Bothin Marsh Geomorphology, Ecology, and Conservation Options

Chapter 1: Physical and Biological Processes Influencing Evolution, Maintenance and Degeneration of Tidal Salt Marshes

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On behalf of

Marin County Open Space District

January 2018

Suggested Citation:

Baye, PR, and LM Collins. 2018. Physical and biological processes influencing evolution, maintenance and degeneration of tidal salt marshes. Chapter 1 in: Bothin Marsh geomorphology, ecology and conservation options, LM Collins, PR Baye, and JN Collins. 2018. Prepared for the Marin County Open Space District, San Rafael CA.

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1.0 Introduction

This Chapter presents an overview of the natural geomorphic processes that govern the evolution, natural maintenance, and degeneration of tidal marshes, and the general effects of people intervening in these processes, with special regard for the Bothin Marsh Complex. Because of the importance of sea level rise and the tides, they are covered in a separate Chapter (see Chapter 2).

1.1 Tidal Marsh Evolution

In a general sense, tidal marshes evolve from non-vegetated tidal flats, such as sand-flats or mudflats, when the flats become high enough to be colonized by marsh vegetation (Byrne *et al*. 2004, Fagherazzi *et al*. 2004, Wallace *et al*. 2005, Palaima 2012, Gunnell *et al*. 2013). An understanding marsh evolution therefore requires some understanding of how flats evolve. It should be noted that marshes can also evolve on terrestrial lands, rather than on tidal flats, as the lands are transgressed due to sea level rise. Accelerated sea level rise is a major concern for tidal marsh protection and restoration, and is addressed separately in Chapter 2.

Tidal flats represent a balance between the deposition and erosion of sediments in shallow areas near low tide (Black 2002, Fagherazzi *et al*. 2007, Bearman *et al*. 2010, van der Wegen *et al*. 2017). Flats are formed when and where the tidal currents and wind-generated waves are not strong enough to prevent suspended sediment from being deposited, or to lift and resuspend deposited sediment. The power of wind-generated waves to resuspend and carry sediment depends on their height, which in turn depends on water depth and the strength of the winds. Higher and more powerful waves occur at the downwind end of longer fetches over deeper water (Karimpour *et al*. 2017). Resuspended sediment can be moved by waves and tidal currents from one tidal area to another. When the winds and waves subside, some of the sediment can be redeposited on the flats (Friedrichs and Aubrey 1996).

Given the right conditions of these factors, there can be enough sedimentation on a tidal flat for it to achieve heights suitable for colonization by marsh vegetation. Different regulatory and management programs use different thresholds for the amount or percent cover of marsh vegetation to indicate when a flat becomes a marsh. The tidal elevation at which the colonization occurs depends on many factors, especially salinity. Plants grow lower in the intertidal zone under fresher conditions (Atwater and Hedel 1976). The species composition of this vegetation also varies with salinity.

Since sea level is rising, the flats and marshes must also rise. The supply of sediments must be adequate for the flats and marshes to rise in pace with sea level, or the flats and marshes will drown, and their surfaces will erode. The amount of sediment that is added to the flats and marshes must be replaced with additional sediment, or there will be a net deficit in the sediment supply, and the flats and marshes will not keep up with the rising sea level.

Marshes do not have to drown to erode. Wind-generated waves and tidal currents can erode the bayward margins of the marshes, here called the foreshore (see Figure 1.1 below), such that the marshes will become narrower. The marsh foreshore tends to be unstable, eroding when the waves are strong and the

Figure 1.1. Aerial view of portion of Bothin Marsh showing relative positions of mudflat bayward of the marsh, foreshore between the marsh and mudflat, and backshore between the marsh and uplands, formed her by the Bay Trail.

supplies of suspended sediment are low, and growing outward when the waves are weak and sediment supply is high (Silvestri and Marco 2004). A narrow fringe of tidal marsh can evolve and persist along the boundary between the Bay or marsh and the land, here called the backshore (Figure 1.1), under various conditions of waves, sediment supply, and sea level rise. In this case, the height of the land determines the height of the marsh. As sea level rises, the fringing marsh migrates upslope and inland (Chapter 2). Under favorable conditions, marshes can grow in size by expanding outward from the backshore fringe, and by the establishment of pioneering plant colonies on the tidal flat away from the backshore (Watson and Byrne 2013).

Not all tidal flats evolve into marshes. Tidal flats tend to persist where the balance between sedimentation happens at a height too low for colonization by marsh vegetation (Friedrichs and Aubrey 1996, Black *et al et al*. 2002, Weerman *et al*. 2010, Gunnell *et al*. 2013).

There are three basic sources of sediment to establish and maintain tidal marshes in Richardson Bay.

- Upland or *terrigenous sediment* includes sands, silts, clays, and large floating debris that are delivered more or less directly to a marsh from their upland sources by rivers, streams, canals, storm drains, and unchannelized flow (i.e., surface runoff outside of a natural or artificial drainage channel). Gravels and cobbles that might be transported along the stream beds are too heavy to be carried onto the marsh surface. The sediment that reaches the Bay is stored there, or is transported out by the ebbing tides. The larger, heavier materials are restricted to the deeper areas and the small, finer materials are stored in deeper areas and on the flats and marshes. Any actions on land that increase erosion or flooding can also increase the delivery of terrigenous sediment.
- Sediments that are circulated within the Bay, or conveyed seaward or landward by the tides, are regarded as *tidal sediment.* Fine sediment stored in the flats that is resuspended by wind-generated waves is considered tidal. The resuspended materials can be delivered to the marshes by the waves and flood tides. Extreme events, such as storm surges, tsunamis, and major river floods can deposit both tidal and terrigenous sediments on marsh surfaces. Dredging that increases the amount of sediment suspended in tidal waters can increase the rate of delivery of tidal sediment to a marsh. Changes in land use can strongly affect local terrigenous and tidal sediment supplies.
- *Autochthonous sediment* includes any materials produced within a marsh that contribute to its height. Most autochthonous sediment of a tidal marsh consists of roots, rhizomes, and other organic materials produced by marsh vegetation (Drexler 2011, USDA 2015, Morris *et al*. 2016). In general, a local watershed contributes more of its sediment to its nearest marshes. Marshes more distant from a local watershed receive more of a mixture of sediment from many watersheds (Byrne *et al* 2001).

Tidal marshes are commonly classified as low or high depending on their surface heights relative to the high tides (Figure 1.2). These height classes can represent stages in marsh development from young to old marshes (Redfield 1972, Kneib *et al*. 2008). As explained above, marshes subject to rapid increases in the frequency or duration of tidal flooding can drown, which can reverse their developmental process, such that high marshes are converted to low marshes or tidal flats. Drowning can result from sea level rise (e.g., Stralberg *et al*. 2011), marsh subsidence (Darienzo and Peterson 1990, Gillespie *et al* 2011), or decomposition of autochthonous sediment (Hartig *et al*. 2002, Deegan *et al*. 2012).

The drainage system of a tidal marsh consists of one or more networks of channels large and small that deliver tidal waters to and from the marsh surface. Each network primarily serves one area of marsh and has its own opening to the Bay, through the foreshore. The largest channels of the more extensive networks in older, larger marshes originate on the predecessor mudflats. The smaller channels of these networks evolve as the marsh gains elevation. The smallest channels evolve on the marsh plain (Collins *et al*. 1987).

1.2 Natural Tidal Marsh Maintenance

Tidal marshes evolved along the shores of Richardson Bay beginning sometime within the last 2,000 years. The ages of the oldest areas of tidal marsh are not known. However, marshes older than 2,000 years are uncommon elsewhere in San Francisco Bay (Atwater *et al*. 1977, Gorman *et al*. 2008, Malamud-Roam *et al*. 2006, Watson and Byrne 2013). The fact that tidal marshes have naturally persisted in San Francisco Bay for thousands of years indicates that they have ways to maintain themselves despite short- and long-term variations in the rate of sea level rise. The ability of tidal marshes to survive any amount of sea level rise depends on the rate of rise relative to the rate of sedimentation. Under moderate rates of sea-level rise, the increased frequency and duration of tidal flooding increases the rate of tidal deposition of silts and clays on marsh surfaces, as well as the development of organic marsh sediments, such as plant roots, resulting in marsh accretion in response to sea level rise (Reed 1995, Morris *et al*. 2002, Kirwan *et al*. 2010, Fagherazzi *et al*. 2012).

The rate of tidal sediment deposition on tidal marsh surfaces decrease with increasing marsh height (e.g., Krone 1987, French 1993, Allen 1994). As the rate of tidal sediment deposition decreases, the role of allochthonous sediments increases. However, the rate of allochthonous sedimentation depends on the rate of plant growth, which tends to be maximum within a narrow range of tidal heights (e.g., Redfield 1972, Orson *et al*. 1985, Morris *et al*. 2005). If the marsh is lower than the optimum range in elevation for plant growth, an increase in the depth of tidal flooding leads to a decrease in plant growth. This can lower the rate of allochthonous sedimentation, which in turn lowers the height of the marsh surface, relative to sea level, which can lead to an increase in the rate of tidal sediment deposition.

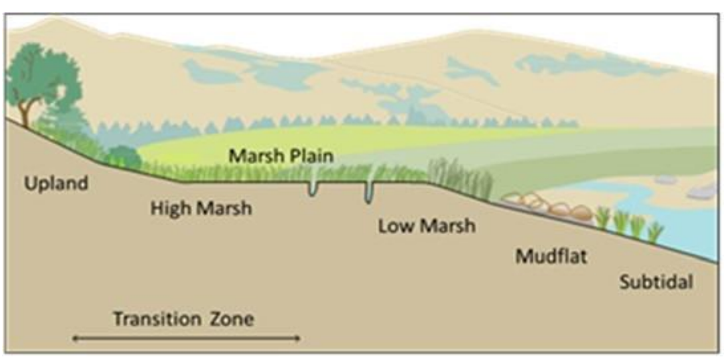

Figure 1.2 Diagram of tidal marsh zones in context pf a complete tidal marsh ecosystem including subtidal areas, mudflat, and upland. Goals Project 2015.

The overall accumulated sediment of a tidal marsh is therefore a mixture of terrigenous, tidal, and autochthonous materials (Church *et al*. 2006, Mudd *et al*.

2010, Morris *et al*. 2016), and the relative importance of tidal and allochthonous sediments to the rise of tidal marshes therefore varies over time. Young marshes tend to be dominated by inorganic tidal sediments. As a marsh matures, the contribution of allochthonous material to the rise of the marsh plain increases. This is evidenced by vertical cores of sediment taken from the interior areas of marshes that show layers of autochthonous and tidal sediments relating to marsh age, different rates of sea level rise, and changes in tidal sediment supply (e.g., De Groot *et al*. 2003, Gorman *et al*. 2008, Watson and Byrne 2013).

Within mature high marshes, these three different kinds of sediment tend to be predictably distributed (Collins *et al*., 1987, Reed *et al*. 1999, Christiansena *et al.* 2000, Sanderson *et al*. 2000, Culberson *et al*. 2004, Collins and Grossinger 2004, Temmerman *et al.* 2005). The relative amount of tidal sediment tends to decrease with distance away from the foreshore, and away from the tidal marsh channels across the marsh plain. Channel beds, banks, and natural levees tend to be almost entirely composed of inorganic tidal sediments, although channels and levees that convey upland runoff can also contain terrigenous sediment. Since terrigenous sediments are relatively heavy, they tend to be deposited in areas nearest their points of input. For example, splays of terrigenous sediment are commonly observed where creeks discharge into marshes. Sediments in the interior areas of a mature marsh tend to be mostly autochthonous. This is because the marsh vegetation effectively filters the inorganic sediment out of the tidal water as it floods from the channels across the marsh plain (Stumpf 1983, Leonard and Croft 2006, Mudd *et al*. 2010). Wave-deposited marsh berms along the foreshore tend be heterogeneous mixtures of coarse mineral sediment (sand to silt) and organic debris deposited by waves. Mature high marshes are therefore maintained by a combination of tidal sedimentation within and along channels and at the foreshore, and autochthonous sedimentation in areas away from channels.

The wave-cut erosional marsh cliffs (scarps) of tidal marshes are inherently unstable (Mariotti and Fagherazzi, 2010). Bayward expansion of flats and marshes can be rapid, up to several meters per year, when the necessary supplies of sediment are available (Winfield 1988, Gunnell *et al.* 2013). Erosion of the foreshore can also be rapid, especially if the energy of waves attacking the shore is increased by gains in sea level, since wave energy increases with water depth. The lack of feedback between the processes of foreshore erosion and those of marsh expansion suggests that the foreshore is always either expanding or contracting (Fagherazzi *et al.*, 2013). Sediment cores taken from marsh foreshores in San Francisco Bay reveal layers of flats and marshes, indicating their repeated conversion back and forth from one to the other, as the foreshore waxes and wanes over time (Winfield 1988).

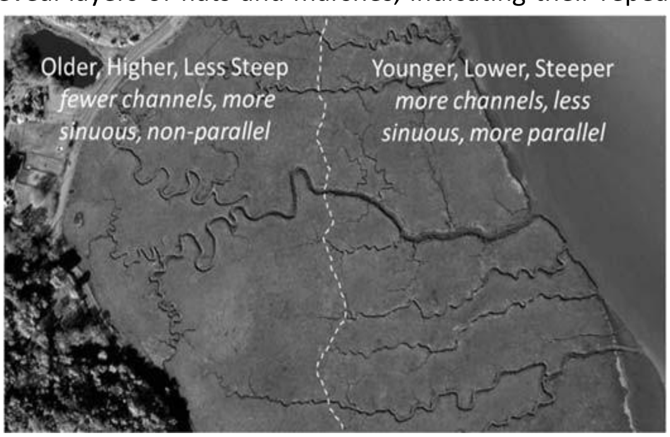

Figure 1.3. Aerial image of San Francisco Bay tidal marsh showing differences in channel networks between marsh plains that differ in age, height, and slope.

The channel networks of mature tidal marshes are remarkably stable over time. Each network tends to be just large enough in terms of its total length and volumetric capacity to deliver and drain the flood tides to and from the marsh surface that it serves (Collins and Grossinger 2004). There is a close relationship between the surface area of tidal marsh and the total capacity of its drainage network (Novakowski *et al*. 2004, Hood 2007). This relationship varies however, with marsh age or height, topographic slope, and salinity regime (Collins and Grossinger 2004).

Higher marshes tend to have smaller networks because they convey less water to and from the marsh surface. Steeper marshes tend to have more linear and parallel channel networks (Figure 1.3). Less saline tidal marshes tend to have smaller networks because the marsh vegetation grows at elevations that would otherwise be mudflat or channel beds (Atwater and Hedel 1976, Atwater *et al*. 1977).

Recent studies of past and present conditions in tidal marshes around SF Bay have revealed some local aspects of sediment movement and deposition applicable to Bothin Marsh. The studies have not matured to peer review publication but are generating considerable interest. The Flood 2.0 initiative and some Total Maximum Daily Load (TMDL) studies have been working with expert teams and local interests to explore future landscape solutions to water quality, flood management, and habitat conservation in the context of climate change. A number of these explorations have identified multiple benefits of restoring natural connections between tidal wetlands and streams. The benefits of utilizing the terrigenous sediment of local streams to nurture tidal marshes are well recognized. A related need is to move bedload through the tidal portion of the stream to prevent the channel from trapping sediment and thus losing capacity to convey floodwaters. It has been recognized that the natural levees that form along the tidal reaches of streams confines their flood flows and thus increases their power to move bedload though the intertidal zone (Marvin-DiPasquale and Cox 2007), especially when the tidal ebb flows entering the channel downstream of the levees contribute to stream power (Collins and Leising 2004, SWRCB 2008). In the cases of streams lacking perennial flow, the concept of allowing wet season deposition of sediment loads to form backshore deltas and fans is commonly considered (SFEI-ASC 2015).

1.3 Spatial Gradients in Tidal Flooding and Soil Salinity between and within Marshes

Local variations in tidal salinity among the tidal marshes of Richardson Bay are due to discharges of freshwater from local streams and storm drains. In general, the salinity of tidal waters will increase with distance away from these sources of freshwater. The differences will decrease during the warm-dry season, as stream discharge decreases, such that the salinity of tidal waters along the foreshore of the Bay becomes more uniform.

Salinity gradients also exist with tidal marshes. Tidal marshes are not flat. Slight variations in height across a marsh surface can result in significant variations in tidal flooding, drainage, leaching, and evapotranspiration, all of which affect soil salinity. As height increases, the sensitivity of these factors to changes in height also increases. Ecologically significant changes in these factors correspond to slight variations in height across a high marsh. For example, a 0.4-inch (1 centimeter) increase in height of a very high, mature marsh surface can result in a 35% decrease in its flood frequency (Collins unpublished). This phenomenon is due in part to the effect of the marsh vegetation on the time it takes waters to cross the marsh plain during flood tide, before the tide begins to ebb. The friction of the vegetation slows the water, such that it does not reach the height in the interior areas of the plain as it would without vegetation (e.g., Leonard and Croft 2006). This effectively raises the height of these areas, relative to the tides.

Floodwater that infiltrates the marsh surface away from channels and the foreshore does not drain away, even at low tide. After infiltration, the height of the groundwater in these areas is very near the marsh surface. Evapotranspiration of this water increases the concentration of salt in the marsh soils. In areas very near the channel bank or foreshore, the surface and subsurface soils drain better. Soil salinity therefore tends to increase with distance from channels and the foreshore (Balling and Resh 1982,

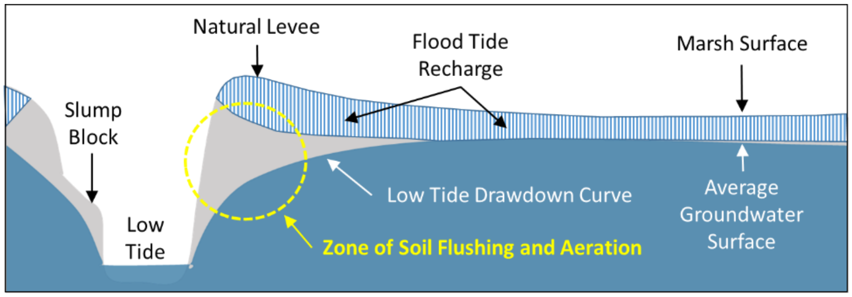

Figure 1.4. Diagram of the channel zone of a mature tidal marsh channel, showing characteristics processes and features (after Balling and Resh 1982).

Fagherazzi *et al*. 2004). However, areas of the marsh surface that are seldom flooded by the tides, such as natural high marsh levees, can be leached of salt by rain. Natural tidal marsh levees and the backshore tend to have zones of decreasing soil salinity with height above the average marsh plain (NOS 1978, Traut 2005, Fagherazzi *et al*. 2013).

There are many processes and features along the margins of a tidal marsh channel that distinguish this area from other areas in a tidal marsh. We refer to this area as the channel zone (Figure 1.4). It incorporates the channel bank, plus any slump blocks, the bank top, plus any natural levee. It also includes the area beneath the marsh surface that is affected by drawdown of the near-surface groundwater through the channel bank during ebb tides, and recharge through the bank and the marsh surface during over-bank flood tides. The clayey banks have very slow hydraulic conductivity, such that recharge through them, as the tide rises in the channel, is negligible. However, the tide spends most of its time at or below mid-bank, such that the water table near the channel is subject to long periods of drawdown. As a result, there is an area beneath the bank top and between the recharge and drawdown processes that tends to be unsaturated (i.e., aerated). The drawdown also tends to lessen the salinity of the soils in this area. This provides habitat in the channel zone for plants with deeper rooting depths and less tolerance of saline conditions.

The sedimentation and sub-surface gradients establish subdued but ecologically significant microtopography, including natural, low-relief levees atop the banks of larger channels in mature tidal marshes (Pestrong 1972, French and Stoddard 1992, French and Spencer 1993, Reed *et al*. 1999). These levees are due to sedimentation gradients from tidal creek sources of suspended sediment, across the tidal marsh plain. Turbulent flood tidal flow in large channels maintains large concentrations of suspended sediment in the upper water column. When overbank tidal flooding occurs, tidal flows spread over the marsh plain where suspended sediment is rapidly deposited due to tidal energy loss from friction of marsh vegetation. Concentration of local overbank sediment deposition at the channel bank top gradually builds a small natural levee as tidal marsh topography matures. As the tidal flood flow proceeds upstream, it slows and becomes more laminar, allowing the suspended sediment to settle, and reducing its availability to the bank top and marsh surface. The heights of natural levees therefore tend to decrease upstream within drainage networks, and the smallest, most head channels usually lack levees (Collins *et al*. 1987).

In a mature tidal marsh, the soils tend to become less clayey and their hydraulic conductivity increases with increased soil organic matter accretion, which increases with distance away from the channel zone. Vertical fluctuations of the water table in these areas are mainly due to infiltration by overbank tides and evapotranspiration; there is very little lateral movement of the groundwater. Therefore, the groundwater and soils in the areas away from channels tend to be more saline.

1.4 Generalized Effects of Alteration

For the purposes of this report, alterations are unnatural modifications to the bottom of tidal bays, the foreshore or backshore of tidal marsh, marsh channels or the marsh plains, or modifications of the adjoining uplands that affect the processes of tidal marsh evolution or natural maintenance.

1.4.1 Reclamation

Reclamation is the diking or leveeing of intertidal or subtidal areas to create arable lands for public or private uses. Partial reclamation of a marsh can lessen the tidal prism (i.e., the volume of tidal water conveyed by a tidal channel), and therefore can also reduce the velocities of tidal currents. Enough reclamation can disrupt the balance between sedimentation and erosion to cause net sedimentation, until a new balance is achieved between the reduced tidal prism, wave and current power, and sediment supply. The sedimentation induced by reclamation tends to first occur as shoaling in the nearby tidal or subtidal channels, followed by channel narrowing, but can also involve the expansion of tidal flats and marshes. The effect of reclamation in tidal rivers or embayments on the dimensions of their inlets is well known (Tao *et al*. 2010, Kidd *et al.* 2017, D'Alpaos t al 2010).

1.4.2 Dredging

Dredging within the intertidal zone (i.e., between MLLW and MHHW), which can include the breaching of dikes to increase the tidal area, increases tidal prism and therefore increases tidal current velocities, which in turn increases the power of the tides to erode bottom sediments and foreshores. Deepening the tidal waters can also increase the height and thus the erosive and sediment transport capabilities of wind-generated waves.

Dredging increases the amount of suspended sediment in the affected tidal waters, and can thus cause the unintended redistribution of sediments by the tides. Mobilized sediments that are conveyed to sufficiently low energy tidal areas can settle and increase local sedimentation rates. Dredging can also exhume contaminated sediments and thus increase their interactions with food webs (Rich 2010).

1.4.3 Water Control Structures

Levees, dikes, and berms are water containment structures addressed in the section above on reclamation, and with regard to managing sea level rise in Chapter 2. Here the focus is on weirs or sills, culverts, tide gates, pumps, and siphons used to control the flow of water into or from a diked or reclaimed area. Weirs or sills are areas of containment structures that are intentional notched or lowered to allow an upper layer of the high tidal waters or upland runoff to pass over the structure, and to control the level of water stored in the diked area. Some sills have ways to be raised or lowered to further control tidal flooding or drainage. Culverts are usually installed in containment structures to allow the flood and ebb of the tides to and from the diked area, or to convey upland runoff to a tidal area. Their height, length, and diameter can be designed to restrict the tidal flow, such that the maximum height of the tides is lowered, relative to adjoining fully tidal areas. Tide gates can be fitting on culverts to enable diked areas to drain at low tide, but not fill with tidal water during flood tide. Tide gates are commonly used at stormwater retention basins, where storm runoff from uplands is stored during high tide, to reduce upstream flood risks, and then release the water during low tide, to make room for additional storm runoff. Unless they are properly maintained, tide gates tend to be fouled by floating debris, such that they do not close or open properly. Pumps and siphons are used to drain diked areas without interfering with the design of containment structures.

Unless they are sized to convey unrestricted tides, culverts reduce tidal prism to some degree. Weirs always reduce tidal prism. Any water control structure that conveys water that is either more saline or less saline than the receiving tidal waters will create an aqueous salinity gradient that can affect the distribution and abundance of tidal plants and animals.

1.4.4 Upland land uses

Upland land uses can significantly influence the quality and quantity of freshwater runoff and terrigenous sediment entering tidal areas. In general, any increase in impervious area will increase runoff to the nearest tidal area, unless the runoff is somehow put into the ground. Impervious surfaces include pavement, roofs, and ground compacted by ranching, dairying, and off-road vehicle use. Wildfires can create impervious soils by increasing their content of plant oils and waxes (e.g., Kalendovsky and Cannon 1997, Neary *et al.* 2008). The quality of the runoff tends to vary with land use type and actual land use practice. Agricultural land uses can increase the loads of nutrients, herbicides, pesticides and other chemicals used in ranching and farming. Runoff from industrial lands can include a wide range of chemicals including heavy metals. Conversion of agricultural lands to industrial and other urban land uses, as well as changes in industrial uses can create mixtures of legacy contaminants in runoff. Urban areas typically provide large amounts of chemicals derived from petroleum, due in large part to runoff from paved vehicular roads. The chemistry of agricultural and urban runoff is the subject of abundant applied and basic research (e.g., USEPA 2016, McKee *et al.* 2003, Lye 2009).

Land uses that increase runoff into earthen channels are likely to increase their erosion. Channels will deepen and /or widen to accommodate the increased flow. Flooding out of the channel during major storms will not prevent the erosion due to increased average runoff amounts. Without bedrock or other natural or artificial feature that prevent channel beds from eroding, channels will continue to deepen as average amounts of runoff increase, through a process called degradation or incision. Channels can eventually incise deep enough to abandon their floodplains. As the channels adjust to contain greater flows, they deepen. Incision can be chronic until the amounts of runoff stop increasing. Incision can lead to bank erosion and collapse, causing significant increases in terrigenous sediment supply to tidal areas.

Land uses that increase runoff to steep hillsides can cause surface erosion as well as landslides. Periods of intense rain plus runoff on hillsides from impervious surfaces can trigger multiple landslides, especially if the geology is prone to landsliding, which in turn can cause pulses of sediment to enter tidal areas though streams and storm drains. Various approaches to reducing runoff and related erosion, such as constructing catchment basins, planting dense vegetation, preventing development on steep slopes, converting from impervious to pervious surfaces, etc., can reduce sediment supplies.

1.5. Relevance to Bothin Marshes

1.5.1 Marsh Evolution

Tidal marshes have always been larger in the upper areas of Richardson Bay than in the more downstream areas. There are at least five factors that help explain this condition.

- Firstly, these areas are the lower reaches of gently sloping valleys where tidal and terrigenous sediments can settle and accumulate as broad tidal flats and marshes. Most of the other lands around of Richardson Bay are much steeper and therefore can only support fringing marshes.
- Secondly, a submarine cliff or scarp about 60 ft high exists across the mouth of Richardson Bay (Figure 1.5). This drop-off tends to cause the tidal waters flowing through Raccoon Strait from the

Figure 1.5 showing scarp at the mouth of Richardson Bay and adjoining deep subtidal area directing the flow of tidal waters through Raccoon Strait (see Figure 1.6) (from Means 1965).

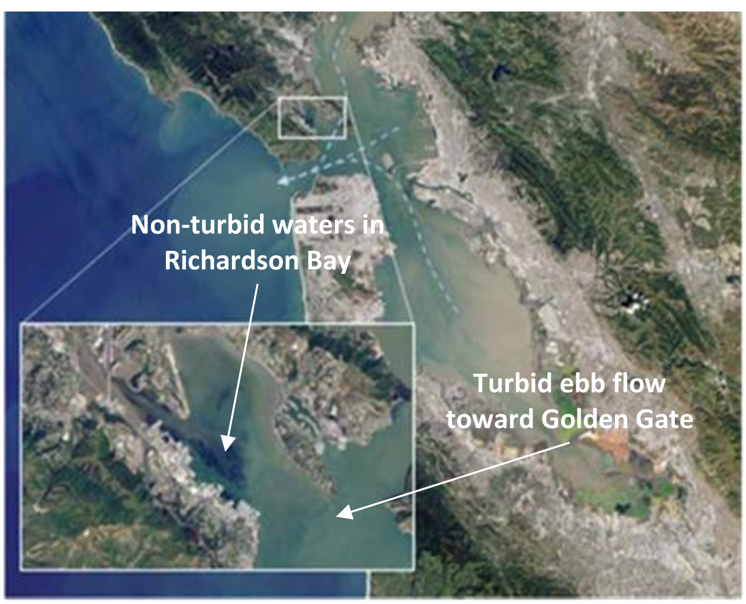

Figure 1.6. Plume of turbid, sediment-laden water (brown in color) of a wintertime ebb tide bypassing the less turbid water (lighter brown and blue) in Richardson Bay.

northern reaches of San Francisco Bay to bypass Richardson Bay (Figure 1.6; Means 1965). Although these ebb flows from the northern areas of San Francisco Bay can carry large amounts of fine suspended sediment, more than 400 parts per million during winter storms (Schoellhamer *et al*. 2013), very little of this sediment enters Richardson Bay.

- Thirdly, since the mouth of the Bay is very near the Golden Gate, the flood tides entering Richardson Bay involve waters from the Gulf of the Farallones. These waters tend to have small amounts of fine suspended sediment, less than about 90 parts per million (Schoellhamer *et al*. 2013). The suspended sediment concentration can be expected to increase during periods of high freshwater runoff from the Sacramento River in the winter and spring, when some of the sediment-laden water that flows out of the Golden Gate during ebb tide will come back in toward the mouth of Richardson Bay during flood tide. For example, perhaps 3 inches of shoaling took place in some areas of the Bay immediately after the historic storms of January 1982, and were subsequently resuspended by waves and redistributed within the Bay by the tides (Williams 1983). Yet, in general, the tidal waters flowing into Richardson Bay lack much tidal sediment.

- Fourthly, although there is no sediment budget for Richardson Bay that quantifies the relative amounts of terrigenous verses tidal sediment that comprise the total sediment supply, a substantial portion of the fine sediment in the Bay clearly originates from adjoining local watersheds (Van Geen et al. 1999). This is indicated by the fact that tidal marshes evolved first in the upper Bay, near the mouths of the local watersheds, beginning with the formation of small deltas or bars of coarse sediment (Connor 1975). Tidal marsh have existing off and on at the mouth of Arroyo Corte Madera del Presidio since about 4,500 years ago, although the historical marshes are less than a few hundred years old (Connor 1975).

- Finally, the net direction of tidal sediment transport is toward the upper areas of Richardson Bay, due to flood tide velocities exceeding ebb velocities, and due to the southeast wave fetch that directs waves into the upper Bay during major storms (Williams 1983) that resuspend sediment from tidal flats and deliver it to the tidal marsh channels, which then directs it onto the marsh surfaces (Krone 1962 as cited in Williams 1983)

1.5.2 Bothin Marsh Eco-geomorphic Units and Tidal Marsh Processes

This discussion applies the general tidal marsh processes reviewed above (sections 1.1 to 1.4) to the eco-geomorphic units defined in Chapter 4 specifically for Bothin Marsh. The eco-geomorphic units comprise a conceptual landscape framework that integrates dynamic geomorphic and ecological features into self-evident components or “working parts” of the marsh system. The eco-geomorphic framework can help place marsh-forming and marsh-maintaining processes in the local context, especially for the translation of physical processes to ecological consequences for focal habitats and populations of plants and wildlife. Habitats, wildlife, and plants have specific interactions with particular aspects of eco-geomorphic processes, landforms and vegetation structure that can be made explicit in the context of general marsh-forming processes. This application of the framework to the Bothin Marsh Complex relies on information provided by local studies as well as complimentary investigations of comparable marshes in San Francisco Bay and other estuaries.

1.5.2.1 Wave Processes at Marsh Foreshore

Despite emphasis on vertical marsh sediment accretion in relation to sea level changes over the Holocene Epoch through the modern era, recent analysis of the Bothin Marsh Complex (Chapter 3) shows that tidal salt marshes are vulnerable to wave erosion and collapse as a result of inherent horizontal instability (Leonardi and Fagherazzi 2014, Fagherazzi 2013). In many locations, tidal marsh resilience in vertical adjustment to sea level rise is greater than horizontal resilience (Kirwan *et al*. 2016). Horizontal marsh erosion is primarily controlled by wave power (Schwimmer 2001), and does not require sea level rise; however, sea level rise can indirectly intensify horizontal salt marsh instability by affecting water depth, which positively affects wave power (see Section 1.1 above).

Horizontal salt marsh erosion in the San Francisco Estuary, and at the Bothin Marsh Complex, can occur at the bay mudflat/salt marsh edge with a variety of morphological variations (Beagle *et al*. 2015). Erosional retreat by erosion of marsh scarps (cliffs in cohesive marsh mud or peaty soil), with slump block rotational failure (Allen 1988), or detachment and toppling of undercut, overhanging marsh sod (root mat/soil masses; Beagle *et al*. 2015, Schwimmer and Pizzuto 2001), is prevalent at bay fringing salt marsh of Bothin Marsh (Chapter 4). As in tidal creek bank slump bloc dynamics (Gabet 1998), slump blocks at the bay margin can either rapidly erode and disintegrate underhigh wave power, or become recolonized by low marsh vegetation (cordgrass), which establishes as seedlings or vegetative fragments in the temporary shelter of eroded slump blocks. Depending on erosion rates, slump blocks can either initiate a phase of fringing marsh recovery and progradation, erode progressively, or cycle between erosion and progradation phases. Intense storms can trigger episodes of marsh scarp retreat, and so can frequent periods of non-storm high wind-wave activity.

The shear strength of sediments and soils in the scarp influence the rate of erosion in response to wave power. Pickleweed marsh soils are relatively strong compared with cordgrass mud or unvegetated bay mud (Pestrong 1965). North Bothin Marsh is currently fringed by salt marsh outside the bay levee, which buffers erosion of the levee. If scarp erosion retreats into the levee, it will expose levee foundations on unvegetated bay mud. Behind the levee is a platform of dredged bay mud fill at the south end of North Bothin Marsh. This substrate may be less erosion resistant than salt marsh soils. At Muzzi Marsh, erosion rates appear to accelerate when the scarp retreats into dredged materials landward of the perimeter levee, after collapse of the levee (P. Baye, personal observation). Scarp retreat processes at North Bothin Marsh may undergo changes in rates and styles of slope failure in relation to the variation in substrates exposed at the foot of the scarp, where wave action undercuts the slope.

Figure 1.7. Caption next page.

Figure

1.7. Wave-cut salt marsh scarps at Bothin Marsh. (A) Active scarp at east end “headland” of south-facing levee, North Bothin Marsh. Note collapsing, undercut salt marsh sod and canopy. (B) Detached rotational slump block (tops still near horizontal) below scarp, submerged at high tide. (C) Cordgrass colonized a narrow zone of slump blocks (submerged at high tide). Pickleweed and other high marsh plants “drown” on blocks rotated to low marsh tidal elevations with excessive duration of daily tidal submergence; cordgrass seedlings colonize the sheltered, stable substrate of blocks and dead/dying high marsh vegetation. (D) Active cliff in compacted, cohesive levee at North Bothin Marsh “headland” at south end. Waves generate visible suspended fine sediment plume from eroding levee scarp. Trampling (public access) compacts soil and waves shear vegetation, producing a prostrate saltgrass turf on levee substrate, in contrast with high pickleweed salt marsh. (E) Abrupt zonation between fringing high salt marsh bayward of North Bothin Marsh east-facing levee north of “headland” (pickleweed, saltgrass, alkali-heath and Jaumea dominants) and uniform narrow cordgrass marsh belt below relict scarp (abrupt change in slope). Vegetation and topographic structure results from post- erosion scarp recovery phase. (F) Progressive active erosion of south-facing bay fringing marsh north of Coyote Creek mouth, with undercut sod and topping failures rapidly disintegrating from erosion by frequent wind-waves (from long fetch towards Golden Gate). Little or no persistent cordgrass colonization occurs in highly exposed scarp segment. (Photo dates: A – June 2012; B – Oct 2015; C-E Oct 2017; F – June 2016)

Figure 1.8. Oblique view of North Bothin Marsh bay-edge salt marsh scarp shows active erosion and retreat indicators. Topping and rotational failures of recent slump blocks at north end are circled. Recent failure is indicted by persistence of high marsh vegetation at top of slump block. April 2017.

Figure 1.9. Areas of low and high wind-wave settings of salt marsh show erosional scarps. (A) Muzzi Marsh bay edge is exposed to chronic ferry wakes at higher tide stages and long wind-wave fetch to south. The old levee has eroded, exposing dredged bay mud fill on which restored tidal salt marsh forms a “crust” over low-strength consolidated mud with no root mats. Slump blocks rapidly deteriorate before cordgrass can establish well-anchored seedlings or clones. August 2017. (B) Manzanita Marsh (south) toppling slump block failure formed during wave erosion phase, followed by mudflat accretion. This cycle establishes sheltered microsites for potential cordgrass recolonization by seedling establishment and spread of clones. April 2013.

1.5.2.2 Wave damping (energy attenuation) by salt marsh vegetation

Waves propagating over the rough surface of a vegetated tidal marsh submerged during high tides rapidly lose energy to bottom friction, which results in rapid wave height decay. Fringing tidal salt marshes cause much more rapid and efficient loss of wave energy (large wave energy loss over short distance/marsh width) than tidal mudflats, and they can effectively cancel significant erosion potential or wave run-up flood potential of bay waves over distances less than 20 m from the bay/marsh edge in shallow, narrow bays (Feagin *et al*. 2011, Möller 2006, Möller and Spencer 2002) like Richardson Bay. Wave damping properties of salt marsh vegetation depend on vegetation height, shoot flexibility, and density of shoots and leafs. Landward high marsh and transition zones are protected from wave erosion by wide salt marsh plains. Protected shorelines include high salt marsh habitat of rare plants and vegetation providing high tide refuge cover for wildlife. Marsh vegetation does not itself protect the erosional bay scarp below it (Feagin *et al*. 2009), but attenuates wave energy landward of the canopy through which waves propagate, significantly protecting landward marsh and shorelines against wave energy impacts on flooding or erosion (Gedan *et al*. 2011). At Bothin Marsh, high salt marsh vegetation that covers the levee crest of North Bothin damps waves during tides that overtop the breached levee. Bay fringing salt marshes from the Coyote Creek mouth to North Bothin Marsh establish local wave-shelter zones with reduced wave erosion intensity along the bike/pedestrian path shoreline.

Figure 1.10. Wave damping at the bay edge of north Muzzi Marsh in low wave energy conditions during high spring tide, January 2011. (A) Waves intercepted by leading edge of pickleweed vegetation. Wave height approximately 10 feet, meeting or exceeding height of pickleweed canopy top. (B) Wave damping zone marked by wave-wetted (darker) pickleweed shoots contrasting with dry (lighter) shoots where waves are damped to height less than pickleweed shoot canopy above still water level. Wave-wetted (wave damping) zones are less than 30 feet-wide.

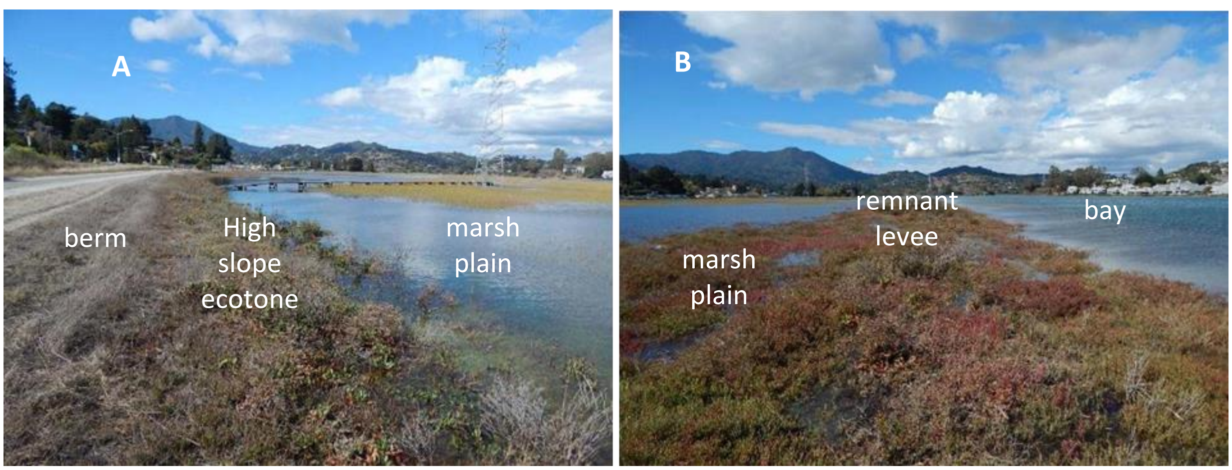

Figure 1.11. Canopy of emergent marsh vegetation is shown during calm-weather spring high tide submergence of (A) the North Bothin Marsh plain and (B) levee crest. Vegetation roughness provides wind-wave attenuation during storm conditions. October 2015.

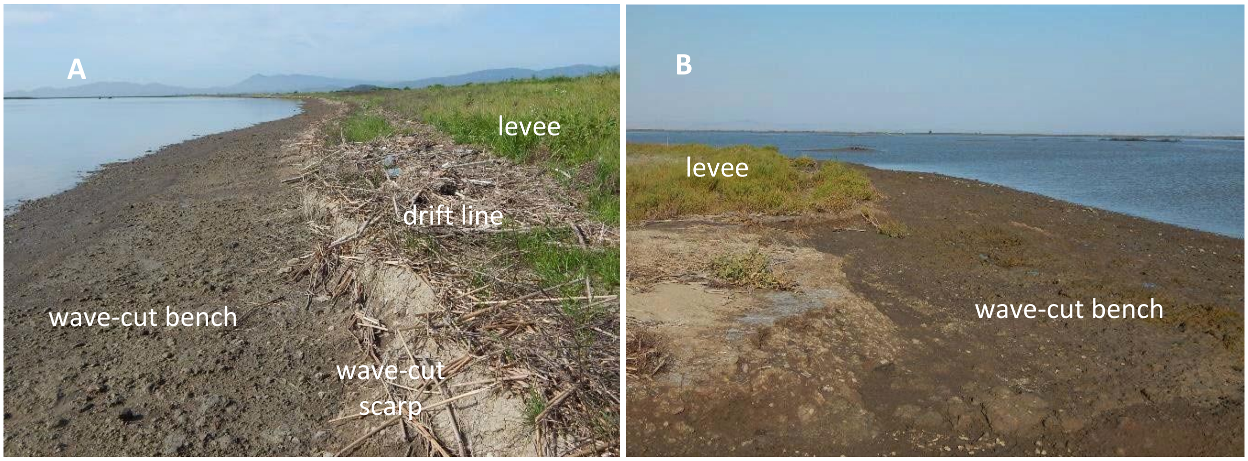

Figure 1.12. An example of wave erosion is shown on salt marsh restoration shorelines that do not have wave-damping intertidal vegetation. Low-gradient "horizontal levee" of new tidal marsh restoration site (Sears Point, Petaluma) in the bare, graded intertidal flats. Rapid, significant erosion of gentle gradient designed for 10:1-20:1 (south-facing levee) in a single year indicates the essential contribution of wave attenuation by marsh vegetation to the stability of low-angle slopes. Steeper slopes (less than 10:1) are most vulnerable to wave erosion unprotected by fringing salt marsh. (A) About 1 to 1.7 feet of high erosion scarp has formed in the levee facing away from dominant westerly winds, and a wide scour zone has removed approximately 1 foot of fill from the south-facing levee (B) one year after tidal breaching. Negative feedback processes (wave-cut bench flattens slope with increased exposure of more cohesive, higher-strength compacted mud with high roughness to trap seeds and shelter seedlings) eventually shifts intertidal profile to frequent seedling colonization phase and marsh shoreline stabilization. August 2017.

1.5.2.3 High Salt Marsh Berm and Beach Accretion (swash bar, beach, marsh-fringe barrier)

Estuarine or bay beaches worldwide can develop along the bay edges of salt marshes, where they form marsh-fringing barrier beaches (Pilkey *et al.* 2009), originally classified as "marsh bars" (marsh berms or barriers) where swash bars (small beach ridges deposited by the swash and backwash of breaking waves) develop along wave-eroded edges of tidal marshes, and develop marsh vegetation (Johnson 1919). Estuarine beaches have morphodynamic processes comparable with, but distinct from, beaches of open sea and ocean coasts (Jackson *et al.* 2002), and provide similar wave-dissipating and wave-break functions. In San Francisco Bay, small marsh-fringing barrier beaches develop from sand, shell hash, and gravel. They shelter salt marshes and levees otherwise exposed to high rates of direct erosion by wind-waves.

During periods of relative stability, the crests of wave-built berms develop well-drained, tall salt marsh vegetation, including gumplant. This is similar to non-maintained artificial bay mud levees. Unlike levees, the crest elevations of marsh berms are maintained or increased in elevation by wave runup, and rapidly adjust to changes in wave height and sea level. At Aramburu Island in Richardson Bay, artificially nourished coarse gravel and sand beaches, spontaneously accreted to elevations approaching extreme high tide levels, in response to storm wave runup. Unlike sand beaches, gravel berms generally accrete during storm wave action and high tides. (Gillenwater and Baye 2016). The unvegetated beachfront is often used by roosting shorebirds at high tide, when mudflat foraging habitat is submerged. Historically, marsh-fringing barrier beaches and barrier spits occurred in Richardson Bay, including the shore opposite from Almonte (North Bothin) Marsh.

Like barrier beaches, coarse beaches can migrate landward rapidly in response to wave overwash (“rollover”: bayward erosion, landward deposition; Allen and Pye 2002). Beaches intercept and dissipate breaking wave energy (Jackson *et al*. 2002). If the foreshore of the marsh lacks a beach then it is unprotected and a wave-cut scarp may occur (Feagin *et al*. 2009). The natural vertical and horizontal adjustment of bay beach profiles in response to storms and sea level makes them function like mobile, flexible self-maintaining levees where coarse sediment supply is provided naturally or artificially. Coarser sand, gravel and shell material develop steeper and more storm-resilient beachfronts and berms. Shell hash is more mobile and less stable than gravel as beach sediment in the Bay. Mobile shell hash marsh-fringing barriers, however, buffer wave erosion of highly exposed (wide bay wind-wave fetch) salt marsh scarps in San Francisco Bay, such as outer Bair Island in South Bay. Naturally formed barrier beaches with gravel also shelter pocket salt marshes and protect segments of levees enough to change the bayward slope of levee to minimize erosion. They have also caused some armored concrete riprap slopes to become vegetated.

Figure 1.13. Gravel bay barrier beach formed from erosion of historic landing fill is shown at Newark salt ponds west of Coyote Hills, San Francisco Bay. (A) Unvegetated levee exposed to waves is armored with concrete slabs and rubble. (B) Salt pond levee in lee of barrier beach supports salt marsh and a vegetated levee slope. October 2014

Figure 1.14. Gravel and sand berm accretion by wind-waves in Richardson Bay under the 101 Highway, south of Bothin Marsh. Local shoreline erosion of fill supplies the coarse sediment. Waves deposit a swash bar over the edge of the paved path. September 2017.

Figure 1.15. Fringing barrier beaches. (A) pocket sand and shell berm at Hayward Shoreline salt marsh ; (B) high marsh berm formed from organic debris and sand, Pinole Creek ; (C) gravel and sand beach capped with high tall gumplant and pickleweed; Emeryville Crescent Marsh, (D) highly mobile, mostly unvegetated barrier oyster shell hash exposed to wind-wave and ship wakes, outer Bair Island, San Francisco Bay.

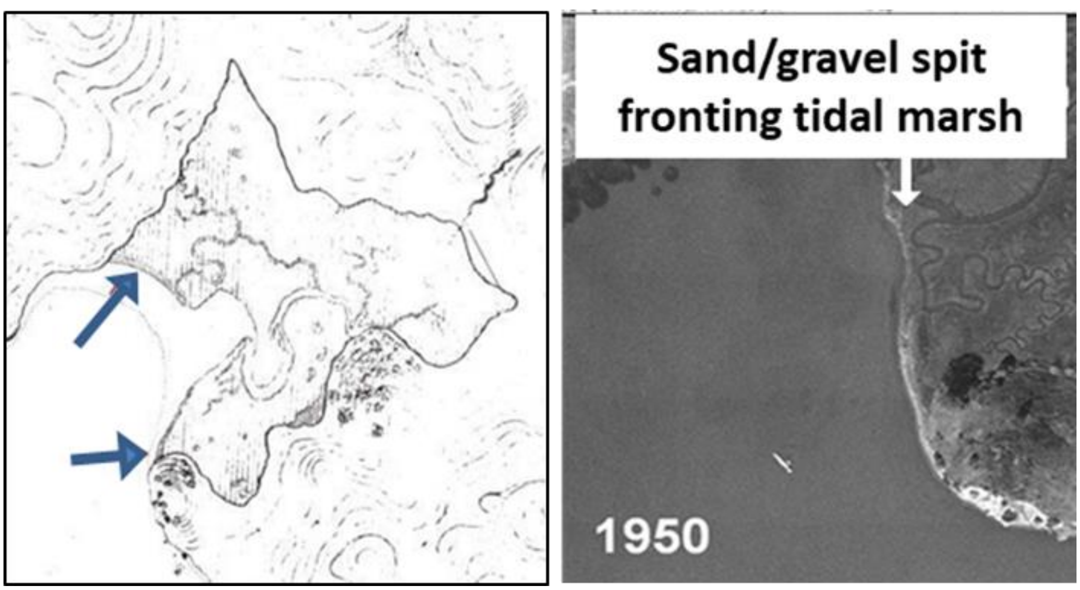

Figure 1.16. (A) Historical barrier beaches fronting tidal marsh and end of Richardson Bay (USCS T- sheet 334N, 1851); and (B) a gravel spit with back-barrier tidal marsh relating to the erosional headland of the Richardson Bay Audubon Center. This gravel spit persisted at least until 1950, when it was developed.

1.5.2.4 Tidal Marsh Creek Sedimentation, Drainage and Vegetation Gradients

Tidal creeks are the arteries of the tidal marsh plain, distributing tidal energy for sediment transport into the salt marsh interior, and tidally "pumping" marsh soil porewater and dissolved oxygen in the root zone of steep salt marsh creek banks (Figure 1.4; Li *et al*. 2005). The distinct marsh vegetation zones, and important wildlife habitat structure of salt marsh creek banks are formed and maintained by strong, steep, tidal sedimentation gradients between the tidal creek edge and a narrow zone of tidal marsh plain bordering it (Section 1.3, this chapter; Culberson *et al.* 2004). The sedimentation gradients establish subdued but ecologically significant microtopography: natural low-relief levees occupy tidal creek banks in geomorphically mature tidal marshes (Reed *et al*. 1999, French and Spencer 1993, French and Stoddart 1992, Pestrong 1972). A local example in an ancient salt marsh (China Camp Marsh) is shown in Figure 1.17.

The combination of the topographic highs (levee patterning) and tidal drainage along tidal creek banks supports a distinct zone of salt marsh vegetation structure and habitat in San Francisco Bay: tall-form pickleweed, and tall nearly evergreen gumplant vegetation delineates relatively well-drained high salt marsh of tidal creek banks, a characteristic signature of mature San Francisco Bay tidal salt marshes (Culberson *et al*. 2004, Pestrong 1972, Hinde 1954). The elevated vegetation canopy of this eco-geomorphic zone (taller vegetation on topographic highs of subtle natural levees) provides critically important sub-habitats that remain emergent above most extreme high tides and wind-wave crests. This eco-geomorphic interaction generates habitat structure essential for marsh wildlife species that maintain territories or home ranges within the interior marsh. Secretive salt marsh birds like California Ridgeway's rails feed and travel primarily under or close to cover of cordgrass/mud edges below tidal creeks banks, sheltered by vegetation canopies and overhanging bank-top sods at low tide.

At high tide, and especially at extreme high tides that submerge the interior marsh plain entirely, rails must find local cover to avoid avian predators (harriers, egrets) and terrestrial predators. Rails are forced to make long-distance cross-marsh movements to find cover when salt marsh plains are submerged, exposing them to higher predation risks, or greater exposure to terrestrial predators along the landward edge of the salt marsh. If high tide cover is distributed in banks above tidal creeks, wildlife access to high tide refuge cover is optimized, and cross-marsh movements from foraging habitat to high tide refuge within the rail's home range is minimized. In addition, high marsh creek banks mantled with tall pickleweed and gumplant also provide the primary nesting habitat for California rails (USFWS 2013, Albertson and Evens 2000). Other salt marsh birds that occur in Richardson Bay, including San Pablo song sparrows and California black rails (Spautz and Nur 2002), depend on the high marsh zone along tidal creek banks for foraging and nesting as well (Trulio and Evens 2000, Cogswell 2000). Small mammals similarly utilize creek bank high marsh vegetation canopies as high tide refuge (USFWS 2013).

In geomorphically immature salt marshes with limited internal tidal creek development or restricted interior marsh sediment supply, high marsh development at creek banks may be slow or fail to develop adequately for important habitat functions even after decades, such as at interior Cogswell Marsh (Hayward) and interior Muzzi Marsh (San Rafael; Figure 1.18)). In contrast, bayward reaches of tidal creeks with mouths connected to sediment-rich mudflats are relatively well supplied with sediment to form tidal creek banks, and develop high salt marsh vegetation zones (Figure 1.19). In restored salt marshes, if high marsh zones are decoupled from tidal creeks, critical tidal creek habitat in high tide refuge, nesting, and foraging habitat functions for wildlife will not developed. This is apparent in most of Bothin Marsh. South Bothin marsh lacks any high marsh near tidal channels: all salt marsh bordering tidal creeks is pickleweed-cordgrass ecotone or pure cordgrass vegetation. North Bothin salt marsh vegetation adjacent to tidal creek banks is dominated by middle marsh vegetation (pickleweed-cordgrass) or nearly prostrate high marsh vegetation (saltgrass mixtures). Gumplant is restricted primarily to artificial levee crests, slopes, and high salt marsh mounds near the outer edges of the salt marsh plain.

Figure 1.17. Tidal creek bank patterning of high marsh showing (A) sinuous zones of dense gumplant, interior prehistoric salt marsh plain, China Camp Marsh, San Rafael; (B) continuous high tide refuge cover from front to back of same marsh; and (D) well-developed creek banks (natural levees in ancient tidal marsh plain) support steep tidal drainage gradients with tall gumplant and pickleweed as refuge; December 2012, and December 2008).

Figure 1.18. Interior Muzzi Marsh tidal channel, after over 40 years of tidal restoration, still lacks sufficient topographic and tidal creek drainage gradients along creek banks to support tall-form pickleweed or gumplant. Olive-green diatom films on channel muds indicate their immobility. The interior marsh plain formed on dredged sediment fill and was ditched to initiate channels and improve internal tidal drainage. It remains continuous monotypic pickleweed marsh with minimal high tide refuge (compared to interior North Bothin Marsh). August 2017.

Figure 19. Bayward Muzzi Marsh tidal creek with mouth directly connected to San Rafael Bay (wave-exposed mudflat with high suspended sediment supply) has developed natural steep banks with high salt marsh levee topography and tidal drainage, supporting dense gumplant and tall-form pickleweed, with local high tide refuge cover. Gumplant delineates banks. (A) August 2017; (B) October 2011.

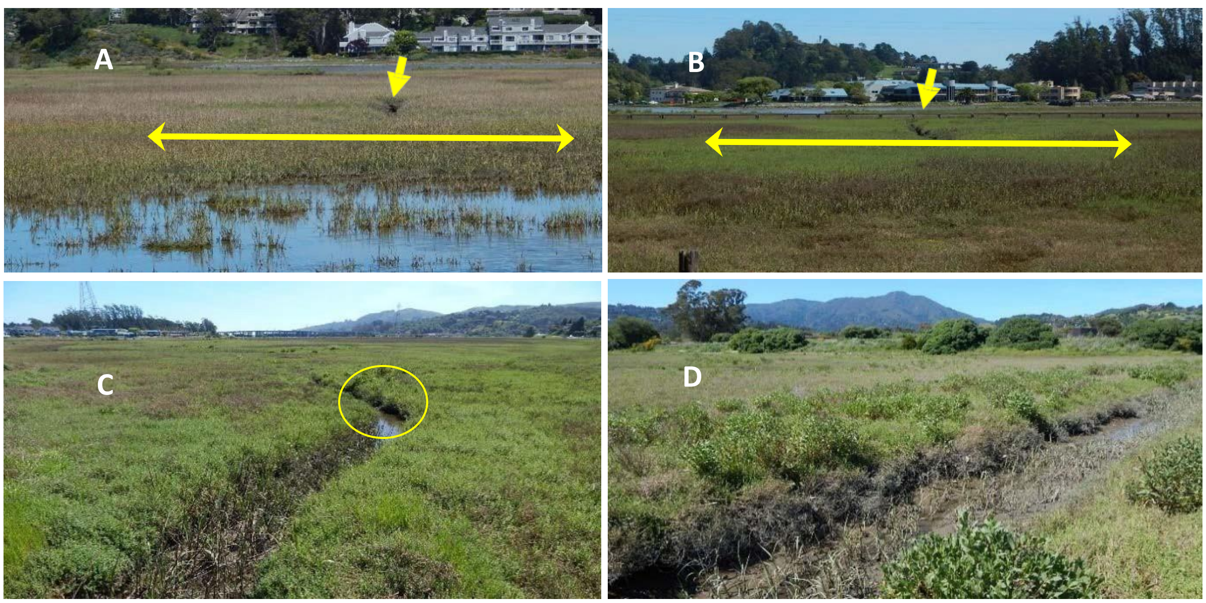

Figure 1.20. (A) Tidal channels in South Bothin Marsh and North Bothin Marsh exhibit some zonation typical of high marsh on banks, despite a lack of natural levees. (B) South Bothin Marsh channels are bordered by cordgrass and short pickleweed (yellow horizontal arrow), and (C) North Bothin Marsh channels are bordered by mid-marsh vegetation (yellow double arrow), with only isolated gumplant (yellow circle). In contrast, (D) Alto Marsh (north of Bothin Marsh) has tall gumplant along natural levees at ancient marsh remnants. Although South Bothin Marsh has been evolving for more than a century, it's tidal sediment supply has been restricted. This is also true for North Bothin Marsh, which has been evolving on natural mudflat and dredged sediment for as long as Muzzi Marsh.

Figure 1.21. Main trunk channels branched near the levee breach, close to tidal sediment sources in Richardson Bay, also lack natural levee. Most of the marsh plain is dominated by intermediate low and middle marsh vegetation. A saltgrass meadow occurs locally along banks closest to the tidal breach, with only scattered individual gumplant. The creek banks are steep, cohesive, and support overhanging root mats – all indicators of normal bank processes, although slump blocks rare. Development of natural levees is still lagging after several decades of tidal action.

Figure 1.22. Small mammals, including voles capable of diving and swimming, are forced to cross open water to reach the nearest emergent cover along the terrestrial edge of North Bothin Marsh, where internal tidal creek banks have not developed high salt marsh vegetation that would provide flood refuge at short distance from, or within, the home ranges of salt marsh wildlife. Like California rails, small mammals are vulnerable to avian predators (egrets, herons, harriers) during daytime marsh submergence. January 2017.

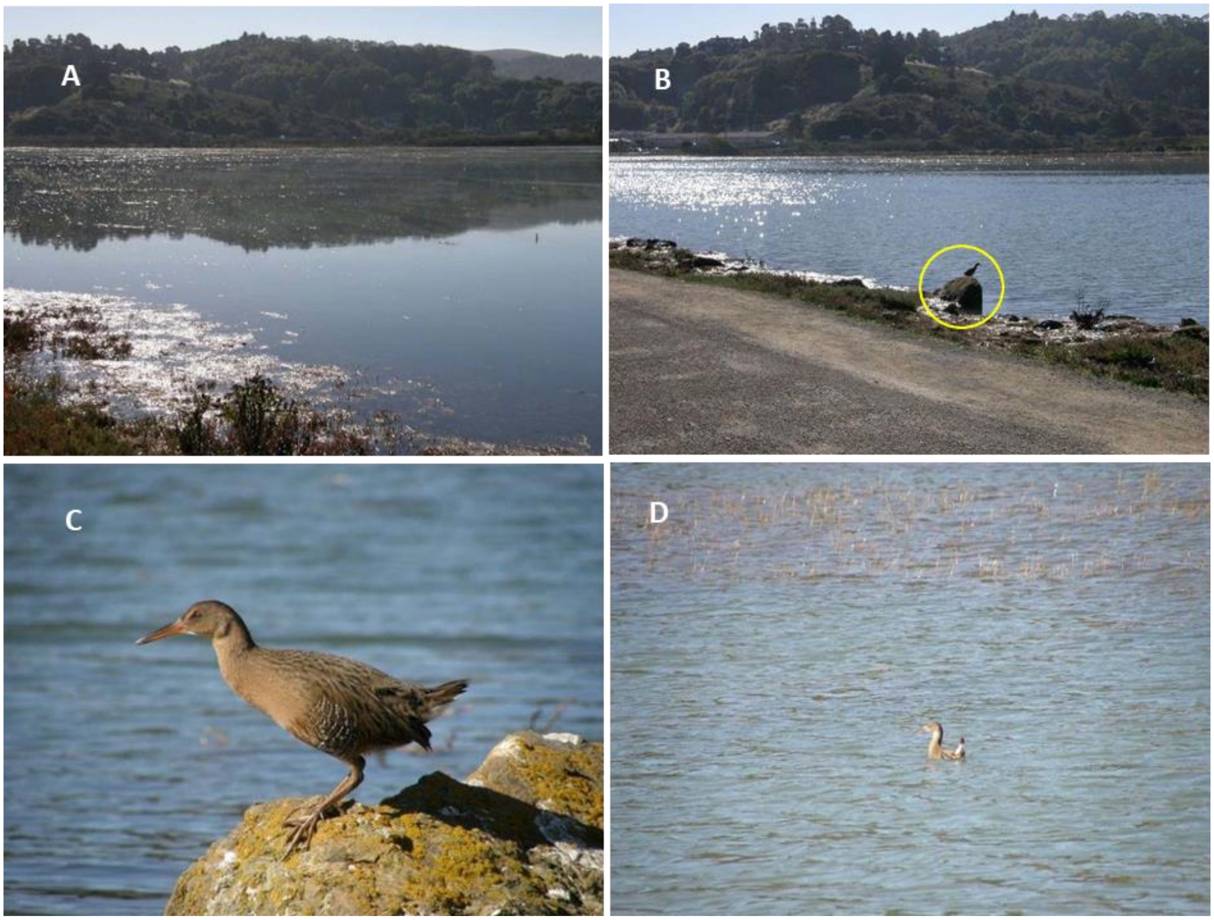

Figure 1.23. Ecological consequences of undeveloped internal high marsh creek banks: The failure to develop internal high marsh along creek banks as the first line of high tide refuge cover in South Bothin Marsh, combined with scarcity or absence of high tide refuge cover along the shoreline, strands vulnerable marsh wildlife during extreme high tides that submerge the marsh. Without internal high tide refuge cover along tidal creeks, extreme high tide marsh submergence has forced California rails to shorelines lacking cover for protection. This deficiency in salt marsh internal and edge structure exposes rails to detection by avian predators during marsh-submerging daytime high spring tides. The following example is indicative of a recurrent ecogeomorphic constraint. (A) All marsh vegetation is completely submerged in South Bothin Marsh in fall of a non-El Niño year (November 2008). (B) California rail displaced from flooded marsh reaches nearest emergent surface: interior berm slope (compacted fill and rock) with prostrate high salt marsh vegetation providing negligible terrestrial ecotone cover. Terrestrial ecotone cover is an alternative to creek bank high marsh refuge. (B-C) California rail remains exposed and highly vigilant, with no available escape routes leading to cover. (D) Rail swims to the first cordgrass cover visibly emergent above the water surface as the tide levels in the basin slowly fall, lagging behind open bay marshes. Duration of rail high tide exposure: over 45 minutes. November 13, 2008.

1.5.3 Large-scale Climate Drivers of Salt Marsh Processes

1.5.3.1 Estuarine Transgression; landward tidal marsh migration with Holocene sea level rise

Landward transgression of the tidal marsh lowland valleys and plains in response to variable rates of sea level rise has occurred throughout the Holocene Epoch in San Francisco Bay, and globally (Atwater *et al*. 1979). Estuarine transgression is an inherent feature of salt marshes, and is not a new or anthropogenic process; it is the process by which the Estuary's tidal marshes initiated in the mid-late Holocene when sea level rise rates were as high or higher than predicted for the Twenty-first Century), followed by marsh plain vertical accretion under low, variable rates of sea level rise and fluctuating climates during the last 2000 to 4000 years (Atwater *et al*. 1979, Malamud-Roam *et al*. 2006, 2007). Climate change-induced global sea level rise has added a new awareness and urgency about the artificial rapid acceleration of this process, but landward transgression has always been an inherent, natural process for tidal marsh evolution as wave and tidal sedimentation/erosion processes drive "normal" tidal marsh evolution.

Kirwan *et al.* (2016) developed coupled numerical models of erosional salt marsh retreat, sea level rise, and landward transgression (without barriers), and concluded that marsh loss is nearly inevitable where topographic and anthropogenic barriers limit migration. Models show that where tidal marshes are unconstrained by barriers however, rates of marsh migration are much more sensitive to accelerated sea level rise than rates of edge erosion: landward transgression over pre-existing lowland plains or valleys can occur without the need for sediment accretion to form new tidal marsh.

Paradoxically, sea level rise can cause tidal marsh expansion during sea level rise, despite marsh edge erosion, where barriers to transgression do not constrain salt marsh encroachment of terrestrial lowlands (Kirwan *et al*. 2016). The geomorphic accommodation space for high tidal marsh transgression in the Bay Area, however, is limited to land uses such as open space and low-intensity agriculture, which are primarily found in the North Bay and Suisun Marsh (Callaway *et al*. 2011). According to the most comprehensive tidal marsh models of ecogeomorphic evolution calibrated for the San Francisco Estuary, (Marsh Equilibrium Model, MEM; Schile *et al*. 2014), the ability of tidal marshes to compensate for marsh loss and submergence under the high rates and stands of sea level rise depends on landward transgression of the tidal marsh gradient over available lowland valleys and plains, especially critical high tidal marsh habitats under moderate to low estuarine sediment supply.

In Marin Baylands, including Richardson Bay, estuarine accommodation space is scarce in steep canyon and hillslope terrain with urbanized valleys that impose a "coastal squeeze" constraint: economic and engineering priority for "holding the line" (stabilization and flood control to protect high-value land uses) at modern shorelines, while bay edges of tidal marshes retreat from increased erosion. "Coastal squeeze" results in relative narrowing and compression of coastal marsh gradients with sea level rise instead of compensatory landward transgression, and measurable impairment of estuarine and adjacent watershed ecosystem functions adjustment to rising sea level (Torio and Chmura 2013, Turner *et al*. 2007).

At Bothin Marsh, landward transgression in the foreseeable future is highly constrained by steep privately owned fill embankments and platforms at Tam Junction, but some estuarine accommodation space for transgression is potentially recoverable from large, steep weed-dominated artificial upland fills placed in historical Coyote Creek tidal marsh during the Twentieth Century (Part 3). Almonte Boulevard road embankments, and the steep hillslope behind it, limit landward transgression of tidal marsh under current/foreseeable land use. Even road realignment with landward set-back would provide relatively modest (but significant) increase in scarce accommodation space, because hillslope topography naturally restricts tidal marsh adjustment to vertical accretion over horizontal migration processes. This makes long-term loss of high tidal marsh bordering hillslopes effectively inevitable under long-term high rates and stands of sea level under moderate or low sediment supply (Kirwan *et al.* 2016, Schile *et al*. 2014, Kirwan *et al*. 2010).

The lifespan of tidal marshes bordering natural topographic barriers like hillslopes, however, can potentially be expanded significantly (for decades) with marsh sediment nourishment methods (Part 5). Providing a broad ramp profile (gentle suitable sediment fill slope from high intertidal to lowland supratidal zones) straddling existing uplands and upper marsh edges can potentially maintain a complete tidal marsh gradient with all ecologically important habitat zones (Schile *et al*. 2014, Parker *et al.* 2011), including critical high salt marsh habitats. This may require bayward encroachment of an existing tidal marsh plain at the lower landward edge of a constructed sediment ramp profile (Chapter 5), leaving less marsh space for valuable tidal creek networks.

1.5.3.2 Extreme climate events and cycles

The late Holocene stratigraphic history of San Francisco Estuary tidal marshes is punctuated with sediment and soil layers that indicate relatively abrupt extreme climate fluctuations and events consistent with infrequent storms, extreme persistent droughts, and deluges (Watson 2008, 2012; Goman *et al*. 2008, Malamud-Roam *et al*. 2006, 2007) that temporarily re-set marsh vegetation and soil conditions, sometimes for long periods. These past climate fluctuations occurred during the slowest sea level rise rates of the Holocene. Future extreme climate events, such as extreme droughts and heat waves, are predicted to intensify and increase in frequency globally and in California (Allan 2014, Scherer and Diffenbaugh 2013, Cornwall *et al*. 2012, Dieffenbach and Ashfaq 2010). Under scenarios of accelerated sea level rise affecting tidal marsh vertical and horizontal adjustments (submergence and erosion; Kirwan *et al*. 2016) extreme climate events are likely to interact with tidal marsh changes forced by accelerated sea level rise. The cumulative impacts of extreme climate events and accelerated sea level rise are likely to substantially change tidal marsh eco-geomorphic functions, vegetation and habitats, particularly in San Francisco Estuary upper (mid to high) tidal marsh zones where soil porewater can concentrate salts during neap tides (Parker *et al*. 2011, Day *et al*. 2008).

Abrupt, extreme climate events may result in many impacts, and some opportunities for Bothin Marsh adaptive management. Adverse impacts may include mass dieback of mature gumplant (critical high tide refuge) and recruitment failure of gumplant during extreme persistent droughts and heat waves causing high marsh hypersalinity (Parker *et al.* 2011), and loss of marsh soil shear strength (erosion resistance) due to root dieback and soil drying and shrinkage during summer neap tides (Allen 1988). Extreme flood events, if coupled with high sediment yield in the Coyote Creek watershed, could result in pulses of sediment to the tidal marsh and Richardson Bay mudflat. This supports longer periods of elevated tidal marsh sediment supply (mudflat resuspension and transport to tidal marsh creeks, trapping sediment in tidal marsh). This would be most likely if tidal constraints between Coyote Creek, South Bothin Marsh, and Richardson Bay were modified to make the tidal marsh receptive to fluvial-tidal sediment transport.

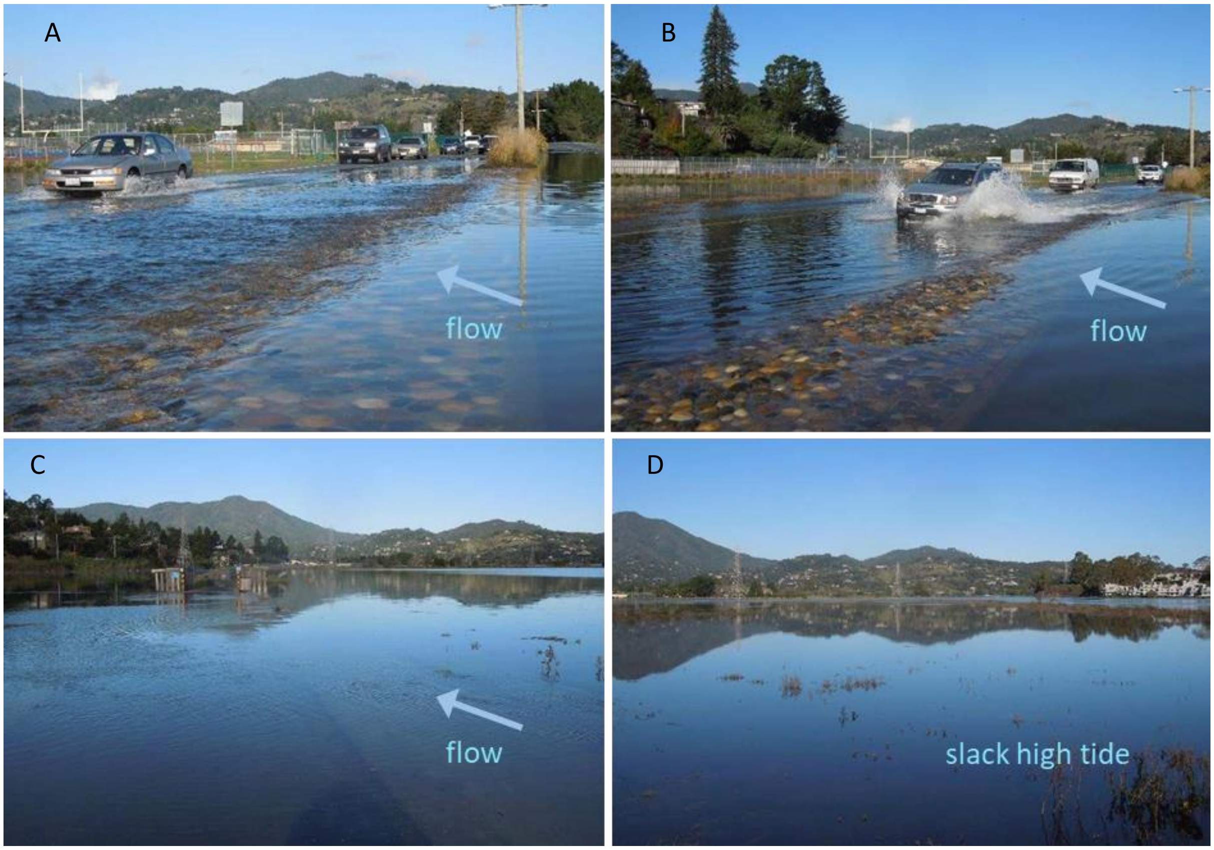

Figure 1.24. Local Bothin Marsh flood tide during anomalously high local sea level event (higher than astronomic predicted tide) during calm weather in a non-El Niño year, before the winter solstice. The median strip of Almonte Boulevard (A, B) became an floodway for the bay, with road is submerged by up to 2 feet of tidal water, and with (C) submerging South Bothin Marsh, (D) North Bothin Marshes and the Bay Trail during slack high tide, December 12, 2012.

1.5.4 Important Local-Scale Drivers of Salt Marsh Processes

1.5.4.1 Alluvial Fan deposition and estuarine submergence

Terrestrial sediment transport processes can significantly influence the landward margins of tidal salt marshes. Ancient stream deltas and alluvial fans or plains form the foundations for tidal marshes that override them during Holocene sea level rise and estuarine transgression (Watson 2012, Atwater *et al*. 1979). Active deltas and alluvial fans can also deposit sediment over tidal marsh surfaces, creating foundations for new tidal-terrestrial ecotones that support important plant and wildlife habitats (Collins *et al*. 2015, Baye *et al*. 2000). Diking, flood control, and shoreline stabilization has minimized terrestrial and fluvial process interactions with San Francisco Estuary tidal marshes, but they are still locally evident in a few intact San Pablo Bay shorelines, such as China Camp and Point Pinole.

At China Camp, a hillslope gulch erosion event deposited a new alluvial fan over tidal salt marsh during winter storms in 2006, shallowly burying high salt marsh vegetation dominated by pickleweed and saltgrass. By 2008, most of the alluvial fan surface, composed of terrestrial sediments (sand, silt, and clay eroded from weathered shale and sandstone subsoil) was recolonized by buried clonal vegetation and lateral spread from contiguous salt marsh. The alluvial fan regenerated high salt marsh gradients, with wider, gently sloping zones in the spring high tide elevation range. By 2012, the fan supported a new salt marsh-terrestrial ecotone including gumplant (Baye, personal observation, 2006- 2012; see Figures 1.25 and 1.26 below). This alluvial fan-tidal marsh depositional process, though extinct at Bothin Marsh, remains relevant because artificial surrogate processes simulate functionally equivalent landforms at restored tidal marsh edges.

At Sonoma Baylands, Petaluma (U.S. Army Corps of Engineers and California Coastal Conservancy tidal marsh restoration project), dredge sediment including sand and shell was deposited hydraulically in diked baylands to raise subsided elevations (Figures 1.27-1.28). The dredge discharge points along the landward levee were moved intermittently, forming a series of sediment splays (dredge sediment fans or mounds, analogous with alluvial fans) around the discharge point in 1995. The fans were stratified with layers of coarser and finer sediment, distributed in variable sediment lobes that established variable soil textures for tidal marsh plant growth. This "constructed" feature (partially removed by subsequent grading) subsequently formed the only high salt marsh vegetation gradients with high tide refuge cover (abundant tall gumplant) in the project's restored tidal marsh plain by 2000. They remain the only wide, gently sloped high salt marsh gradients at Sonoma Bayland.

At Montezuma Wetlands Project (Suisun Marsh), similar hydraulic dredge sediment fans analogous with alluvial fans nearly identical with those of Sonoma Baylands (20 years earlier) were deposited during dredge sediment filling operations. These artificial sediment fans became vegetated with non-tidal salt marsh in various stages of succession (see Figure 1.29). At North Bothin Marsh, shell fragment-rich, sandy to silty old dredge sediment mounds or fans (Chapter 4) persist along its landward edge, bordering the historic railroad berm (Figure 1.30). These historic relict features now support large colonies of the rare salt marsh bird's-beak and most of the tall gumplant colonies that provide high tide refuge cover internal to the marsh (not located on levee and berm slopes).

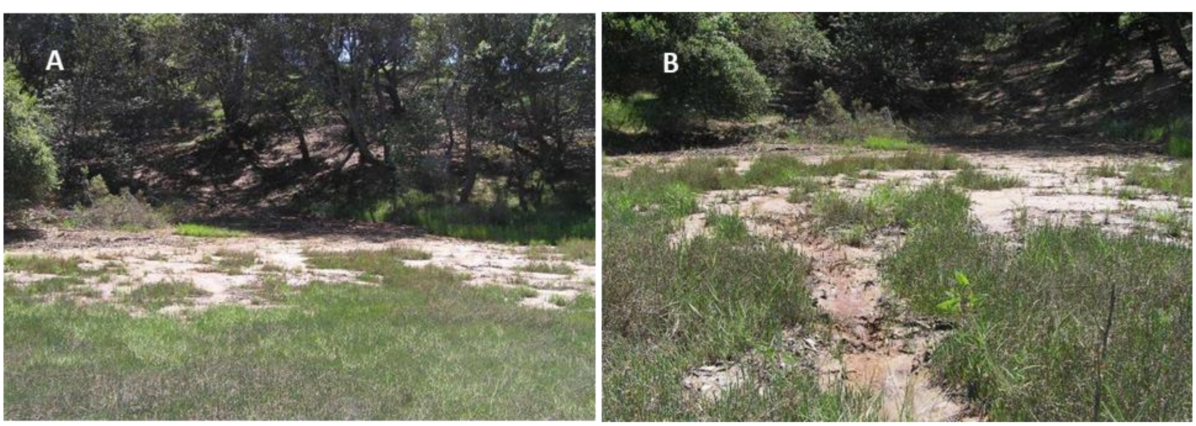

Figure 1.25 China Camp Marsh, new alluvial fan deposited during winter storms at the mouth of a gulch spread over adjacent high tidal salt marsh, shallowly burying saltgrass and pickleweed (less than 1 foot burial depth, mostly less than 0.5 foot accretion). Pickleweed and saltgrass directly regenerated on the raised alluvial fan surface, emerging through shallow terrestrial sediment deposits. May 2006.

Figure 1.26 China Camp Marsh (A, B) alluvial fan over tidal marsh almost completely recolonized by high salt marsh vegetation after two years, leaving only small bare patches of coarse sediment. April 2008, and (B) the head of the fan dominated by tall gumplant vegetation below upland coyote-brush, providing terrestrial-edge high tide refuge.

Figure 1.27. Sonoma Baylands tidal marsh restoration project (Petaluma) unintentionally created dredged sediment fans, analogous with alluvial fans, during hydraulic sediment discharge operations for raising subsided, diked bayland elevation. Fans became vegetated with salt marsh vegetation prior to tidal restoration. Winter and summer 1996.

Figure 1.28 Sonoma Baylands dredge sediment fans deposited in 1996 established extensive high salt marsh vegetation gradients across the fan slopes by 2000. The artificial alluvial fans stabilized high salt marsh vegetation dominated by gumplant and tall pickleweed, similar to natural alluvial fan-high salt marsh succession event at China Camp, 2006-2012. (A) Winter 1996; (B) summer 2006.

Figure 1.29. Montezuma Wetlands tidal marsh restoration project (Suisun Marsh) unintentionally created dredged sediment fans during filling of subsided diked baylands. Fans became vegetated with salt marsh vegetation prior to tidal restoration. April 2013 (Google Earth imagery).

1.5.4.2 Anthropogenic Fill and Tidal Breach Legacy Effects

Natural antecedent topography can exert a persistent influence on the development of tidal marsh features, such as tidal creek drainage patterns (partly inherited from mudflats on which tidal marshes develop), and topographic and substrate gradients at salt marsh edges (such as stream deltas, alluvial fans, splays, beach ridges, natural channel levees and overwash wave-formed berms). These inherited estuarine, coastal or fluvial landforms can initiate and sustain tidal marsh processes long after their original formation, and long after the cessation of the processes that formed them (Allen and Pye 2002). Similar residual influences of antecedent morphology and substrate can be inherited from artificial fills and substrates, which also exert ongoing, persistent effects on the evolution of restored tidal marshes. For example, the residual elevation and consolidation (dewatering, cohesion) of dredged materials, or former compacted soils in diked baylands, can inhibit tidal creek evolution (Williams and Orr 2002).

Figure 1.30. Remnant shell-rich dredged sediment left at the backshore of North Bothin Marsh, (A) during low tide in winter, and (B) during a very high tide in early spring, illustrating the value of the sediment pile as a vegetated topographic high area serving as refuge for resident wildlife.

Bothin Marsh is outstanding in the degree of influence that artificial antecedent topography, drainage, and substrate imprinted the template of the marsh, and exerts ongoing influence on tidal marsh processes, on par with natural processes. Nearly all of the tidal marsh-terrestrial ecotone and high salt marsh at landward edges are formed on artificially constructed or deposited bay mud, hydraulic dredge sediment fans, mechanically placed dredged sediment mounds, levees, and berms. Nearly all rare plant habitat and critical high tide cover and nesting habitat for California rails depends on artificial old fills and their remnants, especially in the absence of naturally formed high marsh on channel banks. Levees and dredge sediment fans or mounds composed of pure bay mud or sand-shell-mud mixtures generally support high salt marsh vegetation.

Many relict artificially dredged and filled Bothin Marsh features, however, contain substrates that appear to inhibit erosion, sediment transport, and morphological adjustment to waves and tidal currents, and alter salt marsh vegetation structure. Resistant, dense sandy to clayey or stony fill forms a foundation on

Coyote Creek banks that apparently inhibit tidal channel incision (forming resistant lag deposits of angular rock in ditch beds), restricting incipient channels to vegetated runnels (shallow, vegetated channels) or rocky lag-armored incised shallow channels. Exposed old pipes at the marsh surface similarly act as weirs or tidal channel grade control structures in South Bothin Marsh.

Dewatered bay mud fill platforms left over from non-tidal bayland filling in the 1970s also appear to have channel-inhibiting residual effects on modern tidal marsh processes. Tidal creek development and extension (headward growth) in North Bothin marsh appears to be inhibited where it intercepts mechanically and hydraulically placed dredged sediments from the 1970s formation. Like the relatively high dredged sediment platforms of Muzzi Marsh that were filled above Mean High Water, portions of North Bothin Marsh that exhibit dredge sediment placement at the south end also appear to resist ecologically important tidal channel development.

At the extreme end of the spectrum of channel erosion resistance, the quarry rock-stabilized tidal inlet of South Bothin Marsh appears to significantly choke tidal flows between the bay and tidal basin enclosed by the historical berm and the Coyote Creek high marsh (fill) bank. Significant tidal choking (undersized tidal inlet cross-section relative to tidal prism) is indicated by the lag in tide levels between the tidal basin and the bay, made visible by steep, turbulent water slopes across the inlet throat, and an ebb tide jet (plume of turbulent water, sometimes with standing waves and foam) discharging to the Bay. The tidal asymmetry between the basin and the bay, and the slow, prolonged residual ebb tide in the basin, is a chronic tidal restriction. Restriction of tidal flows through bridges and culverts is a widespread hydrological and ecological impairment of tidal salt marshes of the Atlantic Coast (Tiner 2013), where it has been the primary focus of many tidal restoration projects (Roman and Burdick 2012). The ecological consequences of significant tidal choking at South Bothin Marsh probably include the very slow succession of low cordgrass marsh and cordgrass-pickleweed marsh ecotones, and failure to develop any significant internal high marsh banks along creeks. The choked tidal asymmetry between the South Bothin Marsh basin and fully tidal Coyote Creek may be responsible for the recent scouring of the former high marsh on the northern artificial levee bank of Coyote Creek: during the ebb phase after extreme high tides, the basin drains by turbulent over-marsh flow across the bank to the lower tide level of Coyote Creek. This process scours runnels that have not yet incised to intertidal depths because concentrated rocky lag from artificial fill impedes erosion. This may change as sea level rise continues.

Effects of erosional resistance of artificial surfaces are evident in some other shorelines of Bothin Marsh, and in adjacent tidal flats. In tidal flat areas subject to dredging in the 1960s and 1970s (Chapter 3), concentration of lag armored surfaces have formed. These appear to develop from wind-wave erosion of gravel-contaminated flats: where gravels are mechanically mixed with bay mud by past dredging, wind-wave and current erosion has winnowed out more mobile fine sediment, concentrating heavier gravel at the surface, where it locks down fine sediment beneath it. Tidal flats composed of naturally well-sorted silt-clay (typical bay mud) are subject to wind-wave erosion and resuspension of fine sediment, which can supply adjacent tidal marshes with suspended tidal sediments supporting marsh accretion (Allen and Pye 2002, Pethick 2002). Lag surfaces stabilize the mudflat surface, locally inhibiting mudflat-marsh sediment exchange. The bay shoreline at the historical railroad berm is a steep, impermeable surface composed of boulder-sized riprap and compacted stony fill that inhibits rooting and anchoring of salt marsh vegetation. It appears to act as a wave-reflective seawall, scouring fine sediment and inhibiting marsh initiation and accretion where rock outcrops are prevalent and a soil or mud veneer (root zone) has been lost to erosion.

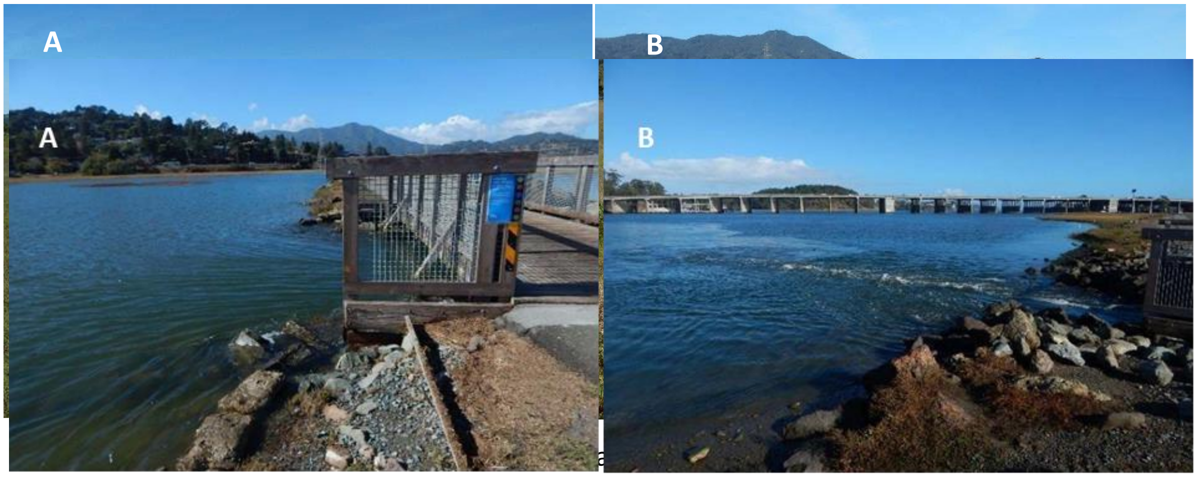

Figure 1.33. Historic infrastructure influences modern tidal hydrology of South Bothin Marsh. The under-sized tidal inlet (see Chapter 3) is a rock-armored breach in the historic railroad berm under the Bay Trail Bridge 2. The tides ebb faster from Richardson Bay than the marsh can drain. As a result, the water level of the Bay drops faster than the water level in the marsh. The difference in water levels can result in very high velocities of ebb flow from the marsh, causing a scour pool on the bay side of the inlet. (A) water streams from the marsh at high velocity, creating (B) turbulent flow through the inlet, creating standing waves in the Bay. Slow drainage of the marsh increases its duration of submergence, relative to fully tidal bay salt marshes.

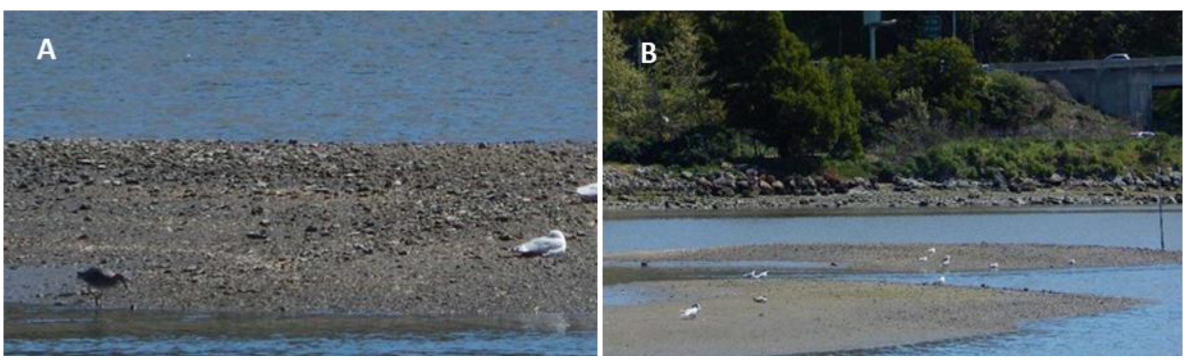

Figure 1.32. Coarse, gravelly sediments form a convex, armored surface on relict old dredge sediments that comprise Richardson Bay tidal flats. The coarse material is concentrated at the surface after wind-wave erosion and tidal currents remove the finer sediment from around the larger particles. The armoring limits resuspension of fines and thus limits their availability to the marshes. April 2017.

Figure 1.35. Old artificial fill and buried structures restrict eco-geomorphic development at South Bothin Marsh. (A) A buried pipeline exposed at the bed of a ditch acts as a grade control structure, preventing the ditch from achieving its equilibrium depth with its upstream tidal prism. (B) Resistant angular gravel in artificial fill along the north bank of Coyote Creek inhibits rapid channel incision and tidal creek evolution through the salt marsh surface (also see Figure 1.34 above). April 2017.

Figure 1.36. Quarried boulders are exposed along the bay mudflat shoreline of the historical railroad berm used for the Bay Trail at South Bothin Marsh, north of the mouth of the Coyote Creek Canal. The resistant, compacted, rocky fill inhibits salt marsh vegetation, which is restricted to shallow, temporary soil pockets or veneers between the rocks. Wind-wave reflection concentrates wave energy and promotes erosion of the soils. The vegetation is unable to gain enough stature and cover to attenuate wave energy. April 2017

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The ditch has cut down through the thin veneer of soft tidal sediment and into the compacted, rocky fill of the old levee. The ditch is slowly widening and deepening as it conveys more tidal prism, yet its rate of erosion is slowed by resistant gravel in the levee. It is, however, evidence of a tidal marsh channel evolution. April 2017.

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