evaluate their performance.

5.1 Rationale

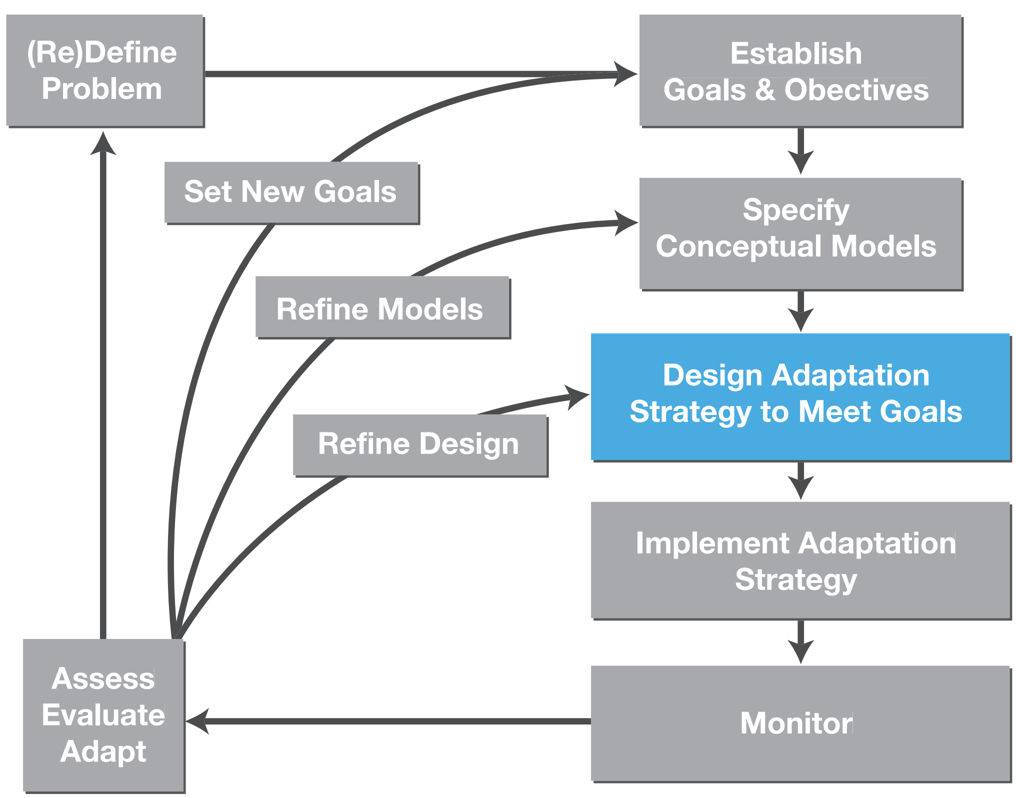
The Corte Madera Baylands can be divided into three distinct tidal marshes of varying geomorphic conditions. Therefore, a distinct conceptual sea level rise adaptation strategy was developed for each marsh. The conceptual strategies consist of multiple management measures to be implemented in two phases. The first phase provides immediate ecological benefits to enhance the existing marsh and to maximize its resilience to 2050 – 2070, when sea level rise rates will still be relatively low. The second phase prepares the marsh for accelerating rates of sea level rise expected after 2070, when rates are likely to out-pace vertical accretion and marshes will need to transgress upland to survive.

Because the Corte Madera tidal marshes are at a relatively high elevation (close to MHHW), they are likely to remain vegetated, even with some loss of elevation. This relatively high elevation gives the marshes substantial “elevation capital” (Cahoon and Guntenspergen 2010), i.e., they have elevation to lose before they convert to unvegetated mudflat. The decision about when to implement each of these measures will depend on the rate of sea level rise, and in particular when certain threshold elevations will be crossed that trigger the need for intervention. **Figure 5-2** illustrates this concept graphically. Because many of the management measures have fairly long lead times for planning, permitting, and construction, decisions about how and when to implement them will have to be made well in advance of when they are needed.

In total, seven management measures to improve baylands resilience were considered and four were selected for the Corte Madera Baylands. The objectives of all seven measures are summarized below, grouped by the key process of baylands evolution they affect, and detailed in **Appendix B**. The measure number corresponds to the location in the geomorphic conceptual model (**Figure 2-1**).

- Mudflat response: Slow the loss of marsh due to erosion along the bayfront edge by **(1) reducing nearshore wave energy** with low-crested berms constructed at or near low water from coarse gravel or oyster shell.
- Marsh edge erosion: Slow the loss of marsh due to erosion along the bayfront edge by **(2) stabilizing with a coarse beach**, protecting the marsh edge (scarp) and dissipating wave energy.

Figure 5-1. Adaptive management cycle.



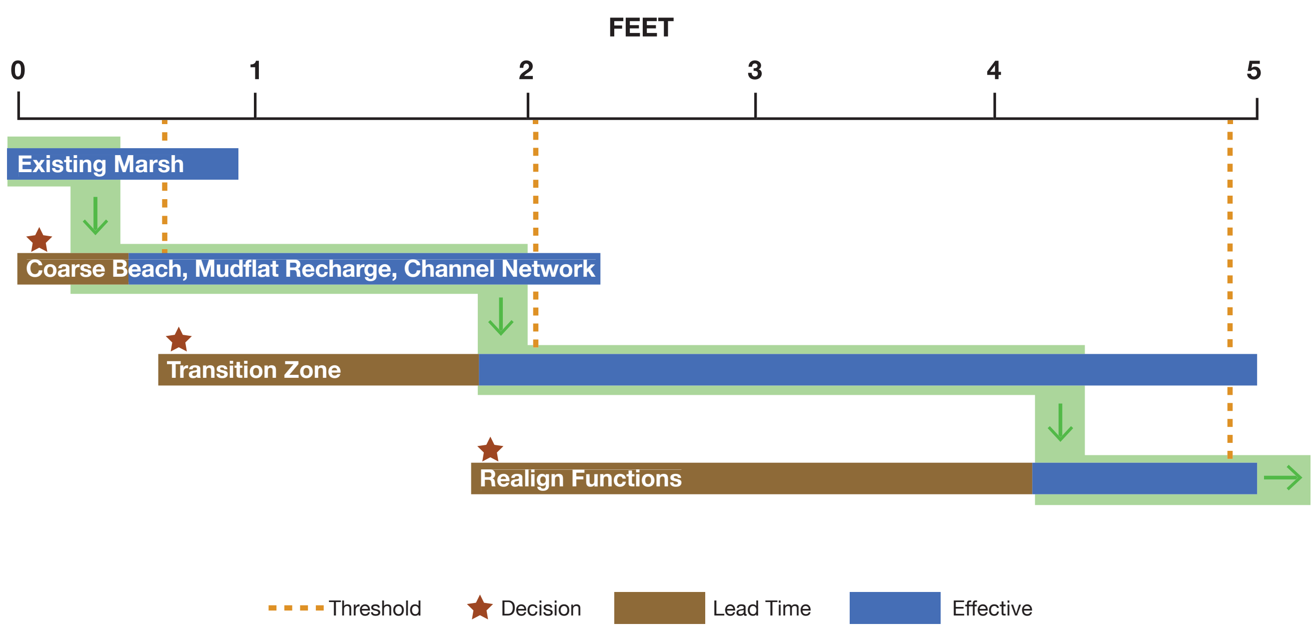
- Vertical accretion: Increase mineral accumulation because, as discussed in this report, this accounts for a substantial component of marsh vertical accretion, especially in lower elevations portions of the marsh. Mineral accumulation also helps maintain marsh elevation, which promotes organic matter accumulation, which in turn helps maintain marsh elevation, avoiding plant stress and the negative elevation-vegetation feedback loop. Building up marsh elevation with mineral sediment can be achieved by **(3) recharging the mudflat and marsh recharge** to increase local sediment availability by introducing fine sediment directly into the water column or by placing sediment on the mudflat to be later be re-suspended by wave action[1], **(4) improving sediment pathways** by increasing the channel network so that turbid Bay water is more distributed on the marsh at high water, promoting sediment deposition, and **(5) enhancing sediment trapping on the marsh** by slowing the flow of incoming tidal water through increased vegetation density or sediment fences emulating this effect.
- Upland transgression: Create space for baylands to migrate inland to avoid the loss of marsh due to "coastal squeeze." Maintaining marsh width and elevation over time, even when low marsh areas may be converted to unvegetated mudflats, can be achieved by **(6) increasing the transition zone** by reducing the slope of the existing transition zone and/or creating a healthy, gently sloping area akin to a lowland floodplain and **(7) realigning levees** by moving them to a new location further inland to allow for a wider region of potential migration.

There are varying degrees of understanding about the efficacy of these seven measures in San Francisco Bay. For example, restoration practitioners have experience improving sediment pathways in Bay tidal marshes, and there is information available on how to design, build, and monitor tidal channel development. However, using eelgrass and oyster reefs (e.g., 'living shorelines') to reduce nearshore wave energy and using coarse beaches

1 This measure also affects mudflat response because higher, wider mudflats provide more wave attenuation.

Figure 5-2. Adaptive management timeline.

The top scale indicates the amount of sea level rise, rather than time because of the uncertainty of the timing of sea level rise over the next century. Each bar represents a management measure; the brown portion of the bar is the lead time for planning, permitting and construction; the blue portion of the bar indicates the range of sea level that the management measure is effective. The green arrow indicates the successive implementation of management measures as sea level rises and various threshold rates of sea level rise that lead to vegetation mortality, elevation loss, or conversion of marsh to mudflat are crossed.



to stabilize eroding shorelines are currently in the early testing phases in the Bay. The remaining measures are untested in the Bay, although some have been tested elsewhere. By initiating and monitoring pilot projects for less well-understood measures, lessons about potential opportunities and constraints can be learned, and future implementation can more readily achieve project goals.

Four of the seven management measures described above were selected for the Corte Madera Baylands based on the geomorphic context, evolutionary history, and current condition of the site, as well as best professional judgment about the efficacy of the measures in the Bay:

- **(2) Stabilizing with a coarse beach** addresses active marsh edge erosion and protects the scarp, assuming wave energy is the cause of erosion;
- **(3) Recharging the mudflat and marsh** addresses the apparent reduction in local sediment availability and takes advantage of sediment from potential sources such as the Corte Madera Creek Flood Control Channel and Larkspur Landing Ferry Channel;
- **(4) Improving sediment pathways** addresses decreasing vertical accretion rates and helps naturally distribute sediment on the marsh; and
- **(6) Increasing the transition zone** addresses the need for accommodation space if marshes cannot keep pace with the rate of sea level rise by regrading backshore fill to create transition zone across which upland transgression can occur.

The other three measures were not selected because it was preferable to enhance existing natural features such as marsh scarps and channel networks rather than intro-

Figure 5-3. Conceptual sea level rise adaptation strategy for Heerdt Marsh (not drawn to scale).

duce new features, e.g., eelgrass and oyster reefs and sedimentation fences. Similarly, there are alternatives to promoting upland transgression that do not require realigning levees at this stage.

5.2 Heerdt Marsh

The first phase of the Heerdt Marsh conceptual strategy (**Figure 5-3**) involves stabilizing with coarse beaches and recharging the mudflat and marsh. Coarse beaches would be created to reduce marsh edge erosion, while introduction of fine sediment would increase vertical accretion rates. Since a dendritic tidal channel network already exists at this marsh, and given the high quality of the existing habitat, no measures are suggested within the existing marsh plain.

The second phase of the conceptual strategy would create a transition zone slope adjacent to the flood risk management levee along the historic railroad alignment. Regrading Madera Bay Park, a large undeveloped semi-circular upland area at an elevation exceeding the marsh plain by approximately 3 to 5 feet, could be used in part to create the fill slope. This measure would provide space for upland transgression of the marsh as well as some additional flood protection to the Industrial Way area.

5.3 North Muzzi Marsh

The first phase of the North Muzzi conceptual strategy (**Figure 5-4**) involves stabilizing with coarse beaches and recharging the mudflat and marsh, both suggested

Figure 5-4. Conceptual sea level rise adaptation strategy for North Muzzi Marsh (not drawn to scale).

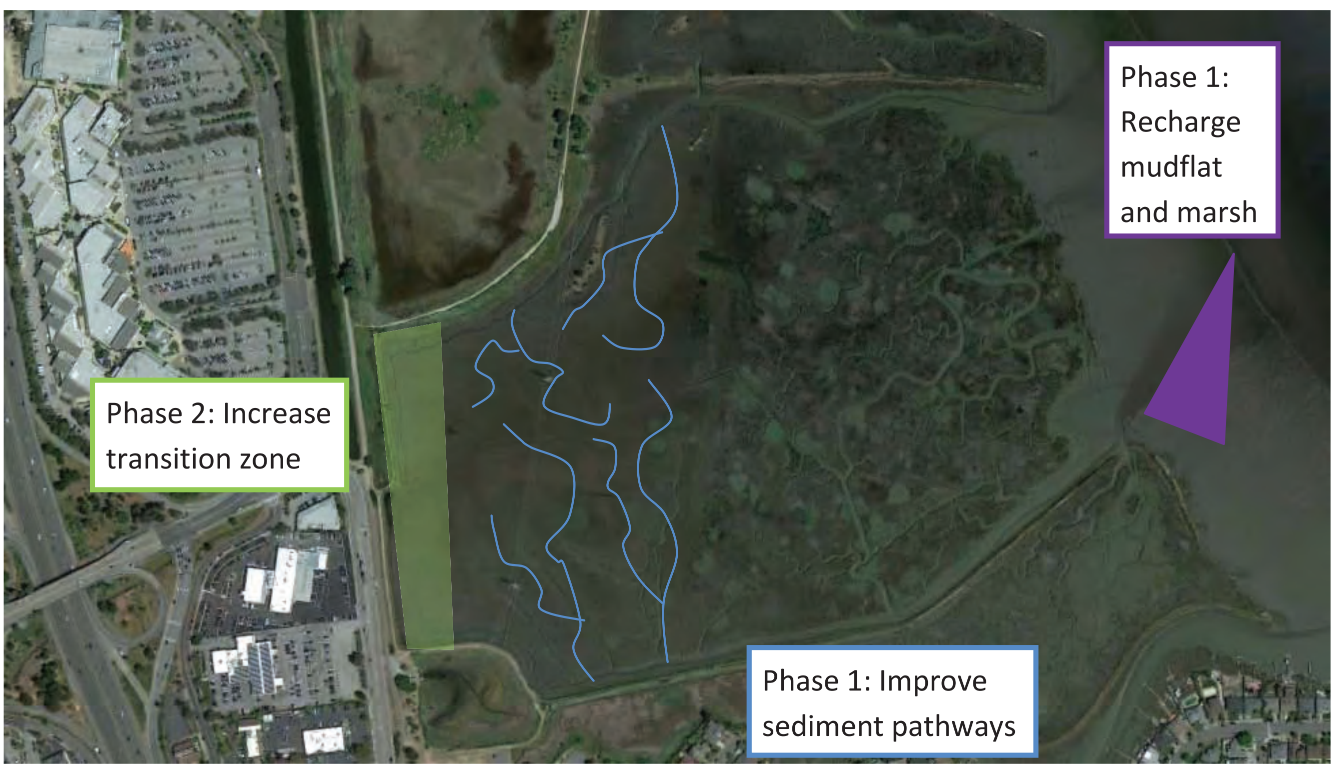
for Heerdt Marsh above, as well as improving sediment pathways. The existing high marsh at North Muzzi would be improved by increasing the density and complexity of the channel network. This would allow more sediment to reach the back of the marsh increasing inorganic sediment accumulation rates and improving drainage. Material excavated from the channels would be sidecast to emulate natural levees.

The second phase of the conceptual strategy would enhance the existing marsh by creating better high marsh habitat and increasing the transition zone to provide space for upland transgression. This would involve regrading the diked baylands area landward of the present marsh to lower it to a broad gradient or platform reaching the elevation range of spring tides. The channel network would be extended into the newly graded area, improving the drainage of areas that presently pond. Excess fill material excavated from this area would be placed along the landward flood risk management levee at a gentle 1:30 slope to increase the transition zone. To create a salinity gradient across the transition zone slope, stormwater from the Shorebird Marsh could be diverted to seep through and occasionally over flow the slope, emulating the soil and hydrology of native moist grasslands (alluvial sedge-rush and floodplain grassland meadows) in transition to brackish marsh edges of tidal marsh. Shorebird Marsh was constructed with tide gates that are operated by Corte Madera Public Works to mitigate habitat loss and flooding problems caused by the construction of the Village Shopping Center. The proposed transition zone would make the tide gates redundant and turn the stormwater channel into a blind tidal slough.

5.4 Muzzi Marsh

The first phase of the Muzzi Marsh conceptual strategy (**Figure 5-5**) involves recharging the mudflat and marsh and improving sediment pathways, both suggested for North Muzzi Marsh above. The historic channel network in the high marsh has been buried by fill and now contains a sparse network of straight cut mosquito ditches, which would be improved by increasing the density and complexity of the channel network.

Figure 5-5. Conceptual sea level rise adaptation strategy for Muzzi Marsh (not drawn to scale).



The second phase of the conceptual strategy would create a transition zone slope adjacent to the existing flood risk management levee. Fill would have to be imported from offsite and placed on the existing high marsh. To have less of an impact on the existing high marsh, the width of the slope at Muzzi Marsh may be narrower than those at Heerdt Marsh and North Muzzi Marsh, which have an upland area and a diked bayland adjacent to the flood risk management levee, respectively. This narrower slope at Muzzi Marsh would have a steeper grade, e.g., 1:30, than the wider slopes at Heerdt Marsh and North Muzzi Marsh, e.g., 1:50. The transition zone would supplement the internal distribution of high tide refugia that would be provided by the sidecast berms adjacent to the enhanced channel networks. During extreme water levels, e.g., El Nino high tides, marsh plain high tide gumplant would be submerged, while the transition zone would provide supra-tidal cover.

5.5 Description of Selected Management Measures

Information on the technical approach, cost considerations, monitoring, and operations and maintenance for the four selected management measures is summarized below.

5.5.1 Stabilize with a coarse beach

The objective of stabilizing with a coarse beach is to construct an analog to natural San Francisco Bay beach systems consisting of a sand foreshore grading up to a steeper mixed coarse sand, gravel, and shell berm in front of an existing marsh scarp. The sand foreshore forms a shallow beach face or swash ramp, where depth-limited breaking occurs gradually over the slope (**Figure 4-5**) and dissipates wave energy at normal tidal elevations. At higher water levels, waves break and dissipate energy along the coarser grain berm. Therefore, this measure can adjust to short-term changes in local wind-wave conditions and provide adaptation to long-term sea level rise. It reduces the considerable amount of erosive energy at the marsh scarp caused by the sudden breaking and deceleration of waves. By decreasing marsh edge erosion, this measure can help maintain marsh width. As described in Section 4.1.2, the marsh inland of the scarp provides additional wave attenuation in particular for extreme water levels.

Outer Bair Island provides the nearest natural analog to this measure, where a sand foreshore grades to a mixed coarse sand, gravel, and oyster shell berm fringes the existing marsh (P. Baye, personal communication, 2013). There is little experience with constructing this type of system in the Bay. The best example of this measure is the recent restoration project at Aramburu Island in northern Richardson Bay, Marin County developed by Peter Baye, Roger Leventhal and Stuart Siegel for the Marin Audubon Society. The design criteria created for that project (Leventhal 2010), which in turn used input from coarse beach studies in Oregon and Montana (Lorang 2002), has been used extensively to inform the management measure developed for the Corte Madera Baylands described herein. Monitoring of the Aramburu Island beaches is ongoing and it is anticipated that lessons learned will be fed back to the restoration design community. Monitoring at Aramburu Island is required for years 1, 2, 5 and 10 and has currently only been funded for the first two years. The first year will consist of two monitoring events (one has been completed) and subsequent years will only include one event per year. Monitoring currently consists of a review of any aerial photos (not collection of new photos) and onsite physical monitoring by surveying along transects along with limited sediment sampling.

The Aramburu Island project identified a number of natural reference sites around the Bay to determine key design criteria, including Outer Bair Island. These had similar profiles with a nearly flat low tide terrace below the sand foreshore swash slope of the upper intertidal profile with a steeper, coarser grain berm above. The reference sites indicated (Leventhal 2010):

- The foreshore is a thin layer of sand mixed with mud that increases sand cohesion and reduces longshore movement;
- Typical sand foreshore slopes range from 25:1 to 50:1; and
- Coarser grain berm slopes range from 5.5:1 to 11:1.

The design approach for the Corte Madera Baylands is to create a marsh edge profile that will reduce marsh edge erosion, attenuate waves, and allow the beach profile to migrate across the marsh, rising with wave runup and sea level rise. The finer sand is expected to move to the foreshore, where it will mix with bay mud during low wave energy periods, making the surface sediment more cohesive and reducing longshore transport of the sand-mud mixture (Leventhal 2010). The coarser grain berm is designed so that it extends to intersect with the sand foreshore. Coarse beaches equilibrate relatively quickly to the incident wave conditions, more quickly than sandy beaches. Equilibrium with short period incident wind waves is expected within about 500 waves (about 30 minutes) based upon wave flume experiments (Powell 1990). When the gravel berm is in equilibrium, the elevation of the berm will approximate the maximum wave runup assuming there is sufficient volume of coarse material in the profile.

There is little sand and gravel at present along the Corte Madera Baylands, so all coarse beach material will have to be imported to the site, perhaps from detention basins in the local watershed that trap coarse sediment. Placement of imported material should factor in the possibility of material moving and take account of the various tidal channels, as coarse sediment can deposit across channel mouths, sometimes blocking them completely. As such, structures such as micro-groins may be needed to hold coarse beaches in place. However, there are existing embayments along the marsh edge created by breaches in the relict levee that could be taken advantage of to slow longshore drift. These embayments have trapped some sand, creating “pocket beaches” that could be nourished. Where there are no existing embayments, it may be necessary to construct micro-groins of imported eucalyptus logs to limit the longshore movement. These would be relatively short groins, approximately 25 – 30 feet long, at a spacing of approximately 200 – 300 feet apart. In addition, marsh edge complexity can be enhanced by placement of smaller branches and wood to create some beach microtopography that helps to trap sediment and stabilize the beach profile.

Technical approach: A mix of sand and gravel would be placed and roughly graded to an approximate 15:1 slope, which will then be reworked and resorted to a more natural profile by wave action, where finer sand will deposit lower in the profile to form a swash ramp and coarser material will build a berm higher in the profile to a height approximately equal to the maximum wave runup. It is anticipated that the width of the berm will be 15 – 25 feet depending upon the volume of coarse material available and will develop a slope of about 7:1 extending down to about MTL. It may be necessary to grade back the remnant levee to a 15:1 slope to allow the beach profile to migrate continuously and gradually landward as sea level rises, although access to the bayward levee may be problematic, as it has been breached in a number of places.

Cost considerations: We used the results of the Aramburu Island project as a first-cut guide to project implementation costs at the Corte Madera Baylands. However, the cost of construction of these types of systems is very dependent on local site conditions (e.g., tides, winds, shoreline morphology, supply of coarse material, and vessel draft requirements) and construction constraints (e.g., access via terrestrial or marine equipment). For the Aramburu Island project, the delivery of coarse grain sediments was accomplished using marine-based construction equipment; however once the material was on the island, it was placed using more conventional land-based equipment. Because of the specialty nature of marine work, the Aramburu Island project expended considerable effort to deal with scheduling and cost issues between marine contractors.

It is anticipated that construction of coarse beaches along the Corte Madera Baylands would be accomplished by transferring sand and gravel of the required sizes from a larger sediment transport barge moored offshore to smaller barges for placement in the zone immediately offshore of the eroding marsh edge. As a result of this ‘double-handling’ of material, the cost to construct coarse beaches along the Corte Madera Baylands will be higher than those at the Aramburu Island project. The increase in cost may be 50%, but this requires further analysis during future design. On the other hand, if suitable material was available from dredging Corte Madera Creek or the Larkspur Ferry channel, transport distances would be less and double handling may be unnecessary if small barges could be used throughout construction.

Monitoring: Monitoring of topography, sediment transport patterns, and vegetation establishment (review of aerial photos, elevation surveys, sediment sampling, etc.) would be required to ensure that the foreshore and berm evolved as anticipated.

Operations and maintenance: Monitoring would document the nature of longshore transport and the need for and/or effectiveness of micro-groins to hold coarse beaches in place. Subsequent placement of material for re-nourishment would also depend on the results of monitoring and may be done on an opportunistic basis as suitable material becomes available and/or as the need arises.

5.5.2 Recharge the mudflat and marsh

The objective of recharging the mudflat and marsh is to increase local suspended sediment concentrations to alleviate some of the long-term erosion at the Corte Madera Baylands and offset the predicted decline in overall Bay sediment supply. Dredged sediment would be introduced *directly* into the water column as a plume or *indirectly* into the water column by first placing the material on the mudflat as a mound to later be resuspended by wind waves and carried by tidal currents into marsh channels and onto the marsh for deposition. The advantages of supplying the marshes in this way, as opposed to filling the marsh, is that it allows natural processes to move the sediment and to shape baylands morphology. This also results in a more gradual accretion of material within the marsh, avoiding burial of existing marsh vegetation. Furthermore, the impacts of equipment and large one-time “lifts” normally associated with dredge reuse activities could be avoided. There may still be local turbidity impacts but they would be expected to be short-term and offset by the benefits to the marsh.

The location of the placement is fundamental to whether the fine dredged material is eventually deposited in the marsh, as some of the sediment will not end up in the desired location due to differential settling and dispersion within the water column. The goal is to maximize the proportion of placed sediment that is eventually deposited on the marsh. Model simulations reported by MacWilliams et al. (2012) confirm that the closer the sediment is deposited to the marsh edge the more likely the sediment will be transported to and retained in mudflat and marsh areas. The deeper placements modeled were much less effective at supplying sediment to the shallow regions of Corte Madera Bay because the sediment was quickly exported to the larger San Francisco Bay.

For this measure, the sediment would be placed as close inshore as possible in the low intertidal in areas with regular wave activity to maximize the chance of resuspension during a flood tide. The placement would also be close to, and ‘updrift’ of, the target marsh to reduce the loss of sediment offshore; the actual location should account for local tidal currents, gyres, and other sediment transport conditions such as freshwater inflows. Placing the sediment close to the mouths of tidal channels would encourage fine sediment transport onto the marsh.

Fine sediment could be placed on to an adjacent mudflat as a mound by either dump scow, floating hydraulic pipe or ‘rainbowing’. Dump scows are the most flexible and therefore proposed for this measure. With dump scows, the location and timing of placement may be varied, and no fixed infrastructure is required, which will reduce costs. The size of the dump scow will determine how close to the marsh the sediment may be released. Standard dump scows have a capacity of 3,000 cubic yards (about 2,000 tons), while small dump scows have a capacity of 400 cubic yards (about 270 tons) (MacWilliams et al. 2012). Smaller dump scow can operate in shallower water. For example, a dump scow carrying 200 cubic yards is able to place material in a minimum water depth of 6 feet. A dump scow carrying 400 cubic yards requires 9 feet. Dump scows could operate even closer to the marsh if they were floated in on high tide and released their load on a flood tide. This latter method restricts the dump scow to one load per tide, however. The dump scows would place fine material at different locations each tide along the Corte Madera shoreline so that there would be no excessive local mounding of material.

Technical approach: It is envisaged that one dump scow continuously, or two dump scows during daylight hours, would place material at times with the greatest wind-wave resuspension in shallow subembayments given seasonally varying winds and bed erodibility (Schoellhamer et al. 2007) that coincided with dredging activities and the least possible impacts to species of concern. The choice of placement every tide or every other tide would depend on the cost of running a 24-hour versus a daylight operation. Given the limited volume of each placement, it is envisaged that the location of placement would be gradually moved along the shore. Placement would occur in 6 feet of water close to the low water mark (MLLW is about 0.1 feet NAVD88, MHW is about 5.3 feet, and MHHW is about 5.9 feet). Approximately 200 cubic yards would be placed resulting in a flat mound about 2 feet high, 100 feet long and 50 feet wide.

Cost considerations: The cost will be driven by the quantity of dredge material required and the distance between the dredge and placement sites. An estimate of the demand for sediment by the three marshes in the Corte Madera Baylands to keep up with sea level rise can be made by multiplying the area of the marshes (192 acres) by the average rate of sea level rise per year (55 inches per century, 0.55 inches per year). This gives an average demand over the century of about 14,000 cubic yards per year for the marsh to keep up. Demand is probably less in the near term as these marshes are close to equilibrium, however demand will increase as the rate of sea level rise accelerates. The efficiency of transferring sediment from the mudflat to the marsh is unknown, although the model simulations reported by MacWilliams et al. (2012) show efficiency increases with increasing proximity of placement to marsh.

To be cost effective the dredge site needs to be close to the placement site. The Corte Madera Creek flood control channel accumulated about 450,000 cubic yards between 1966 and 1986 and 400,000 cubic yards between 1986 and 2004; an average of 22,000 cubic yards per year (Stetson 2011). The rate of sedimentation will slow over time as the channel reaches equilibrium with the flows – the rate between 2004 and 2010 had dropped to 10,000 cubic yards per year. If material were dredged in small amounts on an annual basis, then the channel dimensions would be maintained further from equilibrium, which would also have the effect of maintaining stormwater conveyance for longer. Dredging for Larkspur Ferry Terminal is another potential source of nearby dredged material. Maintenance dredging occurs every three to four years and has amounted to about 2,200,000 cubic yards between 1984 and 2010; an average of about 88,000 cubic yards per year (GGBHTD 2012).

Currently, about 100,000 cubic yards per year of dredged sediment could be available for mudflat and marsh recharge in Corte Madera Bay. Not all of this material would be fine grain enough for the measure.[2] If 90% of the total sediment available was fine sediment, as shown in the dredging records, this would be seven times the average annual demand from the Corte Madera marshes.

If two dump scow loads of 200 cubic yards (total of 400 cubic yards) were placed per day over a 30-day period in two campaigns per year the total placement would be 24,000 cubic yards per year on the mudflat. This amount allows for about 50% loss of volume in moving from the unconsolidated mudflat to the consolidated marsh, as suggested in the findings of MacWilliams et al. (2012). The dump scows would be operating continuously between the placement site and the dredge site. Costs may be reduced if a hydraulic pumping system was used to empty larger dump scows further offshore and a small craft used to carry the floating pipe to the shore, although this would require some form of dewatering such as placement behind brushwood fences. There may also be other approaches to moving and placing sediment using a hydraulic cutterhead dredge and a pipeline with a dissipation head to minimize velocities and turbidity. This approach may work as long as the dredge site location is close to the placement location, as in Corte Madera Bay.[3]

2 At the Ross gage on Corte Madera Creek, there are a few water samples that were analyzed for particle size, where fine sediment is defined as less than 62.5um, and 85% of the total sediment load is usually fine sediment. During the large January 20, 2010 storm sampled, when more coarse grain bedload sediment transport would be expected, there was still greater than 70% fine sediment U.S. Geological Survey 2011). Average bedload sediment at the gage is around 5,000 cubic yards per year (Stetson 2011). Changes in watershed management practices may impact the amount of fines from reaching the Bay in the future.

Monitoring: Monitoring during placement would consist of observations of any sediment plume around the dump scow to ensure maximum suspended sediment concentrations stayed within permitted limits for water quality. If required, turbidity booms would be deployed. Surveys of any permanent "mounding" on the mudflat caused by the placement would also be required to ensure that the material placed was remobilized. Monitoring of impacts of dump scow operation on the mudflat would include physical scarring of the mudflat surface and the burial of biota by the placed fine sediment. In the early stages, more intensive monitoring would be undertaken, which might include fluorescent tagging of particles to determine the ultimate fate of the placed material. Monitoring of suspended sediment concentrations within the tidal channels should also be undertaken during placements and compared against baseline data. In addition, marsh vertical accretion rates should be measured using marker-based and SET methods and compared with observed rates of sea level rise.

Operation and maintenance: The placement of fine sediment on the mudflat could be part of an ongoing program, with relatively small amounts of fine sediment placed on a regular basis. The actual timing of placements would depend in part on the timing of dredging operations, unless material could be stockpiled (probably in a subtidal location) to act as a buffer. Rehandling of fine sediment will increase the cost and also the potential impacts on the water column. Ideally the program would be linked to a local sediment management plan that would incorporate both the dredging and placement to coordinate sediment size, frequency and volume of material moved.

5.5.3 Improve sediment pathways (channel networks with sidecast berms)

Channels serve as pathways for water, sediment, nutrients and species between the marsh and the Bay. Increasing the density and complexity of channels should increase the supply of fine sediment to the back of the marsh and allow for increased vertical accretion rates. Heerdt Marsh and Outer Muzzi Marsh have a high density of channels compared with North Muzzi Marsh

3 One example of this was the Port of Oakland dredging and building the Galbraith gold course by the Oakland Airport, which placed dredged material directly from the Bay onto the land and then graded it for the golf course.

and Inner Muzzi Marsh. Sediment deposition diminishes with distance from the channel, so denser, more complex channel networks are based on the existing channel network at Outer Muzzi Marsh. In addition, the material generated by cutting additional channels would be sidecast adjacent to the channels and managed to emulate natural levees slightly higher than the surrounding marsh plain. These levees would create microtopography and support tall gumplant-pickleweed-alkali-heath cover that serve as critical high tide refugia for Salt Marsh Harvest Mouse and California Clapper Rail, especially in the face of sea level rise.

In addition, excavating the shallow remnant historic tidal channels within the marsh would recreate tidal channel habitat and improve tidal drainage. Tidal drainage is affected by the density and complexity of the channel network. As water drains off the marsh plain, flows are conveyed through tidal channels. Filled portions of the remnant historic tidal channels may be too shallow to efficiently convey tidal flows, causing more water to flow over the marsh plain. Shallow flow and friction over the marsh plain could delay low tide drainage and impede vegetation establishment.

The Tidal Wetland Design Guidelines (PWA 2004) recommend excavating breaches and outboard pilot channels to long-term equilibrium dimensions to restore tidal action and improve tidal drainage. However, to help reduce project costs, the pilot channels can be excavated to the long-term equilibrium channel depth and 60 – 80% of the long-term channel width (i.e., narrower than the breach width at MHHW) with side slopes of 3:1. The pilot channels can be somewhat undersized to reduce the amount of excavation, as they are expected to scour and enlarge. Marsh vegetation will be excavated to the root zone over the long-term equilibrium width (i.e., beyond the excavated pilot channel width) to reduce the resistance to channel bank erosion.

Tidal drainage is likely to be adequate in the long-term, but may be restricted within the first few years after the creation of the channels. An assessment of San Francisco Bay restoration monitoring data (PWA 2002) indicates that after the under-sized breaches scoured to long-term equilibrium widths, the breaches provided adequate tidal drainage. These monitoring data suggest that breaches sized to long-term equilibrium dimensions for marshes with marsh plain elevations similar to the Outer Muzzi Marsh can be expected to provide adequate tidal drainage. The restored marshes in North Muzzi Marsh would initially have a larger restored tidal prism, which would tend to slow drainage at low tides. However, the number of breaches per acre of restored marsh would be greater at North Muzzi Marsh than at Outer Muzzi Marsh, which would tend to improve drainage. If the pilot channels do not scour and enlarge as expected, excavation could be pursued as part of adaptive management.

The ultimate location and extent of starter channel excavation to create a dendritic channel network within the marshes and sidecast berms would be determined during final design to balance the habitat benefits with project funding. For instance, where existing internal berms are located adjacent to the larger tidal channels through the marshes, the need for excavation to create sidecast berms would be a lower priority. By comparison, there are no internal berms within Inner Muzzi Marsh and in the center of North Muzzi Marsh, and starter channel excavation to create sidecast berms would be a much higher priority because these berms would serve a number of critical functions.

Experience in previous restorations indicates that material sidecast too close to the excavated channels was liable to be eroded as the channels scoured and enlarged. Berms would be built up to about +1 – 2 feet MHHW, and soft sediment that has settled in the historic channel would be avoided, as this is not the best material for berm creation. Cuts would be located in the more competent material from the historic channel banks (directly adjacent to the actual channels) for berm construction. The intent would be to use the historic channel planform as the geomorphic template to locate the berms and channels, but to build the berms with good material from areas adjacent to the historic channels.

Technical approach: Four tidal watersheds have been identified for tidal channel improvements – two in North Muzzi Marsh and two in Inner Muzzi Marsh. Channel construction would coincide with outboard levee breach construction. The watersheds are very similar in size, ranging between 25 and 32 acres. Based on the hydraulic geometry sizing approach (Williams et al. 2002), the largest channels in each watershed that would be at the breach through the levee to the Bay or tidal creek, should be cut to a depth of about -2.5 feet NAVD88 with a top width of about 70 feet, the resultant cross-sectional area is about 300 square feet (**Table 5-1**).

Starter channel cross section would have a variable invert elevation with a 3 feet wide bottom width and 3:1 side slopes. Sidecast berms should be offset from the excavated channel by at least 20 feet to prevent erosion. Sidecast berms should extend up to 7.5 feet NAVD88. The sidecast berms would be located on the outside bends of the starter channels and incorporate 50-foot wide gaps in the sidecast berms every 100 – 200 feet to allow small channels that drain into the starter channels. Average channel length within each watershed is about 3,000 feet with about half being cut for the larger channels. Channel construction and sidecasting would require grading of about 5,500 cubic-yards of fill per watershed.

Cost considerations: The costs would depend on the number and size of the tidal watersheds, the depth and location of the channels cut, and the amount of grading required.

Monitoring: Monitoring of channel evolution would ensure that the undersized channels eroded to contain the full tidal prism. If constraints are identified in the cross-section, it is then recommended that they are removed. Observations of poorly drained areas may indicate where additional channels are required. Vegetation monitoring would focus on the establishment of vegetation (such as gumplant) on the sidecast berms and colonization by invasive species. This would trigger interventions as described below.

Operation and maintenance: In the long-term, the channels should be self-sustaining, driven by the tidal prism of the marsh. In the short-term, it may be necessary to remove constraints to channel development. In other restorations hard compacted layers below the surface due to historic agricultural activity or filling has prevented the downcutting of channels. This can be avoided by excavating the channels to equilibrium depth as described above. If necessary mechanical intervention can be used to break up the hard surface and loosen the compacted soils. Methods that could be used to limit colonization by invasive species are limited by access to the sidecast berms, but may include black plastic mulch, herbicide spot treatments, and mechanical and manual weed removal (Baye 2008).

5.5.4 Increase the transition zone

The objective of increasing the transition zone is to prepare uplands adjacent to the marsh to support upland transgression. To increase or create transition zone, a slope would be constructed with the top at the same elevation as the flood risk management levee crest, and the bottom at about MHHW intersecting with existing high marsh. Depending on the area available, this generally results in a 30:1 to 50:1 slope. It is assumed that the upper slope of the transition zone would be planted and hydro-seeded with a native seed mix. The 30:1 to 50:1 slope represents an idealized slope. During final design and construction, the slopes would include some variation both in planform to create benches and shallow depressions to form pannes at a variety of elevations. The intent is to work within the overall idealized slope to create a transition zone slope with some topographic complexity, as subtle differences in elevation, soils, and drainage promote vegetation diversity.

Table 5-1.

Characteristics of the equilibrium channel sizes for North and Muzzi Marshes. The “Inner” and “Outer” zones are distinguished by elevation, where the “Inner” zone is higher (closer to the Town of Corte Madera) and the “Outer” zone is lower (closer to the Bay; see Figures 5-4 and 5-5).

Tidal Marsh Watersheds	Drainage Area (ac)	Breach Invert Elevation (ft NAVD88)	Breach Total Top Width (ft)	Breach Total Cross-Section Area (ft2)	Channel Order
North Muzzi (Inner)	32	-2.6	75	310	3
North Muzzi (Outer)	28	-2.5	74	300	3
Muzzi (Inner – North)	25	-2.45	70	290	3
Muzzi (Inner – South)	25	-2.45	70	290	3

Establishment of transition zone vegetation will involve topsoil preparation and active revegetation using techniques designed to increase target-native vegetation and inhibit weed invasion. Topsoil preparation design will consider numerous factors to restore conditions that facilitate establishment of a self-sustainable, native-dominated target plant community; these factors will include soil chemistry (e.g., salinity), organic matter content, texture, weed seed bank factors (e.g., minimize import of a weed seed bank), and seed bed enhancement (e.g., scarification, imprinting, mulch). Active revegetation (planting, seeding, and intensive weed control maintenance) will be required to establish the target plant communities dominated by native graminoids and forbs due to anticipated rapid, invasive weed recruitment and competition. The dominant sod-forming graminoid species will be planted (rather than seeded) at a high density both because many of these species do not readily reproduce from seed (i.e., creeping wildrye, *Leymus triticoides* and saltgrass, *Distichlis spicata*) and to attempt to preempt invasive weed establishment. Species that can readily reproduce from seed would be established via seeding (i.e., drill seeding and/or hydroseeding). Treated wastewater or stormwater could be allowed to seep through the transition zone slope to support vegetation and provide water quality improvement co-benefits.

To reduce the initial amount of fill required it might be possible to construct the transition zone in stages. An initial, smaller berm could be built at the outboard edge of the transition zone, with fill placed behind it over time as material becomes available until the transition zone is brought to final grade. An alternative may be to maintain a 3:1 slope to a horizontal bench located 3 feet above MHHW. The levee bench could receive fine grading to create backshore pannes and a 30:1 slope will continue downward from the bench to about MHHW within the lower range of colonization elevations. Additional fill would be placed on the bench as required to maintain its position in the tidal frame as sea level rises.

Resources and permits should consider (an allow) the placement over time of additional fill at the higher edges of the transition slope (possibly on habitat areas). Ideally, permitting documents would include placement of fill along the upper edges of the transition in small areas on an annual basis (or in years when fill is available) allowing for limited temporary impacts to habitat in isolated areas along the transition zone slope. Different areas along the transition zone slope would be affected by fill placement over time as the slope is gradually built up in response to sea level rise.

Table 5-2.

Approximate volumes of fill required for constructing estuarine-terrestrial transition zone along Heerdt Marsh, North Muzzi Marsh, and Muzzi Marsh using two different slope ratios.

Slope	Elevation change (ft)	Horizontal length (ft)	Fill volume per linear foot (yd3/lf)
30:1	5.5	165	16.8
50:1	5.5	275	28.0

Technical approach: The top of the transition zone slope would start at the flood risk management levee crest at about 12-feet NAVD88 and intersect with the existing high marsh at about 5.5 to 6-feet NAVD88 to create a 30:1 to 50:1 slope.

Cost considerations: The transition zone slope between 5.5-feet and 12-feet NAVD88 behind Heerdt, North Muzzi and Muzzi Marshes (a total distance of about 1.2 miles) would be constructed with non-engineered fill placed at slopes ranging from 30:1 and 50:1. **Table 5-2** provides approximate volumes for constructing this range of slopes. Costs will depend on the volume of fill used, the distance fill travels to reach the site, and the amount of grading required. Addition costs for vegetation planting, other features such as a freshwater swale, and maintenance and monitoring would also need to be considered. The slope may be constructed in phases, as described above, to reduce costs.

Monitoring: Monitoring would consist of vegetation surveys to study the success of plantings on the transition zone slope with native species and to determine the extent of colonization by invasive species. This would trigger interventions as described below. Vegetation surveys of the high marsh and transition zone slope would allow the process of transgression to be observed.

Operation and maintenance: Dense planting of clonal rhizomatous species combined with a seeded cover crop of annual grasses and forbs designed to minimize invasive species establishment will help increase target-native vegetation, particularly during the plant establishment period (about 3-5 years). In addition, dense plantings can provide competition with invasive species such as perennial pepperweed (*Lepidium latifolium*), fennel (*Foeniculum vulgare*), wild radish (*Raphanus raphanistrum*), mustard (*Hirschfeldia incana and Brassica sp.*), stinkwort (*Dittrichia graveolens*) alkali Russian thistle (*Salsola soda*), yellow starthistle (*Centaurea solstitialis*) and others. However, some weeds are still expected to rapidly colonize the transition zone restoration area during the early plant establishment period. If weeds do become established, an integrated approach using a combination of methods will be the most successful strategy to limit their spread. Methods that could be used to limit the invasions by weedy species include saline irrigation, black plastic mulch, solarization, herbicide spot treatments, and mechanical and manual weed removal (Baye 2008). The methods chosen for weed removal activities should be carefully selected to appropriately match the scale of the invasion. For example, treatment of small patches of weeds may be conducted using manual weed control while larger scale invasions may require large-scale use of herbicides or other methods.


Photograph courtesy of John Callaway

6 Conclusions

Baylands play an important role in attenuating waves, protecting the shoreline from flooding and erosion. As waves travel across Corte Madera Bay, they encounter a broad swath of shallows and mudflats that attenuate waves through depth-limited breaking and bottom friction. Waves entering Corte Madera Bay were reduced in height and energy by as much as 80% by the time they reached the marsh edge. More wave attenuation was observed at low water depths. While waves only inundate tidal marshes at high water levels, such as during storms that occur at high tide, tidal marshes further attenuate waves through depth-limited breaking and vegetation-induced friction. Shallow water over the marsh means waves are closer to vegetation and therefore subject to more vegetation-induced friction. This project found that wave attenuation is relatively insensitive to marsh vegetation species, though the presence of vegetation reduces wave height significantly more than if there is no vegetation. While wave attenuation is largely controlled by water depth, marsh width is an important factor during extreme events, e.g., today's 100-year water level, in the total amount of attenuation. 1,000 feet is an order of magnitude estimate of the minimum width of healthy marsh to attenuate waves to below 1 foot in height and this width would need to be greater to accomplish the same reduction if marshes cannot accrete sediment fast enough to keep pace with sea level rise. Tidal marsh wave measurements are still needed to calibrate and validate wave model results and refine estimates of vegetation-induced friction.

While the Corte Madera Baylands are keeping pace with the current rate of sea level rise (around 0.1 inches per year), geomorphic evidence suggests the system is sediment-limited. The diking and filling of the baylands destroyed large amounts of historical floodplain and disconnected the Corte Madera Baylands from natural pulses of local watershed sediment that once would have flowed onto the marsh during overbank events. Data also show mudflat lowering, active marsh edge erosion, and decreasing vertical accretion rates. Nearby sediment sinks such as the Larkspur Ferry Channel further reduce the local sediment supply that that might otherwise be available for baylands deposition. While low elevations in restored Muzzi Marsh are accreting sediment faster than the current rate of sea level rise, suggesting that the Corte Madera tidal marshes could keep up with *some* increase in the rate of sea level rise, it will become more difficult for them to keep up with accelerating rates of sea level rise coupled with declining sediment supply.

Since a high, wide bayland maximizes wave attenuation, the combined effects of accelerating rates of sea level rise coupled with declining sediment supply will negatively impact the ability of the Corte Madera Baylands to provide this ecosystem service. For example, as sea level rises, the sweep zone will migrate landward and the potential for wave erosion of the marsh edge will increase due to higher water levels and less wave attenuation. To maintain the flood risk reduction benefits provided by baylands, proactive management is needed.

This report presents a conceptual sea level rise adaptation strategy that considers how to preserve the mudflats and tidal marshes that currently exist in the Corte Madera Baylands by helping them evolve with sea level rise. Stabilizing the marsh edge with a coarse beach aims to minimize erosion and prevent landward retreat so that waves continue to break far from the shoreline. Recharging the mudflat and marsh aims to increase the local availability of sediment to be deposited onto the baylands. Improving sediment pathways aims to increase the density and complexity of channel networks to increase sediment supply to the back of the marsh, where access to sediment is often limited. Together, these proactive management measures are intended to support the capacity of the marsh to maintain its width and elevation in the face of sea level rise. However, at some point as the rate of sea level rise will outpace the rate of vertical accretion and the marsh will likely need to migrate inland. The construction of a broad, gradually sloping estuarine-terrestrial transition zone that provides space for upland transgression to occur over time will likely be required to sustain tidal marsh habitat as lower elevation areas convert to mudflat.

Although the Corte Madera Baylands conceptual sea level rise adaptation strategy is based on an understanding of local conditions and focus on protecting the flood risk reduction benefit, the challenges of accelerating rates of sea level rise and declining sediment supply are generally similar across the Bay. The geomorphic conceptual model presented in this report (**Figure 2-1**) is a framework that can be used to understand site-specific information and select appropriate management measures. To develop sea level rise adaptation strategies at other locations around the Bay, we recommend consideration of the evolution history and geomorphic context of the site, local sediment availability and shoreline change because of the importance of marsh elevation and width in determining the amount of wave attenuation, and the relationship to other shoreline resilience planning efforts. For example:

- An understanding of how the site evolved during both the early Holocene (10,000 to 6,000 years ago when sea level rise rates were much higher) and historic past (last 150 years) improves the understanding of how it may evolve in the future. Since baylands evolution processes operate on a landscape scale, it is important to analyze the geomorphic context of the site. Review of historic and present-day bathymetry, topography, and aerial imagery as well as field observations and tide and wave climate data is helpful.
- Measurements of current vertical accretion rates using markers and possibly SETs to understand if the marsh is presently keeping pace with sea level rise.
- Measurements of vertical accretion rates at different locations and elevations within the marsh to evaluate variation across the site. At the Corte Madera tidal marshes, accretion rates were expected to be highest near the marsh edge, as this is almost always the case, however the finding of the opposite pattern raised questions that were very informative.
- Comparison of the current rates of vertical accretion to historic (e.g., using ^{137}Cs and ^{210}Pb) and even geologic (early Holocene) rates from around the Bay, or from the specific site if it is possible to collect cores and conduct the long-term dating analysis.
- An understanding of the extent and rate of marsh edge movement at the site, if any, and a consideration of the possible causes if there is a history or ongoing shoreline change (retreat/progradation).
- An understanding of wave attenuation mechanisms at the site based on the research presented in this report, which is broadly applicable to baylands throughout the region. Depending on the specific site of interest, there may be an opportunity or desire to collect site-specific wave measurements and high-resolution bathymetry to support wave modeling, which will provide a more refined understanding of wave attenuation[1]

A key element of this project was to consider wave attenuation across an entire baylands system. Many efforts focus on offshore wave attenuation in the shallows and mudflats, while others focus on wave attenuation over tidal marshes. The intent of this project was to bridge across systems, bringing physical oceanog-

1 Since the WHAFIS model does not consider the effects of bottom friction (e.g., unvegetated mudflats are not modeled to have an effect on waves, contrary to field observations), SWAN or other 2-D hydrodynamic models are a more preferable modeling platform for baylands analysis.

raphers together with coastal geomorphologists and wetland ecologists. This collaboration highlights the importance of the interface between the Bay and the tidal marsh, and illustrates that further joint studies are critical because sediment transport into and within the marsh remains poorly understood.[2] Greater understanding of the physical processes that control the movement of sediment in mudflats and tidal marshes would improve our ability to protect baylands from of impacts of sea level rise and will help to improve the efficacy of the currently considered management measures and may stimulate the consideration of others. Conducting the following type of research at a regional scale would greatly support closing this information gap:

- Research on marsh vegetation's role in attenuating waves, including deployments designed to measure wave attenuation on different types of marshes is needed to calibrate/validate wave models and to learn more about the physical and ecological factors that contribute to how mudflats and marshes work together to attenuate wave energy.[3] There are only a handful of wave data sets for the Bay, which limits the analysis of wave attenuation provided by baylands.[4] The collection of additional wave attenuation data, ideally within marshes and at sites exposed to both southerly and westerly winds, will help scientists, engineers, and planners better understand spatial and temporal variability in attenuation processes.

- Research on the physical processes that control sediment transport in the Bay and tidal marshes, e.g., it would be beneficial to collect field measurements to determine the temporal and spatial variability of sediment erodibility in the sweep zone and how it is sensitive to accelerating rates of sea level rise and declining sediment supply. Additionally, measuring suspended sediment in the tidal channels and within the marsh plain will help to determine local deposition and erosion potential.

- Research to evaluate how bayland management can be better integrated into coastal zone hazard mitigation in support of climate change adaptation planning (e.g., Shepard et al. 2011). Because of the significant role baylands can play in reducing coastal flooding and potentially limiting the amount of structural protection required, it would be beneficial to have scientifically based, agreed upon criteria that the region can use to take into account the effect of mudflats and tidal marshes on wave attenuation and therefore flood risk reduction benefits to coastal communities.

2 For example, while Sedflume analysis is useful for determining erodibility under large shear stresses at greater sediment depths, such as those encountered during large storms, another technique involving a Gust chamber (recently acquired by Schoellhamer, USGS; Gust and Miller 1997) is better suited for determining erodibility at the surface, i.e., what is resuspended at tidal time scales. Measurements with this technology would improve our understanding of mudflat erosion. Furthermore, measuring suspended sediment concentrations from tidal channels within a marsh or from the marsh plain would improve our ability to model vertical accretion and predict changes to the baylands ecosystem and the ecosystem services it provides.

3 Excellent candidates for modeling include shorelines near Hayward, East Palo Alto, and Richmond. All of these areas have varying degrees of existing mudflat and outboard marsh that could provide additional opportunities to calibrate and apply the WHAFIS model.

4 N. Jones and S. Monismith collected offshore data in Grizzly Bay; J. Lacy and L. MacVean collected offshore data in San Pablo Bay; Sea Engineering, Inc. collected offshore data in Hayward; USACE collected offshore data in the South Bay; and Woods Hole Group collected offshore data near the San Francisco Airport.

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Appendices

A. Sediment Age Profiles

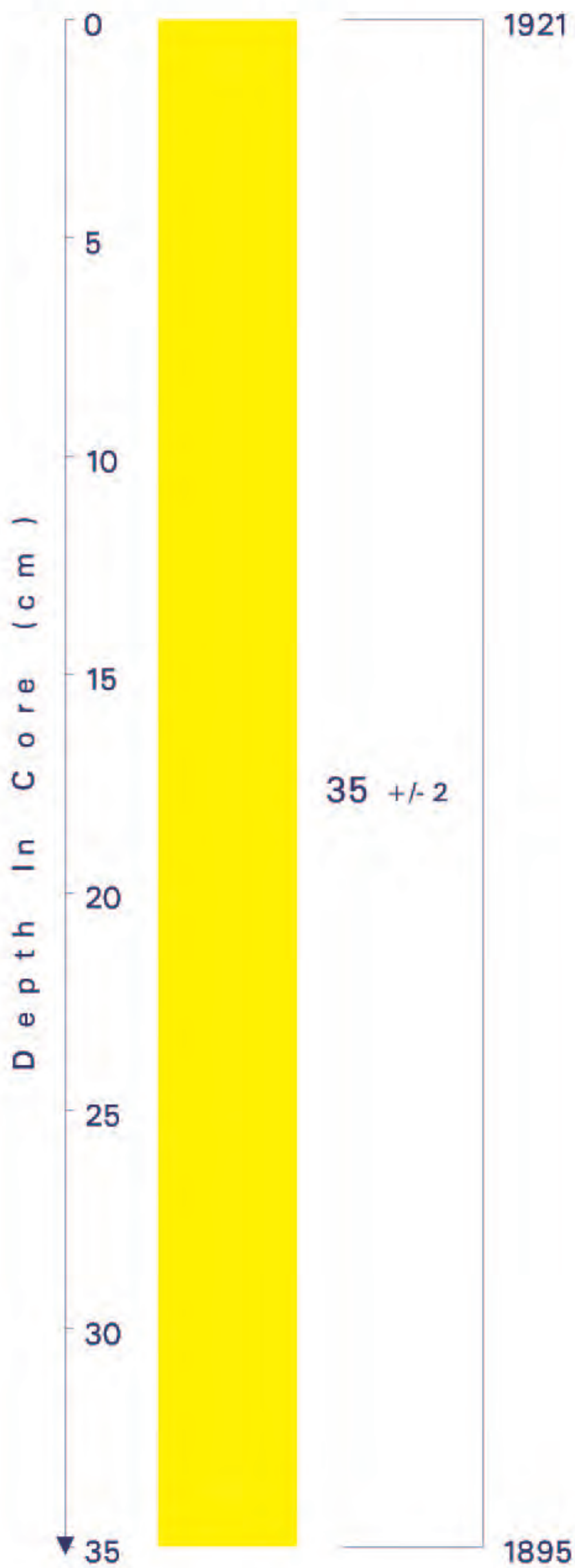
(Fregoso and Jaffe, unpublished)

The core reconstructions that follow show the horizon thickness in cross-sectional profile. The +/- values represent the standard deviation of initial deposition for a 3 x 3 grid cell neighborhood around the location of the reconstruction, indicating the spatial variability of each reconstructed horizon. A high standard deviation relative to the horizon thickness would indicate an area of high spatial variation such as a steep slope or margin of a channel. Such a value should flag the user to be cautious as a small change in location could produce a large change in the estimated profile thickness (Higgins et al. 2005).

For example, core reconstruction at CJ3c located in the Larkspur Ferry channel the standard deviation is greater than the calculated bathymetric change (16 +/- 31 cm); therefore the user should be cautious in interpreting the result that the deposition occurred between 1979 and 2010.

Predicted Sediment Chronology

Core Reconstruction



Location: 543929 m East
4198261 m North

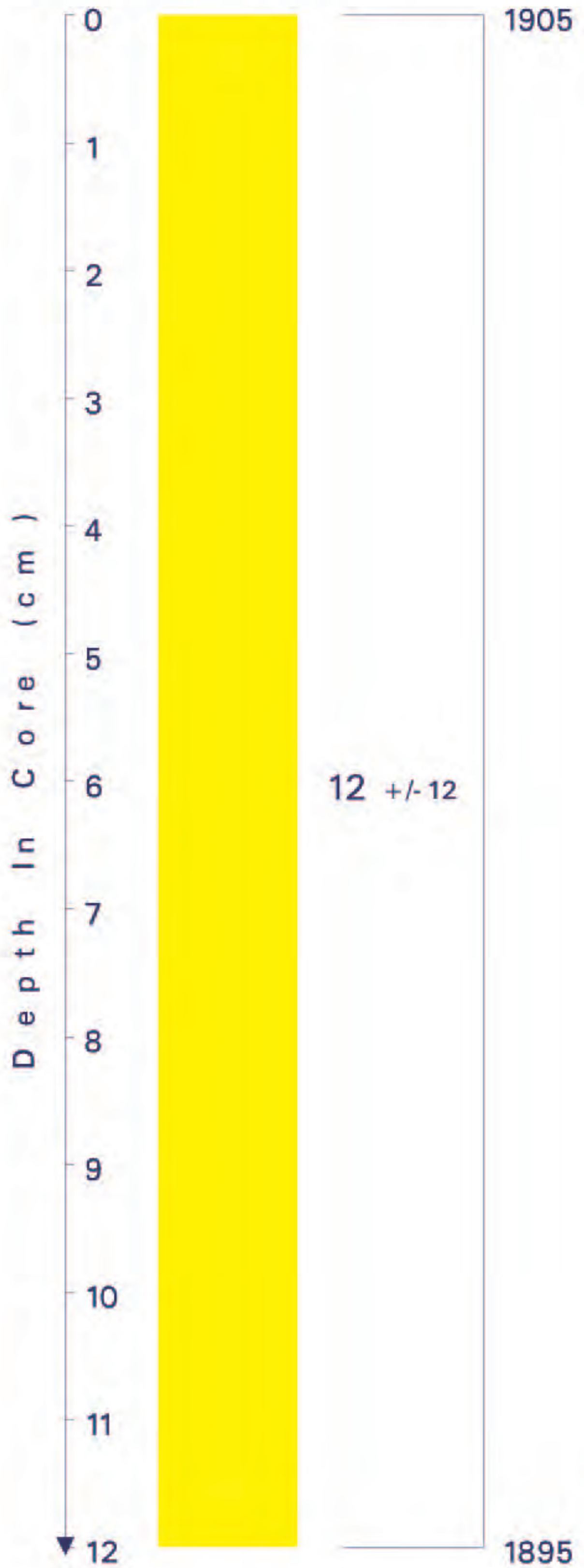
Historical Bathymetry

Survey	Depth (cm)	Change
1855	32	---
1895	-14	-46
1947	56	70
1979	40	-16
2010	21	-19

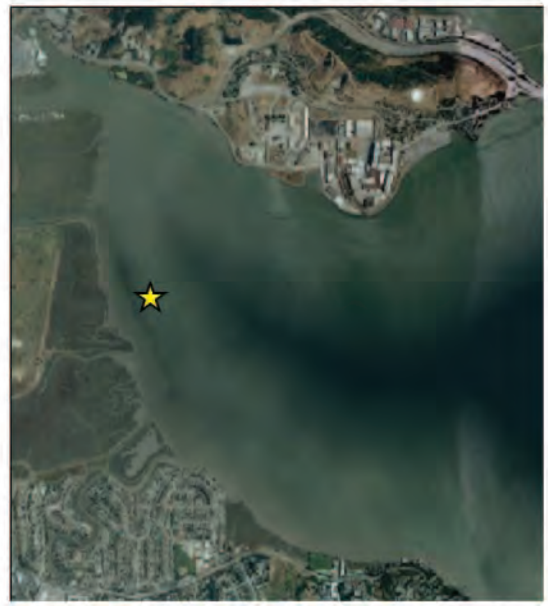
File: core_ML-1.gra
Date: 11/07/12

Predicted Sediment Chronology

Core Reconstruction



Location: 543753 m East
4198524 m North



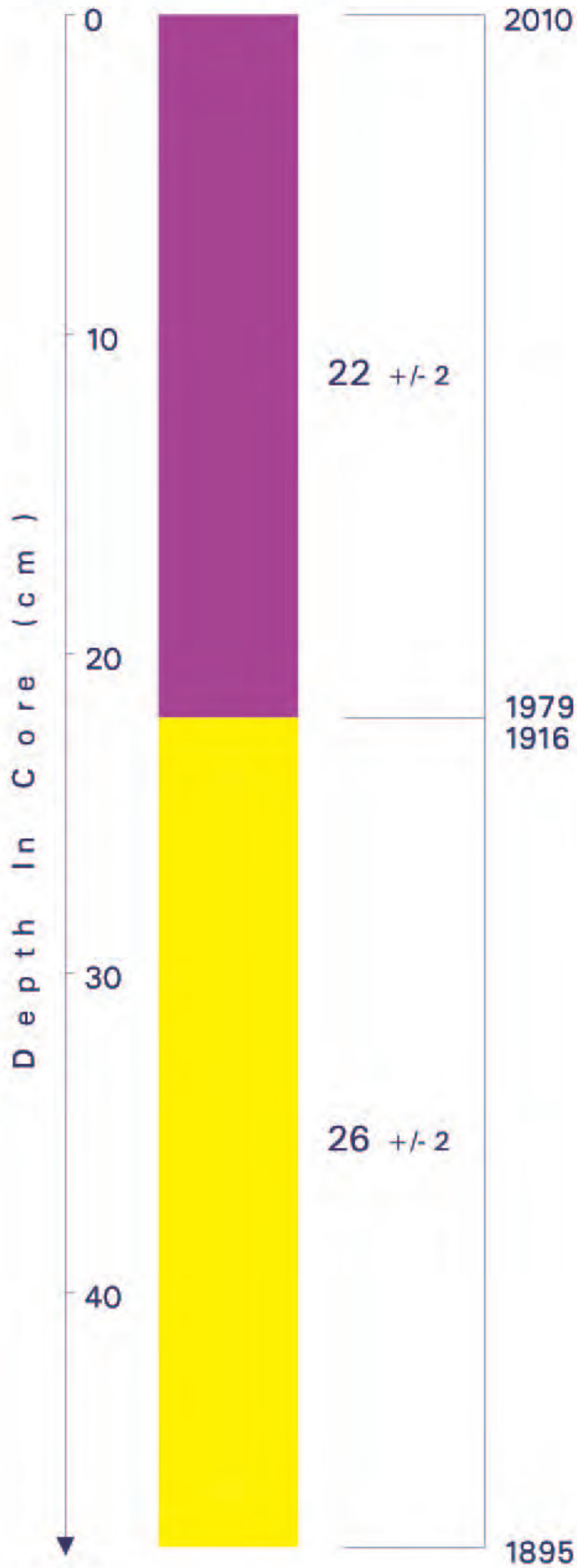
Historical Bathymetry

Survey	Depth (cm)	Change
1855	44	---
1895	3	-41
1947	68	65
1979	52	-16
2010	15	-37

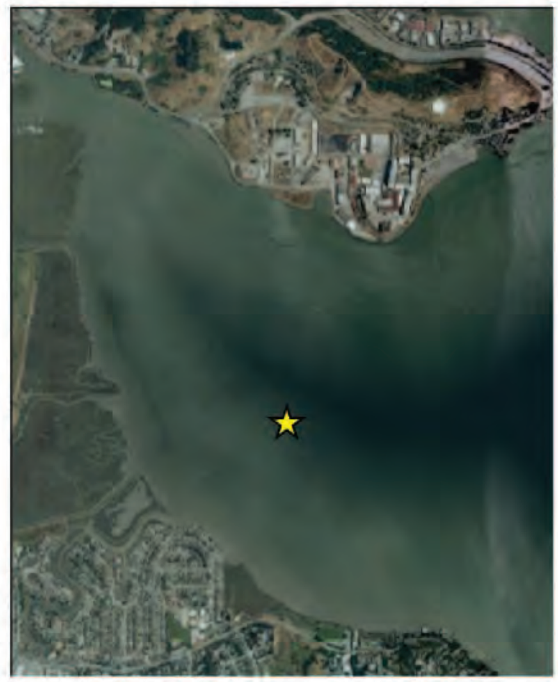
File: core_CJ2b.gra
Date: 11/07/12

Predicted Sediment Chronology

Core Reconstruction



Location: 544436 m East
4198118 m North

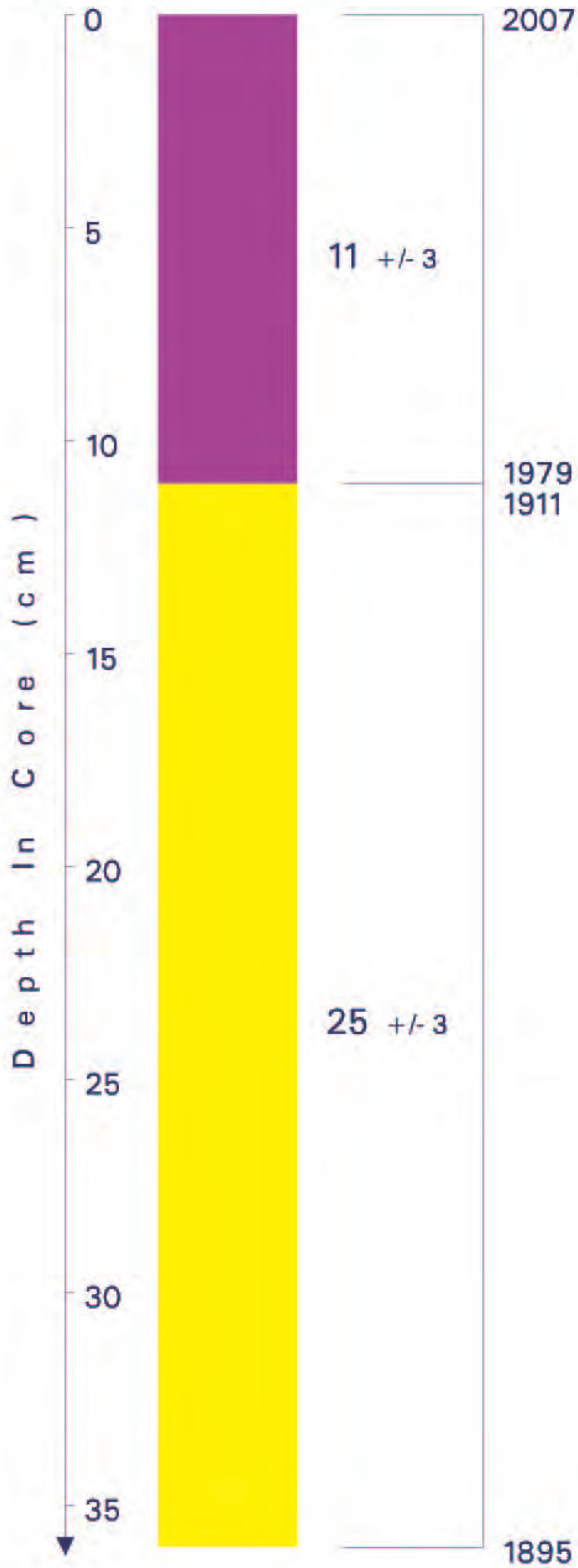


Historical Bathymetry

Survey	Depth (cm)	Change
1855	6	---
1895	-62	-68
1947	3	65
1979	-36	-39
2010	-14	22

File: core_ML-2.gra
Date: 11/07/12

Predicted Sediment Chronology



Location: 544925 m East
4197993 m North

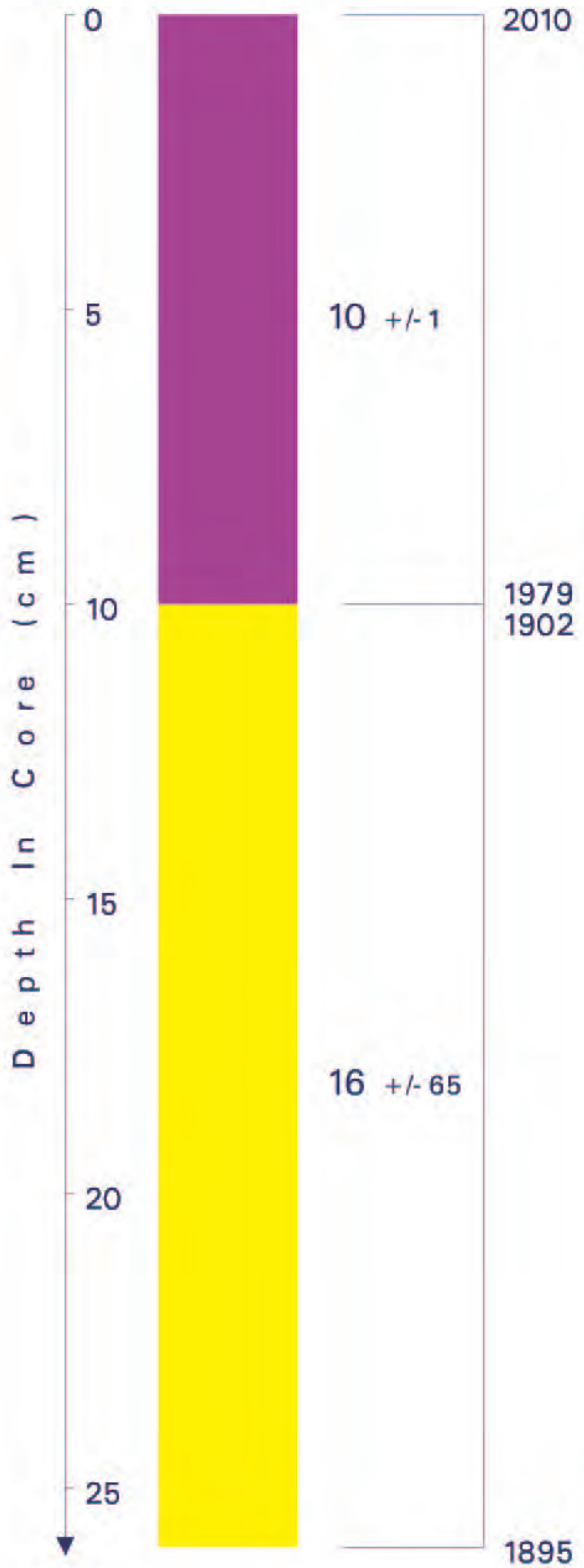
Historical Bathymetry

Survey	Depth (cm)	Change
1855	-28	---
1895	-82	-54
1947	-1	81
1979	-57	-56
2010	-46	11

File: core_S1.gra
Date: 11/07/12

Predicted Sediment Chronology

Core Reconstruction



Location: 545330 m East
4197933 m North

Historical Bathymetry

Survey	Depth (cm)	Change
1855	-84	---
1895	-109	-25
1947	6	115
1979	-93	-99
2010	-83	10

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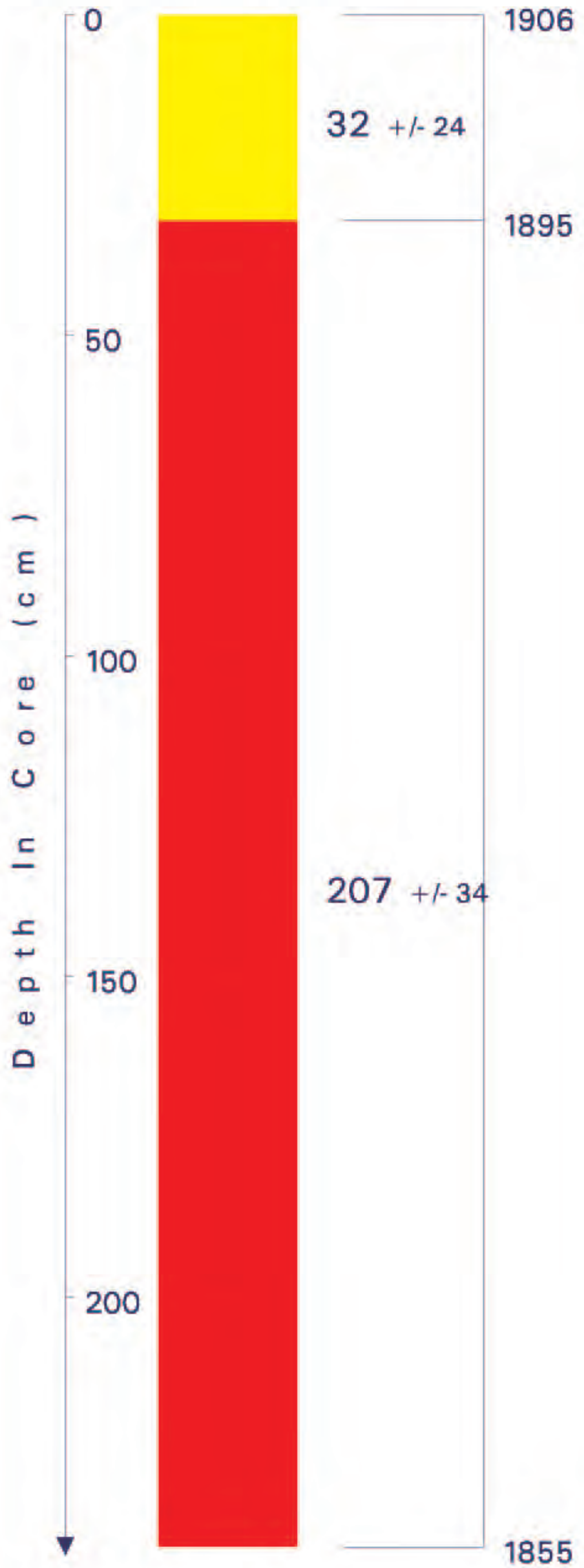
Date: 11/07/12

Predicted Sediment Chronology

Core Reconstruction



Location: 545723 m East
4197928 m North

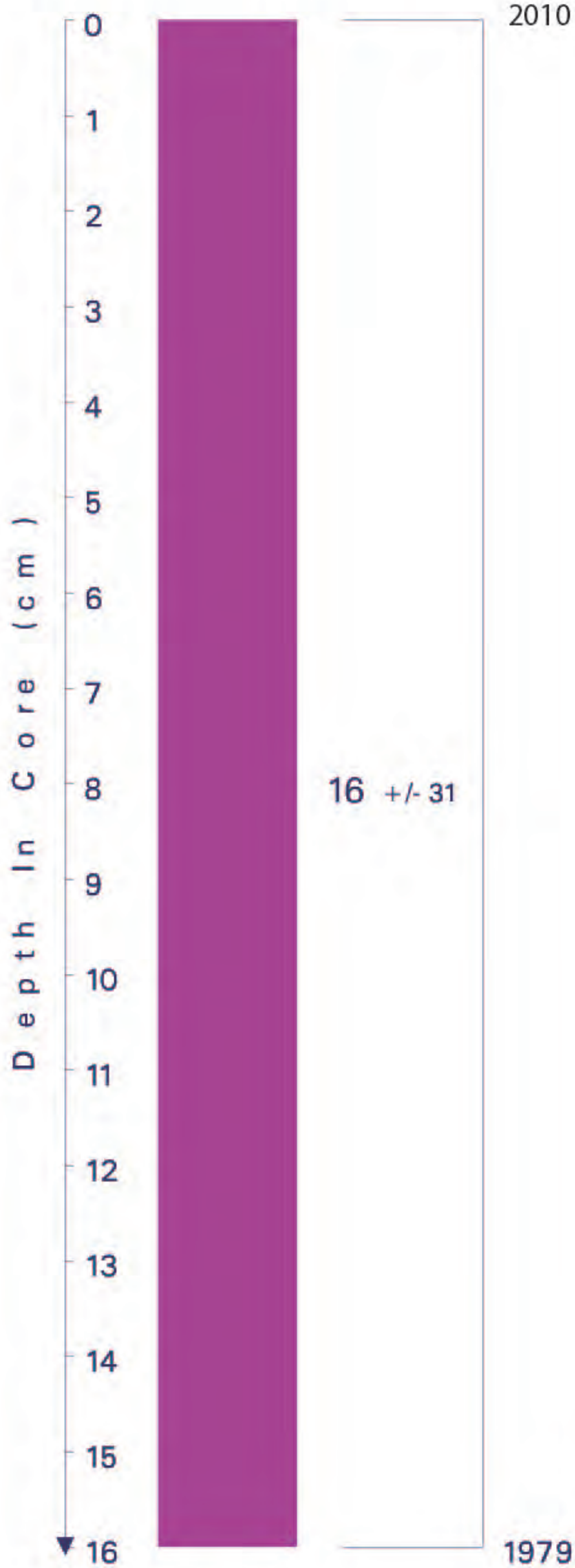
Historical Bathymetry

Survey	Depth (cm)	Change
1855	-396	---
1895	-189	207
1947	-40	149
1979	-153	-113
2010	-157	-4

File: core_S3.gra
Date: 11/07/12

Predicted Sediment Chronology

Core Reconstruction



Location: 543762 m East
4199400 m North

Historical Bathymetry

Survey	Depth (cm)	Change
1855	-4	---
1895	-22	-18
1947	0	22
1979	-327	-327
2010	-311	16

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Date: 11/07/12

B. Suite of Management Measures

APPENDIX B

The seven management measures considered in this project are presented below. Each section begins with a description of the measure and follows with a discussion of the benefits (organized by the four most significant baylands ecosystem services presented in Section 1.2), constraints, implementation details, and natural and constructed examples. The number corresponds to the measure's location in the geomorphic conceptual model (**Plate**). A subset of these measures is discussed in more detail in Chapter 5.

It should be noted that the management measures herein do not include changing the configuration of Corte Madera Creek. Corte Madera Creek is separated from the tidal marshes and, while reconnected flood control channels to surrounding tidal marshes is an option to improve flood control and sediment management, it was beyond the scope of this study.

1. Reduce nearshore wave energy

Low-crested berms constructed from coarse gravel or oyster shell are potential alternatives to conventional offshore breakwaters, e.g., rock or concrete armor units (**Figure B-1**). Berms would be able to adjust to rising sea level by naturally rolling landward, driven by wave forces. They may also enhance rather than conflict with ecological and aesthetic objectives.

Wave transmission across low-crested berms can be expressed in non-dimensional form. The transmission coefficient, K_t, is the ratio between the wave height in front of the structure (H_i) and the wave height behind the structure (H_t). Analytic relationships of K_t as a function of structure dimensions and wave characteristics have been developed for low-crested structures based on experimental data (d'Angremond et al. 1996; van der Meer et al. 2005). For typical nearshore conditions in the East San Francisco Bay, where H_i is 3 feet with a wave period of 3 seconds for a hypothetical 35-foot wide structure, K_t varies from 0.3 during low tide to approximately 0.9 during high tide – in other words, wave heights are reduced by 10 – 70% depending on the tide. The distance from the berm to the marsh edge, together with the length of the structure, will determine how much of the marsh is protected.

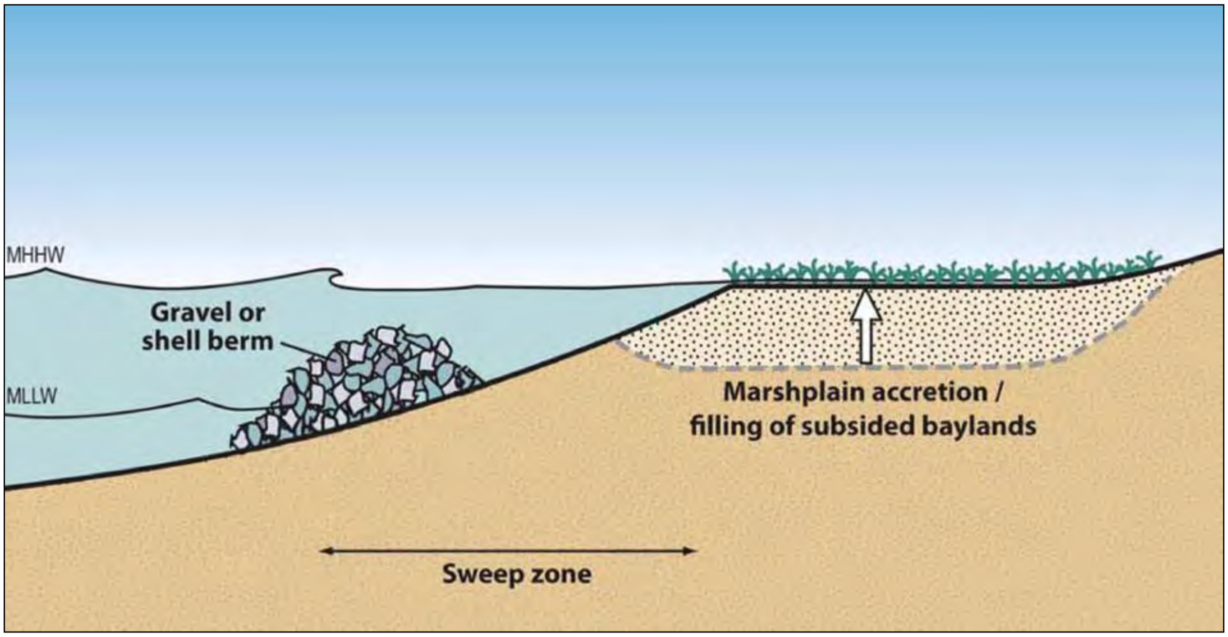

Figure B-1. Gravel or shell wave attenuation berm (note vertical exaggeration).

1.1 Benefits

Flood risk reduction: By attenuating wave energy, this measure helps to protect the marsh edge and therefore encourages the development of a stable baylands profile. For example, Roland and Douglass (2005) quantified the critical level of wave energy (in terms of wave height) that *Spartina alterniflora* can tolerate and proposed low-crested berms to reduce nearshore wave energy to within critical limits.

Biodiversity: Several studies have found that low-crested berms constructed of loose oyster shell provide substrate for oyster recruitment and harbor a more diverse community of invertebrates and fish than control areas without berms. This measure may be seen as an improvement over traditional armoring techniques, many of which have detrimental impacts on nearshore species (Bilkovic and Roggero 2008). This measure also may provide an immediate solution to marsh edge erosion, and could mitigate for the loss of shellfish and fish habitat along already armored shorelines.

1.2 Constraints

Science gaps: While low-crested berms of oyster shell can successfully create valuable habitat, they do not provide the amount of wave attenuation that could be offered by 'hard' engineering designs. More research is needed to understand the trade-offs between the ecological benefits of these types of "ecology-first" practices with the degree of coastal flood risk reduction.

Potential impacts: The potential impacts of low-crested berms include benthic smothering from placement of shell and, if accretion rates are high, local scour around the structures, interference with navigation and recreation, and aesthetics impacts at low tide.

1.3 Implementation

Low-crested berms are generally positioned at or near low water to encompass as much of the intertidal profile as possible and provide protection for most of the tidal cycle. This has the advantage of allowing the circulation of sediment in the intertidal profile to respond to short-term changes in wave energy. In addition, low-crested berms that are installed without shore-connecting structures reduce the disruption of longshore sediment transport processes.

Prior to installation, it is important to assess site suitability to determine the appropriate distance offshore to install the measure, among other design criteria. It may be necessary to re-orientate the berms as offshore conditions change, although this can be expensive. The minimum physical data requirements are therefore:

- historical analysis of maps and aerial photographs to determine the rate of marsh edge erosion and changes in the high and low water marks;
- topographic contour mapping of the baylands, corrected to a tidal datum, to determine an appropriate elevation that may be related to tidal inundation;
- measurement of the tidal regime and wave environment; and
- modeling of the tidal currents, wave climate, and sediment transport to determine orientation and spacing.

Post-construction physical monitoring should include the measurement of wave climate within and around the low-crested berm at intervals to check the design functions and ensure that it is meeting performance criteria.

1.4 Examples

Natural analogs occur along the Hayward Regional Shoreline, e.g., Robert's Landing, Hayward's Landing, and Johnson's Landing. Additionally, two recent pilot projects have been initiated in the San Francisco Bay (Bay) as part of the California Coastal Conservancy's Living Shoreline project. In 2012, eelgrass and oyster reefs were deployed in San Rafael Bay and along the Hayward Shoreline. Because the effectiveness of the measure is unknown, it includes experimental design that allows comparison of various treatments (including no treatment) to inform future restoration actions. Pre-project monitoring included bathymetric surveys, sediment core collection to assess benthic invertebrate species richness and density, and observations of epibenthic, fish, and bird use of the sites. Post-project monitoring will measure biological, chemical, and physical processes through 2017, e.g., growth rates, densities, and recruitment of the eelgrass and oyster reefs; invertebrate, fish, waterbird, and shorebird responses, densities, and behavior; temperature, salinity, pH, dissolved oxygen, and turbidity; and waves, currents, and sediment deposition and erosion (California Coastal Commission 2012).

2. Stabilize with a coarse beach

Coarse beaches are a natural and very effective form of shoreline protection that adjusts to local wind-wave conditions, including those during extreme events. Unlike typical engineered revetment systems, such as riprapped levees, adjustments in beach morphology are an inherent characteristic of the coarse beach system and not an indication of failure. Analysis by Allan et al. (2005) showed that dunes fronted by mixed coarse-grain beaches experienced erosion rates that were typically 20 – 40% of pure sand beaches, highlighting the relative level of protection offered by coarse beaches. In Southern California, researchers have noted that gravel beaches tend to gain material and increase their crest elevations during severe storms, while neighboring sand beaches eroded so significantly that the sand berms present on those beaches disappeared (Lorang et al. 1999, Everts et al. 2002).

Figure B-2 shows a typical cross section of coarse beach stabilization proposed for the Central Zone of the Aramburu Island project. This coarse beach profile has a lower gradient slope than a marsh scarp. Waves energy is dissipated on the beach face, thereby buffering the marsh edge from erosion. At extreme water levels, the berm would “trip” waves, causing them to break. As sea level rises, the coarse beach system would be expected to roll landward, allowing the marsh to maintain its wave attenuation function for longer. Placement of gravel and cobble on bay mud will require consideration of consolidation and subsidence. Micro-groin or similar control structures constructed across the coarse beach will also need to be considered to reduce the rate of longshore drift and increase the residence time of coarse material.

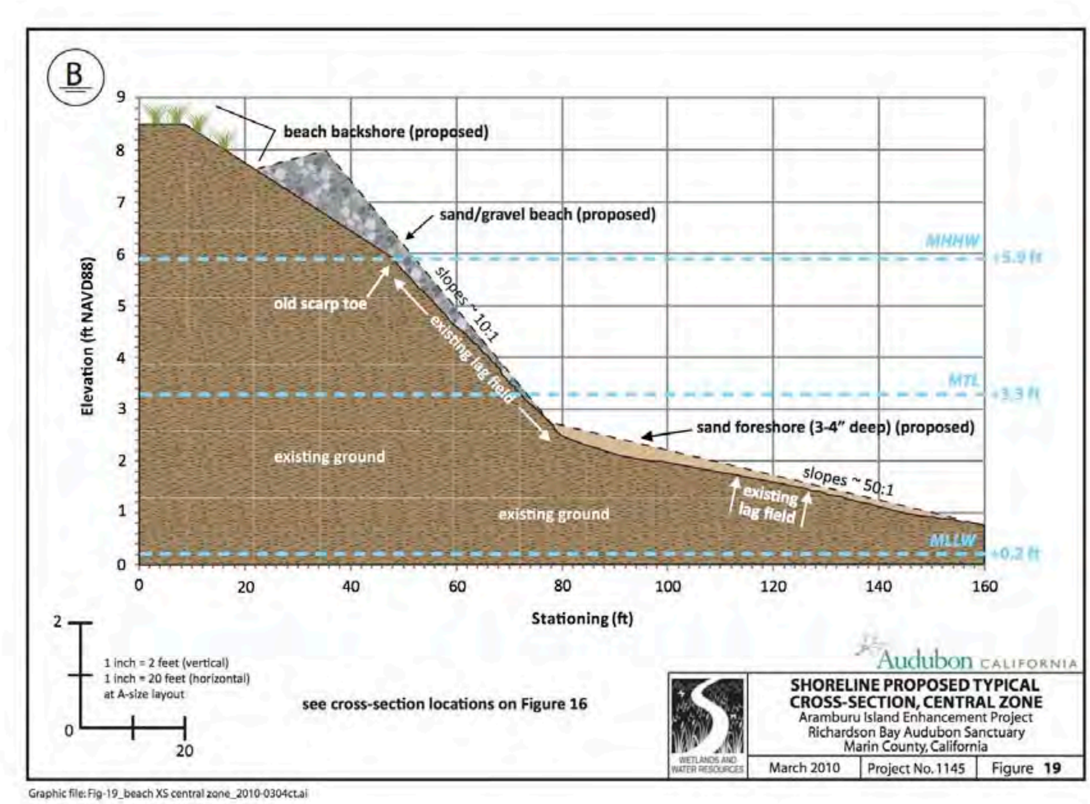

Figure B-2. Typical cross section of coarse beach stabilization proposed for the Central Zone of the Aramburu Island project (WWR 2010). Sand foreshore grades up to mixed coarse sand and gravel berm.

2.1 Benefits

Flood risk reduction: Researchers have long recognized that coarse beaches are one of the most effective forms of coastal protection, exhibiting a remarkable degree of stability and dynamism in the face of sustained wave attack (Ahrens 1990; Ward and Ahrens 1991). Constructing a sand foreshore and coarser grain berm provide a gentle ramp-like profile to dissipate wave energy and maintain marsh width against wave erosion of the edge. The ability of this coarse beach system to adjust their profile upward in response to storm waves and move inland as sea level rises makes it resilient to future changes.

Biodiversity: The measure would change the marsh scarp to a more gradual wave-dissipating profile and change shoreline dynamics from marsh edge erosion to gradual beach transgression. These changes would provide the geomorphic foundation for native vegetation to establish and high tide refuge habitat to form along the coarser grain berm. Furthermore, reducing marsh edge erosion will help to minimize marsh narrowing and avoid resulting stresses from habitats moving closer to developed upland areas.

2.2 Constraints

Technical feasibility: Project designs should consider local site conditions (e.g., water depth, wind fetch, incoming wave energy, shoreline morphology, supply of coarse material, and vessel draft requirements) and construction constraints (e.g., access via terrestrial or marine equipment). For example, depending on the site, longshore drift may require control structures to hold coarse beaches in place. In some locations, suitable sediment may be available nearby and eliminate the need for 'double-handling' sediment from larger to smaller barges for placement, or terrestrial placement may be an option to decrease construction costs. All of these issues require analysis during the design phase.

Periodic maintenance should be included in the project design because longshore currents may transport quantities of beach sediment out of the project area. This may mean returning some portion of the coarse sediment transported out of the project area or periodically re-nourishing with new sediments as the coarse beach volume decreases. Few natural sources of rounded gravels and cobbles for construction are commercially available in the Bay. Quarries capable of producing crushed gravels of a particular size are relatively common, but this rock tends to be too angular, which reduces its ability to adjust to local wave conditions. Production of cobble-sized round rock or quarry rock may require an operator to modify procedures in excavating, blasting, quarrying, sizing, storage, and handling. Angular and slab rock typical with blasting should be avoided as it is uncommon on natural beaches.

Potential impacts: The placement of coarser grain sediment such as sand and gravels may affect benthos and lead to the conversion of habitat types, although there are wildlife values provided by this new type of habitat.

2.3 Implementation

Coarse beaches are significantly easier to construct than a conventional riprap revetments or seawalls, but do require larger areas to accommodate their shallower slopes. Particle sizes used in construction are smaller and generally less expensive than the large armor stones (although rounded cobbles are currently less commercially available then larger quarry rock), and placement of the gravels does not require exact grading, as it will be reworked by incident waves.

2.4 Examples

Natural analogs in San Francisco Bay include Outer Bair Island, Fleming Beach and Albany

Beach. There is one completed demonstration project at Aramburu Island in northern Richardson Bay, Marin County, which was built over two years in 2011 and 2012 (WWR 2010). The project constructed a gravel, cobble, and oyster shell beach with a sand foreshore and large woody debris and rock micro-groins in an effort to create natural shoreline protection mixed with wildlife habitat benefits.

3. Recharge mudflat and marsh

Many tidal marsh ecosystem services are a function of the elevation and inundation regime, and therefore are dependent on the marsh maintaining its position in the tidal frame. Vertical marsh accretion rates are dependent on the local supply of sediment. For example, while typical suspended sediment concentrations in the Bay are on the order of 100 – 200 parts per million (ppm) and typical accretion rates on the marsh are less than an inch per year, observations at the Alviso Marina in the South Bay have shown that concentrations of 450 – 600 ppm result in accretion rates of up to 1 – 2 feet per year (Ruth and Going 1980). A number of methods have been suggested to increase the *local* concentration of fine sediment in the water column to support vertical marsh accretion. These recharging methods are not aimed at increasing the *total* sediment supply; rather the approach is to focus available sediment supply to specific locations.

To increase the local sediment supply in the water column, fine sediment could be *directly* released as a plume from a barge close to the target tidal marsh. To maximize the benefit the release would occur on a flooding tide that would carry the sediment onto the marsh. Alternatively, fine sediment can be introduced *indirectly* into the water column by placing the material on adjacent mudflats, which are the primary sediment source for tidal marshes. Placement would occur as a mound either using a split bottom barge, hydraulic pipe or by 'rainbowing' (**Figure B-3**). Wave action on the mound of sediment placed on the mudflat would then re-suspend the fine sediment into the water column and convey it onto the tidal marsh. Timing would depend on when dredging activities occur, wind-wave resuspension in shallow subembayments is greatest given seasonally varying winds and bed erodibility, and impacts to species of concern are the least. Some form of dewatering such as placement behind brushwood fences on the mudflat might be needed if sediment is placed as a slurry.

In order to increase local marsh accretion rates, local tidal currents and wave climate need to be carefully considered, and fine sediment needs to be introduced close to the target tidal marsh. The intent is to mimic natural sediment re-suspension and deposition processes by making use of natural tidal currents and wave action to transport the sediment into and onto the marsh, avoiding the difficulty of mechanically placing sediment. Recharging the water column and the mudflat provides a considerable benefit, as it allows the choice of when, where, and how much sediment to introduce to the system in a targeted fashion to offset some of the overall decline in suspended sediment forecast for the next century (Schoellhamer 2011). As recharge could take place on a regular basis, perhaps annually, without disrupting the natural marsh, this measure allows for the possibility of matching four variables: the rate of recharge, the availability of dredged fine sediment, the demand for sediment on the tidal marsh, and the observed rates of sea level rise.

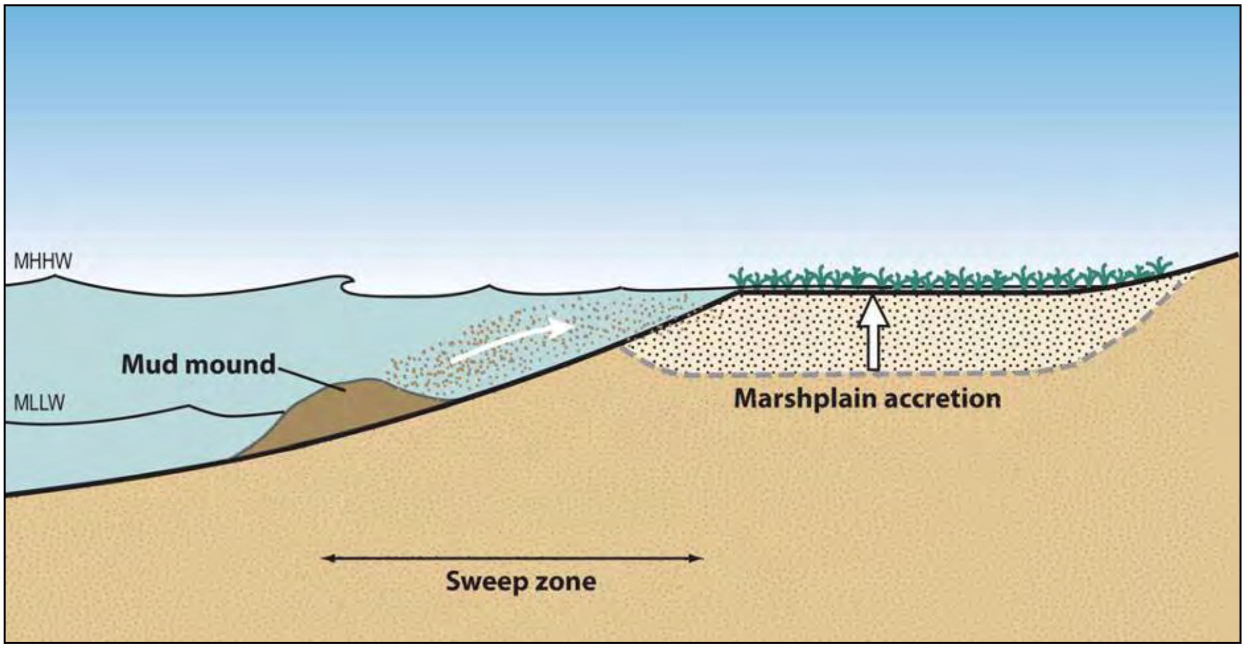

Figure B-3. Mudflat and marsh recharge (note vertical exaggeration).

3.1 Benefits

Flood risk reduction: Since water level is the largest determinant of wave attenuation due to depth-limited breaking, mudflat and marsh recharge will help sustain this benefit by helping baylands keep up with sea level rise.

Biodiversity: By protecting the flood risk reduction benefit of baylands, this measure may delay the construction of harder structures such as levees with their consequent impact on marsh habitat. Since placement of sediment directly on the marsh could lead to burial of vegetation and loss of habitat, recharging the water column or the mudflat could result in less overall disturbance to marsh habitats and therefore sustain a greater degree of biodiversity.

3.2 Constraints

Policy challenges: Both water column and mudflat recharge are untried in the Bay and present significant regulatory challenges. Once the recharge has occurred, there is little control on where and how much sediment will be finally deposited, as natural processes ultimately control the amount of deposition. The location and timing of recharge is therefore very important. Water column and mudflat recharge is likely to work best with relatively small volumes released at frequent intervals so that the recharge would be scaled to the marsh area and long-term sedimentation rate. This may conflict with the availability of dredged materials, which often occur in relatively large volumes at infrequent intervals, and with the policies governing beneficial reuse of dredged materials.

Technical feasibility: Present dredging equipment is designed to accommodate much larger volumes then are feasible for this measure, and may therefore be uneconomical. Additionally, currently used equipment may be too large to get close enough to the mudflat recharge areas. Alternative methods of moving fined sediment, such as by pipe as a slurry (as used at Hamilton[1] and Montezuma[2]), may be more effective. The quality of the source material, for example whether it is anoxic or contains mercury, will also be a key consideration.

Science gaps: Limited information is currently available about how recharge would work in the Bay. MacWilliams et al. (2012) conducted numerical modeling at select locations. New research and demonstration projects will be necessary to develop design and monitoring guidance for this measure, particularly with respect to potential benthos impacts (see below). For example, studies using tracers would improve the understanding of uncertainties associated with this measure, as recharged sediment may be carried a considerable distance from the site, and if deposited in inappropriate areas, could potential damage baylands habitats.

Potential impacts: There are likely to be impacts to both the water column and benthos due to increased suspended sediment concentrations and smothering by fine sediment. Mudflat recharging with fine sediment could result in the burial of existing mudflat habitat, potentially impacting species using this habitat.

3.3 Implementation

Fine sediment will be required for any method of recharge. Ideally the sediment would be compatible with the existing mudflat, and in particular would have similar re-suspension

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[1] For more information, see: http://hamiltonwetlands.scc.ca.gov

[2] For more information, see: http://www.californiawetlands.net/tracker/ba/filesets/1062

characteristics, which are important in determining the eventual fate of the material. It is anticipated that recharge would occur as a regular maintenance activity with smaller volumes of material placed more regularly. Matching local sources of fine sediment to recharge sites would allow for regular recharging especially if there was programmatic environmental documentation in place.

Additionally, since the eventual deposition of the fine sediment is left to natural processes, it may be necessary to 'overcharge' the mudflat to ensure sufficient material reaches the tidal marsh. Monitoring of the measure will be critical, and evaluating increases in mudflat elevation in the near term and vertical accretion on the tidal marsh over the longer term would provide an understanding of the measure's performance.

3.4 Examples

While natural analogs exist on all mudflats, there have not been recharge pilot projects in the Bay. Intertidal recharge experiments have been undertaken in the United Kingdom (UK) in locations with similar wave climates as the Bay. In 1996, 5,000 cubic yards of dredged fine sediment from a nearby harbor was placed on a mudflat in the Medway Estuary using split bottom barges (ABP 1998). Tracer studies were used to identify sediment transport pathways and volumes. The experiment indicated that the mudflat recharge was a success for relatively small volumes of material, with approximately 50% of the sediment retained on the mudflat or entered the tidal marsh.

4. Improve sediment pathways

Tidal channels link the baylands to the Bay, acting both as pathways for nutrients and sediment and habitat for plants and wildlife. Mature, natural marshes tend to have complex dendritic channel networks, often divided into two or more tidal watersheds each with several orders of sinuous channel and its own tidal slough connection to the Bay. These channels convey turbid Bay water into the marshes, allowing sediment deposition to occur at high water. Coarse material is deposited closer to channels, forming natural levees that are higher than the surrounding marsh plain and support particular plant species such as gumplant. Finer sediment is deposited further away from the channel, with the amount diminishing with distance. The rate of vertical accretion therefore depends on the distance from a channel, and if channel density is low, parts of the marsh may be poorly supplied with fine sediment and thus have low rates of vertical accretion (**Figure B-4**).

The characteristics of channels and the channel network are determined in large part by the tidal prism of the marsh, which in turn is controlled by the tidal range and the area and elevation of the tidal marsh. Larger tidal prisms support larger channels, more extensive channel networks, increased sediment transport into the marsh, and generally have higher quality habitat. If there is insufficient tidal prism, then channel networks may not fully evolve. The relationship between tidal prism and channels can be predicted using hydraulic regime theory (PWA 2002, Williams et al. 2002).

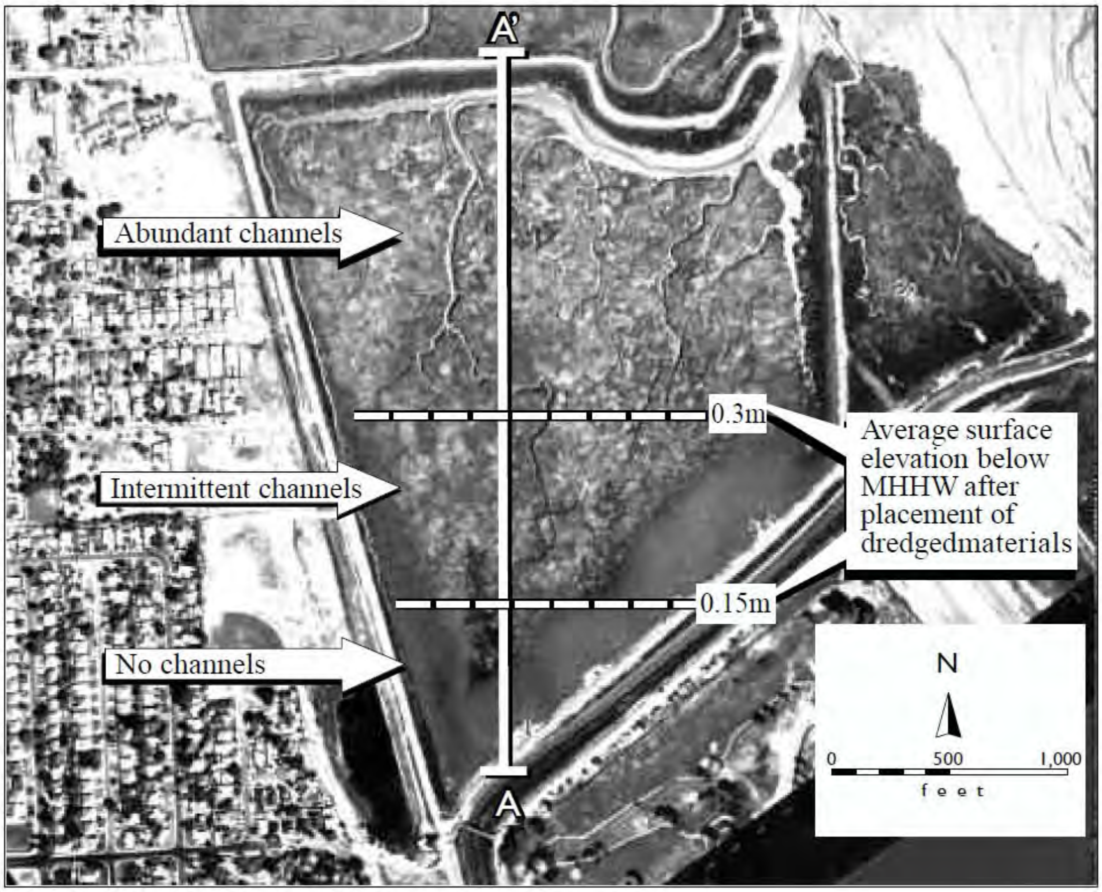

Figure B-4. Example of variation in tidal connectivity across the Faber Tract in between Laumeister Marsh to the north and San Francisquito Creek to the south near the City of Palo Alto, Santa Clara County (PWA 2004). The southern part of the marsh is higher, with less tidal prism and fewer channels.

4.1 Benefits

Flood risk reduction: Channels not only allow tidal inundation, but also drainage. Drainage can be important from a flood management perspective; e.g., after flood events channels facilitate drainage of upland areas, thereby reducing the unnatural persistence of high water levels. Moreover, natural channel levees reduce the wind wave climate.

Biodiversity: A complex channel system that is sized appropriately for the marsh improves the connectivity of the marsh with estuarine tidal processes. A complex drainage system with sinuous channels of a variety of channel orders provides habitat diversity. Many species of plants and animals also rely on channel bank habitat. Excavation of channels can generate fill and sidecasting the excavated material to form low mounds for intertidal or supra-tidal habitat can provide a surface for rapid vegetation establishment. Furthermore, adequate drainage also prevents over-saturation of soil, which can impede plant growth.

4.2 Constraints

Technical feasibility: Tidal channels can be reconnected or otherwise "restored," but at the same time, this may not lead to restoration of the natural tidal hydrology that led to their formation or continued existence. For instance, if a tide gate controls the flow through the channel, the tidal range will remain muted. If the channel flows through a breach or culvert that is undersized, flow velocities in the channel could cause scour within the breach or could cause silting in and narrowing of the channel.

When tidal action is reintroduced to a subsided site, tidal flows tend to concentrate in existing ditches or depressions that then fix the location and shape of the tidal drainage system. Often the existing drainage system consists of straight field drains or borrow ditches on the backside of levees. It is likely that once the existing drainage system captures the tidal flows, its pattern may persist for hundreds of years, therefore it is important consider if actions are necessary to promote the desired network configuration.

4.3 Implementation

New channels can be cut using the historic channel network as a guide. Generally the largest channels need to be fully graded, while smaller channels are simply deepened, as widening can be achieved rapidly by scour and bank collapse. Material from the cut channels is often sidecast adjacent to the channel to emulate natural levees. At a high site, which perhaps was previously filled, sediments may be too compacted to allow channels to scour naturally and disking and excavation may be necessary.

On some subsided former marshes behind dikes, the original dendritic sinuous tidal channel system may still be expressed in the topography, even if the channels have been filled over time or interrupted by interior levees. Suitable selection of breach locations, removal of obstructions, and blocking of borrow ditch channels may concentrating tidal flows into the old channels, scour out the loosely deposited sediments, and rejuvenate the entire tidal drainage system.

4.4 Examples

Laumeister Marsh in Santa Clara County provides one example of a natural dendritic tidal channel network. Tidal marsh restoration in the Bay began in earnest in the 1970s, and since then, the understanding of marsh plain evolution and channel network development has improved significantly. PWA (2004) evaluated and documented restoration experience in the Bay and developed guidance to address practical design questions. This guidance includes promoting the evolution of complex tidal drainage systems and exploring under what conditions the pre-existing drainage system should be modified and new channels should be excavated. During the 1970s, several sites that were filled with dredged material were restored to tidal action (e.g., Muzzi Marsh in the Corte Madera Baylands, Alameda Creek Pond 3 in Alameda County, and Faber Tract in Santa Clara County; PWA (2004)). In all of these sites, the evolution of the drainage system was impeded. At Inner Muzzi and Alameda Creek Pond 3, dredged material was placed too high, with elevations at or above MHHW, leading to large areas remaining poorly drained and barren for many years. In both these projects, large channels were later excavated in the dredged fill material to improve tidal circulation. For the Martinez Marsh restoration in Contra Costa County because the fill material was not dredged estuarine sediment, and might have been erosion-resistant, a dendritic tidal channel network was excavated in the fill to replicate typical natural tidal drainage density and sinuosity.

5. Enhance sediment trapping

Increasing sediment deposition during a tidal cycle may be achieved by decreasing turbulence, i.e., increasing the ratio of particle setting velocities to fluid shear velocities. The rate of deposition is controlled largely by the interaction between tidal current velocities and vegetation. Flocculation also plays a major role in fine sediment particle dynamics and deposition rates.

Traditional sediment trapping methods impound high tide waters so that sediment can settle out before the area is drained ('dewatered') via a sluice gate or the falling tide. Methods were originally pioneered in Holland and Germany and later in the UK, particularly on mudflats in front of eroding marsh edges. The process involved creating a system of 'sediment fields' made of brushwood sedimentation fences to slow the passage of water, thereby facilitating the deposition of sediment in suspension and an increase in vertical accretion ('warping'). Essentially, there are two types of fence placements:

1. Groins generally consist of parallel rows of wooden stakes driven deep into the mud.

2. Polders enclose a width of mature upper marsh together with a similar width of adjacent mudflat by the construction of a perimeter sedimentation fence.

5.1 Benefits

Flood risk reduction: This technique enhances vertical accretion by using natural tidal currents to transport sediment-rich waters across areas of mudflat and marsh, where tide gates, fences, embankments, and trenches can then trap this sediment. This measure maintains marsh and mudflat wave attenuation benefits as long as vertical accretion rates are greater than sea level rise rates.

5.2 Constraints

Technical feasibility: Doody (2008) reviewed several sedimentation fence experiments undertaken in the early 1990s at various locations in the UK, e.g., Cudmore Grove and Dengie Peninsula. Monitoring of these sites suggested that their effectiveness was limited. Sedimentation fences either constructed as groins or polders require intensive management and maintenance and so these techniques may be only feasible for relatively small areas. As infill between the stakes, and the stakes themselves, are damaged or lost over time the fences become less effective. The trenches must also be constantly re-dug to maintain their effectiveness and prevent the accreted sediment from being washed out of the ditches. Additionally, the polder technique is believed only to be successful if the local sedimentary trend is towards deposition. In areas where the trend is towards erosion, the polders have proved ineffective.

Potential impacts: Brushwood and other infill material between the stakes can be swept away by the tide and deposited on adjacent areas of marsh, potentially causing vegetation mortality if not removed immediately.

5.3 Implementation

Different orientations of groin fences have been employed but, in general, the best orientation is perpendicular to the shore. A variety of materials can be used as infill between the stakes, including willow brushwood, geotextile claddings, and straw. Overall, brushwood has been found to be the most durable. The groins reduce wave action, slow currents, promote sedimentation and, to some extent, delay the departure of the ebb tide. Tidal velocities are reduced by the ponding effect and the erosive effects of wave and tide-generated shear stress are diminished, thus allowing the fine-grained fraction of the sediment to settle out (Colenutt 2001). As a result, the sedimentation of suspended matter is enhanced, both behind the groins and in front of the marsh edge.

Polders can be up to 1200 square-feet, although many of the experimental sites constructed in the UK have been smaller, varying between simple groins 90 – 150 feet apart and larger, more complex fields 300 – 450 square-feet. Gaps in the fencing along the seaward line of each enclosure allow the tide to flow into a series of trenches within the area. These are maintained to control the flow and sediment deposition. The main trenches are dug perpendicular to the shore, while other trenches are dug parallel to it. The main ditches direct the waters of the flooding tide onto the upper areas of the mudflat or marsh sufficiently rapidly for them to carry the sediment towards the shore (Colenutt 2001). The sediment that fills in the ditches is excavated and placed in the intervening space, thereby raising the elevation over time, until the process is no longer required.

5.4 Examples

There are no examples known in the Bay. In Europe, the pattern of trenches from historic polders can be seen clearly in some eroding marshes and can provide preferential erosion lines.

6. Increase transition zone

This measure creates an estuarine-terrestrial transition zone on fill slopes located landward of the existing tidal marsh and bayward of the flood risk management levee (**Figure B-5**). There may be opportunities to fill man-made ponds (such as salt or oxidation ponds) located between the levee and the outboard marsh to avoid placing fill directly on wetland habitats. Transition zone slopes would create a habitat type that is missing in many parts of the Bay due to diking, and provide gently sloping uplands to allow for upland transgression, buffering the tidal marsh from coastal squeeze between a rising Bay and steep levee slopes.

Transition zone slopes would be engineered equivalents of seasonal floodplain wetlands (lowland wet grassland and sedge-rush meadows) historically associated with broad, flat alluvial fans that graded into the tidal marshes in most of the South Bay. Recycled fresh water, such as treated wastewater or stormwater, could be allowed to seep through the transition zone slope to support the moist grasslands. Groundwater, soil, and vegetation interactions of wet meadows could support important carbon and biogeochemical nutrient transformation and sequestration processes that are currently limited in diked baylands and tidal marshes disconnected from groundwater discharges.

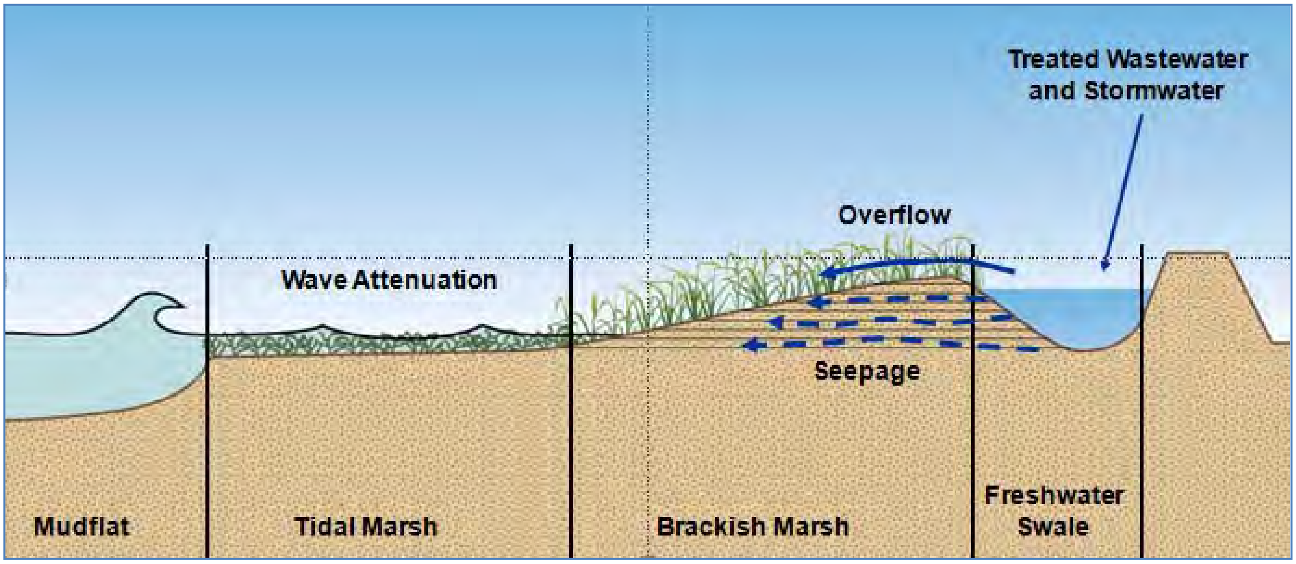

Figure B-5. Transition zone (note vertical exaggeration).

6.1 Benefits

Flood risk reduction: This measure would provide long gentle slopes with a gradient of 1:30-1:50, which is more in keeping with natural upland slopes than steep sided levees. These shallower slopes would allow for upland transgression and help maintain tidal marsh wave attenuation benefits in the face of sea level rise. By reducing wave heights, run up and overtopping, this measure may delay the need to construct harder structures such as levees. Finally, the non-engineered shallow slopes of the upland areas should be relatively stable during seismic events, unlike steeper sloped levees.

Biodiversity: The long-extinct natural "seasonal wetlands" associated with alluvial fan transition zones are not the same as the artificial "seasonal wetlands" familiar in modern diked baylands and derelict former agricultural fields. Seasonal wetlands found on disturbed sites are typically dominated by non-native annual weeds and pasture grasses, e.g., pepperweed (*Lepidium*). Natural seasonal floodplain wetlands (represented by rare remnants) include lowland (alluvial) grasslands dominated by native creeping perennial grasses, sedges, and rush meadows (with associated native perennial forbs) in clay-silt loam soils, and riparian scrub on coarser alluvium with greater permeability, locally associated with relict or active stream distributary channel banks. They are generally associated with fluctuating, shallow groundwater and wet-season flooding (ponding or sheetflow). This now rare groundwater seep-dependent transition zone would provide important spring foraging habitat for the endangered Salt Marsh Harvest Mouse and increasingly important terrestrial high tide refuge for a variety of species as sea level rises.

Carbon sequestration: Vegetation that establishes on the transition zone slopes could provide carbon sequestration benefits.

Water quality improvement: The use of treated wastewater or stormwater to support the vegetation on the transition zone slope can provide water quality benefits as a final polish before discharge. Local reuse will also reduce the need to pump treated wastewater around the Bay, which in turn decreases energy demand and GHG emissions, the vulnerability of the existing infrastructure, and the likelihood of water quality issues caused by seismic or large storm events.

6.2 Constraints

Policy challenges: There may be regulatory challenges associated with converting existing wetland habitat to brackish wetlands and uplands, and mitigation may be required for impacts to existing habitat. Any discharge of treated wastewater to the transition zone slopes would need to be permitted by the appropriate agencies.

The use of dredged material to create the transition zone slopes and the local reuse of treated wastewater would repurpose resources that are currently not reused to the fullest extent possible. In the future, however, new ways to reuse these resources may be found, leading to competition for finite supplies.

Technical feasibility: The construction and maintenance of the transition zone slopes would require large volumes of fill material. Water or land access would be required to allow the placement of fill. Unsorted dredged or upland material would be suitable as the slope is not an engineered structure and is relatively flat. However, the material would need to be coarse enough to allow for infiltration and most maintenance dredging results in relatively fine grain sediment. In addition, clean capping soils, up to a thickness of 3 feet, would be required to accommodate the rooting zone of the terrestrial native species. Banking free, coarse, clean sediment to create large, broad transition zones may be needed in some large projects. If brackish marshes are to be constructed, then a supply of fresh water, e.g., recycled treated wastewater or stormwater, is also required.

Science gap: The extent to which this measure provides water quality co-benefits needs to be demonstrated.

6.3 Implementation

To reduce the initial fill requirements, it may be possible to construct the transition zone slope in stages that are phased based on the observed rate of sea level rise, the availability of dredged material, and financial resources. An initial, smaller berm could be built at the outboard edge of the transition zone, followed over time by filling behind the berm as material becomes available to bring the slopes to final grade. An alternative may be to maintain a 3:1 slope to a horizontal bench located 1 foot above MHHW. The levee bench could receive fine grading to create backshore pans and a 30:1 to 50:1 slope will continue downward from the bench to about 2 feet below MHHW, within the lower range of cordgrass colonization elevations. Additional fill would be placed on the bench as required to maintain its position in the tidal frame with sea level rise. The elevation of the transition zone slope could be modified to keep up accelerated sea level rise by the hydraulic placement of thin splays of sediment or by changes in the vegetation species to maximize peat production. Monitoring of the establishment of natural terrestrial plant communities in the near term and the transgression of the tidal marsh over the longer term would be necessary.

6.4 Examples

Historically, most Bay streams did not directly connect to tidal sloughs, but spread out into broad alluvial fans and discharged diffusely through groundwater discharge and overbank sheetflow to the Bay. Remnant example transition zones persist only in the northern part of the Bay, such as China Camp (Baye 2012), and are represented in the South Bay only by diked vestiges in lower slopes of relatively steep valley seeps of Coyote Hills (Collins 2001). No transition zone slopes have yet been constructed in the Bay.

7. Realign levees

Realignment of the flood risk management levee to a location further inland is complementary to the aforementioned transition zone slope measure as it provides additional space for upland transgression (**Figure B-6**). Realignment would increase the distance between the Bay and shoreline development, allowing for the dissipation of wave energy over distances of several hundred feet or more and allowing the construction of much lower levees inland.

Most bayland slopes behind the existing levees are very flat (1:1000) and are often subsided, which means that once realignment occurs, the rate of shoreline landward migration may be very rapid. For example, if by 2050 sea level rose 14 inches, the shoreline would migrate landward up to 500 yards; if by 2100 sea level rose by 55 inches, the shoreline would migrate landward up to 1,000 yards further for a total of about 1,500 yards. In concert with the landward migration of the shoreline, the flood risk zone will also move inland. Realignment over relatively flat slopes uses large amounts of land, but may provide flood risk reduction benefits for only a relatively short period, particularly if vertical accretion rates and plant establishment rates lag behind sea level rise.

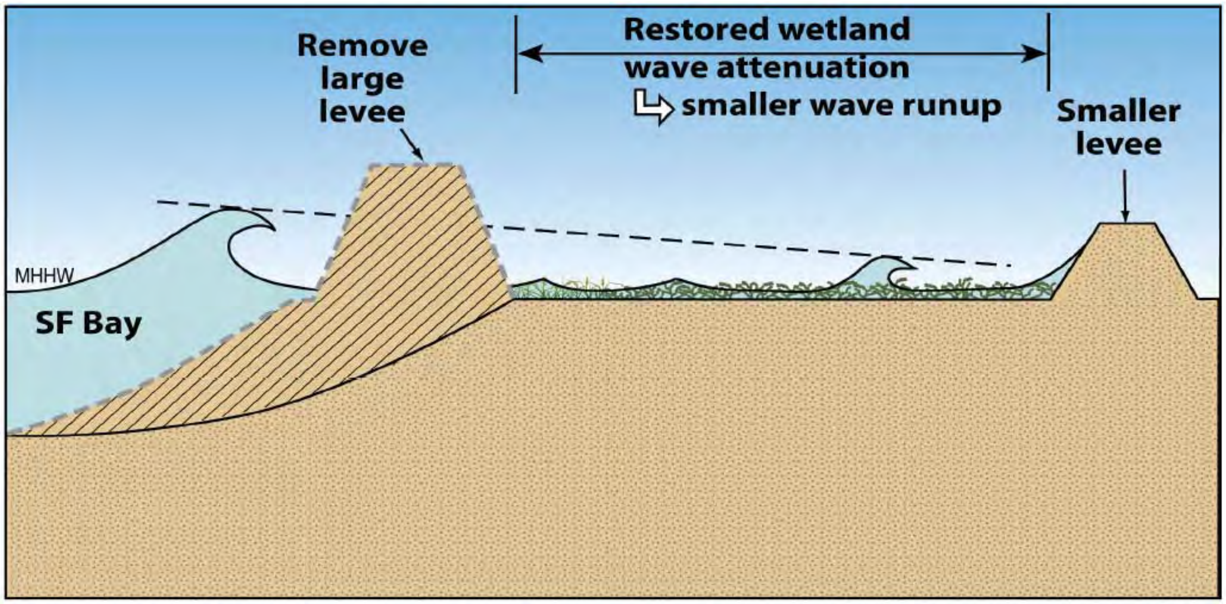

Figure B-6. Realignment (note vertical exaggeration**).**

7.1 Benefits

Flood risk reduction: Realignment takes advantage of the natural wave attenuation benefits provided by baylands so that smaller levees can be built in a new inland location. This reduces the life-cycle (capital and maintenance) costs of the newly constructed, realigned flood levees. Reducing flood risk and levee costs is particularly significant where it is no longer feasible to defend land or where realignment enables the levees to be moved to naturally higher ground. Realignment may also help to avoid abandonment of land uses where absence of management could create greater problems. Finally, it is also possible that realignment could change the hydrodynamics, reducing flood risk at another location or improving the function of the entire physical system (e.g., inundation and sediment regimes).

Biodiversity: Realignment offers the potential to mitigate the effects of past diking and future sea level rise, and can help avoid habitat loss due to coastal squeeze. Realignment can promote biodiversity by creating habitat of greater biological diversity or sustainability than the existing habitat or land use. For example, by providing areas for shellfish beds and creating nursery areas for juvenile fish, thereby expanding the food resource available in the Bay. In addition, there is the potential to create habitat to compensate for a change or loss of habitat of the same type elsewhere.

Water quality improvement: Realignment can create habitat that serves as a valuable nutrient and pollution sink, improving water quality and reducing the undesirable effects associated with eutrophication.

7.2 Constraints

Policy challenges: Realignment will require a multi-agency approach and a stakeholder planning process. Land behind levees may either be subsided, which would require placement of a substantial quantity of fill that will requiring regulatory consideration. There also may not be enough space for either a new inland levee of adequate size, or the necessary room for a large enough transition zone to be constructed.

Technical feasibility: There may be contaminated material within or landward of the existing levee. An example would be the presence of an active or former landfill site in an area that might be considered for realignment. The cost of removing such materials is likely to be high. Therefore, unless the quantities involved are small, holding the existing levee line is likely to be the only acceptable option in the short to medium term. There is also some concern that water could be polluted through the release of farm fertilizers, herbicides, or pesticides from areas newly exposed to tidal action due to realignment.

Potential impacts: It is possible that habitat adjacent to or alongshore of realignment sites may be changed through increased tidal prism, interception of sediments pathways, or increased flow velocities and associated scouring effects. There will also be impacts to the existing habitat protected by the current levee, and this is often seen as a constraint to realignment. In addition, there may be actual or perceived difficulties and uncertainties related to the feasibility of creating new tidal habitat, in particular if a very specific habitat is desired. It is necessary that a balanced view be taken of the benefits and constraints, and that trade-offs are fully considered and accounted for. Even where the creation of high-quality habitat may not be certain, the restoration of a more "functional" shoreline may still be a reason to proceed, especially if doing nothing is projected to result in habitat loss.

7.3 Implementation

Numerous restoration projects in the Bay have implemented realignment by acquiring diked baylands, often used for agriculture, and breaching aging outboard levees to restore tidal flows and create tidal marsh habitat. Hydrodynamic modeling is an important tool for realignment alternatives analysis, e.g., breach location/sizing and levee lowering. The selected alignment is analyzed in a feasibility study and environmental review. Further technical investigations, design, permitting and construction considerations, and public outreach will be necessary depending on the location and scope of the project.

7.4 Examples

PWA (2004) presents observations and experience from monitoring the evolution of subsided sites reconnected to the Bay or a major slough by levee breaching/lowering, e.g., Carl's Marsh (Petaluma River Marsh in Marin County) and Sonoma Baylands in Sonoma County. Restoration of Cullinan Ranch[3] and Sear's Point[4] are more recent projects, and in particular, the Sear's Point project highlights an important lesson of looking not only at project resilience, but also at the matrix of land uses and adjacent infrastructure. For example, building a new levee that could resist the worst-case sea level rise scenario makes little sense if the adjoining levee is vulnerable to moderate sea level rise. Lastly, the South Bay Salt Pond Restoration Project – Phase 2 at Eden Landing is currently underway and working with the Alameda Creek Flood Control Channel on realignment to improve flood protection.[5]

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[3] For more information, see: http://restorecullinan.info/index.htm

[4] For more information, see: http://climate.calcommons.org/sites/default/files/Sears%20Point%20Restoration.pdf

[5] For more information, see: http://www.southbayrestoration.org

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