Final

ANALYSIS OF THE COSTS AND BENEFITS OF USING TIDAL MARSH RESTORATION AS A SEA LEVEL RISE ADAPTATION STRATEGY IN SAN FRANCISCO BAY

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Executive Summary

Introduction

An informal program of tidal marsh restoration has been underway in San Francisco Bay for over thirty years. These marsh restoration projects are part of a regional initiative that has quietly grown into the largest coastal wetland restoration program in the United States. The purpose of the program is to reverse the historic trend of wetland destruction in order to recover the significant benefits provided by tidal marshes and associated wetlands. Those benefits include providing habitat for numerous wildlife species and performing vital flood risk management and pollution abatement functions. Examples of successful restoration projects exist all around the Bay. The fundamental premise of the restoration program is that tidal marshes will restore themselves naturally if the proper conditions are created initially through proactive engineering and intervention. Wetland restoration scientists have learned that natural tidal marsh restoration processes can take from years to decades to subsequently develop a healthy, self-sustaining marsh.

These two basic presumptions— that the primary purpose of marsh restoration is to recover depleted habitat and that the natural processes of restoration should take as long as needed to reestablish healthy marshes— have been called into question by forecasts of sea level rise caused by climate change. Wetland restoration scientists and project managers now believe that many marshes may have difficulty keeping up with accelerating rates of sea levels towards the end of the century if no action is taken.

Rising seas will significantly increase the flood risk of San Francisco baylands in the future, threatening large areas of essential shoreline development. Consequently, it may be possible to modify current restoration strategies to accomplish two new objectives: (1) enable restored marshes to keep pace with sea level rise, and (2) improve flood risk management for developed shoreline areas.

This study considers whether it is possible to accomplish these two objectives by employing a co-beneficial, integrated approach to restoring and managing San Francisco Bay's intertidal zone.

Purpose

The purpose of this study is to examine opportunities to protect San Francisco Bay's recovering tidal marsh ecosystems while helping bayshore communities to manage the impacts of sea level rise. Specifically, it considers the flood risk management functions that tidal marshes perform naturally and evaluates the possibility of integrating those functions into a co-beneficial shoreline management strategy. The study's intended audience is planners, politicians, regulators, and other stakeholders with the authority to make or affect decisions that influence the configuration and use of the San Francisco Bay shoreline. The study examines the current functions of San Francisco Bay tidal marshes as well as existing flood risk management strategies. It considers how environmental conditions are likely to change in the era of climate change, and how we can adapt our marshes and our flood risk management practices to accommodate these changes.

The Problem

San Francisco Bay's existing shoreline flood risk management system is an aging network of earthen levees that is continually sinking into soft bay mud. It was designed in piecemeal fashion, calibrated for present-day sea levels and is inconsistently maintained. Some levees in key locations are regularly over-topped resulting in flooding of vital public facilities, especially heavily used roads and highways. Rising sea level is making the existing levee system obsolete.

Sea level rose in San Francisco Bay by over seven inches between 1900 and 2000 as a result of climate change. The California Ocean Protection Council estimates that sea level will rise an additional fourteen inches by 2050 and to fifty-five inches by 2100. The greatest threat to the developed shoreline in the near term is not posed by increased static sea levels on calm days, but by storms that occur in tandem with high tides.

The Lost Marshlands of San Francisco Bay

Extensive areas of the shoreline of San Francisco Bay consist of former tidal marshes that were filled, diked or drained over the past 160 years. Of 196,000 acres of tidal marshes that existed prior to 1850, approximately 180,000 acres were destroyed by conversion to other uses (Goals Project 1999). Solar salt evaporation ponds and agriculture comprise a large portion of the uses to which tidal marshes were converted. Though more intensive development occurred on some of the 180,000 acres of converted marshlands, (San Francisco's Financial and Marina districts, Foster City, and Oakland Airport, for example,) most of the diked wetlands were not developed intensively. They remain today as salt ponds, hay farms and other open spaces that lie between the open waters of the bay and the developed shoreline (Figure ES-1).

The San Francisco baylands have subsided relative to sea level as a result of having been disconnected from the tidal waters of the bay. Though the original marsh plains once existed at an elevation well above mean sea level, their surface elevation has subsided up to five to ten feet below sea level in parts of the South Bay. An extensive network of earthen levees prevents bay tidal waters from inundating these subsided baylands. The levees are aging in many locations, though levees that protect more intensively developed areas are maintained to a higher standard.

Not surprisingly, the destruction of ninety-two percent of the Bay's tidal marshes has inflicted enormous damage on the Bay's aquatic ecosystem. The populations of wildlife species that relied on tidal marshes during a part or all of their life cycle declined, in some cases to the brink of extinction. Since tidal marshes served as the nursery ground for many estuarine fish, those populations experienced permanent damage. Among other species, salmon and steelhead numbers fell, California clapper rail and salt marsh harvest mice were declared to be endangered, and migratory shorebird and waterfowl species abundance and diversity dropped as suitable winter habitat was severely diminished.

Most of the 180,000 acres of tidal marshes that were converted to other uses were not intensively developed. Almost 40,000 acres were operated as solar salt evaporation ponds, while roughly 50,000 acres became farmlands. About 55,000 acres of tidal marshes near Suisun Bay were converted to managed freshwater/brackish wetlands to serve as private duck hunting clubs.

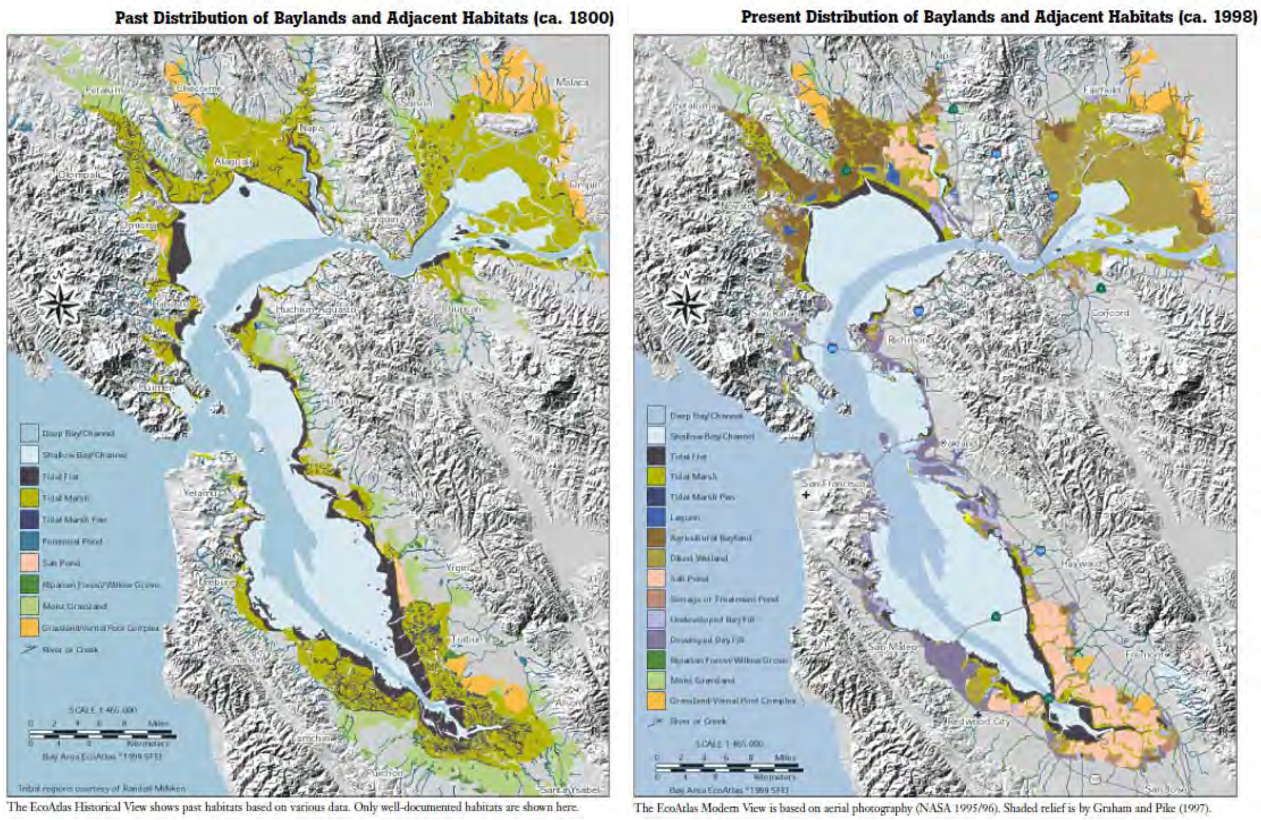


Figure ES-1. Historic and existing baylands habitats throughout San Francisco Bay. Most baylands in the North Bay were converted to agricultural fields, while baylands in the South Bay were largely converted to commercial salt ponds and other industrial uses. From the Goals Project 1999.

Sea Level Rise and Shoreline Flooding

Storm surges occurring atop higher sea levels already are causing increased flooding within the baylands, inflicting damage on both undeveloped and developed areas therein. Major regional roads along the bay shoreline are regularly flooded during winter storms (e.g. Highways 101 and 37). Residential and commercial areas within Bay Area cities similarly are experiencing increased flooding. The aging network of bayland dikes is failing to provide adequate protection and will prove increasingly inadequate as sea level continues to rise during the coming decades. In addition to the threat posed to shoreline development, rising sea levels also threaten to increase the depth of submergence of large areas of tidal marshes, including areas that have been restored over the past thirty-five years.

Blue ribbon panels convened at the national and international level have recognized the multiple threats posed by climate change, and by sea level rise in particular. Restoration of San Francisco Bay's marshes could provide tangible flood risk management benefits during these decades, buying time to plan for long-term solutions to the problem of sea level rise. A restored tidal wetland buffer would reduce the frequency and magnitude of periodic flooding, and thereby also reduce the significant costs of rebuilding. It would also provide significantly expanded areas of habitat for wildlife on the brink, sequester carbon from the atmosphere, and reduce ambient pollution within the Bay.

The Study

This study describes and evaluates the costs and benefits of employing marsh restoration as an adaptation strategy to rising sea levels in San Francisco Bay. The study examined two strategies available to prevent or reduce the impact of shoreline flooding in San Francisco Bay caused by sea level rise. It compared the traditional approach that relies on construction of engineered earthen levees to a hybrid approach that combines tidal marsh restoration with construction of levees. The study analyzed the capacity of tidal marshes to reduce waves during storm surges and, thereby, reduce the need to build larger levees in the absence of buffering tidal marsh. Further, the study calculated the costs of the two approaches to determine whether one is more cost effective than the other.

Findings

Tidal marsh can reduce storm wave heights by over 50% depending on water depth and marsh width. This finding suggests that flood risk management is improved significantly when areas of tidal marsh exist between the developed shoreline and the open waters of the Bay. Further, it indicates that by using tidal marsh in combination with a levee constructed at the landward edge of the marsh, the size of the levee could be reduced significantly while still providing the same level of flood protection benefit as would be provided by a larger levee that was not fronted by tidal marsh.

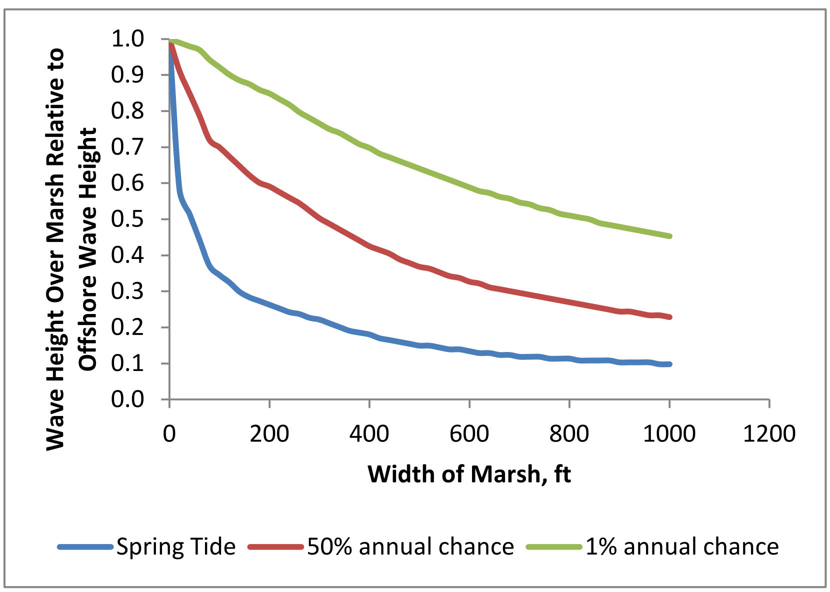


Figure ES-2. Wave attenuation over a marsh for varying water depths (based on BCDC 2013).

Our analysis concluded that a flood risk management system comprising a landward levee and an adjacent tidal marsh provides an equal level of flood protection to that of a much larger landward levee alone. Moreover, the cost of the levee with tidal marsh is about half that of the traditional levee alone. The size of a levee is primarily set by the elevation of the crest height and toe. The crest elevation is determined by how high waves run up the levee, a function of the size of the waves – waves that run up higher than the crest will overtop the levee and cause flooding. The toe elevation is determined by the ground surface elevation. With a marsh in place, waves heights and run-up are smaller so the crest can be lower; the marsh surface is higher so the toe elevation can be higher. Together, reducing crest elevation and increasing toe elevation reduces the size of the levee. Wave attenuation varies with the depth of water. Vegetated marshes are particularly effective at reducing waves at more common, lower water levels which means that the levee is protected most of the time and remains in serviceable condition in preparation for extreme water level and wave events. Wave attenuation increases with width of marsh. A wider marsh will also be effective for longer in areas where there is shoreline retreat. These results indicate that it would be more cost effective to build a flood risk management system that incorporates a tidal marsh than it would to build a conventional earthen levee.

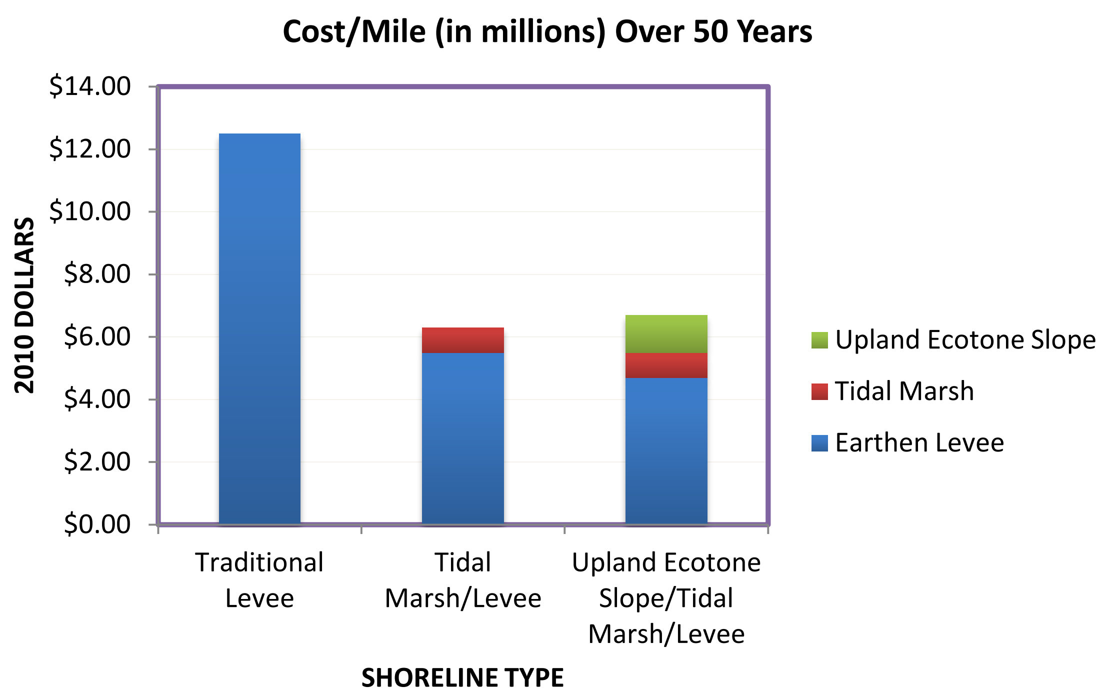


Figure ES-3. Levee cost comparison for various flood risk management scenarios.

New Flood Risk Management Paradigm—the Horizontal Levee

Significant marsh restoration efforts already are underway in San Francisco Bay. What began with a small, one-off project in the late 1970s has evolved into a regional program with the goal of restoring over 100,000 acres of bay marshes. However, that program has only lately come to incorporate sea level rise projections into marsh restoration design. Restoration scientists now recognize that many of the restored wetlands are at risk of being drowned by rising tides. In addition, the decreasing availability of suspended sediment in bay waters also poses a threat to the success of marsh restoration efforts.

A new restoration design is needed in order to respond to these changing conditions. This study describes a new marsh restoration paradigm that is appropriate in many parts of the Bay and that can provide an interim solution to the problem of tidal marsh inundation and low sediment supply. The new paradigm recommends the addition of an upland ecotone slope of moist grasslands and brackish marshes landward of the existing tidal marsh. The upland ecotone slope would provide both elevation and salinity gradients that would allow the tidal marsh to both move landward and accelerate vertical accretion in order to keep pace with sea level rise. In addition, the new marsh restoration paradigm proposes the use of sediment dredged from nearby flood control channels as construction and maintenance material for the upland ecotone substrate. Reclaimed wastewater effluent from existing public water treatment plants along the shore could be used to irrigate the upland ecotone slope.

Figure ES-4. Conceptual cross-section of a "horizontal levee", with an upland ecotone slope bayward of a flood risk management levee and landward of a tidal marsh.

By constructing an ecotone slope adjacent to the landward levee, silt from nearby flood control channels could be captured and applied to restoring marshes to build surface elevation. Further, the ecotone slope would function as a self-maintaining levee, building in elevation as root systems grow. Another significant feature of the brackish marsh would be the ability to receive treated wastewater effluent from existing water treatment plants that ring the shoreline. Those plants currently spend considerable sums to pipe, pump and discharge wastewater at distant locations in the bay. Similar brackish, back-marsh networks existed historically throughout the Bay, but were destroyed to make way for development.

Conclusions

Sea level rise caused by climate change is already causing damage to developed areas of the San Francisco Bay shoreline. That damage and its associated costs will increase as sea level rise accelerates. The current flood risk management system will have increasing difficulty to maintain adequate levels of protection as sea level rises. Important public infrastructure, including highways, bridges, roads, rail lines, utilities, and airports, will experience increased damage from flooding in the coming decades. In the near term, between now and 2070, the bulk of that damage will be inflicted by storms arriving on higher tides.

The traditional and, until now, least costly approach to addressing flood risk has been to increase the height and width of levees. Although it has been recognized for many years that tidal marshes and associated wetlands provide tangible flood risk management benefits, this has not always been included during the planning of flood risk management projects.

A region-wide effort is currently underway to restore tidal marshes and associated wetlands in San Francisco Bay. However, design of the restoration projects has generally not incorporated provisions for long-term sea level rise. In order to fully realize the benefits of the marsh restoration program, new measures must be developed and implemented that can accommodate increasing sea levels.

This study identifies two strategies that can be employed to accomplish two critical public policy objectives. First, tidal marsh restoration can be used as an effective flood risk management method that is more cost effective than traditional approaches. Second, a new marsh restoration paradigm can facilitate marsh survival during the current era of sea level rise and low suspended sediment, thereby protecting valuable marsh wildlife.

Major Conclusions

- The greatest flooding threat to developed areas along the shoreline of San Francisco Bay during the next several decades is from flooding caused by storms occurring during periods of high tides, not from elevated sea levels alone.
- Prior to the latter half of the 21st century it may be possible to adapt to increased sea level and protect existing land uses by employing strategic modifications of the current shoreline management paradigms.
- Later in the 21st century protection of low-lying developed areas along the Bay shoreline may not be sustainable without extensive modification of shoreline protection structures.
- Tidal marshes can provide significant flood protection benefits by attenuating wave energy during storms, and at significantly lower cost than traditional flood risk management structures.
- By combining current regional marsh restoration and regional flood risk management planning into a new shoreline management paradigm, flood protection costs could be significantly reduced while providing equivalent levels of protection.
- A network of restored shoreline marshes could be designed to provide significant flood risk management benefits for several decades if construction begins soon. If construction of an integrated marsh-levee system is delayed for too long, it may be unable to keep pace with expected sea level increases and fail to provide the desired benefits.

1 Introduction

Climate change and sea level rise are globally recognized as threats to the safety and integrity of coastal communities. The San Francisco Bay Area is particularly vulnerable to the effects of climate change, as much of the urban development has occurred on low-lying marshes that surround the estuary. These marshes and associated lowlands are vulnerable to flooding from sea level rise, as well as the stormwater runoff changes associated with urbanization.

Fundamentally, the baylands – the low-lying areas surrounding the bay shoreline – serve as a geographic and physical buffer between the aquatic habitats of the Bay and areas of urban, rural, and suburban development. Over the last 150 years, almost all of the baylands surrounding San Francisco Bay have been fundamentally altered by human activities. Former tidal marshes were diked and drained for farmland, or filled to facilitate urban development. Huge swaths of baylands in the South and North Bays were converted to salt production ponds; while many of these ponds are in the process of being restored to tidal marsh, significant acreages remain in production. The flood protection afforded shoreline communities by their baylands is dependent on the configurations of those baylands, particularly whether or not they include tidal marsh. Indeed, the presence, absence, and condition of tidal marshes are among the primary factors that determine the vulnerability of developed baylands to flooding from rising sea levels.

1.1 Purpose of This Study

The purpose of this study is to examine the function and value of tidal marshes as an adaptation strategy to help bayshore communities manage the impacts of sea level rise. Its intended audience is the planners, politicians, regulators, and other stakeholders with the authority to make or affect decisions that influence the configuration and use of the San Francisco Bay shoreline. This report examines the current functions of San Francisco Bay tidal marshes as well as existing flood risk management strategies. It considers how environmental conditions are likely to change in the future, and how we can adapt our marshes and our flood risk management practices to accommodate these changes. The report is organized into nine chapters, as follows:

- **Executive Summary**
- **Chapter 1: Introduction**
- **Chapter 2: The Problem: Impacts of Sea Level Rise on the Bay's Shoreline.** A description of the threat posed by sea level rise to the developed shoreline community and to the Bay's tidal marsh ecosystem.
- **Chapter 3: Ecosystem Services of San Francisco Bay Tidal Marshes.** A description of a "complete" marsh, its various habitat components, and how the components work together to achieve a broad range of physical and biological processes.

- **Chapter 4: Economic Value of Services Performed by Bay Tidal Marshes.** A description of the various ecological benefits provided by tidal marshes in San Francisco Bay - both direct and indirect – that tidal marshes provide to both local communities and the Bay Area region.

- **Chapter 5: Flood Risk Management**. This chapter discusses adaptation strategies for levees and marshes that can help to decrease the vulnerability of shoreline communities to flooding.

- **Chapter 6: Tidal Wetland Restoration and Flood Risk Management Scenarios.** We present a case study for the Hayward Shoreline with examples of adaptation strategies that incorporate the natural shore.

- **Chapter 7: Using Tidal Wetlands to Reduce Shoreline Protection Costs**. This chapter describes relative costs of implementing different adaptation strategies.

- **Chapter 8: A Shoreline Flood Management Approach During an Era of Sea Level Rise.** Based upon the findings of Chapters 2-7, we outline a flood risk management approach for parts of the San Francisco Bay that reduces the flood risk for bayland communities while maintaining and enhancing ecosystem services.

- **Chapter 9: Key Findings.**

2 The Problem: Impacts of Sea Level Rise on the Bay's Shoreline

San Francisco Bay and its shoreline have existed in a relatively stable form for about the past 2,000 years. Rapid sea level rise that had been occurring since the end of the last ice age had slowed by that time, allowing the formation of a large complex of tidal marshes adjacent to the shore. Beginning with colonization of the region by Europeans in the 19th century, most of those tidal marshes were destroyed and converted to non-wetland uses. The heavily altered marsh ecosystem landscape now lies below sea level, protected from flooding by an aging network of earthen dikes.

In general, previous periods of global sea level rise occurred slowly, in ways that facilitated the graduation evolution, transformation, and persistence of shoreline ecosystems such as wetlands, beaches, and other features. However, climate change is causing sea levels to rise at accelerated rates that threaten to drown remaining and restored tidal marshes and to flood low-lying developed shoreline areas. Shoreline land managers are seeking new ways to protect the ecological and social resources of the shoreline during this new era of sea level rise.

2.1 Historic and Present Landscape

Modern San Francisco Bay as we know it began to form with rising sea levels at the end of the most recent glacial period, approximately 15,000-18,000 years ago. Early in the Holocene epoch, about 10,000 years ago, rising seas flooded the inland valleys that formed the precursors to the modern Bay (Goals Project 1999). Decreasing rates of sea level rise, beginning approximately 5,000-6,000 years ago, facilitated the development of extensive marshes and mudflats (Atwater 1979, Goman et al. 2008).

While the footprints of the modern marshes were generally established by 2,000-3,000 years ago, varying rates of relative sea level rise and sedimentation coupled with changes in estuary-wide salinity have affected the extents and elevations of the marshes and mudflats (Goman et al. 2008). Figure 1, from Atwater 1979, displays estimated shoreline evolution in San Francisco Bay over the past 15,000 years.

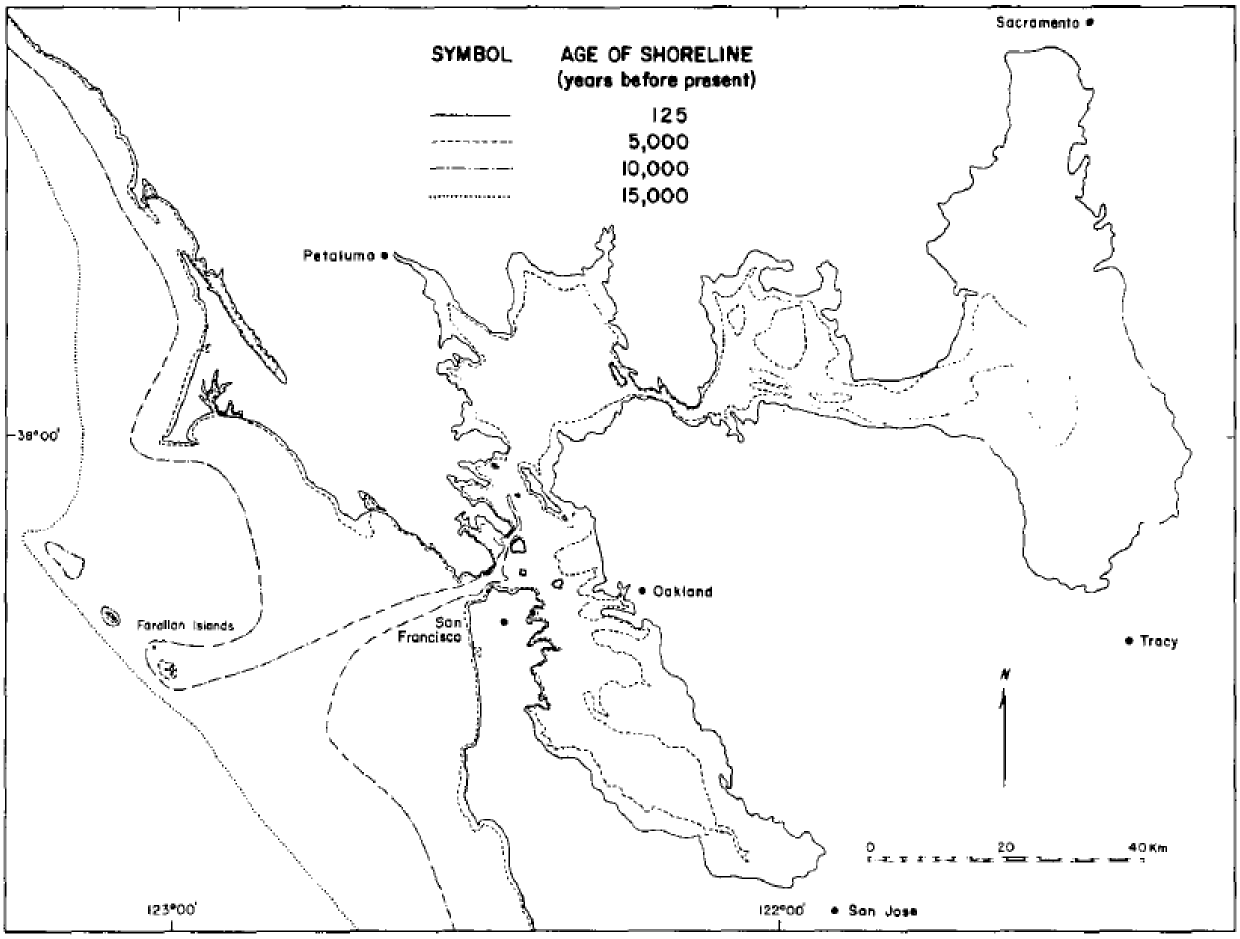


Figure 1. Approximate high-tide shorelines in San Francisco Bay over the past 15,000 years. The shoreline for 125 years ago does not consider human-induced changes such as the diking, draining, and/or filling of tidal marshes and mudflats, nor the effects of hydraulic mining in the Sierra Nevada during the mid-1800s. From Atwater 1979.

Western colonization of the Bay Area began in the 1700s, and by the early 1800s, Spanish missions had become established throughout the area. Given the area’s hilly and often challenging topography, the tidal marshes fringing the Bay contained the most extensive areas of flat land on which infrastructure such as roads and railroads could be built. This fact, coupled with the perception of the marshes as “nuisance” lands that should be reclaimed for purposes such as agriculture and industry, led to the large-scale diking and draining of tidal marshes from the mid-1800s through early 1900s. In general, marsh reclamation moved from west to east, with most marshes of the Sacramento – San Joaquin Delta reclaimed by 1920. Much of this reclamation work was done by immigrant Chinese laborers, who hand-constructed levees with shovels and wheelbarrows for as little as 90 cents a day (Lee 2008, Figure 2).

Figure 2. An illustration of Chinese laborers constructing levees in the San Francisco Estuary. From Family Water Alliance 2012.

At the same time that the tidal marshes were being reclaimed, hydraulic gold mining had begun in earnest in the Sierra Nevada Mountains. The massive quantities of sediment released by this mining moved rapidly downstream to the Bay, where they accumulated on mudflats that were outboard of the levees that now surrounded the former tidal marshes (Jaffe et al. 1998, Figure 3). The rapid accretion of these sediments prevented much of these marshes from forming extensive dendritic channel networks, a prominent morphological and habitat feature of older, more mature marshes. Instead, channels in these marshes tended to be short and linear.

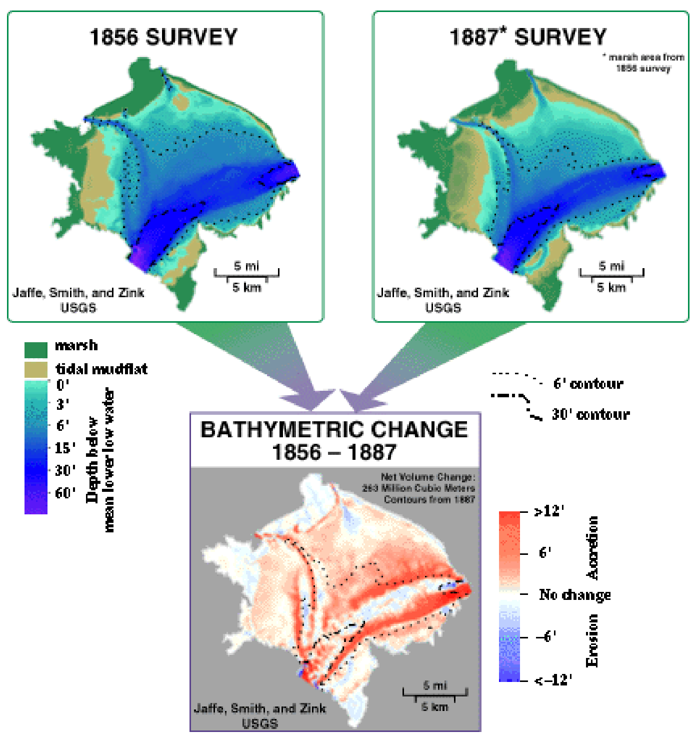


Figure 3. Bathymetric changes in San Pablo Bay due to the accretion of sediment mobilized by hydraulic gold mining. Some portions of the Bay accreted more than 12 feet of sediment during the late 1800s, particularly in areas that bordered the thalweg. From Jaffe et al. 1998, modified by SFSU.

Efforts to manage floods, develop hydropower, and deliver water supplies led to the construction of dams throughout the Sierra Nevada in the early to mid-1900s. The construction of these dams cut off the supply of hydraulically-mined sediment to the Estuary, changing the spatial distribution of accretive versus erosive areas (ibid). By this time, much of the Estuary's margins had taken the form of broad reclaimed and developed baylands fronted by levees, narrow strips of outboard tidal marsh, and extensive mudflats (Figure 4).

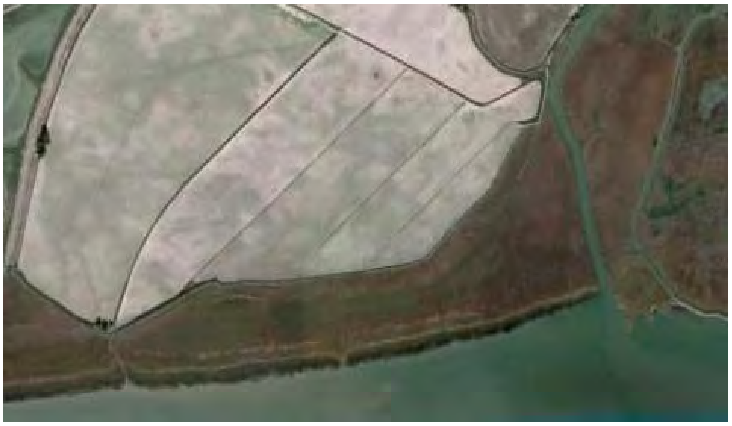


Figure 4. The northern shoreline of San Pablo Bay in the vicinity of Tolay Creek, where agricultural fields (former tidal marsh) lay behind levees and fringing marsh that grew on accreted sediments from hydraulic gold mining. Accretion has shrunk the mouth of Tolay Creek from a formerly broad channel to a narrow slough.

The passing of the pulse of sediment associated with hydraulic mining, increased flood management, and damn construction on large Sierra Nevada tributaries has decreased sediment delivery to the estuary from the Delta by about half (Schoellhamer 2011). This has been observed as a rapid 36% decrease in observed suspended sediment concentrations throughout San Francisco Bay between the 1990s and the first decade of the present century (ibid). As a result, an estuary that once experienced net accretion is now experiencing net erosion, and suspended sediment supply has become a limiting factor for marsh development and restoration (**Figure 5**).

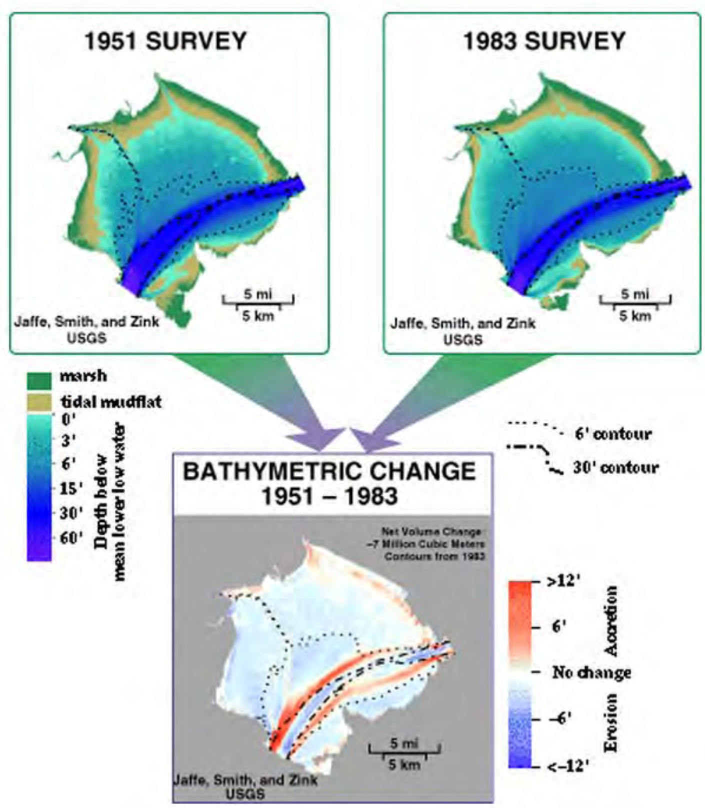


Figure 5. Bathymetric changes in San Pablo Bay due to the depletion of its sediment pool in the late 20th century. During this time period, about 7 million cubic meters of sediment was eroded from the Bay, causing widespread elevation decreases except along the main navigation channel. From Jaffe et al. 1998.

Not surprisingly, the destruction of ninety-two percent of its tidal marshes inflicted enormous damage on the Bay's aquatic ecosystem. The populations of wildlife species that relied on tidal marshes during a part or all of their life cycle declined, in some cases to the brink of extinction. Since tidal marshes served as the nursery ground for many estuarine fish, those populations experienced permanent damage. Among other species, salmon and steelhead numbers fell, California clapper rail and salt marsh harvest mice were declared to be endangered, and migratory shorebird and waterfowl species abundance and diversity dropped as suitable winter habitat was severely diminished.

Most of the 180,000 acres of tidal marshes that were converted to other uses were not intensively developed. Almost 40,000 acres were operated as solar salt evaporation ponds, while roughly 50,000 acres became farmlands. About 55,000 acres of tidal marshes near Suisun Bay were converted to managed freshwater/brackish wetlands to serve as private duck hunting clubs (Figure 6).

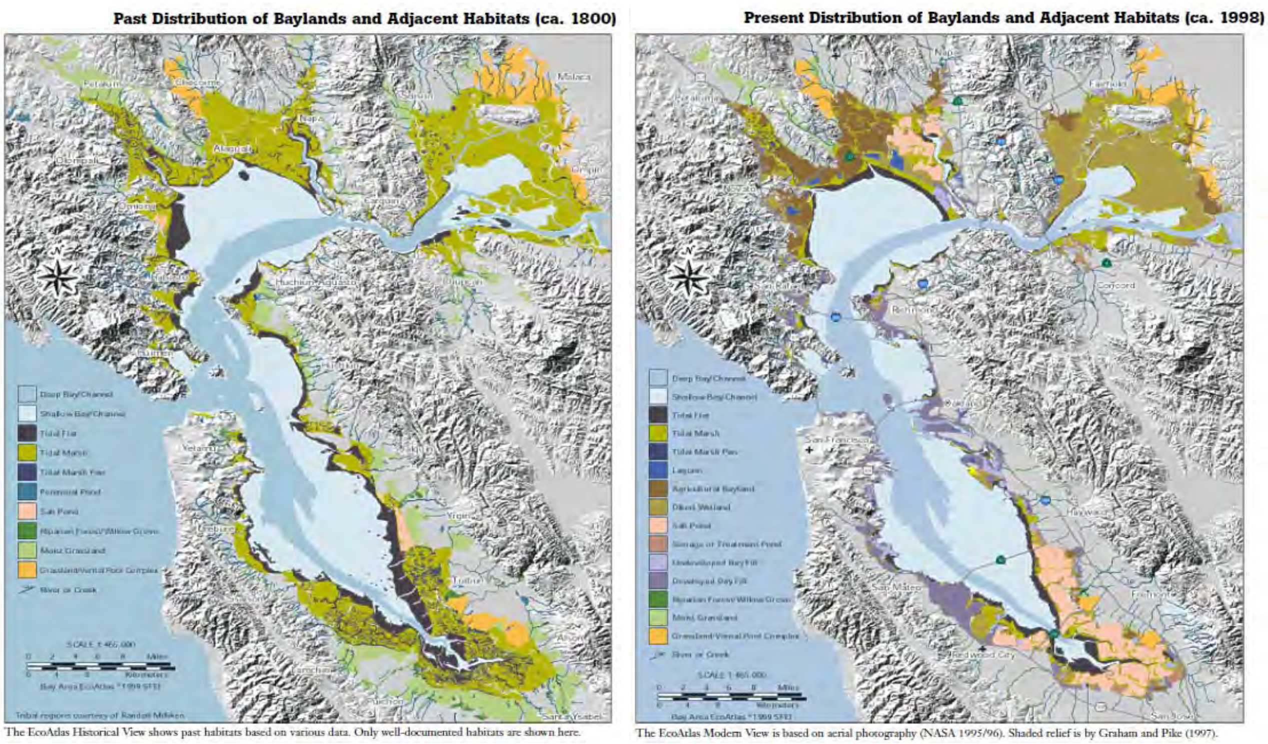


Figure 6. Historic and existing baylands habitats throughout San Francisco Bay. Most baylands in the North Bay were converted to agricultural fields, while baylands in the South Bay were largely converted to commercial salt ponds and other industrial uses. Baylands in the Suisun region were converted into managed wetlands used primarily for duck hunting; much if this continues to this day. From the Goals Project 1999.

2.2 Future Landscape

After 3,000 years of relatively stable sea level and 150 years of a turbid estuary, the Bay is returning to the norm of the Holocene period with rapid sea level rise and clearer water. In response, the baylands will evolve to accommodate higher sea levels and less sediment. Existing tidal marshes will be more dynamic than we have experienced in the recent historic past. There may be downshifting and drowning of high marsh to low marsh and mudflat over the next century; there may be landward movement or transgression of the tidal marshes and mudflats inland; there may be the need to actively manage tidal marshes more than in the past to maintain their ecological integrity.

Existing tidal marshes accommodate moderate sea level rise by a combination of vertical accretion and a gradual landward shift in position of the shoreline and landward edge. The vertical and horizontal movement of these marshes are dependent on three rates:

1. *Vertical accretion rates*, which depend upon the rates of sea level rise, sediment supply, and the rate of organic production,
2. *Horizontal erosion rates*, which depend upon the rate of sea level rise, sediment supply, and incident wave energy, and
3. *Horizontal transgression rates*, which depend upon the rate of sea level rise and the slope of the upland transition zone or barriers.

The factors that govern these rates are described below.

Sea Level Rise. There have been significant advances in the scientific recognition of the risk of abrupt climate change and accelerating sea level rise (OPC 2011). Sea level has risen by about 7 inches on the California coast in the past century. Present sea level rise projections suggest that global sea levels in the 21st century can be expected to be much higher. These projections are summarized in the recent National Research Council Report on West coast sea level rise (NRC 2012) which provided estimates of regional sea level rise for San Francisco (Table 1).

Table 1. San Francisco Bay Regional Projections of Sea Level Rise (NRC 2011)

Year	Intermediate Projection (in) A1B scenario	High and Low Range (in) B1 and A1F1 scenario
2030	5.5	1.7-11.7
2050	11.0	4.8-23.9
2100	36.2	16.7-65.5

Notes:

- The projected global sea level is dependent upon the emission scenario.
- Local steric and wind-driven contributions were estimated from global climate change models (GCMs); the land ice contributions included an adjustment for gravitational and crustal deformation effects; and an estimate was made of regional vertical land movement.

Sediment Supply and Organic Peat Production. As discussed above in Section 2.1, the estuary is currently experiencing a risk of reduced fine sediment availability as the erodible sediment pool is depleted (Schoellhamer 2011). Wetlands build elevation through two main processes: accretion of suspended sediment, and production of organic peat within the plants' root systems. The salt marshes of San Francisco Bay do not produce as much peat as their more brackish and freshwater analogues upstream in Suisun Marsh and the Delta, so their ability to keep up with sea level rise is governed by the amount of available suspended sediment present. Therefore, whether observed declines continue or abate will have a much greater effect on the future trajectory of SSC than climate change. This trajectory has important ecological implications because further reductions in sediment supply will increase the vulnerability of tidal marshes and mudflats to sea level rise (Cloern et al 2011).

Local Topography. Tidal marshes have responded to low/moderate rates of sea level rise in different ways according to local topography. Marshes adjacent to gentle, continuous slopes accommodate sea level rise by accreting vertically with only minor long-term or progressive conversion of tidal habitat types, and by a gradual landward shift (horizontal displacement or landward estuarine “transgression”) in position. Most natural bay margins have this type of topography (Figure 7.).

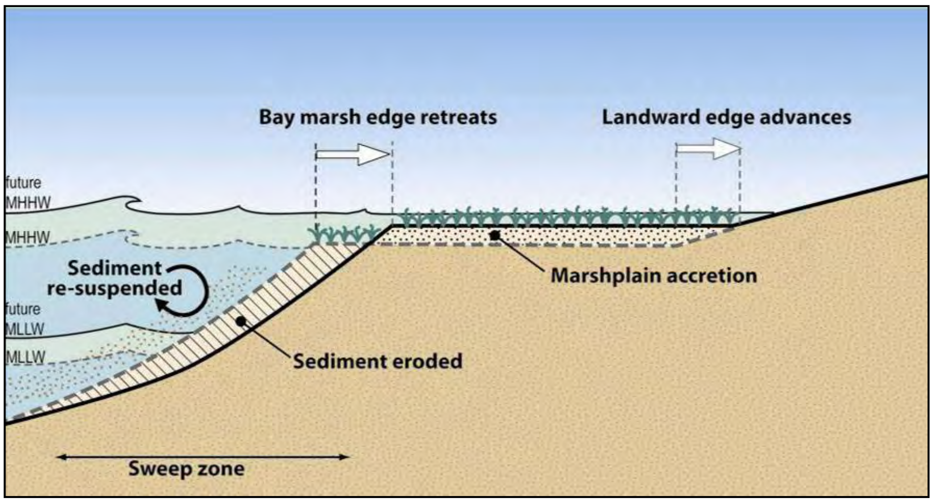


Figure 7. Landscape evolution along a natural bayshore edge.

Conversely, marshes bounded by a steep slope (such as an inboard levee) have a reduced width of transition zone available for transgression; mudflat and marsh habitat will narrow as it is ‘squeezed’ against the levee. Historic diking has steepened coastal gradients around much of the Bay, converting gently sloping baylands edges into steep linear borders backed by subsided basins (**Figure 8**).

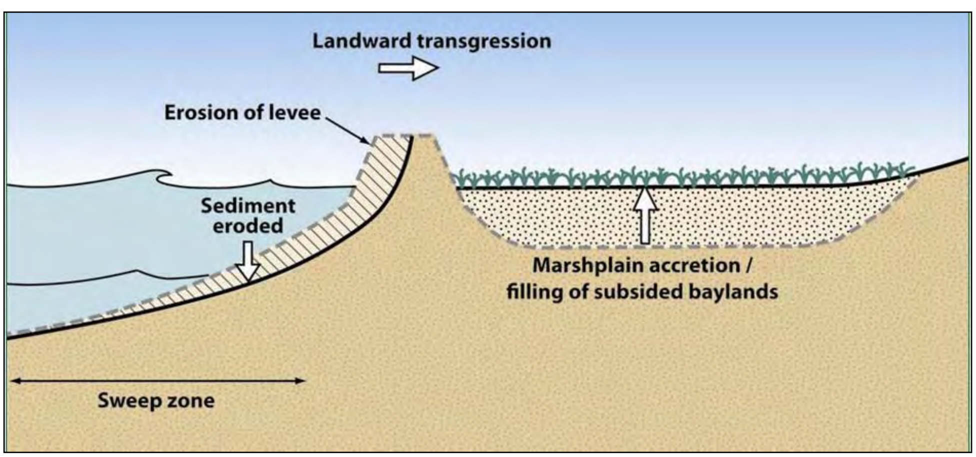


Figure 8. Landscape evolution along a developed bayland edge.

In both scenarios, as sea level rise continues to accelerate, it will eventually outstrip the rate of accretion, and tidal marshes will start to “drown”. If the vertical accretion (mineral and organic) of marshes cannot keep pace with sea level rise, marsh habitats will tend to migrate (or “transgress”) landward. Gradual submergence of tidal marshes increases the period and frequency of tidal inundation, leading to "downshifting" of habitat zones (high marsh to middle marsh, middle to low, low marsh to mudflat). There will also be expansion of tidal marsh pannes and enlargement of tidal channels due to the increased tidal prism.

Wave Energy. Wave energy can further exacerbate habitat conversions along shorelines by depleting mudflats and causing the progressive landward erosion of the marsh edge. Wave erosion (from natural waves, or human activities such as boating) can create wave-cut marsh “cliffs” or scarps in exposed areas. Marshes with robust, healthy vegetation communities are able to dissipate wave energy, and reduce the amount of erosive energy that reaches the shoreline. The vegetation also traps and stabilizes suspended sediment, and produces organic matter in the soil profile. However, marshes that are already stressed from submergence have less rigorous vegetation growth, and are less able to dissipate wave energy, trap suspended sediment, and produce organic peat. Rising sea levels will increase the amount of wave energy along the baylands, further reinforcing the likelihood of habitat conversion.

Landscape Evolution. It is optimistic to project that existing marsh areas around the Bay will not experience varying degrees of habitat conversion. The combination of rising sea levels, suspended sediment supply, peat production, local topography, and wave energy will likely result in the estuary-wide “downshifting” of bayland habitats. The degrees to which particular areas downshift will depend on local conditions and the degree of management that is or is not directed at the area. In a worst-case scenario, accelerated sea level rise at the upper end of projected rates could result in the widespread drowning of marshes. Rapid marsh vegetation dieback could lead to the development of extensive pans (ponds) on the marsh plain that will increasingly fragment marshes, expanding them into tidal flats. Rapid marsh edge and levee erosion and increased flooding of baylands would be likely components of this scenario.

Considering the present projected rates of sea level rise, the most likely outcome for the baylands will be a mix of the above-referenced scenarios until 2050-2070. This reflects the variation of marshes and governing physical processes around the Bay as well as likely temporal variations in sea level. Even in “gradual” sea level rise scenarios, the resulting rates and magnitudes of habitat conversions will not be uniformly gradual. There are significant episodic fluctuations in sea level during strong El Niño events of up to approximately 8 inches above average levels during intense storms. Thus habitat change and biological responses to habitat change caused by sea level rise may occur in pulses.

3 Ecosystem Services of San Francisco Bay Tidal Marshes

Major tidal marsh restoration projects have commenced in San Francisco Bay over the past twenty years. The goals of these *ad hoc* initiatives are to restore at least 100,000 of wetlands within the footprint of the Bay’s original tidal marshes, thereby restoring the multiple benefits provided by Bay wetlands. Restoration projects were undertaken primarily to restore critical wildlife habitat, as well as to provide important recreational and flood risk management benefits. But as climate change science continues to advance, restoration managers have realized that rising sea levels threaten to overwhelm restoration efforts by drowning restored marshes. Managers and other stakeholders are therefore increasingly considering restoration strategies that could enable marshes to persist in the face of sea level rise.

At the same time that rising sea level threatens the viability of Bay tidal marshes, it also increased the threat of flooding low-lying developed areas along the shore. Tidal marshes are known to perform important flood risk management functions. They act as a buffer between the shoreline and deeper open waters. They reduce the wave height and velocity of water as it encounters friction from marsh vegetation and shallow bottom surfaces. Had San Francisco Bay's original 196,000-acre tidal marsh system been left intact, shoreline flooding would most certainly be less frequent and severe than it is today. It is possible to determine the amount of flood protection benefit that marshes provide by quantifying their wave attenuation attributes using standard engineering formulas. To address the flooding risks associated with sea level rise, shoreline land managers are evaluating the merits of a variety of shoreline flood risk management strategies.

In this section, we discuss the multiple services performed by San Francisco Bay tidal marshes and examine the features of healthy tidal marsh ecosystems.

3.1 The Complete Marsh

The economic benefits to society provided by marshes are directly dependent upon the maturity and morphology of the marshes in question. "Complete" marshes, or those that express the broadest possible range of marsh and associated estuarine and upland habitats, tend to provide higher ecological and economic benefits than marshes with a narrower range of habitats.

Within San Francisco Bay, complete marshes include the following habitat types:

Low, mid, and high marsh are inundated at depths, frequencies, and durations that are determined by marsh plain elevations, the movement of tides, and the distance of the plains from tidal channels. High marsh is typically defined as marsh within a foot of MHHW, low marsh the area within a foot of MTL, and mid-marsh the transition between the two (Figure 9). High marsh areas tend to be inundated less often, at lower depths, and for shorter periods of time than lower marshes. As such, the dominant vegetation communities in the marsh types are different: within San Francisco Bay, high marsh is typically dominated by pickleweed (*Sarcocornia* spp.) while low marsh is dominated by *Spartina foliosa* (mid-marsh typically contains varying gradients of both species). Due to tidal inundation dynamics, very small changes in topography can result in considerable changes in associated vegetation and wildlife use. Aquatic organisms such as fish will move with the tides back and forth between low and high marsh areas to maximize their ability to forage. Some terrestrial animals, such as salt marsh harvest mice, primarily stay in one zone (in the case of the mouse, high marsh) while others such as the California clapper rail will move back and forth between high and low marsh, depending on the tides.

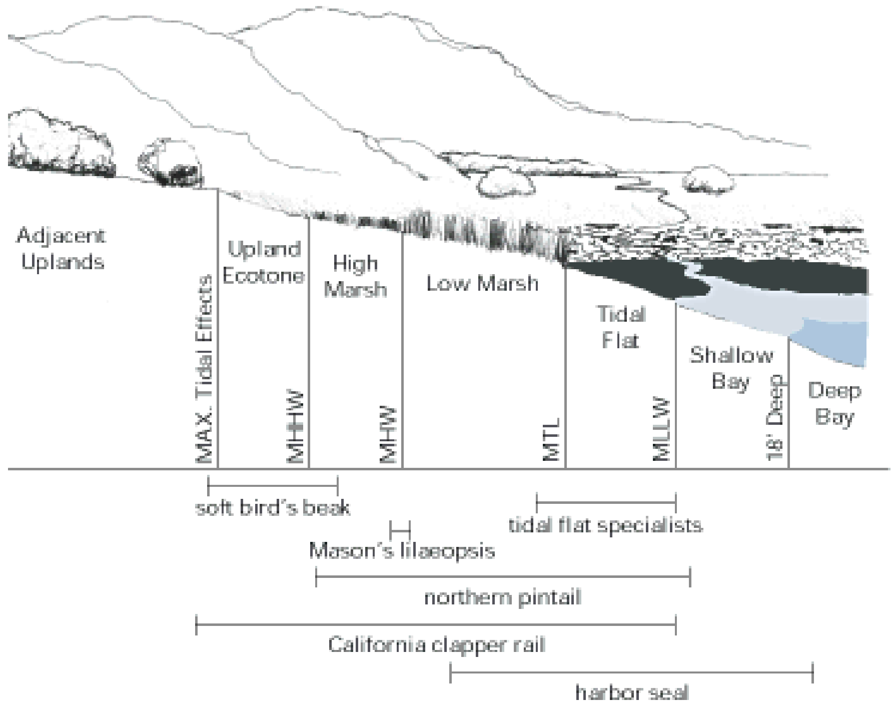


Figure 9. Different organisms utilize different portions of the intertidal zone, though many, such as the California clapper rail, move back and forth between zones. Graphic from the 1999 Baylands Ecosystem Habitat Goals Report.

Dendritic tidal channel networks are the complex systems that link the marsh plain with the open tidal waters of the Bay (Figure 10). These networks are generally only found in mature, ancient marshes such as Petaluma River Marsh and the marshes at China Camp State Park, as their long, branching morphology was formed by the gradual stabilization of local sea levels during the Holocene (Baye 2012). Tidal channels transport flood and ebb tides in and out of the marsh along with tidally-transported constituents such as suspended sediment and nutrients, and provide access for fish and wildlife. Along many tidal channels natural levees provide topographic heterogeneity and are often the preferred habitat of special-status plants such as Mason's lileaopsis. Marshes with more complex tidal channel networks, have more varied topography, higher levels of marsh biodiversity and are more resilient to disturbance (Baye 2012).

Figure 10. An aerial photograph of diked salt ponds in southern San Francisco Bay, displaying the complex, remnant, dendritic tidal channel networks that once flooded and drained the marshes.

Mudflats, which generally exist outboard of marshes between MTL and MLLW (between the marshes and subtidal open water, Figure 11), are the source of most of the suspended sediment that is available to accrete in tidal marshes and play an important role in attenuating waves. Winds and tidal action suspend sediment off of mudflats, which is then transported into marsh interiors via tidal channels. As mentioned earlier, regional decreases in suspended sediment have eroded local mudflats, limiting the volume of sediment that is available for re-suspension and accretion in tidal marshes. Mudflats also provide critical foraging habitat for the Bay's ample resident and migratory shorebird populations. Many shorebirds will move into tidal marshes and forage there (particularly in tidal pannes) when mudflats become inundated by rising tides.

Figure 11. Mudflats within the Palo Alto Baylands are bisected by a channel that is submerged at higher tides.

Ponds/pannes are open-water areas found in poorly drained areas of the mature high marsh plain or the wetland-upland edge, separate from tidal channels (Figure 12). Ponds are usually less than a foot deep, and flood only during extreme tide events. Pannes become hypersaline in late summer due to evapotranspiration. Because they generally lack emergent vegetation, some pannes support submerged aquatic vegetation such as wigeon grass, sago pondweed, and macroalgae, which in turn attract invertebrates such as insects. As a result, pannes are often important foraging areas for waterfowl and wading birds (Goals Report 1999) and are important structural features of mature tidal marshes.

Figure 12. Tidal pannes within salt marsh at the Emeryville Crescent, part of Eastshore Regional Park (pannes appear dark green).

The **upland – estuarine transition** is generally considered to be the area between MHHW and the reach of the highest extreme tide events. This highly dynamic ecotone (transition between the wetland and upland habitats) is critical to tidal marsh biodiversity, as it is home to a broad range of special-status plant species and provides high-tide refugia for terrestrial marsh wildlife such as salt marsh harvest mouse and Suisun shrew. The upland-estuarine transition is a habitat type that has largely vanished from most of the San Francisco baylands due to infill development and the construction of berms and levees. Where tidal marshes would previously form broad ecotones adjacent to gently sloped uplands, most present day upland-estuarine transitional habitats are now compressed into narrow bands of habitat along levees that are less resilient to disturbance. As sea levels rise, tidal marsh will transgress over the upland-estuarine transition, forcing the ecotone itself to move upslope into whatever limited space is available.

Occasionally, in areas where creeks and seasonally drainages feed directly into tidal marsh, the alluvial fans formed by these drainages can form on top of tidal marsh. Tidal marsh can then transgress over these alluvial fans, forming complex, spatially variable “layer cakes” of tidal marsh and alluvial sediments. These systems often support regionally rare plant species that are adapted to these highly variable conditions. While such systems were once plentiful around San Francisco Bay, they now only exist in a few limited places, including China Camp State Park, Rush Ranch Open Space Preserve in Suisun Marsh (Figure 13), and Petaluma River Marsh.

Figure 13. The upland-estuarine transition near the Spring Branch Creek drainage at Rush Ranch in Suisun Marsh. Changes in vegetation communities make it easy to observe the highest extreme tide level.

The five habitats described above are the primary components of a “complete” tidal marsh. Due to geographic variation, not all “complete marshes” will have these features (for example, the tidal marshes of Brown’s Island in the western Sacramento – San Joaquin Delta have no adjacent uplands), but in general they are positive indicators of ecosystem service and tidal marsh resiliency.

3.2 Characteristics of a "Complete Marsh"

The characteristics of the various habitat components of a marsh will to a large degree govern its health and ability to function as a "complete marsh". The California Rapid Assessment Method (CRAM) is a tool developed by researchers to facilitate the rapid assessment of marsh health (Collins 2008). The CRAM systems considers a broad range of biotic and abiotic factors, such as vegetation communities, geomorphology, location within a watershed, surrounding landscape use, and much more. Habitats with good scores are likely to provide high levels of ecological and hydrologic function, while those with low scores provide less. The CRAM system has been used as a part of a comprehensive survey of the condition of San Francisco tidal marshes by comparing the local marshes' CRAM score for physical structure to that for the relatively less impacted tidal marshes along the north coast of California (SFEP 2011).

A number of interesting findings from this study help define what makes a marsh "healthy", and provides guidance for the development of restoration objectives:

- **Marsh size.** Historically, tidal marshes in the estuary tended to be much larger than they are today. The existing proportion of small marshes (1-100 acres) has increased, and there are fewer very large (500-5,000 acre) marshes. The significance of this in consideration of historic and future environmental change is that large marshes tend to be more resilient to disturbance (such as sea level rise) than smaller marshes because they generally contain more heterogenic habitats as well as enough room for these habitats to move across the landscape (Collins 2011).

- **Landscape space.** Accommodating the full complement of marsh features and functions requires space – not just for the wetland itself, but critical adjacent habitats such as upland-wetland ecotones and subtidal areas. Mudflats , marshes, subtidal channels, and upland buffers all have characteristic dimensions set by physical processes which, coupled with ecological requirements such as individual species requirements, help define a minimum functional marsh patch size.

- **Marsh dynamics.** As noted in the previous chapter, the shoreline is dynamic, and will be increasingly so with accelerated sea level rise. Providing space and removing constraints to movement will become increasingly important. In particular, the upland-estuarine transition is critical to future marsh transgression, yet this habitat that has suffered some of the greatest losses throughout the estuary (Bayland Goals 1999).

- **Complexity and heterogeneity.** Many existing marshes around the Bay lack complexity in either their topography or channel network due to their young age. Many of the ancient marshes were diked and filled, leaving only a few examples in the Bay (e.g. China Camp, Petaluma River Marsh). With a few exceptions (e.g. Carl's Marsh along the Petaluma River), more recent tidal marsh restoration sites have not yet had time to develop natural complexity.

The more "complete" a marsh, the better its ability to provide a broad range of ecosystem and economic services. These services are discussed in greater detail below.

3.3 Ecosystem Services

The Bay's tidal wetlands have economic value because they provide services that increase the quality of life for humans and improve the productivity of businesses and communities. Figure 14 demonstrates the core conceptual framework for understanding these ecosystem services. The diagram shows that the ecosystem services stem from three factors: natural capital, ecosystem processes, and socioeconomic demands.

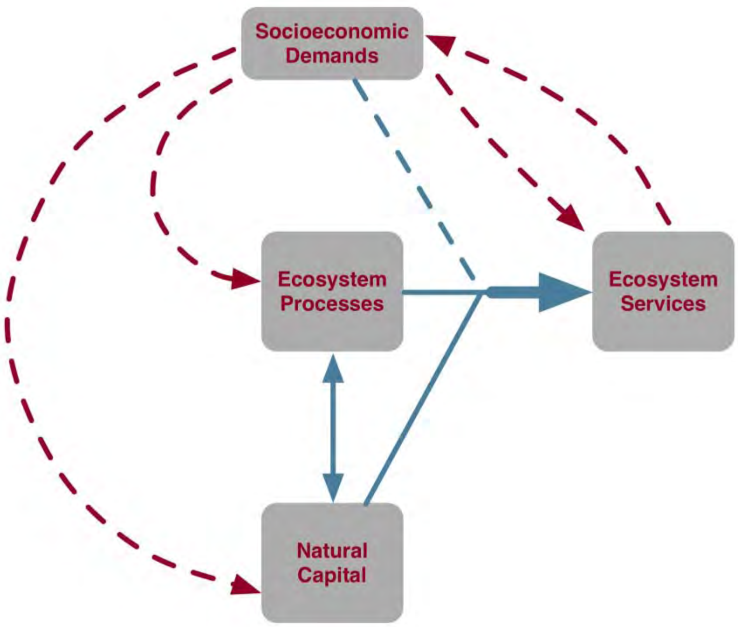


Figure 14. Conceptual Framework for Understanding Ecosystem Services (Source: ECONorthwest)

At the base of the framework lies *natural capital*. This term describes nature's basic building blocks, such as the water, vegetation, wildlife, and soils of the Bay's tidal wetlands. Some types of natural capital, such as an edible fish, may have value as stand-alone goods. Most units of natural capital, though, have value only through symbiotic relationships with other units that, through the complex workings of an ecosystem, provide goods and services of value to society.

These workings, called *ecosystem processes*, lie at the center of the framework. They "are the characteristic physical, chemical, and biological activities that influence the flows, storage, and transformation of materials and energy within and through ecosystems" (USEPA Science Advisory Board 2009, p. 12). The ecosystem processes of tidal wetlands include the cycling and chemical transformation, of nutrients and other substances, the movement and storage of water, and biological activities that convert the sun's energy and carbon dioxide into vegetation, build new soil by removing sediment from the water, absorb energy from tides and waves, and more. Natural capital and ecosystem processes are difficult to consider in isolation. Both are necessary to produce and maintain a viable wetland ecosystem capable of producing valuable ecosystem services.

The product from ecosystem processes and natural capital is considered an *ecosystem service* only if humans derive a benefit from it and have a demand for it. Thus, the top of the framework in Figure 14 displays socioeconomic demands. The interaction between natural capital and socioeconomic demands means that the economic importance of the ecosystem services derived from the Bay's tidal wetlands can vary both in response to changes in the ecosystem's ability to produce them, and also in response to changes in society's demands for them. Changes in productivity might occur as sea level rises and alters the depth of water covering the wetlands. Changes in demand might arise from changes in human preferences, as might occur, for example, when research and education enable humans to understand more clearly that the tidal wetlands can mediate the adverse effects of higher sea levels in the Bay.

3.4 Ecosystem Services Provided by the Bay's Wetlands

Wetlands provide a broad array of physical and ecological functions that benefit ecosystems, including the human component of the ecosystem (eftec 2005). Four of the most significant ecosystem services of wetlands are:

1. Flood risk management and erosion control,
2. Pollution control and improvement of water quality,
3. Carbon sequestration, and
4. Habitat for target wildlife species.

These services are discussed below.

3.4.1 Flood Risk Management and Erosion Control

Since tidal wetlands are typically located between the shore and infrastructure within the baylands (*e.g.* roads, railroads, and utility transmission lines), they often provide the first line of defense against waves and flooding. Wetlands attenuate the energy of incoming waves, reducing their height, erosive force, and ability to inflict damage on shoreline infrastructure. This attenuation reduces (1) the likelihood that shoreline protection may be overtopped during an extreme weather event and (2) the maintenance costs, due to damage by erosion, of shoreline protection structures. Additional information about how wetlands mitigate flood risk is discussed in Sections 5 and 6 below.

While wetlands can provide protection from short-term flooding and erosion events, they can also provide protection from the long-term flooding impacts of sea level rise. When allowed to persist as broad areas of low topographic relief adjacent to upland "buffer" areas, wetlands can provide accommodation space for rising sea levels by transgressing over formerly upland areas (areas that were formerly above the tidal frame). The adjacent wetland and upland areas can buy planners the time to move critical baylands infrastructure to higher ground, or to construct engineered shoreline protection such as levees or seawalls.

3.4.2 Pollution Control and Water Quality

Wetlands remove pollutants from water through a variety of physical, chemical, and biological processes. They function as the estuary's "kidneys" capable of efficiently removing a broad range of pollutants emitted from both point and non-point sources. Some pollutants adsorb to organic or mineral particles within wetland soils, or form particulates or salts that settle out of the water column. For example, heavy metals such as copper and lead can adsorb to complex wetland molecules such as humic acids, or can precipitate out of the water column as sulfide salts. Due to wetlands' unique redox chemistry (combination of reduced and oxidized soils), other pollutants can be converted into less harmful chemical forms. For example, the coupling of oxidized soils around a wetland plant's root zone with adjacent reduced soils can result in the conversion of nitrate (a common nutrient that acts as a pollutant above certain concentrations) to inert nitrogen gas.

The ultimate fates of pollutants in wetlands are dependent upon the pollutants, their biogeochemistry, and the disturbance regime in the wetland. Typically, pollutants that are removed through adsorption or sedimentation, such as some metals and complex molecules, are buried in accreting wetland sediments. If these sediments are disturbed, or if the wetland's chemistry is significantly changed (e.g. change in pH or redox regime), the pollutants can in some cases be re-introduced to the water column. Other pollutants can be taken up by wetland organisms and integrated into their biological structures.

3.4.3 Carbon Sequestration

Wetlands can sequester carbon through the production of both above-ground and below-ground biomass; however, it is the latter that sequesters carbon in the long-term. Most wetland plants have large subsurface structures called rhizomes that function to (1) transmit oxygen from the above-surface parts of the plant to its roots, (2) store energy, and (3) anchor the plant in saturated soils. In most wetland soils, the roots and rhizomes of living and dead wetland plants comprise a majority of the soil volume. As wetland plants die, the lack of oxygen in saturated soils (reduced conditions) prevents the decomposition of the roots and rhizomes, leading to the development of organic peat soils. These soils, and their associated sequestered carbon, can persist for thousands of years as long as they are maintained in a saturated, anoxic environment. In this way, wetland restoration is one of the most cost-effective and efficient ways to sequester excess atmospheric carbon.

The draining and diking of most of the Bay's tidal wetlands in the 19th and 20th centuries resulted in the drying and compaction of wetland soils in these areas. No longer saturated and anoxic, their organic peats oxidized, releasing massive quantities of CO_2 into the atmosphere and resulting in the subsidence of the diked, drained lands (in extreme cases, to below tidal elevations). Restoring these marshes will effectively reverse that process, though the buildup of peat soils and their concomitant sequestration of carbon will take much longer than their oxidation and loss.

3.4.4 Wildlife Habitat

Since mature, healthy tidal wetlands often include multiple different types of habitats (see Section 3), they can host an impressively broad range of plant and wildlife species. Approximately 500 species of fish and wildlife can be found in and around San Francisco Bay. Almost 300 of these species are resident and migratory birds. For the latter group, the Bay is one of the largest and most critical resting and foraging sites along the Pacific Flyway. Almost all shorebird species and a quarter of the waterfowl that utilize the Pacific Flyway spend some time in the Bay's wetland and associated mudflat habitats (Goals Project 1999). Scientists have estimated that over 75% of commercially important fish/invertebrate species, and 95% of recreationally important species, have a life stage that is dependent upon wetlands for survival and/or reproduction (Feierabend and Zelazny 1987). Within San Francisco Bay, dozens of fish species rear in tidal wetlands and associated habitats, including critical threatened and endangered species such as steelhead and Chinook salmon. The loss of tidal wetland habitats throughout the SF Estuary has resulted in significant impacts to populations of these species, particularly ones such as the California clapper rail and the salt marsh harvest mouse that spend most of their life cycle in tidal marshes. The Baylands Ecosystem Habitat Goals Report describes in depth how tidal wetland loss around the Bay impacted its many dependent communities and species (Goals Project 1999).

4 Economic Value of Services Performed by Bay Marshes

The economic value of the ecosystem services provided by the Bay's tidal wetlands is a measure of their contribution to the quality of life of humans or to the productivity of businesses and communities. Economists have long recognized the economic importance of wetlands and many studies conducted in California and elsewhere confirm that wetlands provide ecosystem services with the components of value described in this section (Woodward and Wui 2001; Boyer and Polasky 2004). Most of this research, however, has focused on freshwater wetlands. This section summarizes the few studies that have specifically examined saltwater wetlands, focusing on three types of wetland ecosystem services: (a) protection of shoreline properties from storms and flooding, (b) sequestration of carbon, and (c) other ecosystem services provided by tidal wetlands. The results from these studies provide the basis for the subsequent sections to estimate the potential value of protecting and restoring tidal wetlands in San Francisco Bay.

4.1 Components of the Total Value of Ecosystem Services

Figure 15 demonstrates how the total economic value of all the services derived from an ecosystem has several components. The left side of Figure 15 shows values associated with demands that involve human use of an ecosystem. Sometimes the use occurs directly, as when humans go into a wetland to watch or hunt waterfowl. Other times use of the ecosystem occurs indirectly, for example, when less damage is incurred because the existence of a tidal wetland attenuated wave overtopping waves during a storm. Use values often are indicated by market prices, such as the amount birders pay to view wildfowl, the reduction in the storm damage, or the increase in values for homes located near wetlands. However, it is important to note that there are imperfections in markets that can result in all benefits/costs not being reflected by market prices.

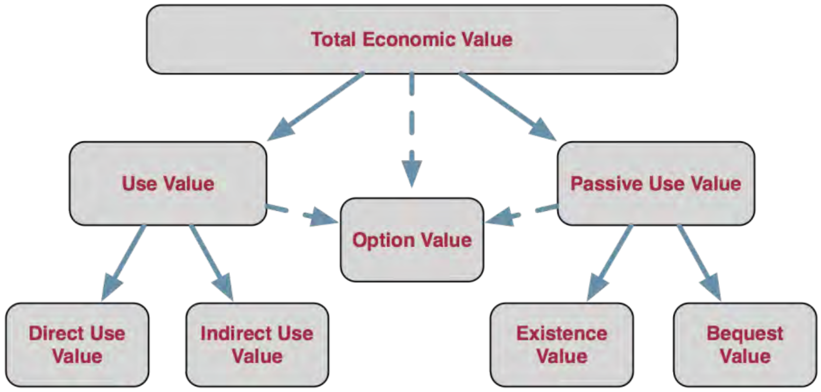


Figure 15. Components of the Total Economic Value of Ecosystem Services (**Source:** ECONorthwest)

The right side of Figure 15 represents nature's values that exist when there is a passive use of an ecosystem. Passive use value falls into two categories. Existence value, comes from people's desire for the continued existence of a species, landscape, or some other aspect of an ecosystem, or of the overall ecosystem as a whole. Bequest value, arises because people desire to ensure that the ecosystem will be available to be enjoyed by future generations. Typically, these passive use values are described in terms of an individual's willingness to pay for an object's current or future existence. For example, if an individual is willing to pay a given sum to prevent the elimination of a tidal wetland, then this amount represents the existence value they place on the wetland. People generally do not satisfy their passive use demands by buying something and, hence, one generally cannot point to a price as a reliable indicator of the value of the associated ecosystem service.

The middle of Figure 15 shows another component of the total value, called option value. An option value refers to the benefit of maintaining an opportunity to derive services from tidal wetlands in the future. It can originate from either side of Figure 15. Use-related option value might exist, for example, if owners of shoreline properties currently feel that the levee in front of their properties provides adequate protection against storm erosion, but they are willing to pay extra on their tax bills to ensure that tidal wetlands in front of the levee remain intact to provide additional protection in the future as sea levels rise.

4.2 The Value of Flood Risk Management and Erosion Control

A search of literature specific to San Francisco Bay did not find any research results estimating the value of storm-protection services provided by the Bay's tidal wetlands. The results of research elsewhere, however, confirms that tidal wetlands in similar settings provide valuable storm-protection services and provide an initial basis for estimating the value of these services in the Bay. Table 2 shows the results from three studies that estimated the value of the storm-protection services provided by tidal wetlands. One recent study examined the ecosystem services derived from the low marsh, salt flat, and high marsh zones of wetlands near Galveston Island, Texas (Feagin et al. 2010). The authors were able to quantify the annual value for five types of services: recreational opportunities associated with birding and hunting; sequestration of carbon; storm protection; habitat and other support for fisheries; and contribution to the value of nearby private property. Table 2 shows their findings suggest the value of storm-protection services, reported as the average value per acre per year, was about $5,700.

Table 2. Estimates from Past Studies of the Value of Storm-Protection Services Provided by Tidal Wetlands

Study	Value of Storm Protection Provided by Wetlands (2010 dollars)		
Feagin et al. (2010)	Different zones of wetlands near Galveston Island, Texas provide storm protection and reduce damage to shoreline private property:		
	Low Marsh	$5,000	per acre per year
	Salt Flat	$170	per acre per year
	High Marsh	$500	per acre per year
Möller (2001)	A salt marsh extending 250 feet in front of a sea wall in the U.K. would reduce the costs of constructing and maintaining the sea wall by about 90 percent, or $3,025 per foot.		
King and Lester (1995)	A salt marsh extending 250 feet in front of a sea wall in the U.K. would reduce construction and maintenance costs by $1,800-3,200 per foot or about $300,000–$500,000 per acre of salt marsh.		

Source: ECONorthwest, with data from indicated sources.

Research in the U.K. estimated the potential cost savings that could materialize when salt marsh, by absorbing the erosive energy of waves, lower the height and, hence, the cost of the sea wall required to protect inland property (Möller et al. 2001). The authors found that, if the cost of building and maintaining a sea wall without a salt marsh would cost about $3,400 per linear foot, then a salt marsh extending 80 meters in front of the sea wall would reduce the size of the sea wall required to achieve the same level of protection and decrease the cost of the sea wall by about 90 percent, or $3,000 per linear foot of sea wall.

A similar study found that, with no salt marsh, a sea wall 40 feet high would be required but, with a salt marsh extending 250 feet in front of it, a sea wall only 10 feet high would provide commensurate levels of protection, and the reduction in construction and maintenance costs for the sea wall would be about $300,000–$500,000 per acre of salt marsh (King and Lester 1995). Most of these savings could be realized with a narrower salt marsh. A marsh extending only 20 feet in front of a sea wall, for example, would yield about 50–75 percent of the savings attainable with an 250 foot salt marsh, and one extending 100 feet would provide about 80–90 percent of the savings. A global review of data found a similar relationship between the breadth of salt marshes and their effect on the height of waves reaching shore. The review found that the initial, narrow strip of salt marsh, next to the upland area, attenuates wave height the most, and the incremental effect on wave height diminishes with each additional increase in the breadth of the sea marsh (Barbier et al. 2008).

These research results provide an initial basis for estimating the value of storm-protection services provided by tidal wetlands in San Francisco Bay. They strongly suggest that tidal wetlands in front of a levee will likely reduce the size of the levee required to provide a given level of storm protection, and the cost savings represents the value of the wetland's services. These values quoted above provide a basis for making initial, rough estimates of the value of storm-protection services provided by tidal wetlands in San Francisco Bay which will be further investigated in section 7. Their utility is limited, however, because they reflect the specific characteristics—water and storm patterns, geologic configuration, shoreline property values, etc.—of the research sites in the U.K. Their applicability to a tidal wetland in San Francisco Bay must be determined on a case-specific basis and will depend on the extent to which it exhibits similar characteristics and any differences affect the value of storm-protection services in a predictable manner. If everything is similar to the underlying characteristics of the U.K. research, for example, then it a site-specific assessment might indicate it is reasonable to assume that a wetland in San Francisco Bay would reduce the costs of a levee or sea wall by a percentage similar to what was found in the U.K.

4.3 The Value of Carbon Sequestration Services

When tidal wetlands sequester carbon by removing carbon dioxide from the atmosphere, they lower these future damages, and this reduction represents the value of the carbon-sequestration services. The value of carbon-sequestration services depends on two factors: the number of tons of carbon sequestered and the value per ton. The amount of carbon sequestered by tidal wetlands will be site-specific, however review of studies from around the world suggests that, as a first approximation, tidal wetlands sequester about 0.9 tons of carbon per acre per year (Chmura and Anisfeld 2003). Many studies have attempted to estimate the value of sequestered carbon. This analysis uses the results from a recent study by several federal agencies, which estimated that reducing emissions of carbon dioxide reduces costs associated with the impacts on climate change by about $5–$67, in 2010 dollars, per ton of carbon dioxide (WGSCC 2010). This range is equivalent to about $20–$250 per ton of carbon stored. Combined, these results indicate that tidal wetlands can sequester carbon with a value of about $20–$220 per acre per year.

Another estimate of the value of carbon sequestered by tidal wetlands comes from a study of a coastal area of about 9,500 acres near Galveston Island, Texas (Feagin et al. 2010 and Table 3). The authors estimated that low marsh would sequester about 27 tons of carbon per acre per year, and high marsh would sequester about 25 tons of carbon per acre per year, but algal salt flat would experience a loss of about 0.2 tons of carbon per acre per year. The larger numbers are about ten times the global average sequestration rate found by Chmura and Anisfeld (2003), but the rate for salt flat shows a loss rather than a gain. Feagin et al (2010) used $21 per ton of carbon, in 2010 dollars, which is about the same as the lower bound of the range estimated by the WGSCC (2010). Their analysis produced the values shown in the middle column of Table 3. The right-hand column shows what the values would have been if the authors had used $250 per ton of carbon, the upper bound of the range of estimates for the value of sequestered carbon from the U.S. Interagency Working Group on Social Cost of Carbon (2010).

Table 3. Estimated Value of Carbon-Sequestration Services Provided by Tidal Wetlands near Galveston Island, Texas (2010 dollars)

	Value of Carbon Sequestered per Acre per Year	
Wetland Zone	**@$20 per Ton of Carbon[a]**	**@$250 per Ton of Carbon[b]**
Low Marsh	$540	$6,800
Salt Flat	-$4	-$50
High Marsh	$500	$6,200

Source: ECONorthwest, with data from Feagin et al. (2010).

[a] Value per ton of carbon used by Feagin et al. (2010); also the lower end of the range of values estimated by the WGSCC (2010).

[b] Value per ton of carbon represents the upper end of the range of values estimated by the WGSCC (2010).

These research results provide a basis for making initial, rough estimates of the value of the carbon-sequestration services provided by tidal wetlands in San Francisco Bay. The data from Chmura and Anisfield (2003) support an initial estimate: $20 –$220 per acre of tidal wetland. Higher values per acre may be warranted if site-specific examination shows that a tidal wetland in the Bay sequesters more rapidly than the rate, 0.9 tons of carbon per acre per year, reported by Chmura and Anisfield (2003).

4.4 The Aggregate Value of Multiple Ecosystem Services

Some researchers have estimated the value of bundles of ecosystem services provided by tidal wetlands. Feagin, et al. (2010) provides estimates of the overall value of multiple ecosystem services provided by tidal wetlands near Galveston Island. Table 4 summarizes the findings for six categories of ecosystem services: storm protection, carbon sequestration, recreational opportunities for birding and hunting, support for fisheries, and amenities that increase the value of nearby private property. The authors report their findings as the average annual value of the services provided by the three wetland zones described above: low marsh, salt flat, and high marsh. The low estimates shown in Table 4 reflect the base-case scenario examined by the authors and incorporate assumptions that the value of sequestered carbon is $21 per ton and the value of nearby private properties affected by wetland amenities grows 3 percent per year. The high estimates assume that the value of properties increases 6 percent per year, and the value of sequestered carbon is $250 per ton.

Table 4. The Overall Quantifiable Value of Six Ecosystem Services Provided by Tidal Wetlands near Galveston Island, Texas (2010 dollars)

	Value per Acre per Year, 2010 Dollars	
Wetland Zone	**Low Estimate**	**High Estimate**
Low Marsh	$9,000	$14,000
Salt Flat	$2,000	$5,000
High Marsh	$3,000	$10,000

Source: ECONorthwest, with data from Feagin et al. (2010).

The low marsh zone provides services with the greatest value, with its support for fisheries, storm protection, and carbon sequestration accounting for most of the difference. Recreational opportunities for birding and hunting are valuable services provided by the salt flat and high marsh zones, with the latter also providing storm protection and carbon sequestration services with considerable value.

Feagin, et al. (2010) also examined the potential impact of anticipated rises in sea level on the overall value of the ecosystem services provided by the wetlands. They considered several scenarios, involving low, medium, and high levels of sea-level rise; with and without sea walls that prevent migration of the wetlands inland as the sea level rises; and with different rates of increase in the value of private property. They found that the total, quantifiable value of the six categories of ecosystem services derived from the three zones likely would exhibit these patterns:

- Low marsh: the value likely would rise is marsh accretion or transgression could keep pace with sea level rise, but fall if the marsh began to drown.
- Salt flat: the value likely would increase in all scenarios.
- High marsh: the value likely would increase except with rapid sea level rise and the presence of barriers such as levees that prevent the wetland from migrating landward.

Other research has estimated the value of multiple ecosystem services provided by salt marshes using the replacement-cost method, i.e., by determining the cost of replacing them once they have been destroyed or seriously degraded. This method relies on an assumption that the services provided by a tidal wetland are worth at least what it would cost to replace the wetland if it were destroyed or severely degraded. A summary of the research (Spurgeon 1998) reports that restoration efforts on the East Coast and in Louisiana have experienced replacement costs of $54,000 – $87,000 per acre. Experiments in the U.K., which involve creating new salt marsh by opening agricultural land behind a sea wall to flooding by the sea incurred much lower replacement costs of about $1,000 – $26,000 per acre.

These research results provide a basis for making initial, rough estimates of the value of multiple services provided by tidal wetlands in San Francisco Bay. This range of values stems from the specific characteristics of the study site, however, and the set of services considered by the researchers. Its applicability to a tidal wetland in the Bay depends on the extent to which it exhibits similar characteristics and any differences affect the value of storm-protection services in a predictable manner. Further investigation is required to determine the applicability to specific sites in the Bay or to develop an estimate of value tailored to the site's characteristics.

4.5 Applying the Estimates of Value to Tidal Wetlands in San Francisco Bay

Though the results from the studies described above are not specific to San Francisco Bay, they include some of the best available data describing the economic values of tidal wetlands. As such, they provide valuable context that demonstrates the likely significant values of the ecosystem services provided by tidal wetlands in the Bay. Households, businesses, and communities realize considerable benefits by the presence of even limited tidal wetland habitats throughout the estuary; these benefits can only increase with the continued implementation of tidal wetland restoration projects.

Some of the most immediately tangible benefits to developed shoreline areas from tidal wetlands are the role these habitats play in flood risk management. Tidal wetlands can provide flood risk management services more economically than more typical infrastructure such as levees or sea walls. These services are described more in Section 5 below.

5 Flood Risk Management

The ability of tidal marshes to reduce flood risk by attenuating wave action, mitigating shoreline erosion, and conveying flood flows is one of the more tangible illustrations of the value of their ecosystem services. These services are relatively straightforward to quantify, and their benefits are becoming well understood and can be translated into economic terms.

5.1 Managing Risk

The risk of damage to San Francisco Bay shoreline infrastructure is likely to increase over the next century due to both climate change (and attendant rising sea levels) and continued development within the shoreline's floodplains. Though this risk cannot be entirely eliminated, it can be managed so that it is reduced to acceptable levels. The definition of "acceptable risk" is dependent upon a wide range of factors – societal, economic, technological – which also leads to questions about who pays for, and who benefits from, risk management. There are different ways of achieving the same level of risk that reflect our society's priorities and attitudes about the environment.

Risk can be defined a number of ways. One common definition of risk is as product of likelihood and consequence. Likelihood is the probability of failure of the *flood risk management* (FRM) scheme to prevent flooding. It is often expressed as a frequency of flooding (= events/year). The consequence of the resultant flooding varies depending not only on the nature of the flood (depth, duration, timing, etc.), but also on the location where flooding occurs (population, property, etc). Consequence itself is the product of potential damages (the value of the asset) and its vulnerability to damage. Consequence can be expressed as the amount of damage caused by the flood (= $/event). In this way risk can be expressed as the amount of damage per year (=$/year):

Risk = Likelihood x Consequence

So how can an acceptable level of risk be achieved? Table 5 and Figure 16 demonstrates how it is possible to achieve the same level of risk with different likelihoods and consequences, which can affect the choice of a risk management strategy. If the likelihood is high and the consequence low, then risk would be better addressed by reducing likelihood (and vice versa).

Table 5. The relationships between likelihood, consequence, and risk.

Risk	Likelihood	Consequence
Moderate	Moderate	Moderate
Moderate	High	Low
Moderate	Low	High

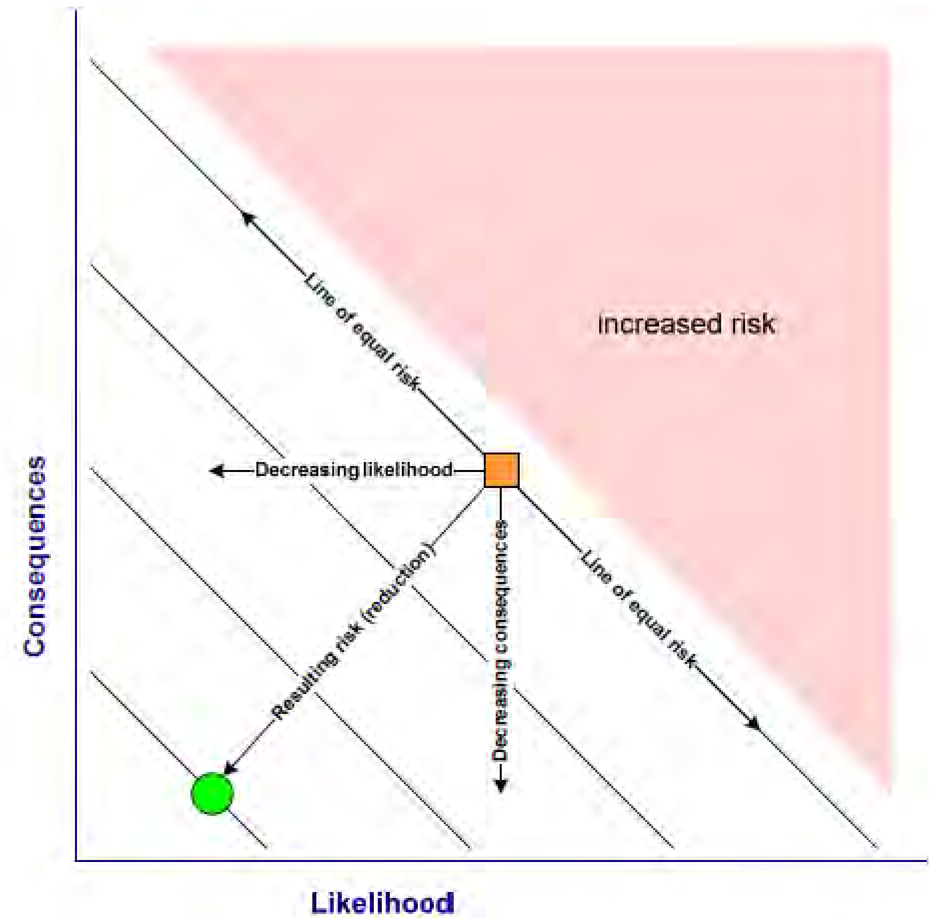


Figure 16. Graphical representation of the relationships between likelihood, consequence, and risk. From SafeCoast (2008)

Within San Francisco Bay, the likelihood and consequences of flooding are likely to change over time even without changes in flood risk management practices. Each asset (such as a road, pipeline, or transmission line) is likely to have its own risk trajectory as both environmental stressors and the nature of the asset change over time. An obvious change in environmental stressors would be the projected higher sea levels and more intense wave action resulting from climate change. The likelihood of flooding will increase as the extreme water surface elevations occur more frequently above the design elevation of levees, seawalls, and other shoreline protection. The consequences of flooding will increase as the depths and extents of inundation increase. Economic development will also change the potential consequences of flooding by changing the value of assets in the flood hazard zone.

We can influence the risk trajectory by choosing an appropriate risk management strategy as illustrated in Figure 17:

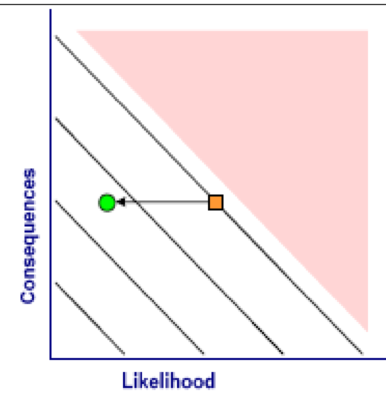
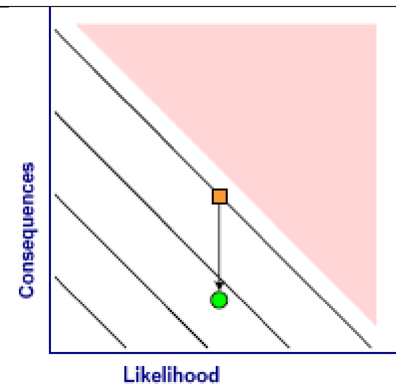
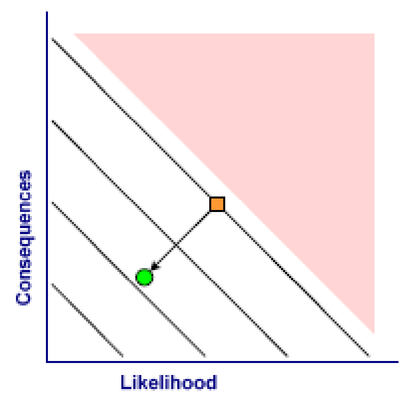
For instance, if a levee is raised, then the likelihood of a flood event occurring is reduced. This may be a temporary respite from risk, though, as the likelihood of flooding may increase with sea level.	
The consequence of flooding may be decreased. If it is assumed the asset retains the same value over time (and hence the same potential for damage), then measures such as insurance, flood proofing, and raising the elevation of the asset may reduce the actual damage.	
The likelihood and consequences of flooding may be reduced simultaneously if the asset is moved out of the flood hazard zone. Moving the asset upslope, away from the Bay, would decrease the frequency of flooding and reduce the depth of flood inundation at the same time.	

Figure 17. Risk trajectories for shoreline flood management.

The choices faced by society in considering various approaches to risk management can be illustrated by comparing the Dutch and American approaches to FRM. In the case of the Dutch, their emphasis has been on reducing the likelihood of flooding to a very low probability. Legal safety standards are set by the Dutch for each levee, with standards ranging from 1:2,000 to 1:10,000 years. This level of protection is achieved through a significant investment in levees estimated to cost 0.2% of annual GDP per year, or $1.7B per year into the next century. The resulting low likelihood of flooding is partnered with the potential for severe consequences if flooding should occur, as 20% and over 50% of Dutch land is below mean sea level or less than three feet above mean sea level, respectively. This flat, low-lying land is home to 60% of the population, which produces approximately 70% of the Dutch GDP ($542B) every year (Tomkiewicz 2013).

The San Francisco Bay Area has a more heterogeneous topography, with considerable developed areas outside the flood hazard zone. Heberger et al. (2012) suggest that about 13% of the population and 13% of GDP ($62B) is at risk of flooding, and estimates the costs of raising and constructing new levees to maintain the present level of protection to be a total of $5.7B. Over 20 years, that averages to an annual cost of about $0.1M per year.

It is instructive to consider the costs of defending GDP and people in terms of unit costs. Table 6 below demonstrates that for every dollar spent each year in the Netherlands, $319 of GDP is protected. In the Bay Area, $235 of GDP would be protected for the same cost. In terms of protecting people, it costs $170 to protect one person in the Netherlands each year while in the Bay Area the cost closer to $900 per year. There are several reasons for these differences:

- The length of defense relative to the population is shorter in the Netherlands. The Bay Area hazard zone is a relatively narrow band around the Bay.
- The density of people in the hazard zone is higher in the Netherlands than in the Bay Area. Conversely, relatively more GDP is generated in the Bay Area hazard zone, perhaps reflecting the local preference of locating industrial and office space close to the Bay, particularly in the South and East Bays.

Table 6. The consequences and costs of flood risk management in the Netherlands and the Bay Area.

	Netherlands	**Bay Area**
GDP	$774B	S479B
GDP at Risk	$542B 70%	$62B 13%
Population	16.7M	7.2M
Population at Risk	10.0M 60%	0.3M 3.8%
Cost to defend per yr	$1.7B/yr 0.2%	$0.3B 0.06%
GDP defended per $1 per yr	$319	$235
$ to defend one person per year	$170	$976

Source: Dutch figures from Vellinga et al/Katsman et al, for the Netherlands Delta Committee (2008); Bay Area figures from (Heberger et al 2012)

Different national approaches to flood risk management have been examined in a European study and are summarized in Table 7 (Safecoast 2008). The Dutch, being risk adverse, focus on measures such as primary levee defenses to increase flood protection, thereby lowering the frequency of inundation. The

English, on the other hand , focus more on limiting the potential consequences of flooding by emphasizing measurers such as restricting new development in flood prone areas, providing warning and evacuation plans, and relying on flood insurance. The English also emphasize managed realignment to create a shorter, more defensible shoreline, and create habitat (salt marsh) in front of levees to attenuate waves.

Table 7. Approaches to flood risk management in the Bay Area, England, and the Netherlands.

Approach	Measures	Netherlands	England	Bay Area
Flood risk management	FRM Levees	●●●●	●●●	●●●
	Managed Realignment		●●●	●●
Limiting potential consequences of floods	Restricting new development in flood-prone areas	●	●●●	●●
	Construction of flood resistant buildings	●	●	●●●
	Storm surge warning	●●●	●●●	●●●
	Risk/crisis communication	●●	●●●	●●●
	Evacuation Planning	●●	●●●	●●
	Flood Insurance		●●●●	●●●●

● Limited importance, ●● Some Importance, ●●● Quite important, ●●●● Very important

Table 7 is based on a table in Safecoast (2008) with the addition of a column for the Bay Area. Like the Dutch and the English systems, Bay Area levees are used extensively to reduce the frequency of flooding; however, Bay Area managers also emphasize reducing the consequences of flooding.

The Dutch have chosen one route which will minimize the likelihood of flooding forced on them by the low-lying land they occupy and the severe consequences of not providing this level of protection. Because of their use of a large network of massive levees they have accelerated the erosion of remaining natural marshes. They have only recently begun to employ tidal marsh restoration as an element of their shoreline defense strategy.

San Francisco Bay enjoys a more favorable prognosis given its geography. San Francisco Bay is a relatively shallow, enclosed body of water that experience less ferocious storms than does Holland.

Further, there is upland away from the Bay – the whole area is not below sea level unlike Holland. We have the experience of managing a dynamic shoreline and we can point to successful tidal marsh restoration projects that continue to build in elevation and which are supporting expansion of vegetated marsh. There are significant opportunities for integrating wetlands into the management of the Bay shore through using the flood risk management benefits of tidal wetlands described below.

5.2 Flood Risk Management Benefits of Marshes

Most flood protection benefits of tidal wetlands can be placed into one of three categories: (1) wave attenuation, (2) mitigation of shoreline erosion, or (3) maintaining flood flow conveyance. These benefits are described below.

5.2.1 Wave Attenuation

Waves – whether generated by local winds or entering the Bay as oceanic swell – deliver significant energy to the shoreline which can lead to overtopping and erosion. Wave overtopping of levees can result in the rapid inundation of low-lying areas (particularly if levees or other water control structures are breached), resulting in local flooding and impacting public safety and wildlife communities.

Wave impacts are a function of multiple factors: the height, frequency, and duration of wave events, water levels, and the composition of the substrate upon which the waves are acting. Long periods of consistent, moderate wave action can do as much damage as short periods of large waves. The height of a wave approaching a shoreline is controlled by many factors, but primary among them are (1) the distance the wave has traveled (fetch), (2) the depth of water, and (3) the speed of the wind. The longer the fetch and the deeper the body of water, the higher the wave can grow. As waves approach a shoreline, they respond to local bathymetry.

When waves approach the shore, their energy is reduced, or attenuated, by the friction generated between the moving water and the underlying mudflat or vegetated wetland, resulting in a decrease in both the height of the wave and the speed at which it can travel. The farther the wave has to travel across a mudflat or wetland, the more its energy will be attenuated (Figure 18). The higher the water level above the marsh, the less waves are attenuated – so extreme events are attenuated less than typical spring tides. The amount of wave attenuation is governed by the water depth, bed roughness, marsh edge characteristics, and vegetation characteristics (height, density, shape of leaves). Salt marshes in particular are very efficient at reducing wave energy, achieving up to 70-80% reductions in wave height over 300 feet compared to 20-30% over mudflats of similar widths (Cooper 2005). Möller and Spencer (2002) measured 44% reductions in observed wave heights over narrow strips of salt marsh 30 feet wide.

Recent work in Corte Madera Bay (BCDC 2013) demonstrates a more complicated picture of wave attenuation over marshes. The relation of depth and wave height tends to limit wave elevations to a narrow height band at the back of the marsh. For a given water depth, high waves will break at the marsh edge such that the maximum wave height is 70% of the water depth and waves are further attenuated as they propagate over the marsh..

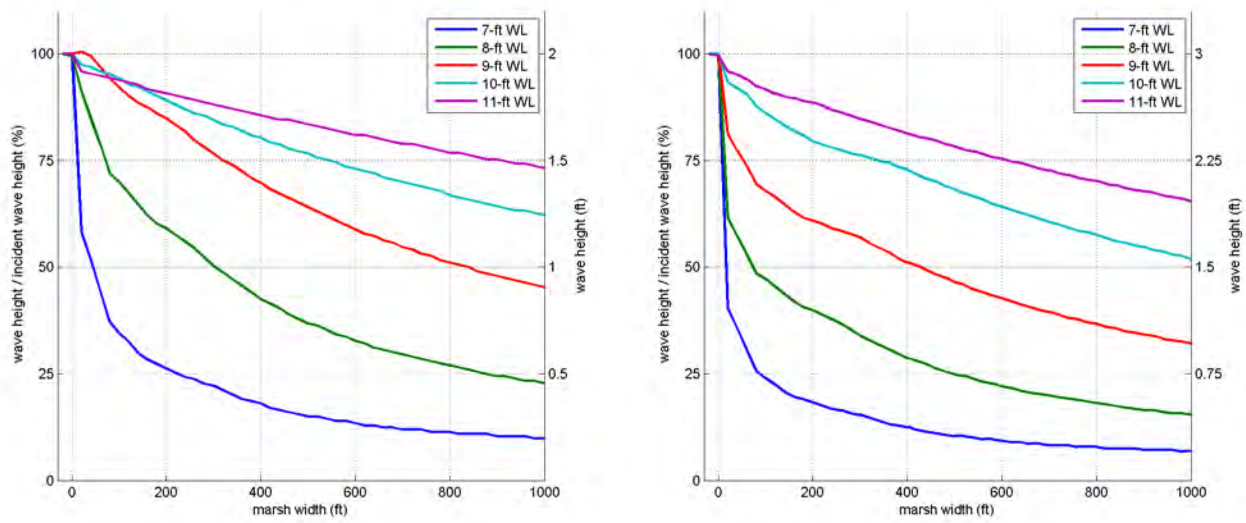


Figure 18. Predicted wave heights relative to incident wave height as a function of marsh width, from the WHAFIS model (see section 7).The incident wave height equals (a) 2 feet and (b) 3ft (BCDC 2013).

5.2.2 Mitigation of Shoreline Erosion

Waves can also damage coastal infrastructure such as roads, buildings, pipelines, and transmission lines by directly impacting infrastructure, or eroding the shoreline upon which the infrastructure is located.

If water depths leading up to the shoreline do not gradually decrease, as in the case of a levee or seawall (or vertical salt marsh scarp), the wave instead breaks suddenly when it meets the shoreline. This sudden deceleration results in most of the wave energy acting upon the local area instead of attenuating gradually over a longer distance. Breaking can damage the structure or erode the substrate, and increases the potential for structural failure and flooding. Maintaining tidal marsh outboard of levees and other engineered shoreline structures is therefore one of the most effective ways to reduce the likelihood of tidal flooding and decrease the maintenance costs for shoreline flood protection structures.

5.2.3 Maintaining Flood Flow Conveyance

Maintaining flood flow conveyance in tidal channels that drain urban areas is an important function of wetlands. Tidal channels in the Bay are prone to sedimentation due to the reduction of tidal prism following diking. Confinement by levees also reduces the bank full capacity of the channel. Wetlands adjacent to the tidal channels can increase the capacity of the channel in two ways. First, wetlands increase the tidal prism of the channel, which increases channel velocities and scours out accumulated sediments. The larger tidal prism creates and maintains a larger channel with increased conveyance.

Secondly, adjacent wetlands allow flood waters to escape from the channel into the wetlands, improving overall conveyance to the Bay and taking advantage of storage within the wetlands. Both tidal scour and flow diversion potential are maximized by placing the wetlands as far upstream as possible within the tidal zone.

6 Tidal Wetland Restoration and Flood Risk Management Scenarios

Given the multiple benefits that tidal wetlands provide to shoreline communities, particularly as part of an integrated flood risk management approach, how can they be utilized around San Francisco Bay to reduce shoreline protection costs? This chapter considers that question by using the example of the Hayward Shoreline, a typical developed Bay shore, to illustrate how tidal wetland restoration can provide flood risk management benefits. This analysis considers three potential approaches to integrated wetland restoration and flood risk management: (1) Holding the Line, (2) Marsh Restoration, and (3) Marsh and Upland Ecotone Slope Restoration. These ideas have been developed from an initial study undertaken for the Hayward Area Shoreline Planning Agency (HASPA 2010).

6.1 The Hayward Shoreline

The Hayward Shoreline stretches along the East side of San Francisco Bay from San Leandro Creek in the north to the San Mateo Bridge (Figure 20). The shoreline is primarily comprised of levees surrounding diked baylands, many of which have been developed or otherwise heavily altered by historic or existing uses. The shoreline is typical of many shorelines along the East, South, and Central Bay, as its matrix of residential development, industrial/commercial development, and open space is criss-crossed with a variety of regionally critical infrastructure, including water treatment facilities, storm drainage channels, pipelines, high-voltage electrical transmission lines, railroads, and freeways (including the eastern approaches to the San Mateo Bridge).

The shoreline includes considerable frontage for the East Bay Regional Park District's (EBRPD) Hayward Regional Shoreline and Coyote Hills Regional Park as well as property owned by the Hayward Area Recreation and Park District (HARD). Many of the open space areas are managed as fully tidal or managed tidal systems that provide a combination of wildlife habitat, flood flow storage, recreation, and wastewater treatment services. The Hayward shoreline is already vulnerable to inundation from coastal flooding – a combination of tides, storm surges, wave run-up and storm water runoff. With higher sea levels, storm surge conditions may combine to create short-term extremely high water levels that can inflict damage to areas that were not previously at risk. Figure 20 displays the potential area of inundation by 2050 and 2100. Within this area there are a large number of parcels owned by public and private entities which serve a number of different functions.

In addition to the residential and commercial properties that are threatened by potential inundation, the Hayward shoreline has important infrastructure close to the Bay shore. For example, the Oro Loma Wastewater Treatment Plant is vulnerable to both coastal and fluvial flooding as well as rising groundwater. Other vulnerable infrastructure includes the East Bay Dischargers Authority pipeline, Pacific Gas & Electric transmission lines, railroads, high pressure gas lines and fiber optic cables. All cross the area and will have to be considered in adaptation strategies. Landfills at the center of the shoreline will have to be protected from wave erosion and water infiltration that could compromise containment. Sea level rise could potentially impact groundwater plumes associated with former landfills.

The area's storm drainage channels are potential sources of fluvial flooding and are likely to be impacted by backwater effects due to rising sea levels. Storm drain systems, designed to flow by gravity, the tide gates on channels, and storm water pump stations will have to accommodate higher sea levels. Groundwater levels are affected by tidal fluctuations and sea level. Stormwater treatment measures which rely on infiltration may therefore be affected by higher groundwater elevations. Higher groundwater elevations may impact existing buildings and infrastructure such as cables, pipes and sewers.

Figure 19. The Hayward Shoreline is owned and operated by a broad range of public agencies, including the East Bay Regional Parks District (EBRPD), Hayward Area Recreation and Park District (HARD), Alameda County Flood Control and Water Conservation District (ACFCWCD), CalTrans, and the Department of Fish and Game (DFG). Source: City of Hayward.

Figure 20. Vulnerability of the Hayward Shoreline to flooding from 16 inches (light blue) and 55 inches (dark blue) of sea level rise by 2050 and 2100, respectively. Modified from BCDC (2009).

6.2 Scenario 1: Holding the Line

This scenario is known as "holding the line" because it involves no realignment of existing levees or restoration of marsh outboard of the levees. Without wetland restoration, the combination of bayward levee erosion, accelerated sea level rise, and reduced local suspended sediment concentrations would continue to convert mid/high marsh habitats within the Hayward marshes to low marsh or even mudflat. Erosion of the outboard levee and conversion of mid/high marsh to low marsh will increase the likelihood that wave energy will impact the landward (eastern) levees, which will increase the need for levee maintenance. The crest elevation of the levees will have to be raised to keep pace with rising sea levels and increasing wave run-up elevations. As sea level rises and water depths at the toe of the structure increase so wave heights on the structure will increase. To maintain the stability of the levee with higher wave forces will require the use of larger armor rock. The larger waves combined with reflection of wave energy from the armored levee will result in erosion and lowering of the mudflat in front of the levee (Figure 21). Holding the line therefore results in an increasingly steep slope (up to 1:3) on the shoreline – the crest increases in height, the toe lowers, the armor increases and the levee stays in the same location. The increased wave energy is dissipated over a shorter distance, increasing the erosion of adjacent marsh/mudflats and increasing the forces on the levee. Existing mid/high salt marsh communities bayward of the levees will be increasingly squeezed against the steep slope. Tidal wetlands at locations such as Oro Loma and Cogswell Marshes will likely shrink and lose native species diversity as lower marsh zones expand and upper marsh zones contract.

Invasive plant species populations (such as brome and fennel) are likely to expand where levees are maintained more frequently or armored, potentially intensifying conflicts among trail users, levee maintenance, and marsh resource protection. With an increased likelihood of levee damage, subsided diked baylands landward of the Hayward marshes could experience more frequent overtopping, breaching, and/or failure (conversion to open water).

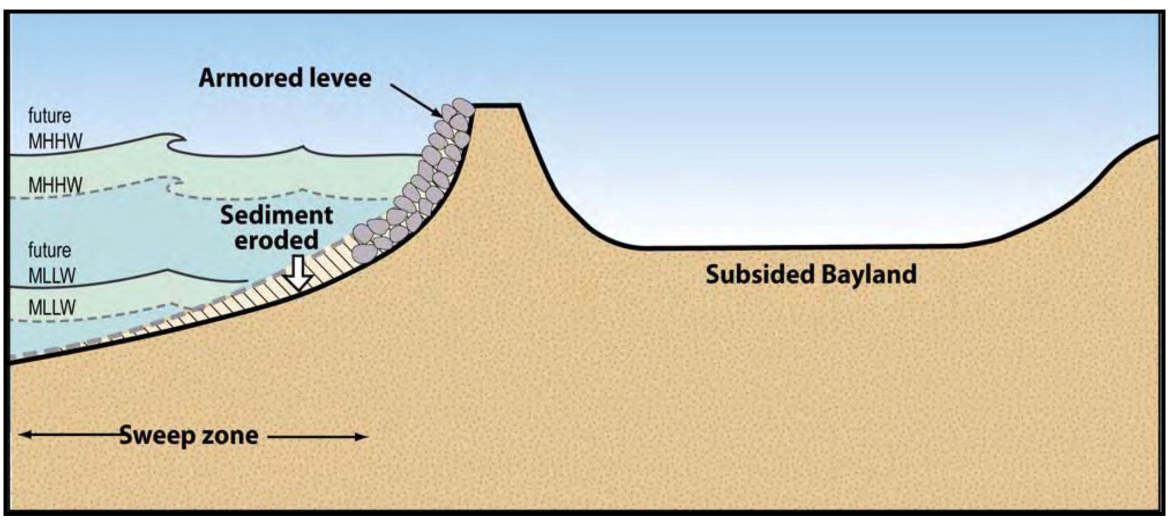


Figure 21. “Holding the line” results in the gradual erosion of the shoreline.

Management Strategy

Under this scenario, local stakeholders would have to agree on an alignment for “holding the line” that would (1) facilitate continued inundation of areas that are already intertidal and (2) protect areas behind levees that are not slated for long-term tidal restoration (e.g. landfill areas, and areas with critical infrastructure such as wastewater treatment facilities). A potential alignment is displayed in Figure 22. The development of a single alignment would help to avoid spending money to improve levees that would not be necessary in the long-term, so available funds are focused on protecting the highest-priority areas. Levees would have to be raised to provide adequate (at the very least, equal to existing) protection against the tidal flooding of developed baylands and infrastructure east of the levee. The required increase in levee crest elevations to maintain existing protection would be on the order of sea level rise, plus subsidence resulting from added fill. The stable rock size to prevent erosion would increase with the depth of water at the toe of the structure.

Figure 22. A potential alignment for "holding the line." (HASPA 2010)

Levees that might be lower priorities for raising include the existing bayfront levees along Oro Loma and Cogswell Marshes. These levees do not currently provide flood protection, but primarily serve to support the Bay Trail and dissipate wave energy that would otherwise threaten actual flood risk management levees that are farther landward. In the long-term, improving the bayward levees may not be cost-effective, as rising sea levels (and subsequent marsh drowning) would eventually result in the levees becoming "peninsulas" that would be surrounded on all sides by open water, leaving them vulnerable to damage from wind-wave erosion and subject to increased long-term maintenance costs. Therefore, it might be more cost-effective in the long-term to abandon these levees, and focus levee improvement efforts on an alignment that would strictly protect critical baylands infrastructure and areas such as landfills that cannot be tidally inundated.

6.3 Scenario 2: Levee and Wetland

An alternative to "Hold the Line" is to move the levee to a new location further inland, east of the alignment proposed in Scenario 1 above (Figure 23.). This allows existing marshes and mudflats to transgress landward naturally. This also requires relocating existing infrastructure out of the hazard zone while restricting new construction in vulnerable areas. Realignment takes advantage of the natural protection provided by marshes and mudflats to reduce the risk of flooding and erosion allowing smaller levees to be built. The restored tidal marshes will reduce wave heights, and reduce the height to which levees must be raised to provide adequate flood management.

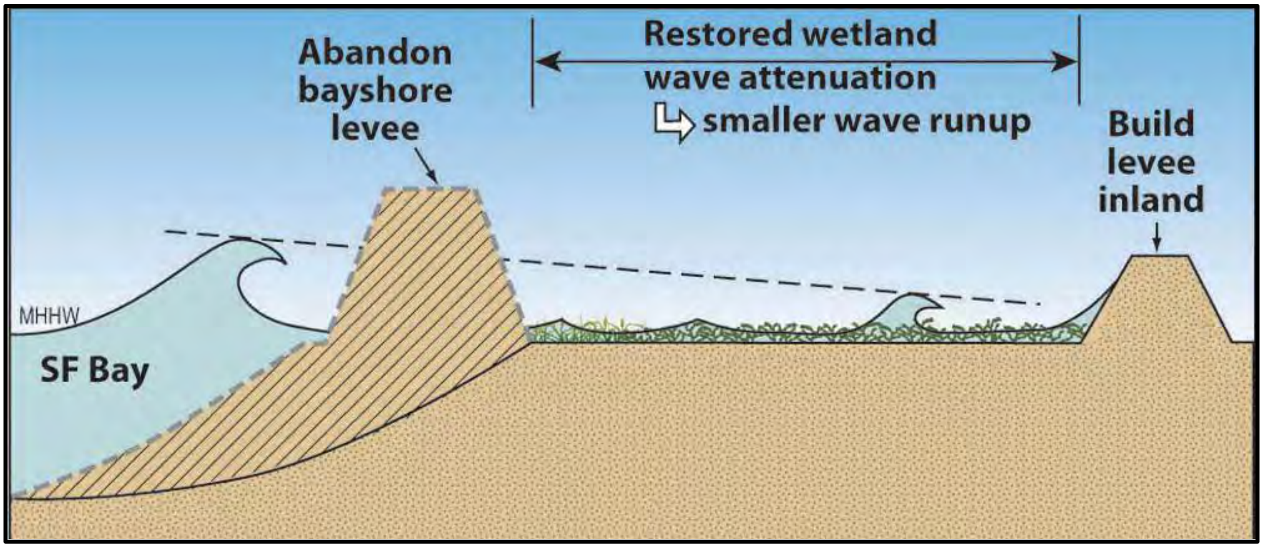


Figure 23. Wave attenuation over restored tidal wetlands limits how high realigned levees have to be in order to provide equivalent flood protection to larger, bayshore levees.

Management Strategy

On the Hayward shoreline, the levee line could be realigned to the landward edge of Oro Loma, Cogswell and Hayward marshes (Figure 24) allowing these marshes to transgress landward naturally. The existing bayshore levee would be maintained in front of the landfills and wastewater treatment plants. The realigned level could also be located east of the landfill, but the existing bayfront levee would have to be managed or reinforced in such a way as to prevent damage to the landfill. Realignment would decrease the slope of the shoreline; dissipating wave energy over distances of several hundred feet or more and allowing the construction of much lower levees.

Figure 24. A potential alignment for levee realignment. (HASPA 2010)

The alignment presented in Figure 24 would result in the conversion of significant amounts of diked baylands to tidal marsh. Some of these areas, such as the oxidation ponds landward of Cogswell Marsh, would require restoration so that they become suitable for tidal flooding and colonization by emergent tidal wetland plants. Likely activities include soil grading, substrate removal, excavation of tidal channels, and potential pre-vegetation to encourage the post-breach deposition of tidally transported suspended sediments. This option would also require Hayward Marsh to be re-engineered so that it could support tidal marsh instead of the brackish marsh that is currently fed by treated wastewater effluent from the EBDA line. The treatment capacity currently provided by Hayward Marsh would have to be relocated to a new position landward of the improved levee, or provided through alternate treatment technology. In addition, the habitat values provided by Hayward Marsh (foraging and breeding habitat for a broad range of waterfowl and shorebirds) would have to be mitigated for elsewhere in the vicinity. If the levee were instead constructed around Hayward Marsh, the marsh would no longer be able to gravity-drain to the Bay, and treated wastewater would have to be pumped over the levee to the Bay.

6.4 Scenario 3: Levee, Wetland and Upland Ecotone Slope

Even without the threat of sea level rise, the area of potential inundation on the Hayward shoreline is considerable. Looking ahead, the East Bay shore will become increasingly vulnerable to inundation by 2050. Ideally, any adaptation strategy to such changing conditions should:

- Dissipate wave energy over a long shallow slope;
- Provide a mechanism to increase the surface elevation at about the rate of sea level rise;
- Allow for adaptation to varying rates of rising sea levels;
- Slow down both habitat and hazard zone migration.

The Hayward shoreline has some space to realign, but also has two other opportunities to exploit.

Firstly, large amounts of treated fresh water pass through the Hayward shoreline in the EBDA pipeline, from treatment plants in the south and east to be discharged at the mid-bay outfall. This pipeline running north-south across the baylands severely constrains the realignment of the levees. Redirecting the output from the wastewater treatment plants to local treatment marshes and disconnecting the EBDA pipeline would remove a major constraint on the Hayward shoreline and improve the resiliency of the EBDA system. The input of fresh water at the inland edge of the tidal marshes would create more productive brackish marshes, with higher accretion rates, thereby better able to keep up with rising sea levels compared to saline tidal marshes.

The second opportunity is the local availability of sediment. Sediment is at present being trapped at San Leandro Marina and along the flood channels leading to the Bay. In the past this sediment would have entered the Bay and accreted on mudflats and marshes; this connection has now been broken. Levees, flood control channels, and urban development have isolated the bayland marshes from natural pulses of watershed sediments along the tidal marsh edges. Natural sediment depositional landforms such as crevasse splays (delta-like overbank sediment deposits on marshes or floodplains) and alluvial fans (washes) no longer form in diked baylands to provide natural widening and sediment nourishment in the upper tidal elevation range of the bayland edges. The sediment presently trapped could be recovered and hydraulically placed on the bayland edges. Artificial high marsh berms on the outer marsh edges could be actively maintained or managed to keep pace with sea level rise and erosion by periodically raising their crests with thin deposits of sediment (berm capping), in phases or staggered patterns to ensure continuous mature vegetative cover.

Management Strategy

The Wetland and Ecotone Restoration scenario combines the EDBA outflows and local sediment availability to create a more sustainable shoreline that can accrete vertically and does not transgress landward so rapidly. It combines the virtues of the “Hold the Line” and “Levee and Wetland” options, but does not alleviate impacts to land uses and costs. Figure 26 displays a cross-section of the Hayward shoreline displaying the main elements:

- The existing bayshore levee line would be realigned further inland behind the marshes. An impermeable berm would be constructed, perhaps with a cut-off wall to limit saline groundwater intrusion. The crest elevation of the impermeable berm would be set by still water levels, and would be relatively low as it would not be subject to wave overtopping. If space was limited, then an impermeable wall could be used in place of the berm.
- A freshwater swale would run parallel to, and bayward of, the impermeable berm. This swale would act as a manifold, distributing freshwater from the wastewater treatment plants along the length of the shoreline.
- Forming the bayward bank of the freshwater swale would be a seepage berm. This would be a berm slightly lower than the impermeable berm with a long, shallow (1:100) bayward slope down to tidal marsh elevation. This berm would be constructed from a poorly sorted coarse and fine material dredged from the flood channels. Water from the swale would then seep through the berm as shallow groundwater discharge to the back of tidal marshes, above tidal elevation, where brackish marsh would form (Figure 26).

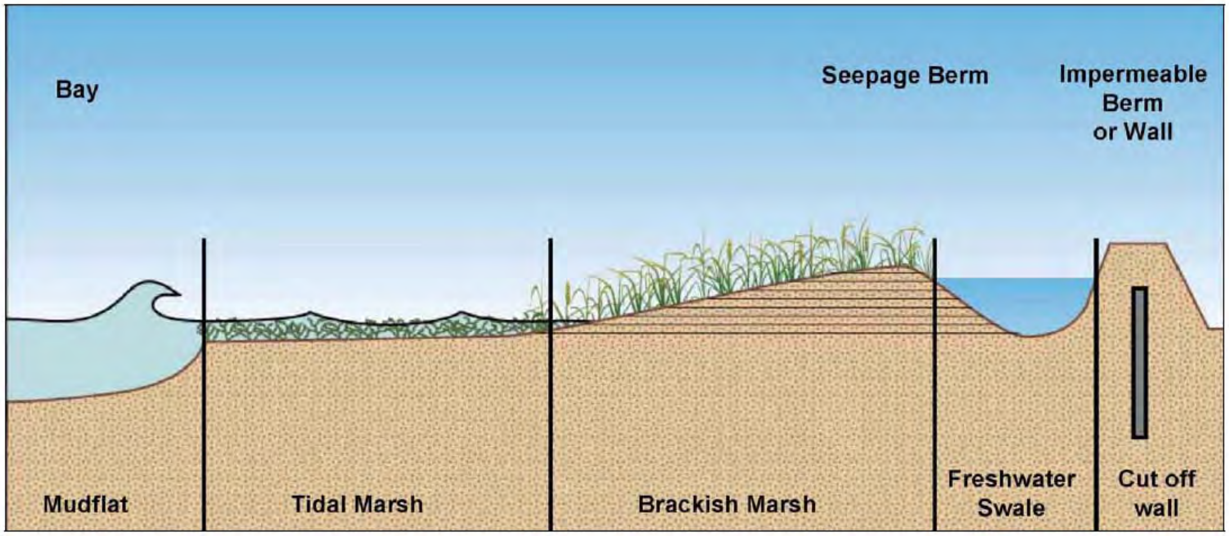


Figure 26. Design elements for a flood protection levee with upland-wetland ecotone.

Figure 27 displays the general arrangement of the marshes, swales and berms in plan view. The saline tidal marshes would accrete and transgress naturally up the 1:100 slope while the brackish marsh will accrete more rapidly due to the greater organic production. Over time, as sea level rises, the slope should gradually steepen rather than transgress landward. This will slow down the landward transgression of wetlands and "squeeze" some habitats, yet maintain the wave attenuation functions of the marshes.

Figure 27. A potential alignment flood risk management levee with upland-wetland ecotone. (HASPA 2010)

Sediment from the flood channels could be used not just to construct the original seepage berm, but also to periodically raise it. A pipe could be run on top of the berm through which would be pumped a sediment-water mixture. This mixture would be released on a regular basis in an alternating pattern of splays in small amounts so as not to bury the existing vegetation.

7 Using Tidal Wetlands to Reduce Shoreline Protection Costs

The scenarios above describe flood risk management regimes in which wetlands play a fundamental role. The integration of wetlands into a flood risk management strategy can lead to cost savings through three primary mechanisms:

1. A reduction in wave height due to the attenuation of waves over the marsh results in lower run-up elevations, lower crest height, and a smaller levee size.
2. The presence of a vegetated marsh results in a higher initial surface elevation upon which the levee is constructed; the toe of the levee is located at about MHHW rather than MTL. The height of the levee, and therefore overall size of the levee, is therefore reduced.
3. Wave attenuation is greater as depths over the marsh decrease. For lower, more frequent water levels (e.g spring tides), wave forces on the marsh-fronted levee will be significantly reduced. Without a marsh, waves will impact the levee on every tide. It is likely that maintenance requirements on the levee without marsh will be higher, and the levee may be in an eroded condition when an extreme event does occur.

The cost analysis below considers these factors, and demonstrates the flood risk management cost savings resulting from implementing the strategies that incorporate wetlands and upland ecotone slopes. All costs are relative, calculated per unit length or per unit area and are in 2010 US dollars.

7.1 Cost Analysis

Previous studies (such as King and Lester (1995) discussed in section 4.2) describe the potential cost savings associated with the presence of a marsh in front of a levee. In these studies, the cost of constructing a levee was calculated to provide a specified level of protection for the 'no marsh case'. The width of marsh was varied in front of the levee, and the size and cost of levee was calculated to maintain the same level of protection.

This analysis utilizes a similar methodology and, in addition, calculates the cost of marsh restoration and marsh/levee maintenance over 50 years. The total cost of the combined marsh and levee for over 50 years was then compared for levees with different marsh widths per unit lengths of shoreline. The cost savings of having a marsh are expressed as savings per acre of restored marsh relative to the levee with no marsh. In addition to varying the width of the marsh, the cost of creating and maintaining an upland ecotone slope was also considered.

Cost Calculation Details

This analysis utilizes a number of simplifying assumptions to allow for a simple comparison of costs. The first is that the shoreline in question is a realistic representation of a developed Bay shoreline, with an aging outboard levee and the resulting choice to (1) maintain the levee in place or (2) realign the levee landward and restore a marsh. If levees are maintained in place, the analysis assumes that the new levees would be constructed along existing alignments. If levees are realigned, the analysis assumes that no new land has to be purchased for the levees or marsh; all new fill is on the bayward side of the levee. All costs are expressed in 2010 dollars.

Water Surface Elevations, Waves, and Wave Run-Up. Calculating the size of the levee requires specifying the total water level, or TWL. The total water level is defined as the combination of a high bay water level and wind-wave run-up. This preliminary analysis used the joint occurrence of a 100-year bay water level and a 100-year wind wave event to estimate the TWL and the required levee crest. The TWL analyses used in the cost estimate are preliminary, but provide a basis for approximate cost estimates.

Extreme water levels. Total water levels were based on a 100-year return elevation of 12 ft MLLW from the USACE San Francisco Bay flood analyses (USACE 1984) and are representative of the Central Bay. This analysis added an additional 14 inches of sea level rise by 2050, which is a relatively high projection (OPC 2011, NRC 2012).

Waves. Waves of 2 feet and 2.5 seconds were selected for the wave condition at the marsh edge. These were chosen as the depth-limited waves for 100-year return water level; higher waves would break at the marsh edge. Estimates and observations of significant wave height in the Bay suggest that typical 1% significant wave heights range from 2 ft to 4 ft at the mudflat edge for most of the Bay's marshes (DHI 2011, Lacy and Hoover 2011) although observations suggest higher waves may be experienced in part of the Bay. The actual extreme wave heights depend on local bathymetry, wind speed, wind direction, and fetch. Sites subject to local sheltering experience waves in the lower portion of this range. Areas just inside the Golden Gate, which are exposed to larger ocean swell, and portions of the South Bay with the longest fetches, experience waves at or above the high end of this range.

Wave attenuation. Wave attenuation across the marsh was calculated using WHAFIS, developed by FEMA to predict wave conditions associated with storm surge (FEMA 1988).with standard parameters derived for San Francisco Bay vegetation (BCDC 2013). The attenuation curves in Figure 1 were derived as part of the BCDC *Innovative Wetland Adaptation Techniques in Lower Corte Madera Creek Watershed* project (BCDC 2013).

Run-up. Wind wave run-up elevation was calculated using van der Meer (2003) as described in FEMA's *Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast* (FEMA 2005), and is a function of wave height, period, levee slope and construction. This was added to the extreme water level to define TWL for the scenario and to set the levee crest elevation.

Levees. The analysis assumed each levee is earthen, with a trapezoidal shape. The main factor affecting the cost estimates is the required height of the levee, which is the required crest elevation minus the approximate elevation of the existing grade. The existing grade was assumed to be MHHW if a tidal marsh was present, and MTL if not present. The conceptual design elevations are based on 100-year TWLs with an additional 1 ft allowance for freeboard. Levee cross-sections without a marsh are assumed to have inboard and outboard slopes of 3:1 (H:V), a crest width of 15 ft, and a foundation depth below grade of 2 ft. The approximate cost for engineered fill was $30/CY. The only difference for the levee cross-section with a marsh was to broaden the side slope to 7:1. To prevent levee erosion, new levees are assumed to be armored with rock. The armoring design used in the cost estimate is a rock revetment to be placed between the toe and the crest of the levee. For the levee without a marsh, 0.5 ton rock was used for armoring; for the levee with marsh, the rock size was reduced to 0.25 ton. The approximate cost for armoring was $110/cubic yard. Initial fill volumes will likely include an "over-build" to compensate for the initial subsidence. It is estimated that the subsidence on bay mud could be as much as 30 percent of the levee height. To account for this, an additional 30% of soil was added to the design cross-sections of all levees.

Marshes. The analysis assumes that marsh plain elevation is 9 ft MLLW, and that tidal marshes would be restored by breaching any outboard levees and relying on natural sedimentation for the accretion of a marsh. While relying on natural sedimentation for the accretion of a marsh plain, there are a number of restoration measures that can be added to a project accelerate the evolution and to enhance the habitat. Some common features are: levee breaches, pilot channels, starter channels, side cast natural levees, and ditch blocks. The average cost for these features in previous restoration projects in San Francisco Bay is about $10,000 per acre.

Cost Calculation Details (cont.)

Ecotone Slope. For the upland ecotone slope, the analysis assumed the top of the transitional-upland area would be sufficient to accommodate the extreme water level; the bottom of the upland-ecotone was assumed to be at marsh plain elevation. The analysis assumes an idealized side slope of 30:1 (H:V); during final design and construction, the slopes would include some variation both in planform to create a more natural shoreline and along the slope to create benches and shallow depressions to form pannes at a variety of elevations. The intent of this approach is to work within the overall idealized slope to create an upland transitional zone with some complexity. To reduce the initial fill requirements it may be possible to construct the ecotone slopes in stages. The approximate cost for poorly sorted, unengineered fill is $15/CY.

Maintenance. The analysis assumes that that the maintenance requirements for the levee, tidal marsh and ecotone slope are 1% of initial construction cost per year for 50 years. The analysis considers costs over 50 years, with construction costs of both levees and tidal marsh occurring at Year 1, and maintenance costs occurring at a constant rate over the next 49 years. Society generally places a greater weight on costs that would occur in the near future versus costs that would occur further in future, all else being equal. To account for this time preference, the stream of maintenance costs is converted to its equivalent present value using the discounting process and a discount rate of 4% per year.

7.1.1 Cost Savings: Levee With Wetland Restoration

Figure 28 displays the total cost per mile of constructing a levee without a marsh compared to the cost of a levee with varying widths of marsh for a 100 year water level with 14 inches of sea level rise. The total cost for the levee without a marsh over 50 years is just over $12M per mile. With a 200 foot wide marsh in front of the levee ,the cost of the levee is reduced to about $5.5M per mile. Restoring a 200 foot wide marsh costs about $0.8M per mile, for a total cost of about $6.3M.

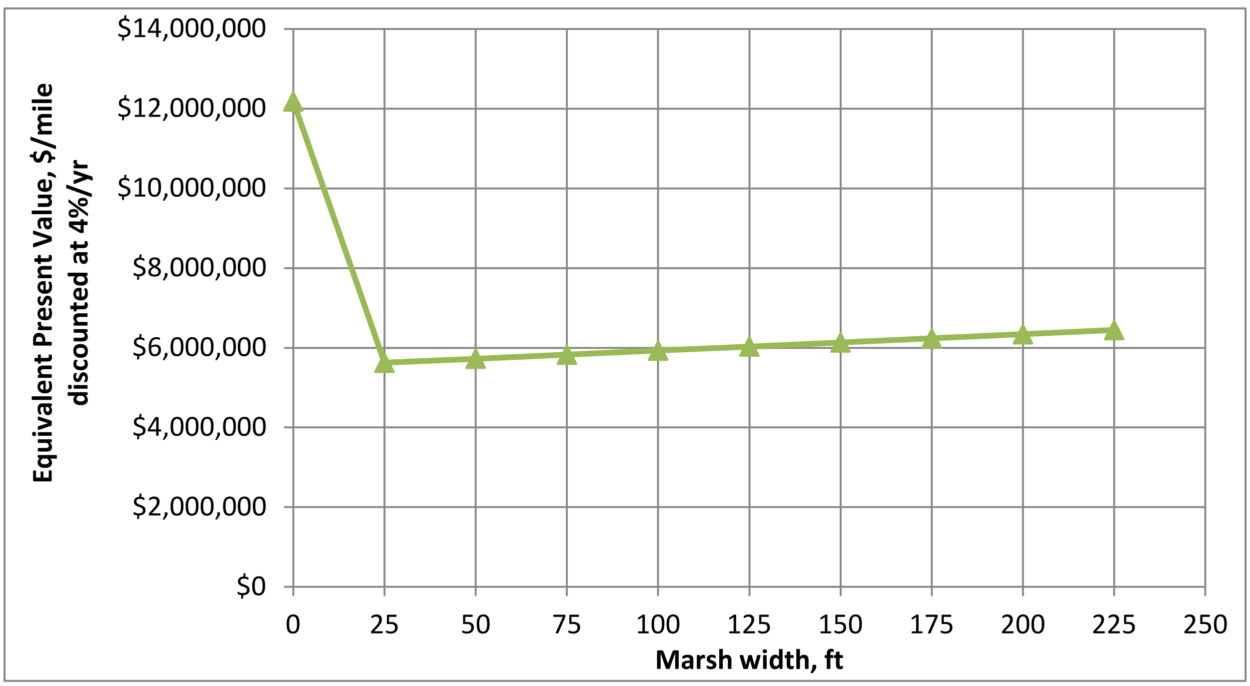


Figure 28. The total cost of levee construction over 50 years drops considerably when fronted by a marsh, due to the effects of wave attenuation.

In this example, there is a saving of about $6M per mile for a 200 foot wide marsh over 50 years. This would require creating about 80 acres of marsh per mile, so the value per acre of marsh in this scenario is approximately $75K (Figure 29). As the marsh width increases, the cost saving decreases. Most of the benefit from the marsh is realized in the close to the bay edge of the marsh where the reduction in wave height is greatest, a finding echoed in previous studies (King and Lester, 2001; Möller et al. 2001). For a marsh 100 feet wide, only 40 acres need be restored, and the value of each acre (equivalent reduction in levee costs) comes to about $160K per acre. However, many of the other ecosystem services described in section 3 benefit from much wider and larger areas of tidal marsh. These services benefit from larger acreages that are not confined to narrow bands close to the shoreline. Broader marshes would also serve as buffers for marsh edge erosion, which could otherwise cause the marsh to narrow over time. Wider marshes would therefore facilitate wave attenuation for relatively longer periods of time.

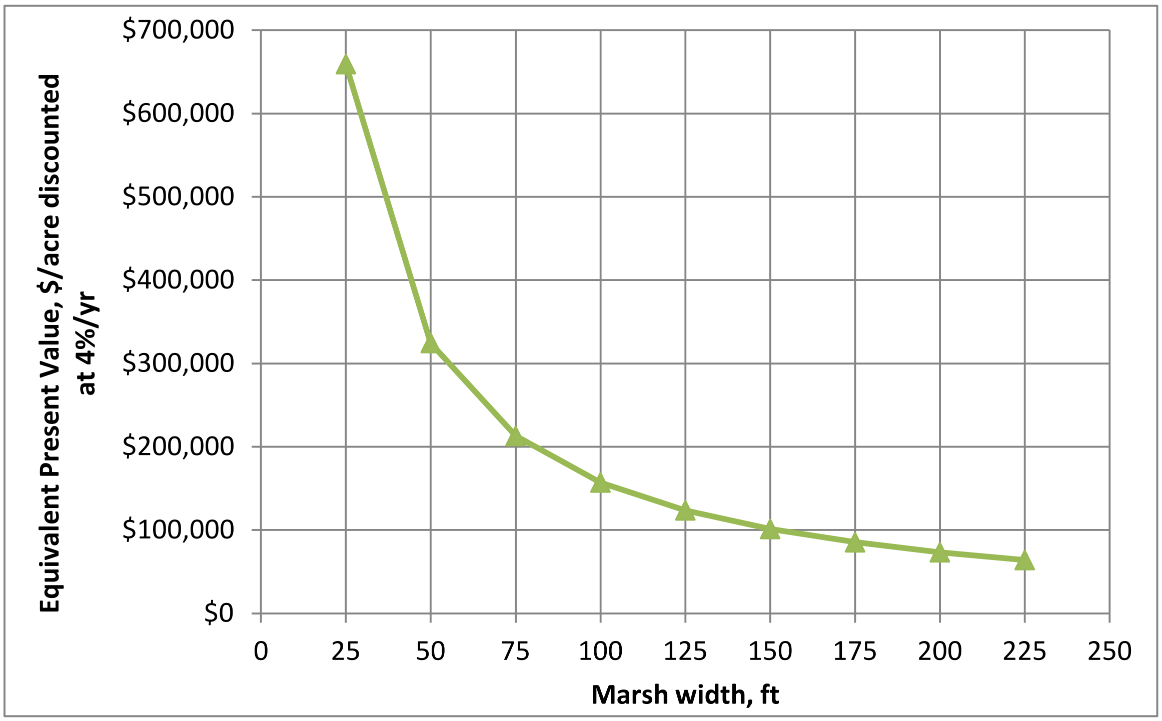


Figure 29. Cost savings per acre of wetland (averaged over 50 years) vs. marsh width.

7.1.2 Cost Savings: Levee With Wetland and Ecotone Restoration

The preceding scenario assumes that the marsh will accrete at a sufficient rate to keep up with sea level rise and maintain its wave attenuation function at least until the second half of the century. Accretion rates on marshes measured in the Bay show that this may be a reasonable assumption at least until 2060-2070 (Takekawa et al. 2012). However, at some point sea level rise may accelerate past the rate at which the marsh can accrete vertically, and the marsh may start to move landward. The construction of an upland-wetland ecotone slope could provide a buffer area into which the marsh could migrate landward, while maintaining sufficient width to attenuate waves. As discussed in the preceding sections, the presence of an ecotone slope provides additional ecological benefits to the marsh, contributing to the restoration of a "complete marsh". However, the construction of such a slope would require additional fill.

Figure 30 shows the total cost per mile of constructing a levee with a marsh and ecotone slope compared to the cost of a levee alone. As with Scenario 2, the total cost for the levee without a marsh for over 50 years is just over $12M per mile. With a 200 foot wide marsh and an upland ecotone slope in front of the levee, the cost of the levee is reduced to about $4.2M per mile as the ecotone slope also attenuates wave action. Restoration of an upland ecotone slope and a 200-foot-wide marsh costs about $2M per mile, for a total cost of about $6.3M per mile over 50 years.

The cost saving per mile is about the same for the scenarios with and without the ecotone slope. The ecotone slope does require more fill and maintenance; however, the additional reduction in wave run-up allows the crest elevation of the levee to be lower. For the scenarios discussed here, these two costs appear to balance each other out; while the upland ecotone slope has a larger volume, it is constructed from lower-cost unengineered fill and does not require armoring.

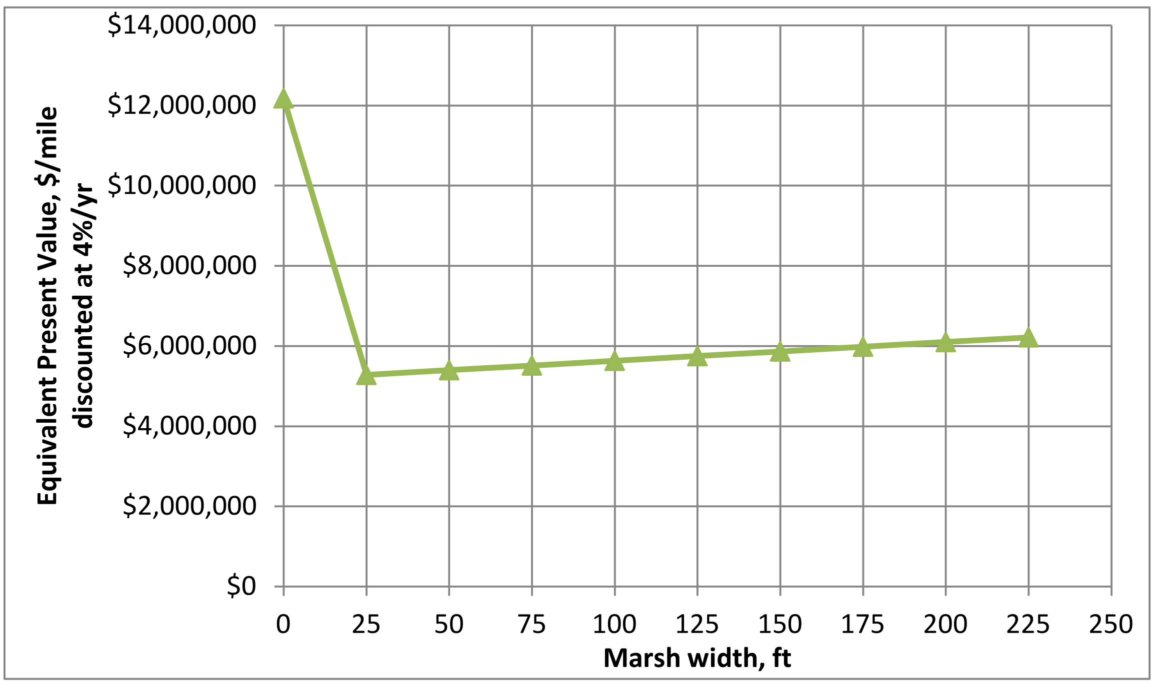


Figure 30. Marsh width versus equivalent present value per mile over 50 years for a levee with a marsh and upland ecotone slope.

Cost Savings Summary. Figure 31 summarizes the relative costs of the three scenarios (holding the line, levee realignment with marsh restoration, and levee realignment with marsh and ecotone restoration), shown in relation to each other for a 200-foot-wide marsh. It is important to note that the total economic benefits of incorporating tidal marsh restoration into flood risk management strategies would exceed the value estimated by this analysis, since it only considers flood risk management and not other ecosystem services such as wildlife habitat, carbon sequestration, and water quality improvements as described in section 3.

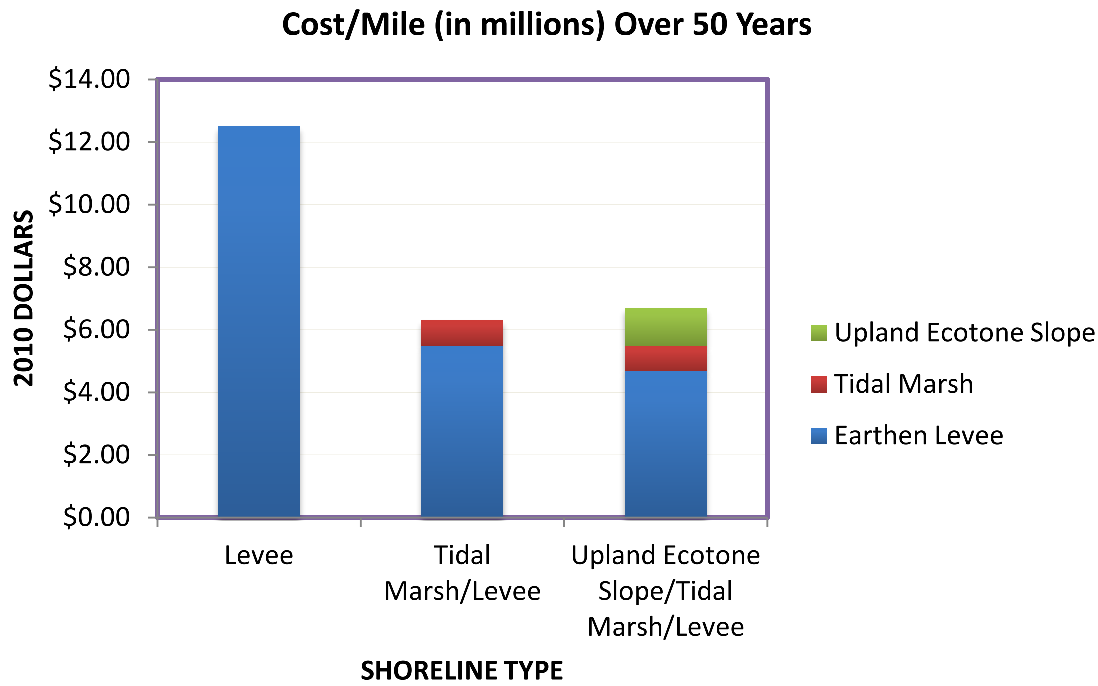


Figure 31. A comparison of the total potential costs of various flood risk management scenarios.

8 A Shoreline Flood Management Approach During an Era of Sea Level Rise

The response to sea level rise and flood risk management will vary around the Bay depending on the particular conditions of the site. There is no single strategy that will fit all locations. This study identifies a shoreline management approach that would take advantage of adjacent landscapes and land uses for particular locations to increase flood risk management benefits and reduce their costs. This approach is one that could have significant benefits beyond the flood risk management savings described here.

8.1 The Horizontal Levee

The significant flood risk management benefits that can be provided by vegetated tidal marshes, have been recognized in the Bay for a long time. Over the last two decades a number of restoration projects such as Warm Springs , Sonoma Baylands and Hamilton Airfield have made use of gentle slopes and benches which mimic marshes to attenuate waves. The Dutch have begun to integrate similar elements into their shoreline defense planning that they describe as "the horizontal levee."

We expand and elaborate on the "horizontal levee" concept by modifying its design to include a dynamic ecotone slope; effectively rendering it into an exaggerated version of the levee with restored tidal marsh and ecotone that is described in section 6 and shown in Figure 32. The horizontal levee shoreline management system for San Francisco Bay includes a vegetated tidal marsh adjacent to the

Bay open waters, landward of which is constructed an ecotone marsh, followed by a fresh water swale and terminating in a smaller flood risk management levee (Figure 32).

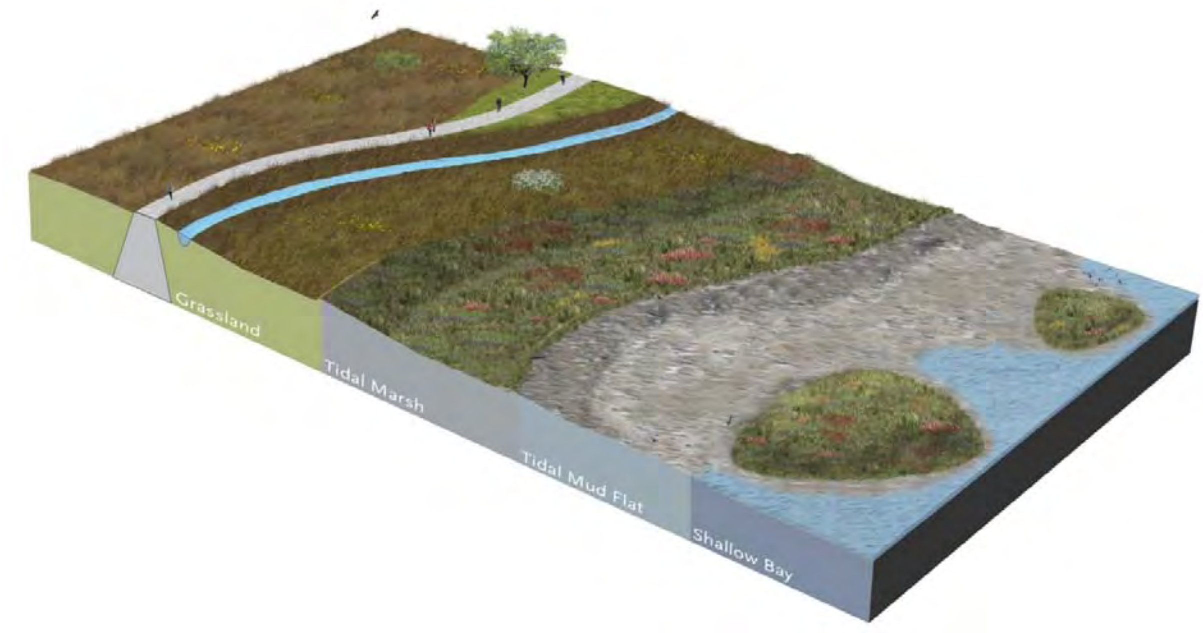


Figure 32. The “horizontal levee” design concept.

This horizontal levee system is partially self-maintaining, providing space for the marsh to transgress with rising sea level and enabling the ecotone marsh to build in elevation as sea level rises. This feature can extend the utility of the flood risk management system over time and significantly reduce operation and maintenance costs of the entire shoreline management system. It takes advantage of natural marsh processes that have been operating in the Bay for thousands of years.

The horizontal levee system can capitalize on the existence of a large-scale marsh program that is already underway in San Francisco Bay, and it can enhance the success of that initiative by providing a solution to the threat of rising sea levels. Absent the redesign, present marshes may not be able to keep up with accelerated sea level rise towards the end of the century and may inundate and drown. The horizontal levee offers an interim solution to critical problems facing the region over the coming decades as sea level increases.

The horizontal levee provides a vegetated buffer that reduces the destructive wind and wave energy associated with storms. The horizontal levee would increase in elevation over time, enhancing the ability of the flood risk management system to keep pace with sea level rise, reducing damage to the levee and reducing maintenance costs. Traditional flood risk management levees would need to be overbuilt or raised periodically as sea level increased. The horizontal levee would provide upland for adjacent tidal marshes as the system evolved. As suspended sediment concentrations in Bay waters are declining, depriving marshes of a key building material, transgression of the marsh is more likely.

8.2 An Integrated Shoreline Management System

Flood protection along the shoreline of San Francisco Bay has been accomplished almost exclusively by constructing engineered barriers and associated water control structures, such as tide gates and pumping stations. The vast majority of the engineered barriers are earthen levees, though seawalls have also been employed where conditions require. These structures have generally been designed for the sole purpose of providing flood protection, without consideration for accomplishing other shoreline management objectives.

By considering opportunities to accomplish related objectives, especially habitat restoration and water quality improvements, the horizontal levee offers significant advantages over conventional single-purpose design. By recognizing the flood risk management benefits provided by tidal marshes, the opportunity arises to build those benefits into the ongoing Bay wetland restoration program, something that has been done in an *ad hoc* fashion to date. Further, by considering marsh restoration needs when operating the flood risk management system, options present themselves to collaborate across programs that otherwise would not be considered.

The horizontal levee approach within a shoreline management paradigm includes an upland ecotone slope immediately adjacent to the landward edge. By considering this upland ecotone slope from the point of view of accomplishing multiple management objectives, it becomes clear that three objectives can be attained that at first appear unrelated.

First, construction of the ecotone slope restores a component of the historic wetland ecosystem that has been almost completely eliminated by development, thereby providing habitat for important plant and animal species. So, not only does it serve as a flood protection barrier, but it replicates a valuable component of the original marsh ecosystem, enhancing our existing marsh restorations. Second, if the upland ecotone slope is managed by using treated waste water from adjacent water treatment plants, it reduces the need for treatment plants to pump waste water long distances to discharge points. This reduces energy cost (electricity for pumping) and maintenance costs (for the buried discharge pipeline) to the treatment plant operator. Third, the upland ecotone slope is constructed using dredged sediment such as excavated from adjacent flood control channels, thereby increasing sediment volumes applied to the marsh and reducing costs to flood districts that currently excavate channel sediment and transport it to distant disposal sites.

There is however, a need for urgency if the value of wetlands is to be realized. The natural evolution of tidal marshes is a gradual process that occurs over years and decades. Sea level rise is projected to accelerate, sediment supply in the Bay is projected to decrease. The sooner that marsh restoration is initiated, the sooner the marsh will begin to build in elevation and for vegetation to establish.

9 Key Findings

Utilizing tidal wetlands in conjunction with more traditional hard-engineered flood risk management approaches such as levees is cheaper and more cost-effective than simply relying on traditional approaches alone. Unlike traditional approaches to flood risk management, tidal wetlands also confer a broad range of additional ecological and economic benefits to the landscape. They provide habitat for fish, birds, and wildlife which has been lost due to diking in the 19th and 20th centuries. They sequester carbon from the atmosphere and use it to build up organic peat soils. Finally, they help remove pollutants from a Bay severely impacted by runoff from developed areas.

The key findings of this study are as follows:

- Sea level is rising in San Francisco Bay at an accelerated rate. The California Ocean Protection Council estimates that sea level will rise to 14 inches by 2050 and to 55 inches by 2100.

- The existing shoreline flood risk management system in San Francisco Bay consists of an extensive network of earthen levees in varying degrees of repair, as well as sea walls and water control structures in select locations.

- The greatest flooding threat to developed areas along the shoreline of San Francisco Bay during the next several decades is from flooding caused by storms occurring during periods of high tides, not from elevated sea levels alone.

- Prior to the latter half of the 21st century it may be possible to adapt to increased sea level and protect existing land uses by employing strategic modifications of the current shoreline management paradigms.

- Later in the 21st century protection of low-lying developed areas along the Bay shoreline may not be sustainable without extensive modification of shoreline protection structures.

- Tidal marshes can provide significant flood risk management benefits by attenuating wave energy during storms, and at significantly lower cost than traditional flood risk management structures. Tidal marshes located adjacent to levees can significantly enhance flood risk management benefits compared to those provided by the levees alone.

- By combining current regional marsh restoration and regional flood risk management planning into a new shoreline management approach, costs could be significantly reduced while providing equivalent levels of protection.

- A "horizontal levee," a hybrid marsh-levee flood risk management system as described in this report, is one approach to help the Bay shoreline keep pace with sea level rise over the next century in critical locations.

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