# Science Foundation Chapter 1
# The Dynamic Workings of the Baylands

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## INTRODUCTION

This chapter describes many of the important factors which will govern the future evolution of the baylands. It describes conceptual frameworks for how baylands evolve, particularly in the light of climate change. The importance of sediment supply and topography are highlighted. The geologic and historic record is then examined for clues to how marshes have responded to significant change in the past. Looking to the future, the likely drivers of change that will govern bayland evolution over the next century are examined.

The 1999 Goals Report discusses some of the lessons learned in tidal marsh restoration that occurred in the 1980's and 1990's. With more restoration happening in San Francisco Bay now than ever before, our understanding of tidal marsh restoration processes continues to advance. However, just as important is our increased awareness of the interconnectedness of adjacent habitats. Given the complexity of the tidal conditions and freshwater inputs to San Francisco Bay, the baylands are actually a dynamic continuum of habitats, and drawing boundaries between the functions of the open water bay, intertidal mudflats, tidal marshes, and the adjacent uplands is difficult and sometimes arbitrary. Over the next century we expect climate change and other drivers to create a more dynamic landscape with shifts in the location and nature of these habitats.

A more accurate way to consider this continuum of habitats involves the concept of a 'complete marsh,' which emphasizes all aspects of a baylands ecosystem and the full gradient of functions and values. Restoring a tidal marsh alone, without considerations of how it connects to the lower elevation mudflats and open water and the higher elevation uplands, may result in an incomplete marsh in terms of ecosystem services. Therefore, this update expands our look at the baylands into the subtidal and upland zones to emphasize the importance of this complete marsh concept and how they may evolve in the future.

## HOW DO BAYLANDS EVOLVE?

Habitat evolution in the light of climate change and sea-level rise in particular, can be related a number of factors which together govern the condition and extent of the habitat:

- migration (also called transgression) - upland migration based on sea level, hydrology, sediment supply, plant processes, topography, and subsidence
- drowning - vertical accretion and change in inundation regime of the marsh surface
- erosion - horizontal/shoreline change along the marsh edge

Migration will in large part be governed by the upland topography landward of the marshes. The concept of 'elevation capital', discussed later, provides a framework for describing drowning. Sediment supply and wave energy may be a framework to describe erosional processes. Brinson et al (1995) provide such a framework for addressing the transformation from one habitat class to another as sea-level rises; from uplands through wetlands to mudflat and subtidal. This is illustrated in Figure 1.1 where estuarine-terrestrial interaction can be described as one of four possible interactions based on two conditions at the landward transition zone edge ('migration' versus 'squeeze') and two at the bayward marsh edge ('prograding' versus 'eroding').

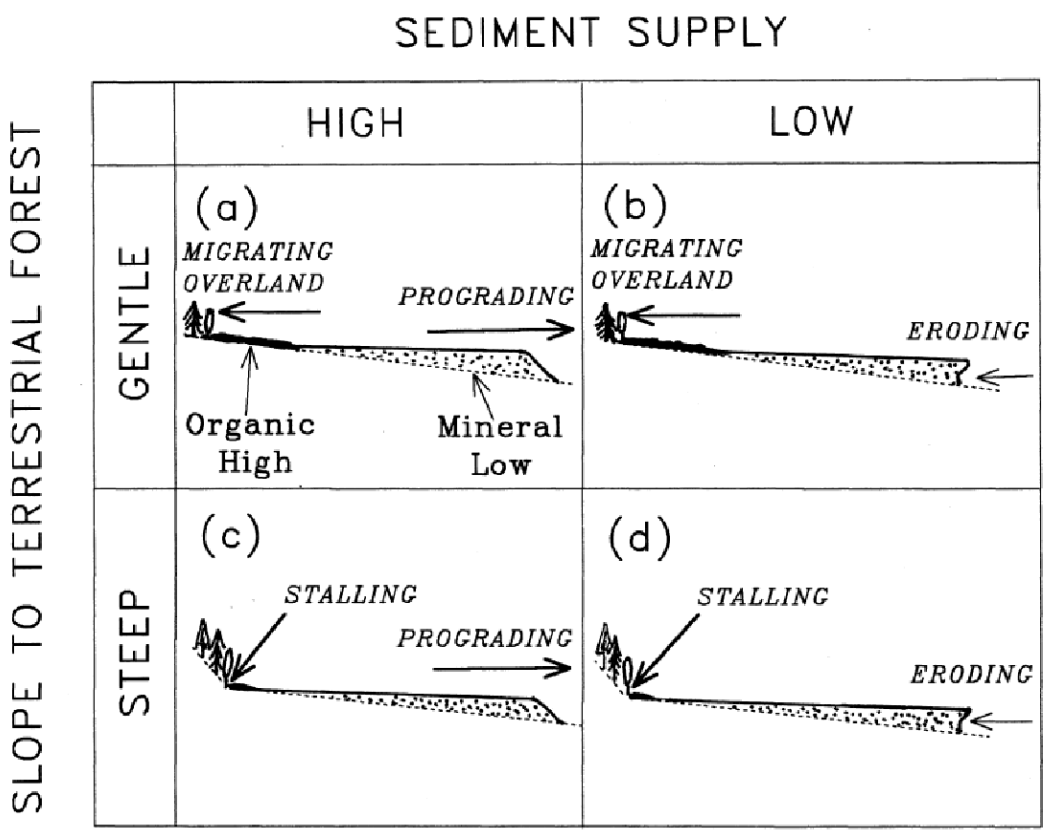


**Figure 1.1.** Classes of the response of the marshes to sea-level rise as a function of extremes in sediment supply and upland slope, after Brinson et al (1995).

To begin, we will look at factors controlling the evolution of the marsh plain and then look in more detail at shoreline processes and accretion processes.

Because tidal marshes are highly sensitive to elevation, their sustainability will depend on the balance between sea-level rise and marsh sediment accretion (Michener et al. 1997, Morris et al. 2002). As sea-level rises, tidal marshes will have to accrete sediment more rapidly in order to maintain current elevations relative to tidal levels. As with present processes, this vertical accretion of sediment will be a combination of both organic (primarily from plant production) and mineral matter accumulation to offset sea-level rise and vertical land movement (Figure 1.2a).

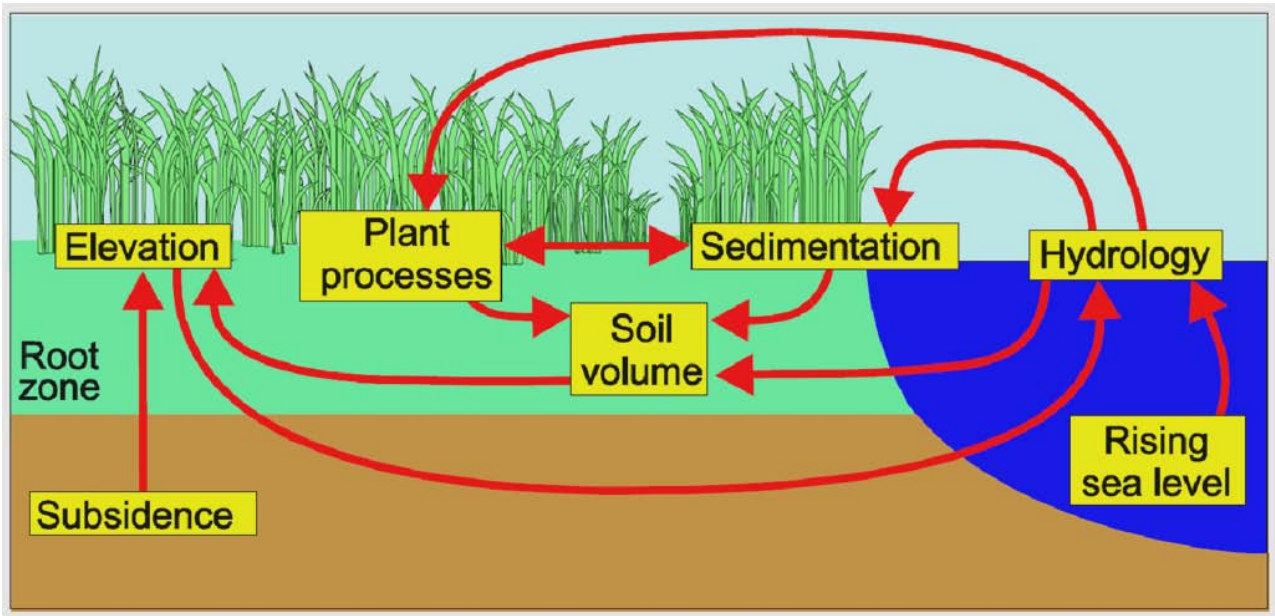


**Figure 1.2a.** Relationships influencing marsh elevation. Source: Cahoon 1997.

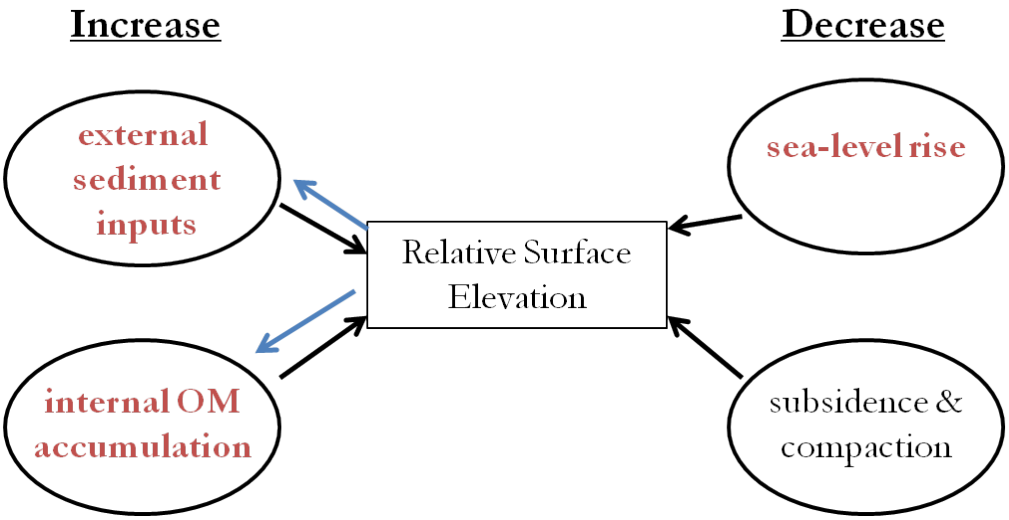


**Figure 1.2b.** Factors affecting elevation within the marsh. Mineral and organic accumulation as positive factors and sea-level rise, local subsidence, and compaction leading to elevation loss.

There are substantial uncertainties surrounding future predictions of both sea-level rise and suspended sediment concentrations, and with interactions between factors there is even greater uncertainty in predicting sustainability of tidal marshes. If sea-level rise is at the low end of future predictions, and suspended sediment concentrations are not dramatically reduced, it is likely that tidal marsh elevations will remain similar to current conditions (i.e., existing tidal marshes remain highly sustainable, along with relatively rapid development of newly restored tidal marshes). However, if future rates of sea-level rise are closer to predicted high rates, or if suspended sediment concentrations drop substantially, tidal marshes are likely to begin to lose elevation, and restored marshes will develop much more slowly (or not at all, in worst case scenarios). The rate of elevation loss will be influenced directly by the interacting effects of increases in water level and decreases in suspended sediment concentrations (Figure 1.2b).

Most existing Bay tidal marshes are currently dominated by high marsh vegetation and are found at the upper elevation range for tidal marsh ecosystems. Marsh vegetation is directly affected by elevation. It is one of the most important factors affecting frequency, depth and duration of tidal flooding. Site-specific elevations of tidal marsh plants are also affected by exposure and soil type. In general vegetation occurs from just above mean sea level (MSL) to just above mean higher high water (MHHW). *Spartina foliosa* is found at lower elevations, while the marsh plain (at an elevation close to MHHW) is dominated by *Salicornia pacifica*, along with a number of other species depending on local elevation, drainage, soils, site history and other factors (Baye et al. 2000, Grewell et al. 2007). Similarly, frequently flooded brackish marsh sites have characteristic species (e.g., *Schoenoplectus* spp.) with more salt tolerant vegetation on the marsh plain (Vasey et al. 2012). The fact that most Bay tidal marshes are relatively high elevation marsh plains implies that they will remain vegetated even with some loss of elevation. Their relatively high elevation gives them substantial 'elevation capital' (Cahoon and Guntenspergen 2010). In other words, they have a large amount of elevation to lose before they are converted to unvegetated mudflats. The concept of elevation capital with specific reference to San Francisco Bay will be discussed in a subsequent section.

If tidal marshes cannot keep pace with sea-level rise and begin to lose elevation, tidal marsh habitat will be lost and converted to unvegetated mudflats when elevations within the marsh drop below the threshold for survival of marsh vegetation. In places where adjacent areas are relatively flat and at slightly higher elevations, marshes could migrate inland. However, there are areas around the Bay surrounded by levees or other areas with abrupt elevation changes and migration will be constrained. In areas where migration is physically possible, there also are potential limitations depending on land ownership and future land management decisions.

Simultaneous with changes in elevation due to sea-level rise, salinity is likely to increase due to the increased marine influence, as well as to changes in freshwater inputs associated with climate change. Increasing salinity, especially during the summer growing season, will affect vegetation, with a likely shift of more salt tolerant vegetation establishing inland. However, migration of vegetation inland may not be so simple, as there are large differences in soil conditions from freshwater tidal marshes to salt marshes, and dispersal and recruitment of vegetation could be limited. Freshwater wetland soils typically have very high organic matter content and correspondingly low soil bulk density; whereas, salt marsh soils have relatively low organic matter content and much higher soil bulk density (Nyman et al. 1990). Movement of propagules is typically downstream within the estuary (from freshwater marshes to salt marshes), and dispersal and recruitment of vegetation upstream could be much less predictable. As a result of such factors, salt water intrusion can lead to the conversion of freshwater or low salinity wetlands to open water rather than to more salt tolerant vegetation in some systems.

## EROSION

Sea-level rise in the Holocene slowed significantly about 6,000 years ago and the marsh edges of San Francisco Bay have been evolving over the last 2,000 to 3,000 years. While marsh plain evolution has been well documented for San Francisco Bay (Goals Project 1999), less attention has been paid to the low marsh-mudflat transition zone or evolution of marsh edge over time.

The major physical drivers of marsh edge evolution and shoreline change include wind-wave energy and direction, sediment supply, vegetation and sea-level rise (Allen 1989, Schwimmer 2001, Moller and Spencer 2002, Pedersen and Bartholdy 2007) (Figure 1.3). Conditions at the marsh edge are governed by the mudflat which influences the size and energy of waves reaching the marsh – mudflats and marshes are interdependent.

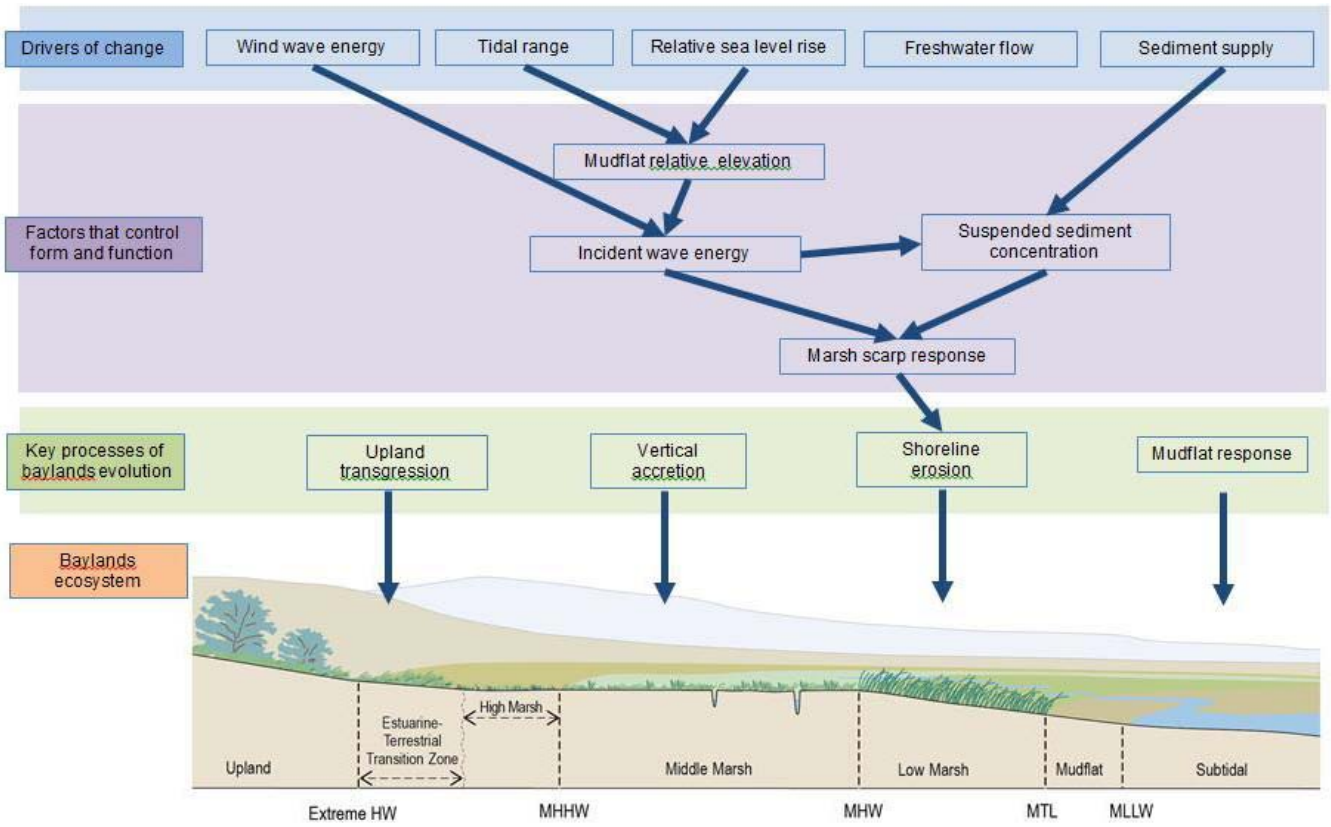


**Figure 1.3.** The major physical drivers of marsh scarp evolution and shoreline change.

Within the normal tidal range, mudflat serves to filter offshore waves to a narrow height band. Small waves increase in height as the water depth shallows and large waves break and are attenuated due to friction (Lacey and Hoover 2011). The result is that waves at the shoreline are relatively constant in height. Mudflat slope and shape may thus control the position of the shoreline. It erodes to widen the mudflat until wave energy is reduced sufficiently so that erosion no longer occurs (this is the same idea as a shore platform/cliff retreat model, e.g., Trenhaile 1987)

A combination of sediment supply and wave energy may control shape and elevation of the mudflat (Bearman et al. 2010), which in turn determines wave energy inshore at the scarp edge. If the mudflat is

high enough, large waves would only reach the shoreline at extreme water levels. If this is the case, scarps may be active for limited periods of time. Where the mudflat is lower, more energy is delivered inshore and wave energy is higher at the shoreline more frequently.

If mudflat does not keep up with sea-level rise, more wave energy will reach the shoreline leading to changes in rate of change and typology. A hypothesis for shoreline evolution of San Francisco Bay is described below, based on a multi-decadal analysis of shoreline change over time in San Pablo Bay and a review of current scientific literature (Figure 1.4).

In this conceptual model, a given marsh scarp (1) fails under pressure from wind wave energy and wave run up. Undercut blocks, or cantilever failures, deposit sediment (with or without vegetation) in front of the marsh scarp (2). The block of sediment dissipates wave energy until it is scoured away and redistributed on the mud flat or marsh plan, creating an erosional environment as wave energy is then directed back to the marsh scarp, increasing marsh retreat. If the failure is large enough to redirect wave energy for longer periods of time, the failed blocks may create an environment for sediment deposition and trapping between the old scarp and the failed block (3). A ramped profile begins to fill in the scarp, and build elevation, creating new low marsh, and leaving behind a remnant scarp (4). This ramping continues, and dissipates wave energy such that the low marsh vegetation traps sediment, building up to mid-marsh habitat (5). When the new mid-marsh levels, the ramped profile steepens and wind wave energy begins to erode the new mid-marsh creating a new scarp (6) and the cycle continues.

## DROWNING

Historic data indicates that tidal marshes in San Francisco Bay can withstand greater rates of sea-level rise than currently exist (2-3 mm/year, NOAA 2005), as long as suspended sediment concentrations remain relatively high and other factors, such as subsidence, remain relatively constant. For example, many low marsh stations within San Francisco Bay tidal marshes have accumulation rates of 6 mm/year or more. Data from other regions in the country that have experienced marsh loss give some help in identifying threshold rates of sea-level rise that may lead to tidal marshes losing elevation. For instance, in both Chesapeake Bay and Louisiana, substantial wetland loss has occurred in regions with high rates of local subsidence, with few areas able to keep pace with rates of sea-level rise greater than 10 to 12 mm/year. Thresholds for a particular location will also be affected by suspended sediment concentrations, wave regimes, and other factors. Very few sites can maintain elevation if local rates of sea-level rise are close to these values, unless suspended sediment concentrations are very high. In addition, a number of modeling studies indicate that thresholds for maintaining marsh elevation in the face of increased sea-level rise are likely in this range (see Science Foundation Chapter 2).

Increases in rate of sea-level rise will lead to changes in sediment processes within tidal wetlands (Figure 1.5). An increased rate of sea-level rise will lead to a higher frequency, greater depth, and greater duration of tidal flooding. Both mineral and organic matter accumulation will respond to this increase. Increased tidal flooding will likely increase rates of mineral sediment deposition because of longer time periods for suspended sediment to drop out of the water column, as well as greater inputs of suspended sediment with a deeper water column. However, greater water depths could lead to greater wave effects, effectively reducing sediment accumulation and potentially promoting sediment erosion. As indicated above, any local changes in suspended sediment supply would also directly affect the rate of sediment accretion at a particular location.

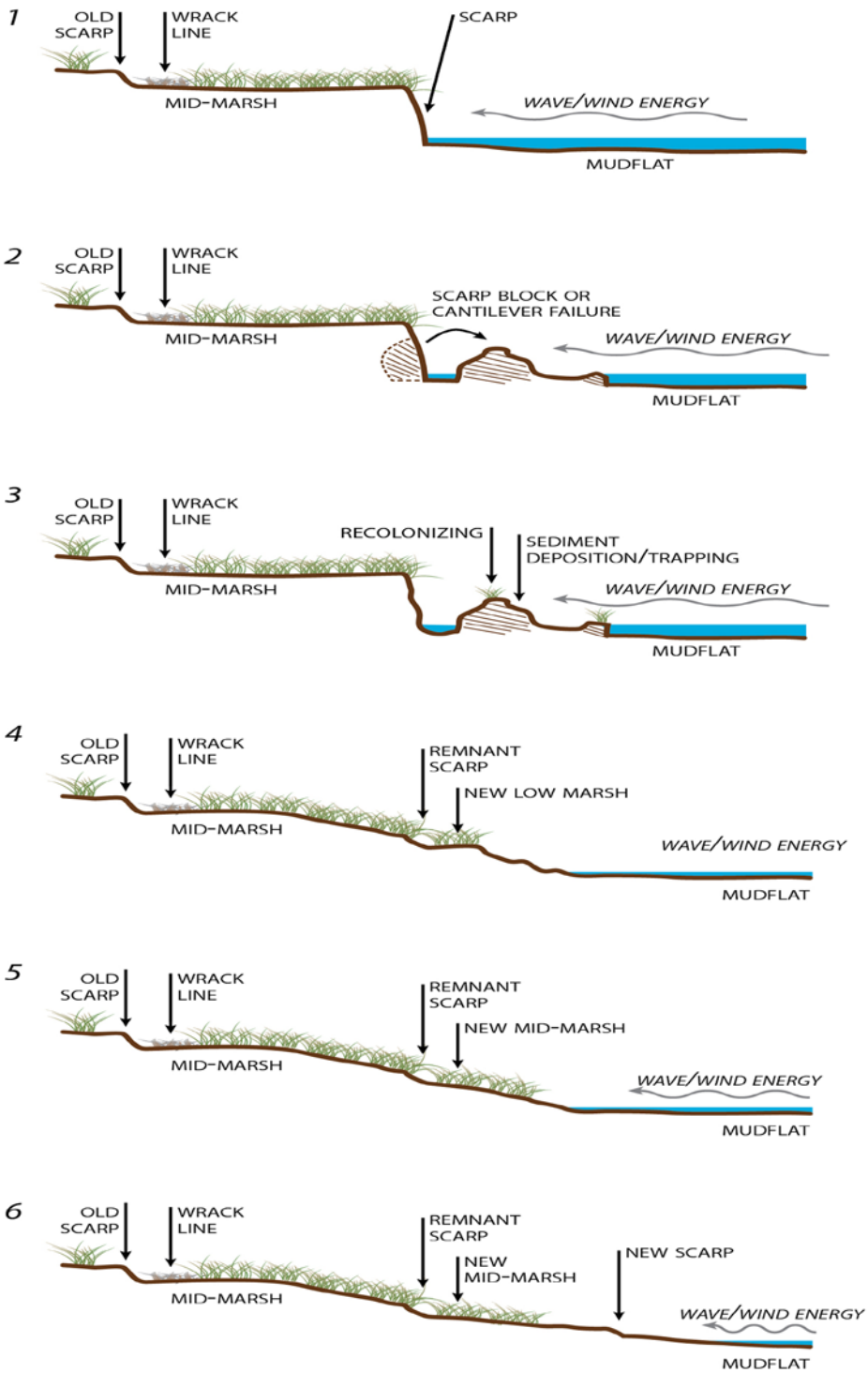


**Figure 1.4.** Conceptual diagram of marsh scarp evolution for prograding marsh (Beagle et al. (2015), adapted for San Pablo Bay from Allen 1989).

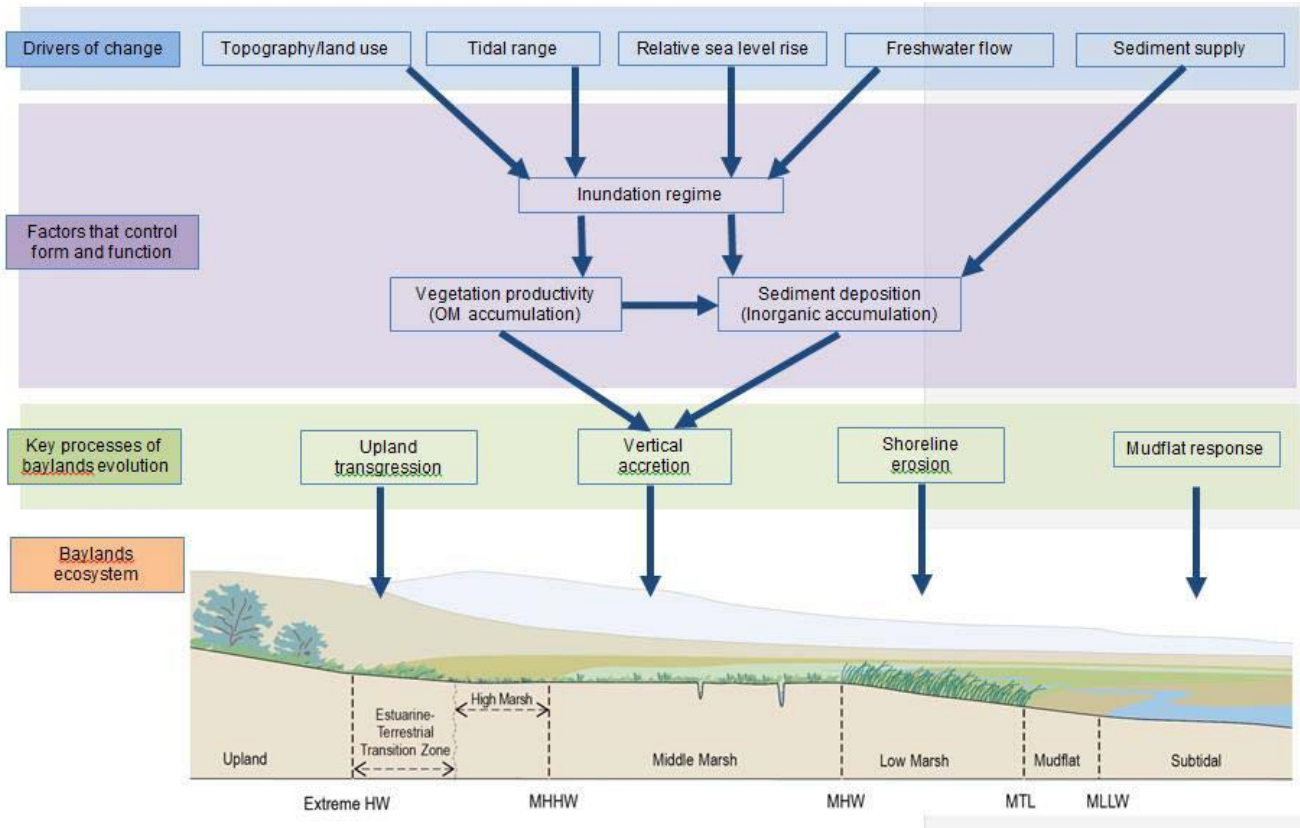


**Figure 1.5.** Conceptual box and arrow model showing major drivers of vertical accretion.

Within a particular marsh, there are also predictable spatial patterns in mineral sediment deposition, with greater rates of accumulation closer to tidal breaches, as well as bordering tidal channels (and leading to creation of slightly elevated natural levees along tidal creeks). For example, accretion rates at stations within the restored Island Ponds (Pond A21) in the Far South Bay were highly correlated with distance from tidal breach (Callaway et al. unpublished data). Similar results have been found for the effect of distance from a sediment source on mineral accumulation rates within natural salt marshes. As marshes are flooded more, there will likely be some positive feedback to maintain elevation, as lower elevations will lead to greater rates of mineral sediment inputs. However, this feedback depends a lot on the concentration of available suspended sediment.

Similarly there is a strong feedback between the inundation regime (frequency, depth and duration of flooding) and organic matter accumulation rates within the marsh. At very low elevations within the marsh, primary production is inhibited by increased stress from anaerobic conditions associated with high rates of inundation. At the upper end of the marsh, salt stress (and potentially competition with non-wetland species) leads to a reduction in wetland primary productivity. Together, these two factors typically result in a peak of productivity somewhere close to or just below marsh plain elevations (Morris et al. 2002). Schile (2012) found support for this these critical elevation bands favored by specific plant species across tidal marshes in San Francisco Bay, and it also has been shown to occur in a number of other tidal marsh ecosystems.

As a result, a slight increase in inundation rates could lead to an increase in plant productivity, as long as the initial plant community is at a starting elevation above the elevation of peak productivity. If inundation

is increased at initial lower elevations (or if cumulative increases in tidal flooding are great enough over time to push the plant community over this threshold elevation), it will result in reduced plant productivity. Plant productivity reduction will lead to a positive feedback that causes further loss of elevation and increased inundation because reduced accumulation in organic matter will not offset the increased rate of inundation.

If a marsh does begin to lose elevation, it may take substantial time for a marsh that is at a high starting elevation (i.e., has substantial elevation capital (Cahoon and Guntenspergen 2010) to lose enough elevation to get to the critical point at which marsh production begins to be reduced. However, if this point is reached, the marsh is likely to lose elevation even more quickly as organic matter productivity is reduced. Eventually the marsh will reach elevations that are so low that no tidal marsh vegetation can continue to grow.

## ELEVATION CAPITAL

Elevation capital is determined in large part by comparing the absolute elevation of a marsh with the local water levels and tide range (Cahoon and Guntenspergen, 2010). Swanson et al (2013) presents a dimensionless indicator (z*) of elevation capital based on mean sea level and tide range:

$$z^* = \frac{z - MSL}{MHHW - MSL}$$

This non dimensional parameter is simple to calculate using existing data (marsh elevation, e.g., from LiDAR and a nearby tidal datum) and makes it possible to compare marshes with different elevations and tide regimes. Figure 1.6 shows an example of z* for a portion of San Pablo Bay in San Francisco Bay. Many of the remaining tidal marshes have a high elevation capital (z*>1), while some diked and subsided areas further inland lie well below the tide range (z*<1).

As sea-level rises, wetlands can increase elevation capital by growing vertically through inorganic sedimentation and organic accretion. Inorganic sedimentation occurs when high tides inundate the marsh and suspended sediments settle out onto the marsh. As sea-level rises, the marsh is inundated more frequently, which increases the amount of sediment available for deposition. Organic accretion occurs through accumulation of organic matter from above- and below-ground plant growth. Morris (2002) provides one of the first measurements of aboveground productivity in a salt marsh from South Carolina, where organic accretion plays a large part in building elevation capital. Figure 1.7 shows the Morris 2002 results in terms of z* values. In this case productivity peaked at approximately 40 cm below Mean High Tide (z* = ~0.3). Below this elevation (at higher levels/frequency of inundation) the system becomes unstable and plants begin to drown.

Swanson et al (2013) fitted similar curves to four marshes in San Francisco Bay (also shown in Figure 1.7) and found that peak organic accretion occurred at a lower rate and at higher z* values than the South Carolina site. This study also estimated inorganic sedimentation at various water levels for the four San Francisco Bay sites, shown in Figure 1.8.

Organic and inorganic accretion must be considered together because each process is a function of a marsh's elevation relative to the tide range and therefore each influences the other. Figure 1.9 shows the

two processes added together for the San Francisco Bay sites. It is notable that this figure does not differ significantly from Figure 1.8 because inorganic sedimentation dominates at these sites and so sediment supply is an important driver for accretion rates. The maximum rate of inorganic sedimentation is between 15 and 60 times greater than the maximum rate of organic accumulation. Inorganic sedimentation will therefore be the primary process for San Francisco Bay's marshes to build elevation capital with increasing sea levels. Fortunately, inorganic sedimentation increases with decreasing elevation and does not exhibit the same instability that organic accretion experiences at low elevations. However, as the rate of sea-level rise increases and sediment supply decreases, the maximum rates of accretion/sedimentation may eventually be unable to maintain elevation capital.

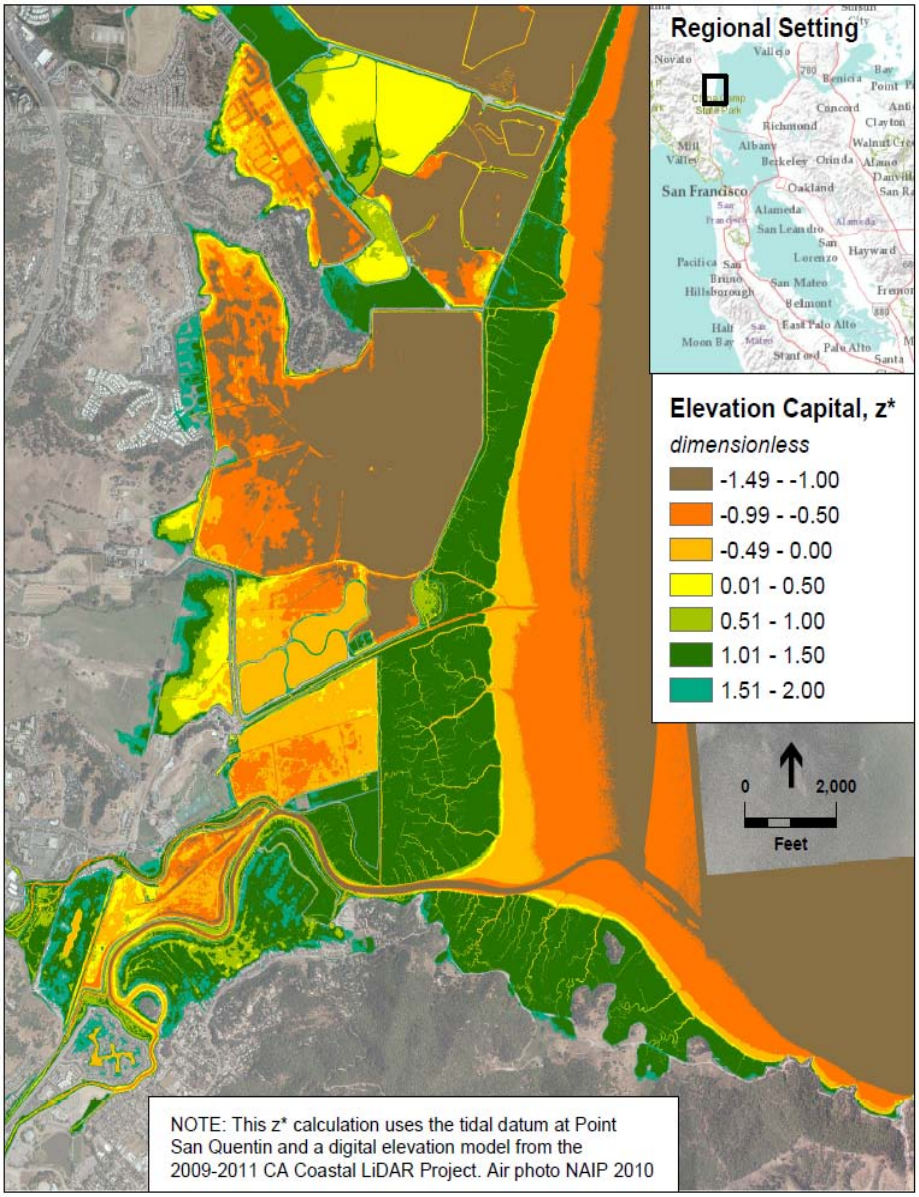


**Figure 1.6.** Elevation capital (z*) at China Camp and neighboring marshes.

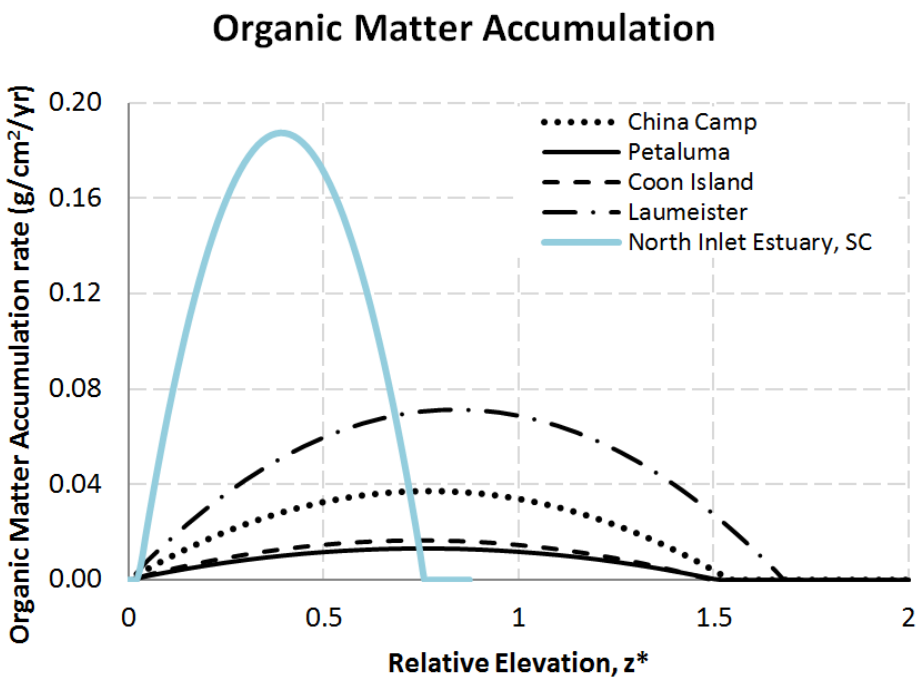


**Figure 1.7.** Salt marsh productivity at various water levels. Organic matter accumulation increases with elevation. Above the peak productivity, marshes are stable because as sea-level rises, organic accumulation will increase (up to a certain threshold). Below the peak productivity marshes are unstable (as water levels rise, salt marsh productivity will go down). Derived from Morris 2002 and Swanson et al 2013.

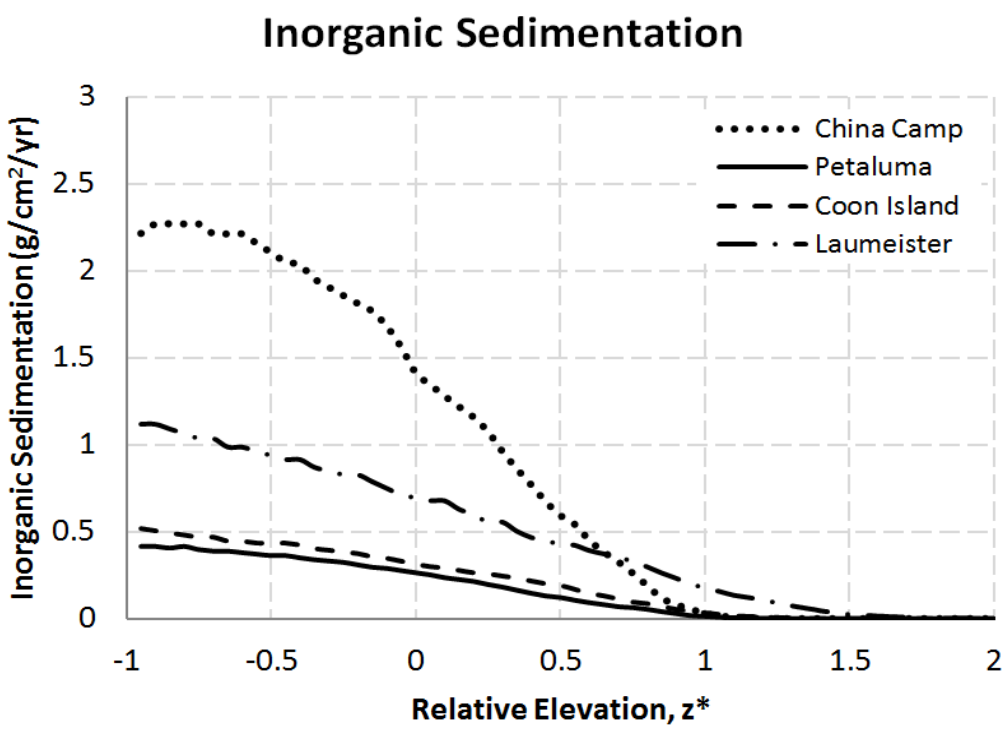


**Figure 1.8.** Inorganic sedimentation for varying elevations relative to the tides. Inorganic sedimentation is higher for marshes lower in the tide range. Derived from Swanson 2013.

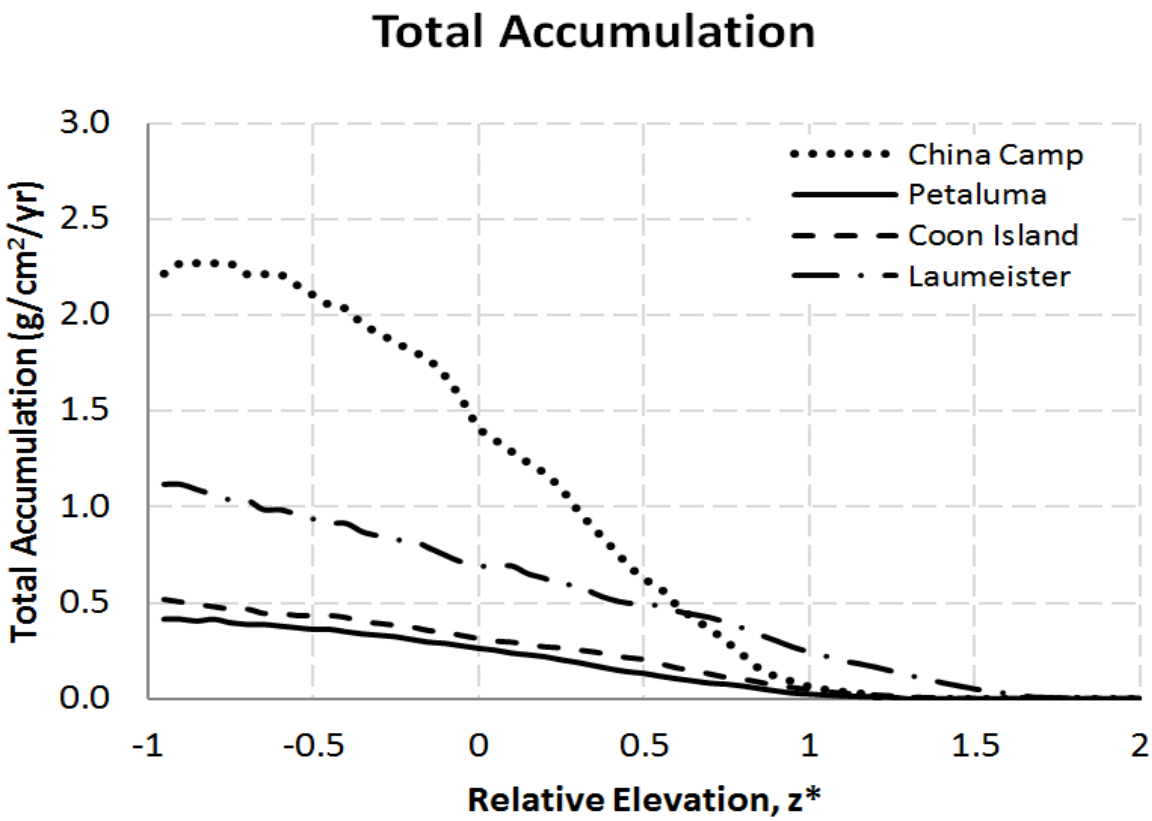


**Figure 1.9.** Total accumulation (inorganic sedimentation and organic accretion) for four sites in San Francisco Bay. Derived from Swanson et al 2013.

## HOW HAVE THE BAYALNDS EVOLVED IN THE PAST?

The Bay's evolution during the historical and late Holocene periods suggest the potential for resilience to climatic variation as well as the challenges and opportunities for enhancing that adaptive capacity. This section looks to the past to show how the Baylands have adapted to significant environmental stressors and how they might do in the future. The Goals Project (1999) briefly considered Holocene geomorphic evolution of the estuary, and its historical ecology, in relation to future climate change as context for the formulation of regional and subregional goals:

"Between 2000 and 3000 years ago, mudflats and tidal marshes began to form around the edges of [prehistoric baylands]…Some of the current global climate change models predict future rates of sea-level rise that exceed the early rates for the Estuary (Gleick et al. 1999). How the baylands might respond to such a rapid increase in sea level is unknown. Their response will depend on the supplies of sediment and runoff, which may increase or decrease with climate change, depending partly on how the land is managed." (Goals Report 1999).

The Goals Project (1999) greatly advanced the understanding of pre-modification Baylands habitats, their ecological functions, and associated physical drivers as to inform the setting of habitat goals (Goals Report 1999, Gedan et al., in press).

Scientific understanding of late Holocene evolution of the Estuary's tidal marshes, especially in relation to paleoclimate and rates of Holocene sea-level rise, has continued to develop in the decade following the Goals Project (Malamud-Roam et al. 2007). This provides an opportunity to update regional wetland ecosystem goals and also provide evidence of long-term ecosystem responses to similar environmental drivers that face us in the future. These include higher rates of sea-level rise, limited sediment supply, warmer and drier climates, and extreme flood events.

Using cores, Atwater et al. (1977, 1979) established robust estimates of millennial-scale marsh accretion rates under late Holocene sea-level rise, and accurate ages of tidal salt marshes. They found that the tidal marsh bayland landscape began developing only 2000-3000 years B.P., and only after rates of sea level slowed to 1-2 mm/yr. This has been recently confirmed by analysis of cores and sedimentation modeling in the South Bay, which shows that marshes in the central portion of the southern San Francisco Bay dated to 500 to 1500 years BP, while expansion of marshes in southernmost San Francisco Bay dated to 200 to 700 years BP (Figure 1.10).

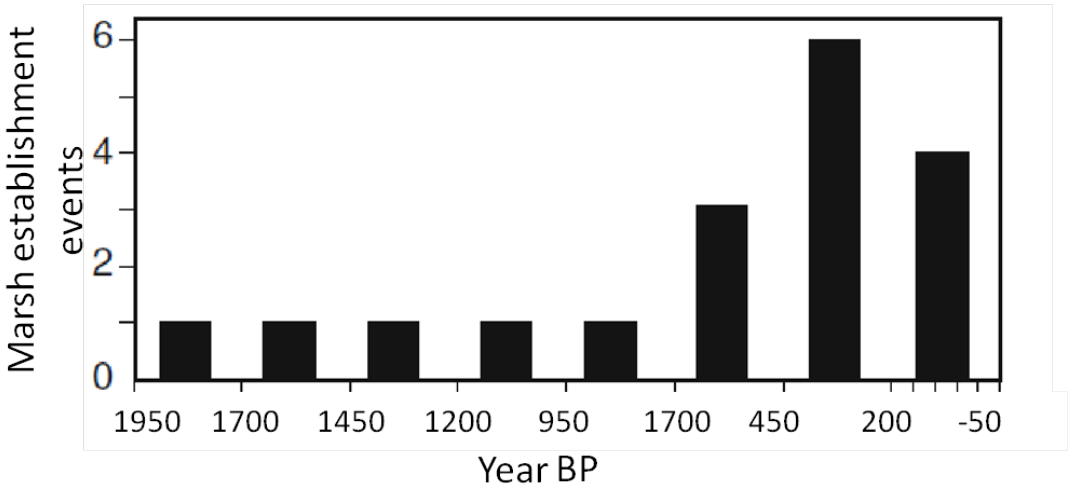


**Figure 1.10.** South San Francisco Bay marsh establishment for 250-year periods over the last 2000 years. From Watson and Byrne (2013).

The USGS San Francisco Bay cores also show that tidal marsh plains either did not develop or were eroded in the early-mid Holocene epoch. Estuarine erosion rates were as rapid as 30 m/year during this period (a combination of horizontal shoreline erosion and submergence of alluvial plains) and sea-level rise rates reached an average of about 20 mm/year or about 10 times the 20th century rate (Atwater et al. 1977). The estuary was characterized by migrating fringing or deltaic marshes (on the time scale of centuries) rather than stable tidal marsh platforms. Drainage of these marshes was somewhat different than mature tidal marsh and creek systems appearing later as they were delayed until sea-level rise rates were less than 1-2 mm/year. Nascent San Francisco bay tidal marshes at low but rapidly rising sea levels 8000 years BP did not extend farther inland than Hunters Point, San Francisco, and they were brackish, due to relatively small tidal prism, and grew more saline as the Bay submerged and enlarged (Atwater et al. 1977).

The earliest stages of San Francisco Bay historical salt marsh development indicate instability as sea-level rise gradually slowed. Basal marsh sediment sequences alternated with lower intertidal and subtidal bay mud, indicating that fringing marshes were drowned by rising sea levels and then subsequently re-formed (Atwater et al. 1977). More recent high-resolution cores of prehistoric remnant marshes at China Camp

(Goman et al. 2008) and Rush Ranch (Byrne et al. 2001) are also consistent with repeated reversion between marsh and mudflat, perhaps due to accelerations of sea-level rise or erosional processes.

Analysis of stable carbon isotopes, pollen, plant macrofossils, and other salinity proxy data in cores reveals that Suisun and San Pablo Bay marshes have alternated between brackish and salt marsh vegetation over multiple centuries of warm and dry or cooler and wet climate periods (Malamud-Roam et al. 2007). Centuries of higher-than-average salinity in the Estuary have been associated with reduced fresh water inflows during 1600–1300 years BP, 1000–800 years BP, 300–200 years BP, and from about AD 1950 to present. Periods of lower-than-average salinity due to increased fresh water inflow occurred before 2000 years BP, from 1300 to 1200 years BP and from about 150 years BP. to AD 1950 (Malamud-Roam and Ingram 2004). These records suggest that California's climate since A.D. 1850 has been unusually stable and benign compared to climate variations during the previous 2,000 or more years.

Paleoecological investigations of the Estuary's tidal marshes have also contributed to a greater understanding of marsh dynamics in response to climatic variability. Brackish tidal marshes at Rush Ranch in Suisun Marsh originated as salt marshes alternating with mudflats only about 2500 years ago, and they did not evolve into a stable equilibrium state of brackish tidal marsh. Tidal marshes in Suisun Bay alternated between phases of high salinity and low salinity lasting several centuries (Byrne et al. 2001), consistent with paleosalinity history of other marshes in Suisun Bay and Carquinez Straits (Malamud Roam and Ingram 2004). Evidence of repeated extreme storm events was also detected in some marsh cores, such as sand layers (consistent with extreme slopewash and alluvial fan deposition) deep into tidal marshes at China Camp (Goman et al. 2008). This suggests that the Estuary's tidal marshes have been responding to wide swings of climate and extreme meteorological events during their brief 2000-3000 year history. While the Estuary's marshes have exhibited dynamic responses in vegetation characteristics, morphology, and extend during the late Holocene, they have also exhibited substantial persistence through climatic variations, presumably sustaining native species through the shifts. This is likely possible because of factors that conferred resilience on the baylands ecosystems, including habitat connectivity, uninterrupted sediment supply, and adjacent transition zone migration space.

Modern biological conservation implications of the Estuary's recent paleoecological investigations are just beginning to be applied to climate change adaptation planning (Grewell et al. in press). The late formation of mature channel systems and prolonged fluctuations between brackish and salt marsh salinity regimes in the northern Estuary during the late Holocene, suggest that species distributions associated with past marsh salinity gradients and habitat configurations have either adapted or moved across whole subregions of the Estuary, and they persisted for centuries before abruptly switching with climate shifts.

Paleoecological studies of nearby West Marin marine lagoons, such as Bolinas Lagoon, provide additional insights into how tidal marsh assemblages similar to those of the Estuary cope with much higher rates of relative sea-level rise. For example, instantaneous submergence events of 45 cm associated with co-seismic subsidence of San Andreas fault activity recur about every few centuries, in addition to sea-level rise, causing higher rates of relative sea-level rise (Byrne and Reidy 2005). Interestingly, tidal marshes of Bolinas Lagoon persist or regenerate in confined reaches of the lagoon where deltas are deposited by fluvial and tidal processes (Byrne and Reidy 2005) and this could be a guide for more resilient shoreline types in the Bay. Other subsided San Andreas Fault lagoons with high relative sea-level rise (Bodega Harbor, Tomales Bay; Niemi and Hall 1995; Grovel et al. 1995) also exhibit coupling of tidal marsh development with fluvial delta sedimentation, consistent with global coastal geomorphic models of tidal marsh development in submerging lagoons (Woodroffe 2002, Cooper 1994).

## DRIVERS OF CHANGE

This section reviews existing drivers of change and how they are likely to influence the evolution of the future baylands landscape. These drivers include sediment supply, freshwater inflows, and salinity coupled with new drivers due to climate change, namely sea-level rise, as well as temperature and precipitation.

### Sea-level rise

The sea-level rise projections for the West Coast have recently been provided by the National Academy of Science National Research Council study (NRC, 2012). For San Francisco Bay, NRC (2012) project a regional sea-level rise, including an allowance for vertical land motion, of between 5 to 24 inches by 2050 with a mid-projection of 12 inches and 17 to 66 inches by 2100 with a mid-projection of 36 inches (Table 1.1).

**Table 2.1.** San Francisco Regional Sea-level rise Projections Relative to Year 2000 (NRC 2012, OPC 2013)

| Year | Projection (A1B scenario) | Range (B1 and A1F1 scenario) |
|---|---|---|
| 2030 | 6 inches (14 cm) | 2-12 inches (4-30 cm) |
| 2050 | 12 inches (28 cm) | 5-24 inches (12 to 61 cm) |
| 2100 | 36 inches (92 cm) | 17-66 inches (42-167 cm) |

The NRC values include subsidence of 1.5 mm $yr^{-1}$ for all of California south of Cape Mendocino due to deep tectonic movements. This is a rough estimate that does not take into account localized variations in vertical land motion due to shallow subsidence and local tectonic movement. Observations of vertical land motion more specific to the South Bay (Burgmann, 2006; Gill, 2011; USGS 2012) are inconsistent in direction, and ranged from 1 mm/yr of subsidence (USGS 2012) to 1.5 mm/yr of uplift (Burgmann, 2006). For consistency with the NRC approach and to provide a slightly more conservative (higher) estimate of sea-level rise, we use the NRC assumption of vertical land motion for this study.

The selection of sea-level rise scenarios depends on the planning horizon of the study. Projects implemented during the planning timeframe must be built not just for sea-level rise at the time of construction, but for sea-level rise occurring during the life of the restoration. At the same time, projection too far forward in time becomes increasingly uncertain and may be better accommodated by providing adaptive capacity in the design of the project:

*"Until 2050, there is strong agreement among the various climate models for the amount of* SEA-LEVEL RISE *that is likely to occur. After mid-century, projections of SLR become more uncertain; SLR projections vary with future projections due in part to modeling uncertainties, but primarily due to uncertainties about future global greenhouse gas emissions, and uncertainties associated with the modeling of land ice melting rates. Therefore, for projects with timeframes beyond 2050, it is especially important to consider adaptive capacity, impacts, and risk tolerance to guide decisions of whether to use the low or high end of the ranges presented."*

page 3, OPC (2013)

The projections of sea-level rise relative to the year 2000 used in this study, is consistent with NRC (2012), OPC (2013) and the South San Francisco Bay Shoreline Study, are:

- 12 inches by 2050
- 36 inches by 2100

## Extreme Water Levels and Recurrence Intervals

The above discussion centers on mean sea level. However, the first impacts of sea-level rise that will affect marshes will be from extreme events as shown in Figure 1.11 below. Storm conditions represent a lower frequency event, they come with a larger potential flooded area with deeper flooded depths, higher velocities, and a greater likelihood of wind driven waves that could increase erosion. Figure 1.11 shows that as mean sea level raises so will the elevation events of a fixed recurrence. For a fixed elevation the frequency of being inundated will increase over time and inundation depths will increase. In the example shown in Figure 1.11, a marsh inundated with a 10 year return interval in 2020 will become a 1 year return interval by 2045. For marshes, extreme events will have a much earlier impact before mean sea level. The inundation regime will be changed well before the site is permanently inundated by mean sea level.

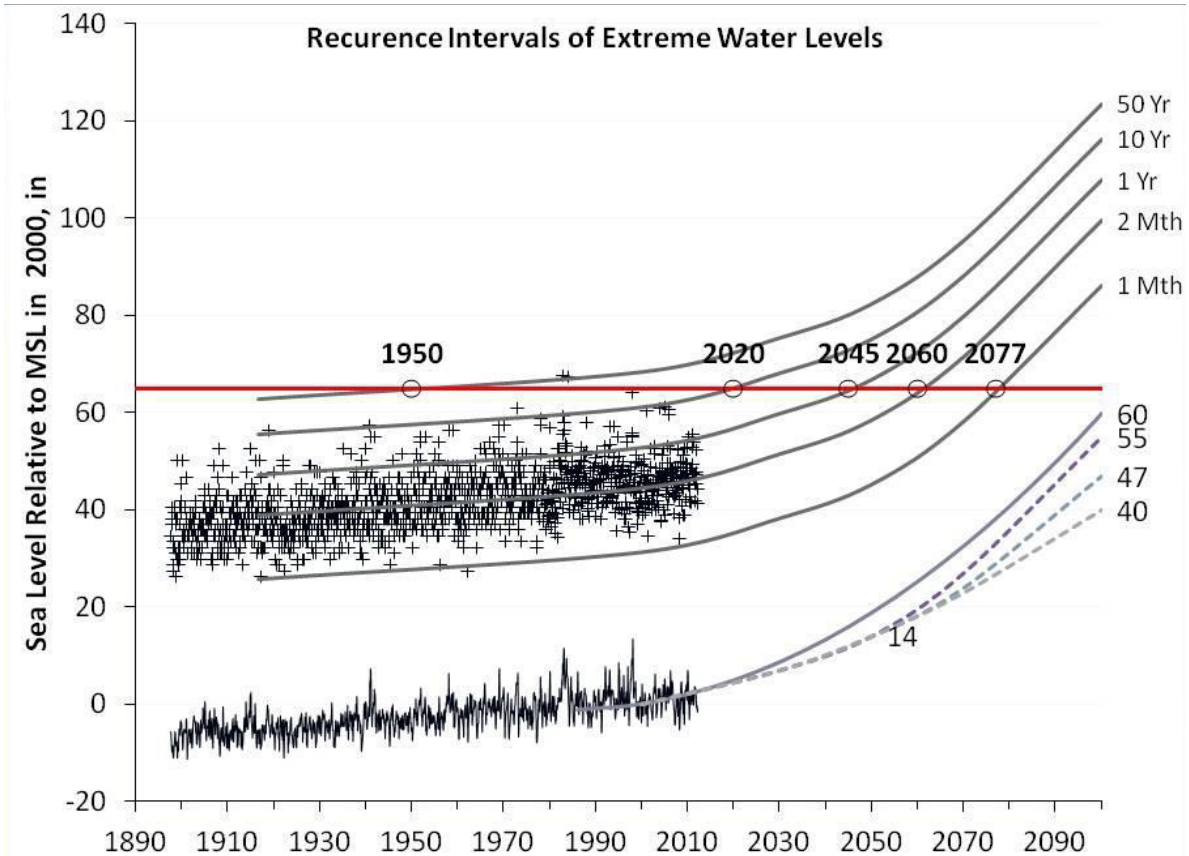


**Figure 1.11.** Recurrence Intervals of Extreme Water Levels in San Francisco Bay. NOTE: Historical (solid black line) and annual extreme water levels (black crosses) from Presidio tide gauge. Dotted lines indicate NRC 2012 projections. Year 2000 recurrence intervals from ESA PWA (2011). Developed from an idea of David Kriebel, USNA.

## Sediment Supply

The Goals Report (1999) emphasized the role of fine sediment (bay mud) depositional processes in development and maintenance of tidal marsh and mudflat habitats within the Baylands ecosystem. Coarse sediment – sand, shell, and gravel – was also identified as the substrate of historical and modern estuarine beach habitats within intertidal and supratidal zones of the Estuary. Sediment supply to the Bay has seen considerable variation over 170 years in common with many other estuary systems. Disruptions in Bay watersheds increase sediment loads, followed by dams, water diversions and altered river management that reduce variability and thus sediment supply (Barnard et al., 2013). Future availability of both fine and coarse sediment in the Estuary is likely to continue to change and will likely impact evolution of existing beaches and wetlands and also constrain the adaptation measures that might be considered in response to climate change.

Extensive hydraulic mining in the Sierras, coinciding with a period of abnormally high regional precipitation mobilized large volumes of sediment to San Francisco Bay during the late 1800s (Barnard et al 2013). This led to significant changes to Bay bathymetry, beaches, and fringing tidal marshes: a comparison of 1856 and 1887 bathymetric surveys of San Pablo Bay by Jaffe et al. (2007) shows that the estuary accumulated sediments during this period, with intertidal mudflats expanding by 60%. Efforts in the early to mid-1900s to manage floods, develop hydropower, and deliver water supplies led to the construction of dams trapping sediment throughout the Sierra Nevada which, together with cessation of mining in 1884, cut off the supply of hydraulically-mined sediment to the Estuary (Schoellhamer, 2011; Wright and Schoellhamer, 2004). The main pulse of bed sediment passed Sacramento by 1950 (Meade 1950).

Simultaneously, levee construction isolating floodplains from the main rivers together with logging, urbanization , agriculture and grazing activities increased sediment yields from local watersheds in the mid to late 20th century (Lewicki and McKee, 2010). As urban areas matured and erosion rates stabilized at the end of the 20th century so sediment yields have decreased in a number of watersheds (McKee et al 2004). Ganju et al (2008) estimated decadal sediment input from the Delta as shown in Figure 1.12.

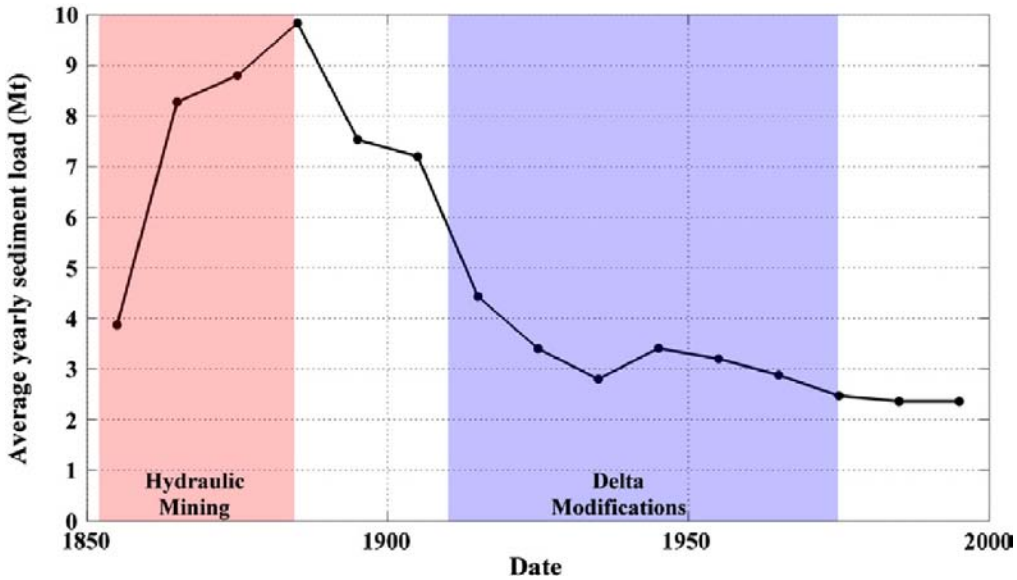


**Figure 1.12.** Decadal sediment load from Sacramento-San Joaquin Delta (from Ganju et al. 2008) showing periods of hydraulic mining and Delta modification. Source: Barnard et al. 2013.

At least 200 $Mm^3$ of sediment has been permanently removed from the Bay by navigation dredging, aggregate mining and borrow pit mining (Dallas and Barnard 2011). Sediment was also taken out of the system by filling and diking 90% of the Bay's tidal wetlands, trapping the sediment behind levees making it unavailable to mudflats and marshes (Atwater et al. 1979).

Reduction in supply and continual removal of sediment from the Bay has impacted suspended sediment concentrations (SSC) in a measurable way. Schoellhamer (2011) shows observations of near-surface and mid-depth SSC at most deep channel sites in the Bay from the early 1990s to water year (WY) 1998 were almost double that from WYs 1999 to 2007; the only exception was San Mateo Bridge. Figure 1.13 shows such a step change for observations made in San Pablo Bay. In general there was a statistically significant 36% decrease in SSC in San Francisco Bay from water years 1991–1998 to 1999–2007.

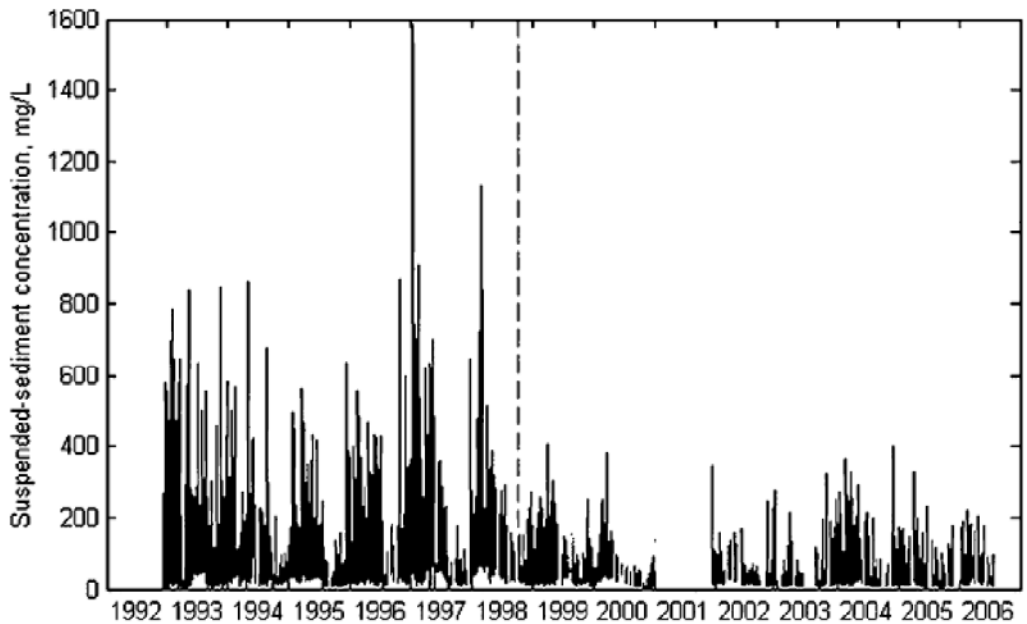


**Figure 1.13.** Suspended sediment concentration, mid-depth, Point San Pablo from 1993 to 2006. The vertical dashed line indicates when the step decrease occurred. Source: Schoellhamer 2011.

These steps cannot be explained by variations in fluvial sediment supply, rather Schoellhamer (2011) provides a hypothesis that the Bay had an erodible pool of sediment that was depleted in the late 1990s and the Bay switched from a transport-regulated regime to a supply-regulated regime. A quantitative conceptual model demonstrates that crossing the threshold between regimes can rapidly reduce suspended sediment mass and lead to rapid clearing of the water column (Figure 1.14).

Prior to the step decrease, Bay SSC would remain high in water years with little watershed sediment supply because the erodible sediment pool supplied suspended sediment and SSC was transport-regulated. Schoellhamer (2011) estimates the erodible pool in the mid-1900s was about 60 times the volume of the mean annual sediment supply. As sediment supply diminished over the 20th century, so the erodible pool was depleted although it was still transport-regulated. When the erodible pool becomes sufficiently depleted, however, its buffering action lost. Then the suspended sediment becomes supply-regulated and much more sensitive to the supply from the local watersheds, increasing their importance and the

desirability to reconnect them with the tidal marshes. This appears to have occurred in 1999 in San Francisco Bay.

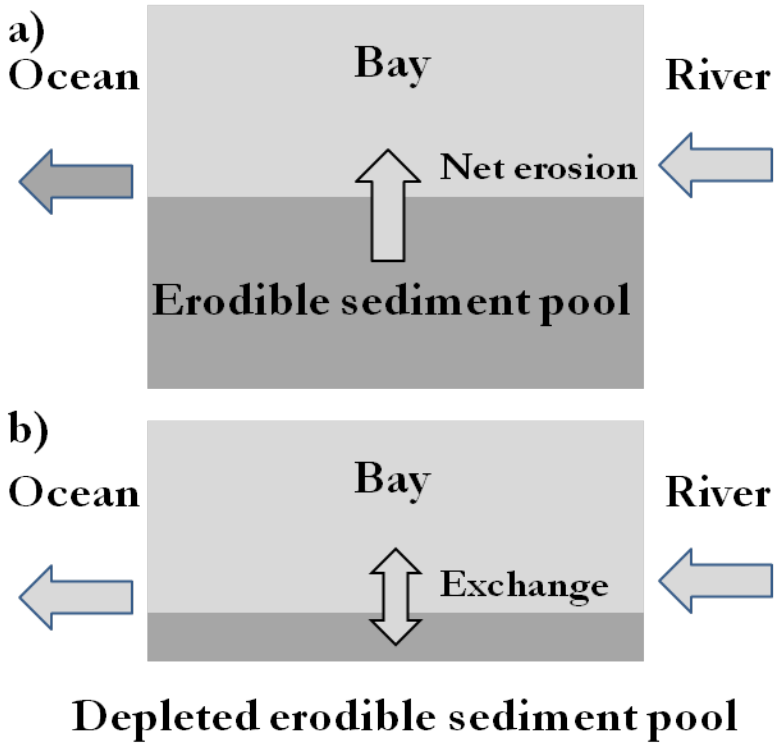


**Figure 1.14.** Conceptual model of an erodible sediment pool that becomes depleted (a), reducing suspended sediment concentration (b). Source: Schoellhamer 2011.

Looking ahead and noting the size of the erodible pool in the last century it is likely that, even in wet years (e.g., 2006), rivers will not be able to supply enough sediment to restore the pool. Thus, SSC is likely to remain low in the future. As SCC becomes more closely linked to the supply during individual water years, it will also reflect decreases in the river supply. Hestir (2004) found that river supply to the estuary decreased about 1.3% per year between 1975 and 2008, so future reductions in SSC should be anticipated.

There is a high probability that the sediment budget is likely to shift toward deficit because of sediment demand and retention in old and restored or recreated marshes as well as inadvertently flooded Delta islands. The sediment supply to the estuary may decrease further, particularly if more instream storage is built, although that trend is uncertain (McKee et al. 2006, Cloern et al. 2011).

### Sediment Demand

Jaffe et al. (2011) made preliminary estimates of the volume of sediment needed per year to maintain tidal flats, tidal marshes, marsh restoration, and for the bay floor to keep up with projected future sea-level rise. Figure 1.15 depicts scenarios for the present sediment demand, from the present to 2050, demand averaged from 2050 to 2100, and demand projected for the year 2100. Jaffe et al. (2011) suggest that without marsh restoration efforts there may be enough sediment in the South Bay to keep pace with sea-level rise. With the projected additional demand for sediment under various marsh restoration scenarios, sediment supply

may also not be able to keep pace with the demand. These projections just evaluate inorganic sediment contribution to marsh maintenance. The organic contribution (life plant growth) to marsh accretion was not considered. Organic contribution to marsh sediments in San Francisco Bay salt marshes is between 7 – 15% (Watson 2004, Callaway et al. 2012).

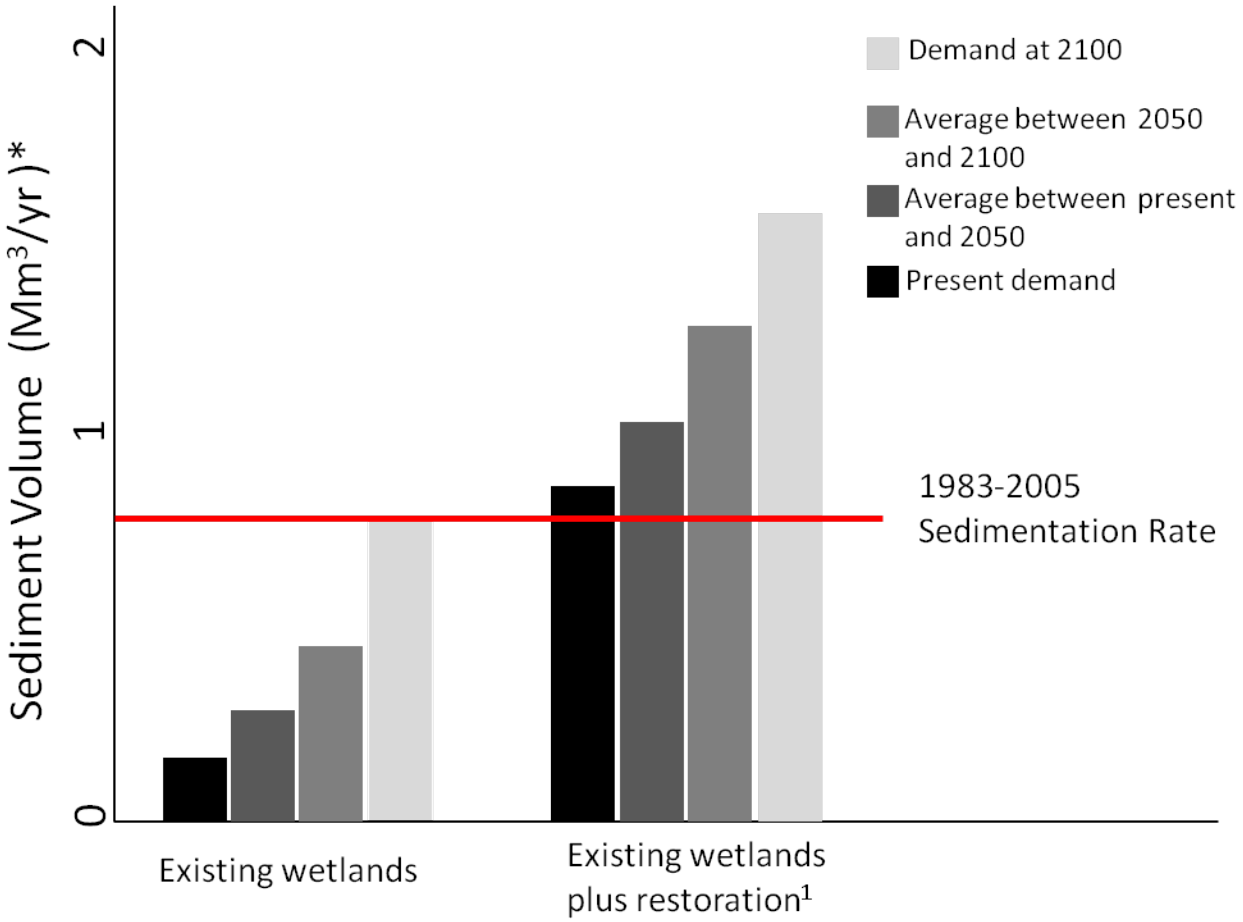


**Figure 1.15.** Projected sediment demand from tidal flats and marsh restoration under future sea-level rise scenarios ($Mm^3$ = million cubic meters). *Does not include organic contribution to marsh accretion. [1]35 $Mm^3$ over 50 years = 0.7 $Mm^3$/yr (Shoellhamer et al. 2006).

The basic assumption is that processes and inputs that control tidal flat and marsh maintenance will not change in the future. Although the basic processes (e.g., wind wave suspension) are not likely to change, their effectiveness may change with sea-level rise. For example, if future sea-level rise does not result in bed sediment accumulation (and therefore an increase in vertical elevation), there will be larger waves, which could result in more erosion of the mudflat and therefore less mudflat. The main controlling factor is sediment supply (from tributaries, and erosion of tidal flats north of Dumbarton Bridge): if it decreases, particularly with the loss of the erodible pool of sediment, and switches to supply-limited regime postulated by Schoellhamer (2011), then sedimentation rate decreases, and mudflats extent decreases.

### Topography

Topography is key not only to the location of tidal habitats but also to its quality. Within-marsh complexity has been lost in the last 40 years during restoration as restored marshes have not established for a long

enough period for complex channels and topographic features to develop. New marsh restoration techniques in recent years have been more focused on creating topography within the marsh. However as sea-level rises the upland topography adjacent to the marshes will play an increasingly important role in facilitating or preventing the landward migration of marshes into the transition zone (transition zones are described in detail in Science Foundation Chapter 4). Transition zones provide much of the land area that will serve as accommodation space as sea-level rises. Accommodation space provides area for marshes to migrate landward with increasing sea levels as new tidal marsh is created at the margin of existing marshes. The width of this new marsh is controlled by the topographic slope along the margin of the bayshore, in addition to other factors such as rates of sea-level rise, suspended sediment concentrations, freshwater inputs, and organic matter inputs.

Most of the historic transition zones around the baylands have been diked and leveed, partly filled, and are part of the built environment. Where available land exists, there are competing interests for preservation and development. Transition zones will be squeezed between a rising bay and human developments as the seas rise. Developed areas may in turn provide accommodation space in the future if they are abandoned due to rapidly rising sea levels.

In the remaining areas where land is still available, these transition zones are narrower where the tidal range is lesser and the land is steeper. Narrow transition zones will be short-lived with increasing water levels. Where the tidal range is greater and the land slopes more steeply to the bayshore, the transition zone is wider provided there is no development in the way. Broad areas where migration can accommodate the services of the transition zone can increase the landward extent of the transition zone, particularly in areas that are not steep. Wide gently sloping transition zones will last longer if connected to active estuarine and terrestrial processes.

Artificial levees comprise much of the existing transition zones and most of the existing levees provide very little transition zone habitat with virtually no accommodation space. Most of these existing levees cannot persist in response to increasing water levels. However, where levees are adjacent to low-gradient upland slopes there are opportunities to create accommodation space.

### Water

Freshwater flow into the estuary comprises on average about 99% outflow from the Delta and about 1% from wastewater treatment plants and local streams (MacWilliams et al. in prep.). Delta outflow results from quantity, timing, and location of precipitation, snowpack storage, groundwater, and reservoirs, and losses to evapotranspiration and export flows from the southern Delta. For simplicity, long-term changes in wet and dry seasons are considered separately (Figure 1.16).

Long-term changes in precipitation in the Central Valley watershed are expected through two mechanisms. Warming will reduce snowpack in high mountains, resulting earlier peak runoff (Aguado et al. 1992, Dettinger and Cayan 1995). Changes in total precipitation may occur as a result of climate change, but modeling support is weak (Dettinger 2005), and total precipitation is already highly variable. Thus the likely future scenario is for runoff that is higher in winter and lower in summer, with continued variability at all time scales.

Increasing runoff means less runoff will be captured in reservoirs and groundwater, and winter flows in the rivers and through the Delta will be higher (Figure 1.16). The likely human response will be to increase

storage capacity, which will increase variability in Delta outflow by capturing lower flows and passing through higher flows.

During the dry season, flows in high-elevation streams will be lower because of earlier snowpack loss. Water stored in reservoirs and groundwater will be used for irrigation. Industrial and residential use and wastewater will be returned to the watershed except for evapotranspiration, which will increase because of the higher temperature and the need for more irrigation water. This may be offset by improved irrigation practices and urban water conservation.

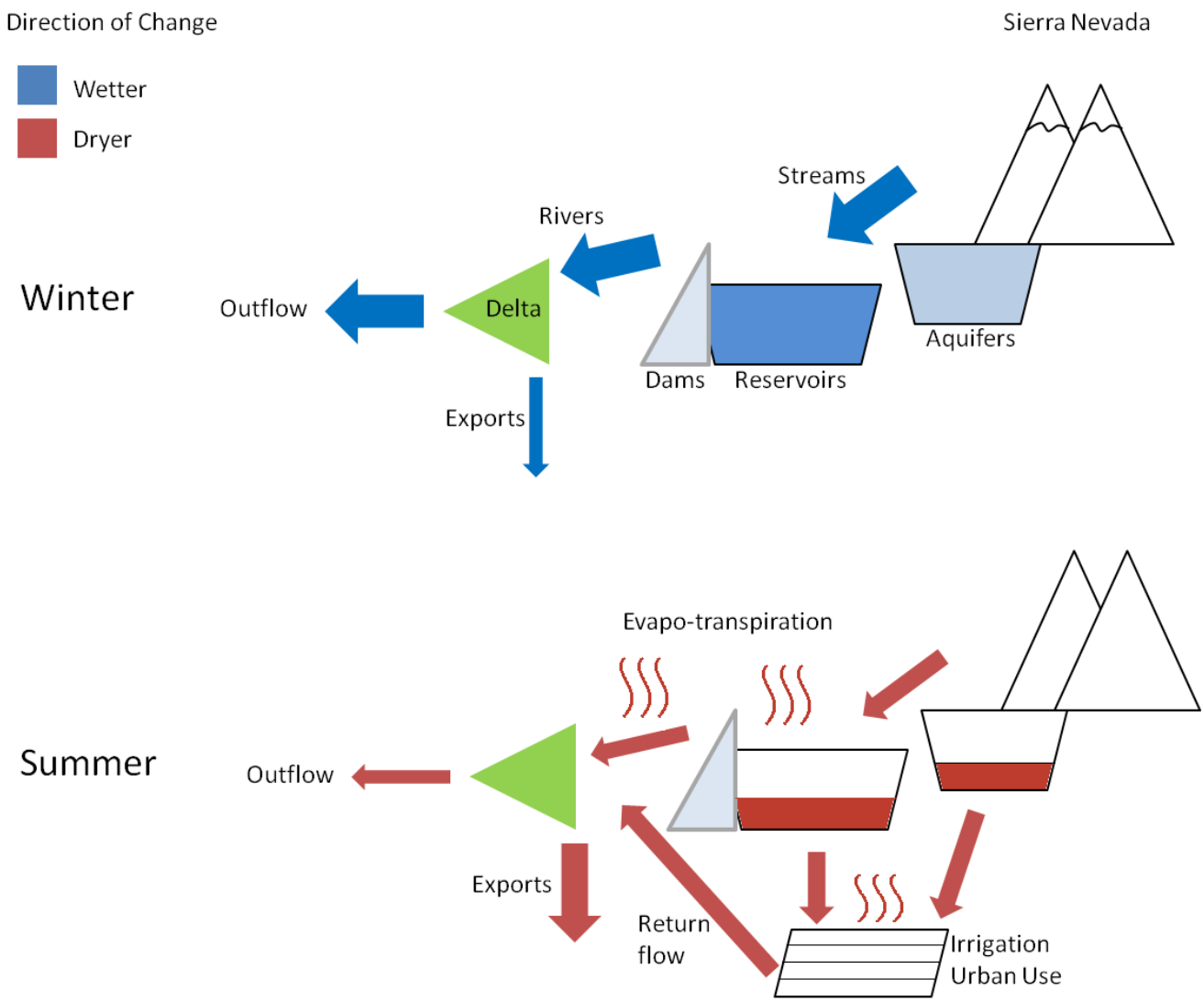


**Figure 1.16.** Schematic diagram of forecasted changes in the hydrology of the Central Valley during the wet winter season (top) and dry summer season (bottom) with an increase in air temperature. Arrows represent flows of water, with width representing relative magnitudes of changes in flow. Blue arrows represent flows or processes consistent with overall wetter conditions, and red arrows represent those consistent with dryer conditions.

Reduced inflows, greater demand, and increased evapotranspiration will reduce flow going to the Delta. There, increased demand to the south will require increased export flows from the south Delta (as now) and presumably from a new facility to be built on the Sacramento River. Some of that water will return via the San Joaquin River, some will be lost to evapotranspiration, and some will go to cities and farms outside the watershed. Additional transfer of water for urban use in San Francisco and the East Bay will also likely increase. The net result of these changes will be reduced Delta outflow.

Small streams entering the estuary are likely to see an increase in winter flows due to increased runoff from impervious surfaces as urbanization increases, and possibly also increased frequency of large storms.

Summer flows will decrease because of increased evapotranspiration in the warmer, dryer local watersheds. Flows from wastewater treatment plants and urban runoff will increase with population growth.

Changes to freshwater input are highly probable. The first observed signal of climate change effects on the estuary was the shift toward an earlier snowmelt peak (Roos 1989). This shift, caused by warming in the high Sierra, is expected to continue with warming. The outcome will be a shorter, more intense period of runoff in winter and early spring, and a protracted dry season. Thus, irrespective of any change in storm intensity (see below), the winter hydrograph will be flashier with higher flows during wet winters. During drier winters, much of the snowmelt peak may be captured in expanded reservoirs and exported in new water diversion facilities (Section 2.1E, BDCP 2013). This will likely amplify the current high interannual variability in flows through the estuary.

The mixing of freshwater with ocean water will lead to the creation of estuarine salinity gradients. The salinity distribution responds to freshwater flow, tides, sea level (affected by rising sea level in the ocean and by atmospheric pressure gradients and coastal wind), and wind within the bay. Each of these influences has a different time scale of influence on salinity. Many attributes of the estuary are in turn affected by the extent of the salinity gradient.

Freshwater flow is the predominant control of the salinity gradient on timescales of a week or longer. The position of the salinity gradient in the estuary is indexed by X2, which is the distance in kilometers up the main channel of the estuary from the Golden Gate to where the salinity is 2 ppt, roughly the center of the low-salinity zone (Figure 1.17). A large X2 value means salinity has intruded farther into the Delta. X2 is related to the freshwater discharge from the Delta with a time lag of about 2 weeks (Monismith et al. 1996, 2002).

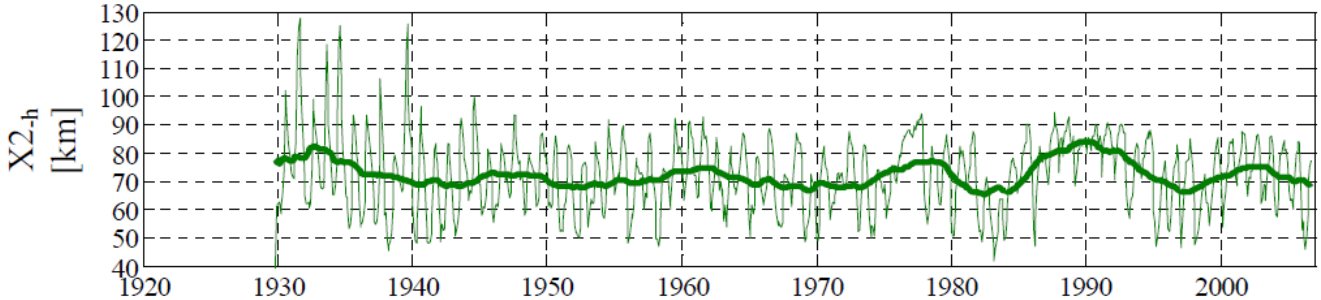


**Figure 1.17.** Location of X2 (km from Golden Gate) under historical flow conditions (CCWD 2010).

Tidal currents mix estuarine waters longitudinally through (a) tidal trapping, by which water masses that split into different channels, or channels and shoals, become separated from each other; and (b) by tidal pumping, by which tidal currents over irregular bathymetry induce a net circulation. An important additional influence on salinity is gravitational circulation, a density-driven circulation consisting of up-estuary tidally-averaged flow near the bed and down-estuary flow near the surface, which in turn generates vertical stratification. Strength of gravitational circulation and stratification depends on the degree of vertical mixing induced by tidal currents, which break down stratification. Frequency and strength of stratification increases with water depth, because vertical mixing affects a smaller fraction of the water column in deep water. Thus, deeper channels of the estuary can be regions of strong up-estuary salt flux, and these areas in effect limit responsiveness of X2 to flow by increasing up-estuary salt flux as freshwater flow increases (Monismith et al. 2002).

Sea level, wind setup along the coast, and atmospheric pressure gradients influence tidal height at the bay mouth and, therefore, tidal currents. Wind-driven circulation over shoals can alter the local salinity gradient, and vertical mixing due to waves set up can break down vertical stratification. These effects are ephemeral and have relatively little effect on the large-scale salinity gradient.

Several trends are likely to alter the salinity gradient. Sea-level rise will move the gradient up-estuary, because deeper water causes increased landward penetration of saline waters on the bottom[1]. This tendency would be enhanced by lower freshwater flow in the dry season and probably opposed by elevated flows during winter. This means that the salinity gradient could move seaward more frequently or further in wet winters than it does now. However, the dry season will be drier and last longer than it does now, resulting in a persistent landward position of the salinity field and persistently high salinity. The net effect on the salinity gradient is very uncertain, mainly because of uncertainties about future freshwater flows.

### Climate

Trends in air temperature with climate change are poorly defined. The air temperature gradient between the ocean and the Central Valley should increase, resulting in a greater pressure gradient driving stronger northwest winds along the coast. These winds in turn may increase the frequency and intensity of upwelling (Snyder et al. 2003), potentially increasing the loading of nutrients and organic matter from the ocean to the bay. Summer wind speed over the Bay might also increase, although model estimates of wind do not support a future increase (Rasmussen et al. 2011). The frequency of large storms has been forecasted to increase together with increasing intensity of the largest (Dettinger 2011).

Water temperature will track air temperature in the upper estuary as it does now (Wagner et al. 2011), but ocean temperature could actually decline (Snyder et al. 2003), so water temperature in the Delta will rise more than in other reaches of the estuary. These effects will result in steepening of the spatial temperature gradient in summer and flattening in winter.

### Nutrients

San Francisco Bay has long been recognized as a nutrient-enriched estuary. However phytoplankton growth and accumulation appear to be largely controlled by a combination of factors, including strong tidal mixing, light limitation due to high turbidity, and grazing pressure by clams (Cloern et al. 2012). These

[1] i.e. the landward bottom velocity associated with gravitational circulation scales with the cube of water depth for a given slope of the salinity gradient; Monismith et al. 1996.

controls have meant dissolved oxygen concentrations found in the Bay's subtidal habitats are much higher and phytoplankton biomass and productivity are substantially lower than would be expected in an estuary with such high nutrient enrichment (RWQCB 2012).

In the future these controls may be less successful, particularly as turbidity decreases and water temperatures increase. There is a growing body of evidence that suggests the historic resilience of San Francisco Bay to the harmful effects of nutrient enrichment is weakening. Since the late 1990's, regions of the Bay have experienced significant increases in phytoplankton biomass and significant declines in DO concentrations. In addition, an unprecedented autumn phytoplankton bloom in October of 1999, and the 2004 red tide event occurring in the North Bay, further signal changes in the Estuary (RWQCB 2012). Improved understanding of the relative importance of these controlling factors is needed, how they vary around the estuary, how they vary in time and how they may be impacted by climate change.

Another recent issue is the potential impact of ammonia/ammonium on the Bay. Recent studies argue that elevated levels of ammonium limit primary productivity in Suisun Bay (Dugdale et al., 2007, 2012; Parker et al., 2012a), and perhaps elsewhere in the Estuary (Parker et al., 2012b). However, there is currently disagreement within the scientific community about the potential role ammonium plays in limiting primary productivity (RWQCB 2012).

Tidal marshes play a role in improving water quality by cycling nutrients. There is uncertainty as to how bayland restoration will influence nutrient cycling due to the variability and complexity of the system. However, marshes are known to assimilate nitrogen, particularly in the form of nitrate. Wetlands can be highly effective at removing nutrients from wastewater (e.g., Jasper et al., 2014). Marsh restoration helps to transform anthropogenic nutrient inputs to the estuary by retaining and transforming nutrients into less harmful forms. Thus, restoration of marshes may enhance the resiliency of the bay ecosystem with respect to human inputs of nitrogen.

As part of assessing the potential effectiveness and feasibility of this approach, a number of factors need to be evaluated, including:

1. The desired load reduction. Achieving the desired load reduction depends on a number of factors that will in turn have major influences on design considerations, in particular the required wetland area to ensure sufficient residence time and sufficient N removal, and include:

a. Whether the same load reduction is required year round or can vary seasonally.

b. Seasonal variability in flow and load. Currently, EBDA's flows and loads vary by as much as a factor of 2. Treating high flows would require at least twice as much wetland area as dry flows.

c. The form of N (as NH4+ or NO3--), and its influent concentration. If N arrives primarily in the form of NH4+, in general nitrification of NH4+ to NO3- must occur first, followed by denitrification (unless N loss goes forward by anamox)

d. Seasonal variability in removal efficiency due to the effect of temperature. For a given area and flow or loading rate, removal efficiency can vary by more than a factor of 5.

2. Designing wetlands such that they achieve the combined effect of increased wetland habitat, nutrient removal, and wetland accretion to stave off sea-level rise, which may require some compromises on all three fronts to achieve an overall optimum design.

### Human Interventions

Over the time period of the climate forecasts above, several important human interventions are likely to occur or are already occurring. Human population around the estuary will continue to grow, adding impervious surfaces, increasing waste production, and demanding more ecosystem services such as freshwater and recreational opportunities. These demands, particularly for freshwater, could be offset to some degree by increased efficiency of water use, fallowing of lands, or changes in cropping patterns.

The Delta will almost certainly be replumbed either as part of a deliberate, planned process or in response to an emergency such as a massive levee failure (see 2.1E; Lund et al. 2007; BDCP 2013). This could exacerbate the shift in runoff timing, as water will be even more valuable for cities and farms in dry summers.

Despite the increase in human population, nutrient loading from municipal wastewater plants is likely to decrease as the plants are upgraded to meet water-quality standards. This may result in a substantial decrease in ammonium discharge.

Alterations of shorelines will occur both as adaptation to sea-level rise and as part of planned activities to protect and restore wetlands. Restoration activities have begun under the guidance of the Baylands Habitat Goals Report, and the Bay-Delta Conservation Plan also calls for massive wetland restoration in the Delta and in Suisun Marsh (BDCP 2013). This will result in an altered tidal prism and therefore altered tidal heights and currents that will depend on where the alterations occur. Construction of hard structures to protect human uses is likely to increase reflection of waves with unknown consequences for erosion in other locations.

Deliberate or accidental introductions of invasive species will likely continue. Quagga mussels were found in Lake Havasu in 2007 and were established throughout southern California a few years later. Zebra mussels were found in 2008 in a reservoir near Hollister, about 100 km south of the Delta. Both of these highly invasive species are likely to arrive in the freshwater reaches of the estuary despite ongoing efforts to halt their spread. Other introductions are difficult to predict.

There are also a number of events with low annual probability but large consequences. There is a high probability of multiple levee failures in the Delta, resulting in flooding of several highly subsided Delta islands (Mount and Twiss 2005, Lund et al. 2007, Bates and Lund 2013). Such an event, likely driven by an earthquake but also possible through storm-driven flooding, would very quickly increase the tidal prism in the Delta. Reversing this flooding could take years, if it is done at all. If it is not, the result would be a permanent increase in the tidal prism, resulting in greater salinity penetration than occurs now and a shift in currents and spatial distribution of residence times. The actual outcome will depend heavily on how many islands flood, where they are, and when the flooding occurs in relation to the annual hydrologic cycle. The outcome for the lower estuary will be higher salinity at any location and an alteration in tidal currents, which may affect how sediment and organisms are transported around the estuary. Widespread levee failures in Suisun Marsh would have similar consequences. These events have a low probability in any one year but over the time period considered for climate change they may be very likely.

## SUMMARY

The preceding sections describe in some detail the existing drivers of change that are likely to influence future Baylands landscapes. In addition to sea-level rise projections, these drivers also include sediment supply, topography, water quality and supply, nutrients, climate and human interventions.

Sediment supply and its ability to support intertidal Bayland habitats is a critical factor in shaping the future of San Francisco Bay. As sediment supply to the Bay decreases, we will need to carefully match up supply with need to ensure the long term sustainability of our marshes and mudflats.

Human interventions will continue to shape the Bay and its ability to respond to climate change. Region-specific topography and land use will dictate whether we are able to realign levees, restore wetlands and create new upland transition zones, or if we must continue to rely upon traditional engineered flood protection measures.

Regardless of sea-level rise, climate change related shifts in precipitation patterns will influence the amount and timing of freshwater inputs to the Bay. Higher sea levels combined with potentially protracted dry seasons will result in changes to the salinity gradients. These could be exacerbated by levee failures in the Delta.

Changes in other climate variables such as temperature and wind patterns may also affect upland and estuarine habitats and species. Shifts in runoff patterns, nutrient transport, and wind velocities may result in higher water temperatures and changes in turbidity that can increase the potential for eutrophication in the Bay.

Despite these numerous challenges, there are still options available for planners and land managers to adapt to these differences. For example, multi-objective and multi-habitat project designs can maximize cumulative benefits for climate change adaptation. By thoughtfully integrating design features that can have habitat and physical benefits, projects can achieve more than one outcome and increase overall project success by including design components that support each other. The following chapters will examine these strategies to offset the drivers of change.

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