


New Life for Eroding Shorelines:

Beach and Marsh Edge Change in the San Francisco Estuary




SFEI San Francisco Estuary Institute

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A technical report associated with the New Life for Eroding Shorelines Project

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As this is just the first phase of deliverables for the New Life for Eroding Shorelines project, we are looking forward to integrating these results into the outcomes of the rest of the team's work, and continuing to add to our understanding of physical and ecological shoreline processes towards the goal of greater shoreline resilience in the face of climate change.

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GLOSSARY

Accretion
The vertical accumulation of sediment causing growth of a landform.

Backwash
The gravity-driven flow of water back down the slope of a beach after the swash of the preceding wave (Tarbuck and Lutgens 2008).

Bar
Elongated intertidal or subtidal sand body with a wave or ridge form, deposited by (tidal) currents or waves; wave-deposited bars are generally aligned nearly parallel with the shore (Price 1951, 1968). Bars deposited by swash and backwash of waves are termed *swash bars*. Large, persistent swash bars deposited at the limit of constructive wave action at the backshore are also called *beach berms* (Pethick 1984, Davis and FitzGerald 2004).

Baylands
General term describing areas around the margin of a bay, including mudflats, tidal marsh, and transition zone (Goals Project 2015).

Beach
Deposit of unconsolidated sediment ranging from cobbles to sand, formed by wave processes along the shoreline. The beach extends from the landward limit of wave action at the base of cliffs, bluffs, dunes, or a marsh platform, to the seaward or bayward limit of wave action and beach sediment (Davis and FitzGerald 2004, Pilkey and Young 2009).

Beach berm
A nearly horizontal portion of the beach or backshore formed by the deposition of sediment by the receding waves (Komar 1976).

Beachface
The sloping section of the beach profile below the berm where the swash and backwash of waves occurs at high tide, eroding or depositing beach sediment (swash slope) (Komar 1976).

Berm crest
The linear break in slope marking the seaward limit of the berm and landward limit of the beachface (Komar 1976).

Cusps
Regularly spaced shoreline landforms (spacing typically between a few meters and a few tens of meters along the shore) consisting of small (< 1 m) embayments between protruding ridges. They are a common feature of reflective beaches (Mangor 2019).

Drift aligned
Drift alignments are found on beach-fringed coasts where the dominant waves arrive obliquely to the shore and (with accompanying currents) maintain a beach parallel to the direction of the resulting longshore drift. They are typically found on straight coasts where the obliquely-arriving waves move sediment alongshore (Bird 2019).

Fringing beach
A narrow strip of beach at the toe of a mainland bluff, cliff, or levee. Narrow beaches along the outer salt marsh edge are termed marsh-fringing barrier beaches (Pilkey and Young 2009).

Groin/micro-groin
An artificially constructed obstruction to longshore drift of beach sediment, designed to cause local beach deposition. Micro-groins are short groins restricted to the beach berm and beachface, which allow significant bypassing of longshore drifted beach sediment.

Lateral erosion
Landward movement of the shoreline. Also known as marsh edge retreat or recession.

Living shoreline
A shoreline management system designed to protect or restore natural shoreline ecosystems through the use of natural elements, and, if appropriate, manmade elements. Any elements used must not interrupt the natural water/land continuum to the detriment of natural shoreline ecosystems (Restore America's Estuaries 2015).

Low tide terrace (estuarine)
The intertidal flats (sand, mud, or other mixed sediments) bayward of a low-energy beach, where wave action is highly attenuated or eliminated at low tide (Jackson et al. 2002)

Marsh edge (bayward edge of the marsh plain)
The estuarine marsh edge is conventionally the bayward boundary between tidal marsh vegetation canopy and unvegetated tidal flats, where a significant change in wave attenuation and estuarine habitat structure occurs (Möller and Spencer 2002, Glancy et al. 2003). For the geographic context of the San Francisco Estuary, we treat the marsh edge as the geomorphic discontinuity in topography, slope, and soil shear strength at the scarped or ramped bayward edge of the marsh platform, where incident waves attack consolidated peaty mud bound by plant root mats (Valentine and Mariotti 2019, Hopkinson et al. 2018, McLoughlin et al. 2015, Francalanci et al. 2013, Schwimmer 2001). Either unvegetated bay mud or low cordgrass marsh with very low shear strength compared with the marsh platform (Pestrong 1969) occurs bayward of the marsh edge.

Marsh scarp
Steep or near-vertical wave-cut cliff (approximately 1-2 meters high) in the tidal marsh platform; erosional face between the salt marsh and the tidal flat (Francalanci et al. 2013, Allen 2000).

Overwash (process)
The flow of water and sediment over the crest of a beach system when the run-up level of waves or the water level, often enhanced by storm surge, exceeds the local beach or dune crest height (Donnelly 2008).

Pocket beach
Beaches formed in narrow embayments, coves, or indentations (pockets) in cliffed shores, where beach sediment is trapped, and beach sediment transport or loss is restricted.

Progradation
Lateral bayward or seaward growth and movement of the shoreline; expansion of the marsh or beach edge.

Spit
A type of barrier beach formed by longshore drift or tidal inlet breaching, extending into an embayment, tidal inlet or tidal flats (Evans 1942, Davis and FitzGerald 2004).

Swash
Turbulent water that washes up the beachface when waves break.

Sediment grain size
Beaches in the San Francisco Estuary are dominated by different sediment grain-size types: sand (0.063-2 mm), gravel (2-4 mm), cobble (64-256 mm), and shell hash (e.g. Udden-Wenworth scale). Grain sizes vary based on local sediment sources, wind-wave conditions, geographic setting, and other factors.

Shoreline (coastline)
The intersection of the land with the water surface. The shoreline shown on charts represents the line of contact between the land and a selected water elevation (NOAA 2020).

Swash aligned
Swash alignments develop where beaches have been shaped by wave crests arriving parallel to the shore, usually in curved patterns resulting from wave refraction. They are typically found in embayments where longshore drift is limited and beach shorelines run parallel to the crests of incoming waves (Bird 2019).

Transgression
The landward and upstream migration of the compete tidal marsh ecosystem including the intertidal zone and the adjoining terrestrial-estuarine transition zone due to sea level rise (Goals Project 2015) .

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CHAPTER 1: INTRODUCTION

Wind, waves, storms, and changing water levels have reshaped shorelines for millennia and continue to do so today. The current shape of the San Francisco (SF) Estuary shoreline is relatively new; 15,000 years ago, the California shoreline was west of the Farallon Islands and 140 meters below its current level (Cohen and Laws 1992, Malamud-Roam et al. 2007). By approximately 6,000 years ago (the end of the last glacial epoch), the sea had risen to nearly its present level and filled what is now San Francisco Bay, allowing marshes to form and maintain themselves (Atwater 1979). More recently, humans have changed the shape of the shoreline. During the 1850s, many marshes expanded extensively due to increased sediment supply from hydraulic mining in the Sierra Nevada (Gilbert 1917, Goals Project 1999). Diking, dredging, and filling of marshes for agricultural and urban development began in the late 19th century and continued through the first half of the 20th century.

Today, humans continue to reshape the shoreline through continued diking, dredging and filling as well as restoration projects, urbanization of watersheds, ferry wakes, and many other means. The most wide-ranging impact of human activity on the shape of shorelines is global climate change caused by greenhouse gas emissions, which is accelerating the rate of sea level rise worldwide (OPC 2018). Sea level rise is likely to cause much more dramatic changes in the shape of shorelines than have been seen in recent centuries. The magnitude and pace of change will depend on the rate of sea level rise, existing shoreline conditions, and the ability of shorelines to adapt.

Research to date indicates that there are three ways, individually or in combination, that marshes can respond to sea level rise: (1) lateral erosion of the bayward marsh edge or progradation of the bayward marsh edge; (2) vertical accretion or down-shifting; and (3) transgression of the landward edge. Vertical accretion potential is determined by the initial marsh elevation, inorganic sediment supply, and organic matter accumulation. Landward migration (i.e. transgression) potential is determined by availability of undeveloped upland transition zone space adjacent to the marshes. Lateral movement of the bayward marsh edge can be either landward or bayward, resulting in marsh retreat or progradation. The direction and rate of these changes are driven by varied physical and ecological factors, such as elevation with respect to the tide, wave energy and direction, vegetation type, shoreline composition, sediment supply, and land availability (Schwimmer and Pizzuto 2000).

Like tidal marshes, mudflats and beaches are dynamic and evolve over time. Changes in mudflat and beach morphology are largely dependent on forcing by water levels, waves, and currents, and on sediment supply. The upland-to-subtidal baylands profile is connected in terms of the movement of water, sediment, and species, and so the profile must be considered as a whole rather than as individual parts (Goals Project 2015). For example, if mudflats erode, then wave energy at the marsh edge increases and the marsh may retreat; if coarser material collects along the shoreline then beaches can form and protect marshes. The time frame of these shoreline changes varies. Larger glacial and tectonic changes occur on the order of millennia, while shoreline change drivers such as sediment supply and wave energy may vary from year to year and decade to decade. Some changes on the shoreline are a result of discrete events like large storms or earthquakes.

Estuarine beaches are distinct from beaches formed along the open coast. The connection to the Pacific Ocean through the Golden Gate limits the amount of swell that reaches the SF Estuary, creating a fetch-limited environment in which wave heights are influenced by local wind conditions (i.e. wind direction, duration, and speed) and bathymetry (Jackson et al. 2002). In contrast, the wave action along open coasts can be much greater since these coastlines are subject to regular ocean swell and long fetches. The beach and bar formations within estuarine environments tend to be smaller than those on the open coasts as a result of limited wave action (Nordstrom and Jackson 2012). Estuarine beaches are often fronted by tidal flats or low-tide terraces which are relatively stable morphologically, limit the exposure of the beaches to waves, and attenuate waves that do reach the beaches. Relative to open coast beaches, there is limited longshore sediment movement on estuarine beaches, which rely more on local sediment inputs (e.g., eroding bluffs, creek mouths) (Nordstrom and Jackson 2012).

One of the most direct impacts of sea level rise on ecosystems in the SF Estuary may be the continued loss of tidal marsh due to lateral erosion of the marsh edge. Even in the absence of rapid sea level rise, lateral retreat due to wave-induced edge erosion has caused loss of mature tidal marshes today (Fagherazzi 2013). Well-documented in other systems, this wave-induced erosion of the bayward edge of tidal marshes is also an ongoing phenomenon in the SF Estuary (Beagle et al. 2015). Understanding lateral changes in the position of the marsh edge is important because marsh retreat (as opposed to drowning) is widely cited as the primary mechanism of coastal wetland loss worldwide (Francalanci et al. 2011, Marani et al. 2011, Fagherazzi 2013). Sea level rise will exacerbate this loss as waves will be less attenuated and more wave energy will reach the marsh edge, increasing shoreline erosion (Wigand et al. 2017).

Sediment inputs will impact the sea level rise adaptation potential of SF Estuary baylands habitats such as marshes and beaches. While coarse sediment inputs to the SF Estuary and outer-coast ocean beaches historically were transported from the Sierra Nevada (Barnard et al. 2013), sediment sources for estuarine beaches and other bay margin habitats were mainly from local bluff erosion and local tributary watersheds (Schoellhamer et al. 2018). Both sources have greatly reduced in volume over the course of the 20th century, partly due to sand and gravel mining (Barnard et al. 2013), and partly due to rip rap and shoreline development. Fine sediment inputs have also decreased over the last 30 years (Schoellhamer 2011, McKee et al. 2013). Coarse sediments are necessary for continued beach nourishment and fine sediments are necessary for marsh progradation and accretion. Therefore, reduction in sediment inputs may result in decreased capacity of marshes and beaches to respond to rising sea levels.

AN INTEGRATED BAYLANDS SYSTEM

Several regional goals projects and resources support the need to understand the interface between the Bay and the baylands habitats, and suggest actions for establishing a more natural upland-to-subtidal baylands profile. The Baylands Ecosystem Goals Update suggests integrating subtidal habitat elements into nature-based adaptation strategies, as these features can help attenuate waves at lower water levels and promote sediment accretion of mudflats, reducing the impacts of sea level rise and other stressors on the baylands (Goals Project 2015). One of the actions suggested in the SF Bay Subtidal Habitat Goals is to design projects with subtidal habitat components to buffer wave action and reduce wetland erosion (Subtidal Goals 2010). The Adaptation Atlas (SFEI and SPUR 2019), building on the two goals projects, suggests potential locations for subtidal and coarse beach adaptation measures. All recommendations emphasize that understanding local shoreline dynamics (both existing and historical) is important when designing projects that include these living shoreline elements, but information on erosion and evolution of marshes and beaches in the Estuary is limited. This report helps provide higher resolution data on the locations and types of shoreline and subtidal adaptation measures that will be necessary to effectively manage these integrated ecosystems as the climate continues to change.

(Left) An example of an integrated marsh-beach system: a delta sand shoal intermixed with tidal marsh at Long Beach near the mouth of the San Lorenzo Creek flood control channel, photographed in 2010.

Willets and marbled godwits forage on a low tide terrace at Long Beach, Roberts Landing.

Erosion of marshes and beaches leads to loss of critical habitat that provides multiple benefits to people and wildlife, both today and in the face of climate change (Elsey-Quirk et al. 2019). Many ecosystem services associated with tidal marshes, including flood protection, wildlife habitat, and carbon sequestration, could be reduced and eventually lost as erosion progresses. Tidal marshes are home to the endangered Ridgway's rail (*Rallus obsoletus*) and small mammals that rely on tall marsh vegetation canopy for high tide refuge. A decrease in the abundance, distribution, diversity and quality of high tide refugia in the SF Estuary has had a detrimental impact on these species. However, there are also some benefits to erosion in the short term; for instance, released sediment can be redeposited on the marsh surface, and erosional undercuts of marsh scarps are used by shorebirds for foraging and resting. Ecosystem services provided by beaches will also be impacted by sea level rise. Beaches buffer waves and can protect terrestrial areas from storm surges. They also provide important habitat for wildlife, including high tide roost and nesting habitat for birds. In sum, marsh and beach habitats are a valuable buffer that can reduce impacts of sea level rise on landward areas, but active adaptation interventions will be required to prevent their total loss from increased erosion.

The most common solution to combat erosion of levees and developed shorelines has been to use rip rap. There is as much as 160 miles of rip rap along the SF Estuary shoreline (Doehring et al. 2016). Rip rap tends to reflect wave energy instead of dissipating it, create a physical barrier along ecologically important gradients, and interrupt flows of water, sediment, and species between related wetland habitats. A natural beach profile can retreat landward as water levels rise, if there is sufficient space, but a rip rap shoreline cannot adjust in this way. Rip rap also degrades habitat quality and reduces shoreline recreation opportunities. Adaptation solutions that do the same job of reducing erosion but that are more flexible and multi-beneficial than rip rap (or that can be combined with rip rap) are needed to promote shoreline resilience for SF Estuary habitats.

A NEW LIVING SHORELINE APPROACH

Beaches and marshes were both part of the historical SF Estuary system, and could be reestablished and managed together to provide short- and long-term sea level rise adaptation benefits.

Re-establishing marsh-fringing barrier beaches at erosional tidal marsh edges could be a valuable new living shoreline approach. Historical beaches and today's remnants, primarily in the central Bay, provide prototypes for this beach type. Beaches and mudflats can form the first line of defense in attenuating waves, slowing erosion, and promoting deposition of sediment. Landward migration of beaches with overwash and the rollover of beach ridges could help maintain high marsh berm elevations, depending on coarse sediment supply. These types of beaches are adaptable, adjusting during storms and, to some degree, as sea levels rise.

High tide refuge is another essential element to consider in the design of a new living shoreline approach. High tide refuge can consist of tall, emergent vegetation and high areas such as natural levee and marsh islands that are above the extreme water level. Gumplant (*Grindelia* spp.) is a typical example of high-tide refuge vegetation, found on natural levees adjacent to channels. Climate change may cause greater periods of hypersalinity, resulting in gumplant dieback, cover loss, and height reduction, as well as longer recovery time post-drought. High tide refuge vegetation that is more resilient to these climatic changes would benefit the baylands wildlife that depend on this limited habitat.

California Sea Blite (*Suaeda californica*), a rare and endangered plant, once occupied this high tide refuge niche in parts of the Central and South Bay. Prior to reintroductions to the region, the species was presumed extirpated in the SF Estuary, with extant populations to the south in Morro Bay (USFWS 2010). Reintroductions have been successful in reestablishing *Suaeda californica* at some sites, but the distribution is still limited. *Suaeda californica* can grow and climb above the highest tides in beach, high marsh, upland bluffs, and dune habitats. The species is a drought-resistant, highly salt-tolerant perennial shrub that can provide persistent high tide cover. Wild populations climb bluffs, driftwood, and shoreline trees like vines. This "arboring" trait may help elevate resilient high tide refuge cover along salt marsh edges, especially in combination with beaches along eroding marsh edges (Figure 1).

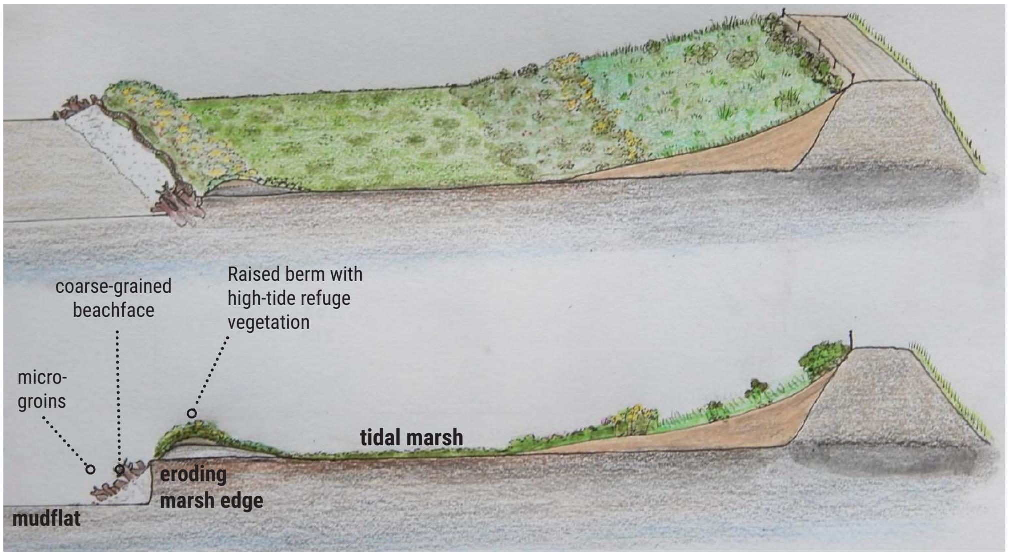

Figure 1. Conceptual oblique and cross section of an integrated baylands ecotone. In this example, large woody debris is used to create microgroins to trap coarse sediment and protect the eroding marsh edge behind it. A beach berm provides a raised area for high-tide refuge plants to grow. A gently sloping marsh protects the levee while providing space for marsh to migrate upslope with sea level rise.

The New Life for Eroding Shorelines Project

To implement a new living shoreline approach that effectively addresses the issues of marsh erosion and lack of high tide refuge, we need to understand certain basic conditions of the SF Estuary shoreline. The project consists of four main parts:

1. **Understanding present marsh erosion patterns.** To implement locally appropriate living shoreline adaptation measures, we need more information about present rates of marsh erosion. A better understanding of the patterns of marsh progradation and erosion around the Bay can help illuminate where these interventions may be most needed and most successful.
2. **Understanding present dynamics of estuarine beaches**. Understanding the dynamics of existing estuarine beaches, including interannual variation and storm impacts, can help us design new beaches to slow marsh erosion. Several beach construction projects have already been undertaken in the SF Estuary, and lessons learned from those pilot projects can be used to inform the next generation of adaptation strategies. Our approaches build on monitoring at a successful pilot "soft shoreline" enhancement project at Aramburu Island (north Richardson Bay) and ongoing studies at the 12-year-old Pier 94 (San Francisco) shoreline enhancement project.
3. **Understanding the ability of *Suaeda californica* to grow in SF Estuary environments**. Because *Suaeda californica* has been extirpated from SF Estuary environments, controlled experimental tests of behavior in wild populations in Morro Bay and San Francisco Bay pilot projects are needed to understand their response to varying environmental conditions, how arboring can help them grow, and how they may trap sediment and influence marsh resilience over time. The project team is also in the process of testing new nature-based methods for establishing resilient and sustainable high marsh vegetation structure along wave-eroded marsh edges, focusing on projects in Marin County.
4. **Developing conceptual designs for coarse beach projects along eroding marsh edges that integrate high tide refuge.** This report also sets the stage for conceptual designs for forthcoming coarse beach projects at two sites in Marin County: Greenwood and Brunini beaches (often referred to as Blackie's Pasture) and Corte Madera Ecological Reserve. The concepts proposed are alternatives to conventional coastal engineering stabilization methods that armor shorelines at the expense of marsh habitat quality.

This report in particular ("Beach and Marsh Edge Change in the SF Estuary") focuses on the first two components of the larger project by providing new methods and relevant data about patterns of change observed along several marsh shorelines and beaches in the region.

The report is organized as follows:

- Chapter 2: Identifying and quantifying where marsh shorelines are eroding in San Pablo Bay and the bay-side Marin shoreline over time.
- Chapter 3. A technical introduction to estuarine beaches in the SF Estuary.
- Chapter 4. A review of estuarine beach evolution in the SF Estuary using remote sensing and field observations, including observations of how different types of estuarine beaches throughout the SF Estuary have changed over time;
- Chapter 5. A geomorphic and ecological assessment of SF Estuary beach habitat pilot projects: evaluating lessons learned from two beach restoration projects.

Nature-based shoreline designs that rely on natural processes are more likely to be resilient to changing conditions, but also will necessitate regular and more standardized regional monitoring of the baylands to support adaptive management, as proposed in the forthcoming Wetlands Regional Monitoring Program (WRMP). This research may help us implement living shorelines projects that are adaptable to sea level rise and are grounded in the place-based geomorphology and ecology of the SF Estuary.

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CHAPTER 2:
MARSH EDGE CHANGE

Tidal marshes provide essential ecosystem services for people and wildlife in the San Francisco Estuary. These services include providing critical habitat for a wide range of species such as shorebirds, waterfowl, and fish (Goals Project 1999, Goals Project 2015), enhancing flood protection capacities, acting as storm surge buffers (Cooper et al. 2001, BCDC 2013), storing carbon, and providing chemical/physical filtration of urban and agricultural storm waters (Odum 1990, Goals Project 2015).

Tidal marshes of the SF Estuary are constantly in motion and have undergone many changes in configuration, position, and elevation over the past 200 years. Marshes tend to adjust to changing conditions in the following ways: (1) lateral erosion of the bayward marsh edge or progradation of the bayward marsh edge; (2) vertical accretion or down-shifting; and (3) transgression of the landward edge. Physical and ecological factors such as wind-wave energy, wind-wave direction, and sediment supply influence the direction and rate of change (Schwimmer and Pizzuto 2000). Changing sea levels will cause tidal marshes to continue to shift; higher water levels, storm surges, and wind waves will likely erode and drown marshes if strategic management actions are not implemented. Though vertical marsh elevation changes have been studied in the SF Estuary (Patrick and DeLaune 1990, Goals Project 1999, Stralberg et al. 2011, Swanson et al. 2014), there has been less attention on the dynamics of the bayward marsh edge. Though lateral marsh erosion is thought to be the leading mechanism by which coastal wetlands are being lost globally (Francalanci et al. 2011), it is not regularly analyzed or monitored in the SF Estuary.

In 2015, SFEI used a systematic, empirical, and repeatable approach to map the bayward marsh edge around San Pablo Bay (in the northern part of SF Estuary) at three points in time: ca. 1855, 1993, and 2010 (*Shifting Shores: Marsh Expansion and Retreat in San Pablo Bay*, Beagle et al. 2015). These shorelines were then used to quantify changes in marsh edge position and identify zones of progradation and erosion over the two time periods. Results indicated that the position of the marsh edge in San Pablo Bay shifted dramatically both in direction and rate of change. As sea level rise and changing sediment regimes continue to drive changes to the marsh edge, a method to regularly and systematically track changes in marsh edge position will be essential to help guide, prioritize, and assess adaptation efforts.

Goals of this project

In this study, we expand the *Shifting Shores* study to further understand short term trends in marsh edge evolution and inform future sea level rise adaptation concepts. The goals of the current study are to (1) map a more recent time step of the shorelines using aerial imagery from 2018 and (2) expand the geographic scope to include the marsh edges of all of Marin County and San Pablo Bay. We used GIS and tidally-controlled satellite imagery to analyze recent trends in marsh edge change. The geospatial and temporal analyses performed here help us explore the rate, distribution, and mechanisms of marsh edge change over the long- and short-term. The data created through this process can be used to identify marsh edge adaptation options along the dynamic Bay shore. In particular, the data can be used for the design of coarse grained beachfaces meant to slow erosive forces, which are expected to increase with sea level rise and climate change.

Study area

The study area for this project consists of the tidal marsh edges of San Pablo Bay (from Point San Pedro in eastern Marin County to Point San Pablo in western Contra Costa County) and portions of the Central Bay marsh edges along Marin County's southeastern shoreline (Figure 1). Drainage from California's Central Valley, several sizeable rivers and creeks (including Las Gallinas, Novato, Petaluma, Sonoma, Napa, and Wildcat), and many smaller streams enters San Pablo Bay, bringing sediment and freshwater to the marshes, mudflats, and deep water channels of the Bay.

The southeastern Marin shoreline is characterized by small valleys bounded by headlands that protect pocket marshes and smaller beaches. Much of the southeastern Marin shoreline is developed or is characterized by steep rocky shores.

Figure 1. San Pablo Bay, part of the Central Bay, and the shorelines (black) analyzed in this study.

Drivers of change (adapted from *Shifting Shores*)

The major physical drivers controlling marsh edge dynamics in the SF Estuary include wind wave energy and direction, topography/bathymetry, mudflat elevation, sediment supply, vegetation, and relative sea level rise (Allen 1989, Schwimmer 2001, Möller and Spencer 2002, Pedersen and Bartholdy 2007) and other factors such as ferry wakes and biological activity (Pethick 1992, van der Wal and Pye 2004, Francalanci et al. 2011). Figure 3 provides a conceptual model of these drivers.

WIND WAVE ENERGY AND DIRECTION

Wind direction is a significant driving force determining energy directed at the shoreline. Wind direction in San Pablo Bay in particular is mainly northwesterly, with speeds up to 9 m/s during the summer (Jaffe et al. 2007 from Miller 1967). There has been some documentation of a San Pablo Bay Gyre, which rotates clockwise around the North Bay (Walters and Gartner 1985). The Gyre likely influences wave direction and energy, as well as sedimentation patterns around the Bay. Wave energy in San Pablo Bay tends to be high relative to other sites in the estuary (with significant wave heights of 0.8-1 m) because of several factors, including orientation relative to the prevailing winds and long fetch (Walters and Gartner 1985, Bever and MacWilliams 2013). In comparison to San Pablo Bay, the more sheltered embayments of the southeastern Marin County shoreline have lower wave energy, with significant wave heights ranging from 0-0.7 m (DHI 2011, DHI 2013).

MUDFLATS

San Pablo Bay is generally shallow (less than 2 m deep at Mean Lower Low Water [MLLW]), with wide mudflats that are exposed at low tides ringing the northern and northeastern sides (Bever and MacWilliams 2013). Mudflats are narrower and less extensive in southeastern Marin County, where there has been more urban development in the baylands.

SEDIMENT SUPPLY CHANGES

San Francisco Bay lies at the bottom of the Sacramento-San Joaquin River watershed, which drains approximately 200,000 km^2. During the late 19th century, extensive hydraulic mining in the Sierras coincided with a period of abnormally high regional precipitation, which mobilized large volumes of sediment delivered from the watershed to San Francisco Bay (Gilbert 1917, Barnard et al. 2013). This led to changes in bathymetry, as well as the location and extent of beaches and tidal marshes. A comparison of bathymetric surveys in San Pablo Bay between 1856 and 1887 by Jaffe et al. (2007) shows that intertidal mudflats expanded by 60% during this period.

In the mid-1900s, efforts to manage floods and develop hydropower and water supply led to the construction of ring dams throughout the Sierra Nevada. The dams, in conjunction with the cessation of mining in 1884, cut off the supply of Sierran coarse sediment to the Estuary (Wright and Schoellhamer 2004, Schoellhamer 2011). Conversely, sediment yields from local Bay

CONTROLS ON THE MARSH EDGE:
Shoaling and mudflats

To understand the dynamics of the marsh edge, we need to look at the relationship of water depths, wave dynamics, and mudflats to the marsh edge. While the orientation of a given shoreline reach with respect to wind direction often determines its exposure to wave erosion, mudflat width and elevation may be particularly important in determining wave energy reaching the shore. The mudflat serves to temporarily store sediment for resuspension and filter offshore waves. As small waves grow with shoaling, they break or are attenuated due to friction on the mudflat and marsh surface. Wave heights tend to be lower in deep open water, and increase in height close to the shoreline as the water becomes shallower, resulting in higher wave energy at the shoreline (DHI 2011, Veloz et al. 2013; Figure 2).

As waves travel from deep to shallow water, they slow down and steepen due to the decreasing water depth and bottom friction, and break once they reach a limiting depth. At high water levels, such as during storm surges occurring at high tides, waves flood the marsh and attenuate via the same process of depth-limited breaking. In this case, the friction of the vegetation at the surface (together with the mudflat) causes the wave to lose energy.

Within the normal tidal range, mudflats can knock down offshore waves to a lower height; if the mudflat is high enough in the tidal frame, high energy events will only reach the marsh edge at extreme water levels (Lacy and Hoover 2011). Where the mudflat is lower in the tidal frame, or narrow, wave energy at the marsh edge tends to be higher. Thus, the effects of mudflat slope and shape on shoreline position likely represent a negative feedback loop; the marsh edge may erode, depositing on and widening the mudflat until wave energy is reduced sufficiently so that erosion no longer occurs (Lacy and Hoover 2011). If mudflat elevations do not keep pace with sea level rise, more wave energy will reach the shoreline more frequently, thus increasing exposure of the marsh to higher wave energy and increasing the risk of shoreline erosion (BCDC 2013).

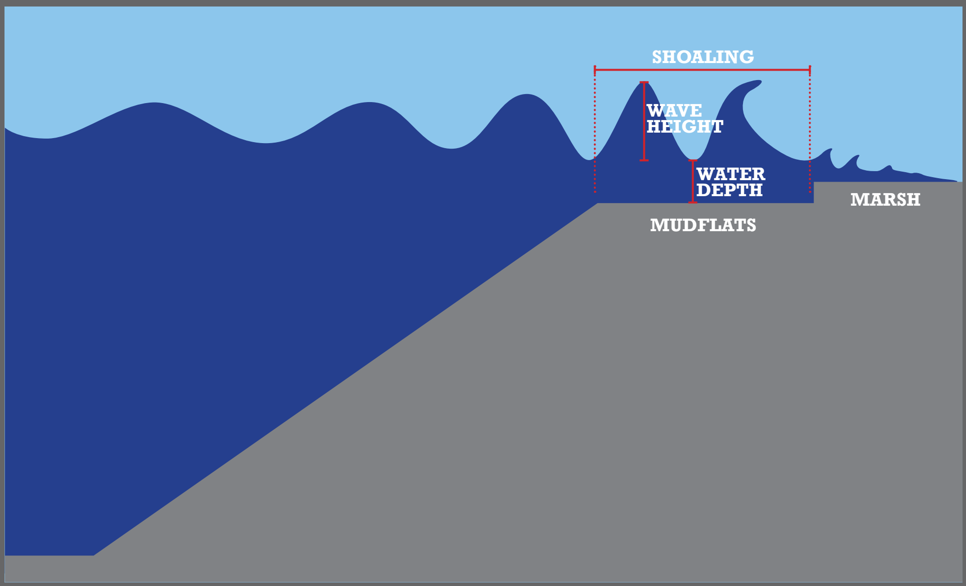


Figure 2. Wave shoaling across a mudflat and marsh. As a wave propagates from deep water to shallow water, the wave length is reduced. The energy flux remains constant and the reduction in speed is compensated by an increase in wave height (and thus wave energy density) which helps explain why wave heights can be higher at the shoreline. However, a wave breaks when it reaches a limiting depth (or when wave height is 0.6 times the water depth) which often occurs over mudflats (adapted from BCDC 2013).

From *Shifting Shores* (2015)

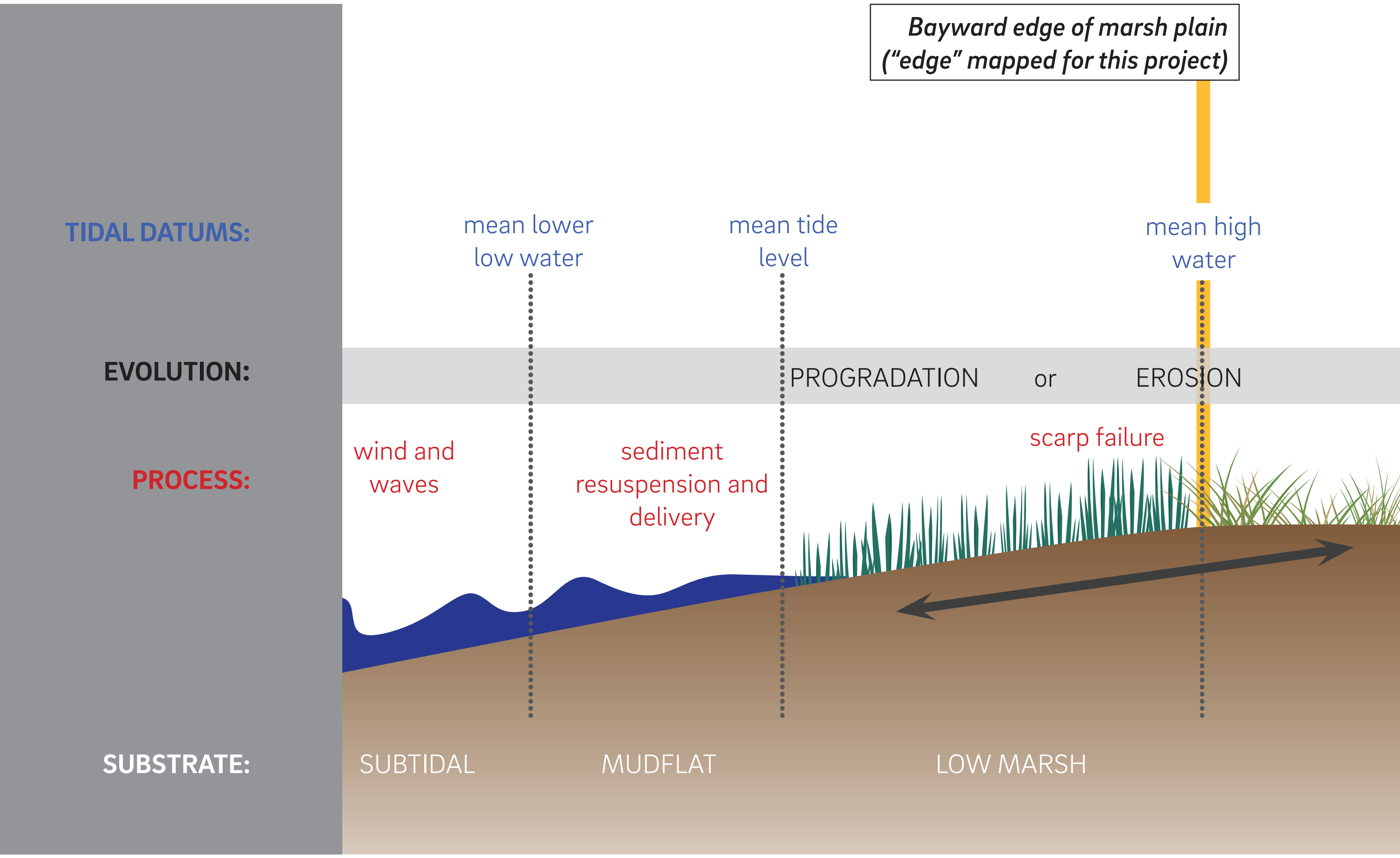
watersheds increased as a result of levee construction, which isolated flood plains from rivers in the mid to late 20th century (Lewicki and McKee 2010).

In the late 20th and early 21st centuries, sediment yields have decreased in a number of local watersheds (McKee et al. 2013). Reflecting these changes, there has been an observed deficit in suspended sediment concentrations in the San Pablo Bay in recent years (Schoellhamer 2011, Schoellhamer et al. 2013). According to Jaffe et al. (2007), by 1983 the bathymetry of San Pablo Bay had responded to these changes as well, becoming much simpler and net erosional. Most of the side channels filled with sediment and there was widespread erosion on the shallower flats (van der Wegen and Jaffe 2013), leading to an overall loss of mudflats (Goals Project 1999).

VEGETATION PATTERNS

The flux of sediment delivery to the shallows of the estuary is only one part of the story of marsh evolution. Salt tolerant vegetation, such as pickleweed (*Sarcocornia pacifica*) is a key factor controlling the evolution of tidal marsh plains and unvegetated tidal

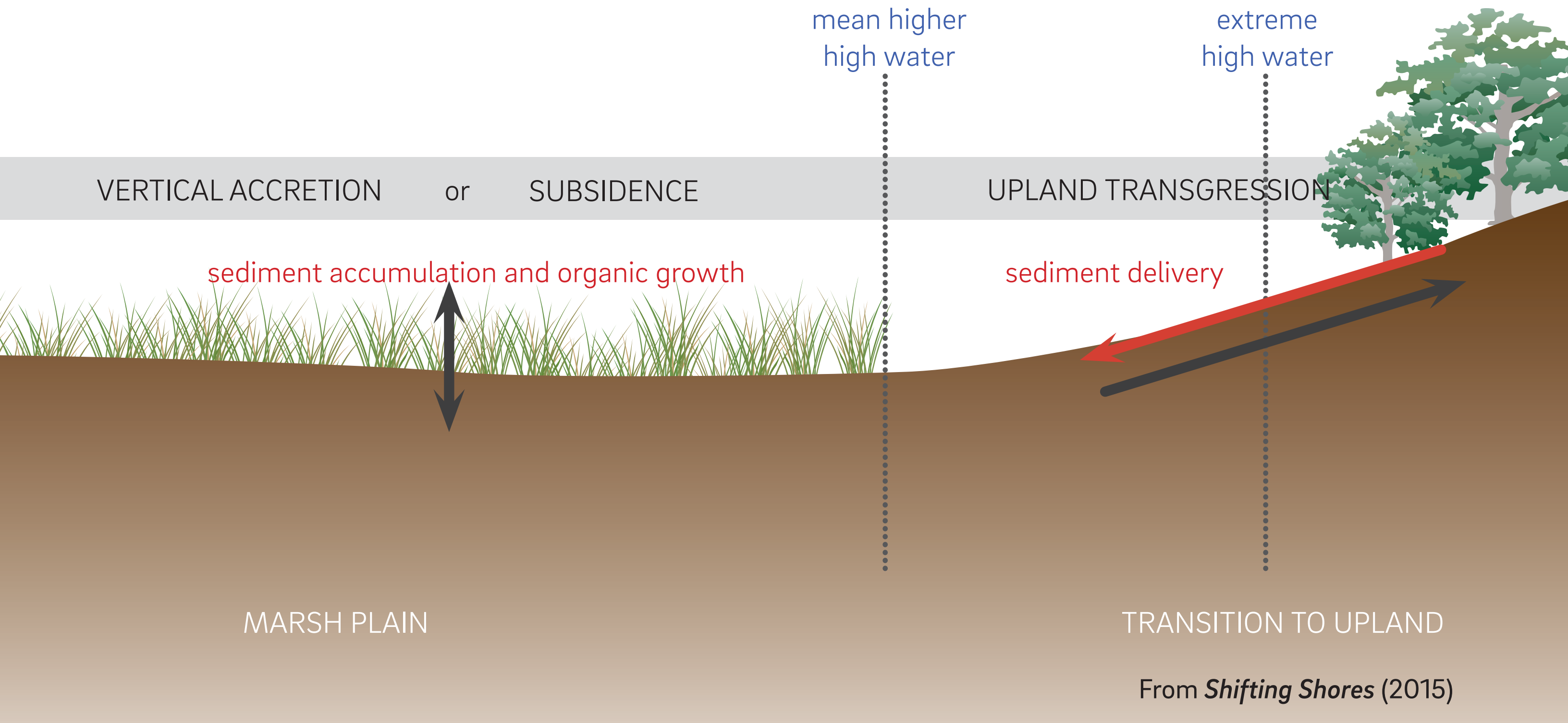
Figure 3. Conceptual model of marsh evolution. This cross section stretches from the subtidal reaches of an idealized shoreline through the marsh to the upland transition zone. It illustrates the different drivers and processes controlling the evolution of the marshes, and of the shoreline in particular. (adapted from PWA)



channels (Temmerman et al. 2005). Root strength can hold marsh scarps in place, increasing the stability of the shoreline (VanEerdt 1985). Vegetation can also re-establish on fallen marsh blocks, initiating marsh expansion even in a high energy environment (Allen 1989). The interplay between physical and the biological processes often produces distinct morphologies such as scarps between salt marshes and tidal flats that can influence evolution of the shoreline (Fagherazzi et al. 2012).

RELATIVE SEA LEVEL RISE

As sea level rise accelerates, the depth, duration, and frequency of inundation of tidal marshes could increase (unless sediment supply and bio-accumulation keeps pace), stressing marsh vegetation and resulting in increased wave energy and increased erosion along the marsh edge (Fagherazzi 2013). If the nearshore sedimentation rate is higher than the rate of local relative sea level rise, then the marsh edge can prograde (Schwimmer and Pizzuto 2000). If the reverse is true, the mudflat elevation may not keep up with sea level rise, allowing more wave energy to reach the marsh edge.



From ***Shifting Shores*** (2015)

METHODS

To measure short-term and long-term changes in marsh edge position, we mapped the eastern Marin County and San Pablo Bay marsh edges at three points in time: 1993, 2010, and 2018. We used the same protocol developed for *Shifting Shores* (Beagle et al. 2015) and mapped only areas that had marshes present. *Shifting Shores* mapped 1993 and 2010 marsh edges for much of the study area; this report expands the study area and adds data for 2018.

For the 1993 marsh edge, we used 1993 grayscale imagery from DOQQ (USGS). For the 2010 marsh edge, we used 2010 NAIP imagery, 2010 LiDAR-derived DEMS and Hillshades (NOAA/OPC), imagery from Google Earth, and BING map imagery. For the 2018 marsh edge, we relied on 2018 NAIP imagery and high-resolution imagery of Marin County (QSI/Marin County). We also completed repeat drone surveys at two sites in Marin County in Fall 2018 and Fall 2019 to attempt to capture changes of the marsh edge at a finer scale.

Defining the marsh edge

We define the marsh edge in this report as the geomorphic change in topography, slope, and soil shear strength at the scarped or ramped bayward edge of the marsh platform. Either unvegetated bay mud or low cordgrass marsh occurs bayward of the marsh platform edge, while consolidated, mostly vegetated marsh plain dominated by pickleweed (*Sarcocornia pacifica*) occurs landward. We use "shoreline" as shorthand to describe this edge. Because the intertidal zone can be very dynamic over space and time, a visible transition between low marsh and mid-marsh was identified in the field (Figure 4) and matched with the corresponding delineation in aerial imagery, which we used to guide our GIS mapping procedures (Figure 5).

We used the Digital Shoreline Assessment System (DSAS) version 5.0 software (Himmelstoss et al. 2018), which requires ESRI ArcGIS software, to calculate the rates of change for three time intervals: two short term (1993-2010 and 2010-2018) and one long term (1993-2018). DSAS computes multiple rate-of-change statistics for a time series of shoreline data. The statistic we included in this report is annual endpoint rate (EPR) (meters per year). Endpoint rate is the rate of

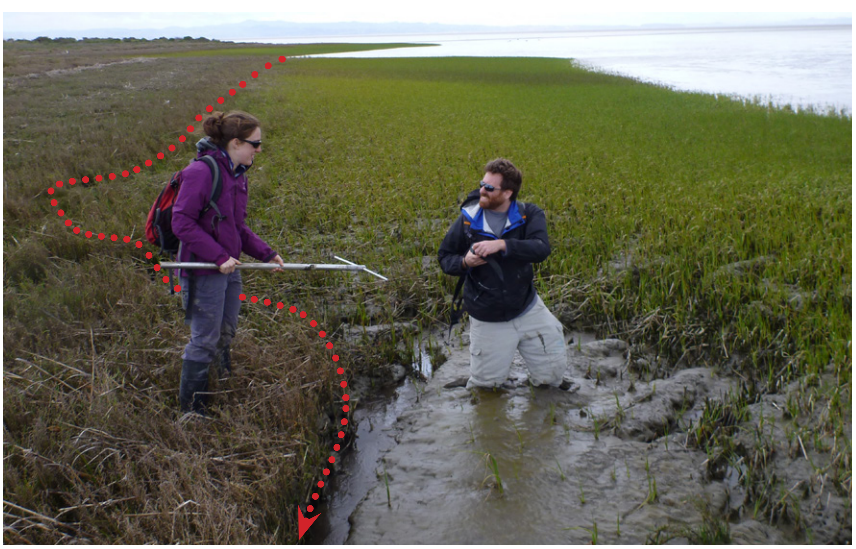


Figure 4. The mapped shoreline. The red-dotted line in this field photo corresponds to the boundary between the consolidated marsh plain and unconsolidated cordgrass-dominated low marsh (where staff sunk up to their knees). Photo taken along the Highway 37 marsh in Solano County (photo by Julie Beagle, April 2012).

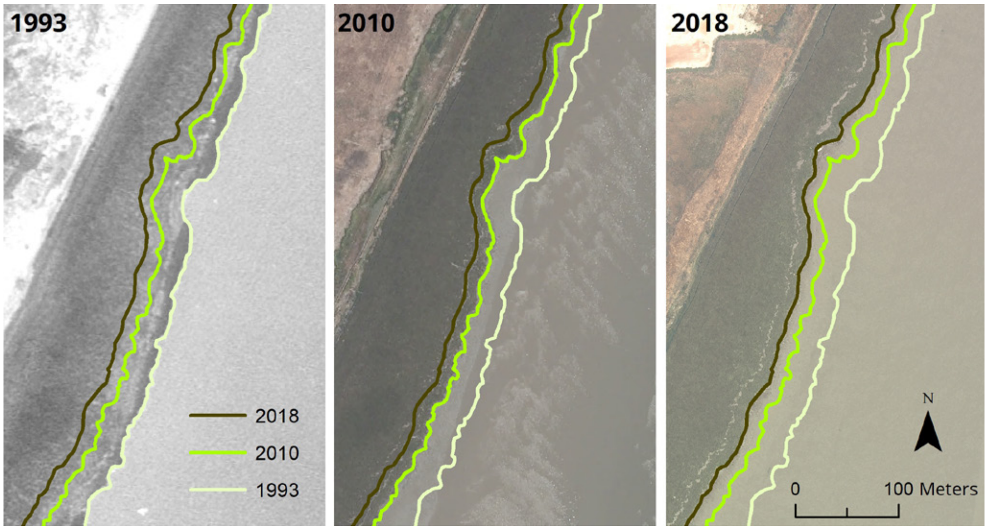


Figure 5. Mapped marsh shorelines for 1993 (light green), 2010 (green) and 2018 (dark green). The imagery from the three time steps shows the progressing erosion of the shoreline at this location.

change for the shoreline over time, or the net difference between the shoreline at the earliest and most recent time periods divided by the total number of years. The EPR metric is useful because it provides an estimated rate of change that allows comparison between time periods, even though the actual rate of change within each time period may vary quite a bit.

The following steps were performed in DSAS: (1) creation of a baseline that was roughly 20 meters from all mapped shorelines; (2) casting of perpendicular transects that extended 200 meters from the baseline (spaced 20 meters apart and using a smoothing distance of 500 m); and (3) calculation of EPR for time intervals using the Calculate Rates tool. Once calculated, the transects were clipped to the shorelines for visualization.

Mapping uncertainty and error estimation

Different parts of the study area had different amounts of positional uncertainty due to varying image interpretability based on shoreline edge type, image clarity, tide level, shadows/sun angle, and other factors. Certainty values for shoreline position of two meters or ten meters of accuracy were assigned to segments of the two shorelines (1993 and 2010) based on the interpretability of the digitizing imagery and ancillary data. For the 2018 shoreline this was not included as the images were much clearer and interpretation was more certain. The 2018 effort lacked a current DEM but used higher resolution imagery data (0.15 m resolution in Marin County, 0.6 m NAIP in the rest of the study area).The DSAS tool incorporates the error assumed in the creation of the shorelines, which includes error associated with source datasets (e.g., spatial referencing of source imagery, unevenness in quality within imagery) (Hapke et al. 2011). For the 1993 and 2010 shorelines, the margin of error for endpoint rate (EPR) was ±1 meter/year for most of the shoreline; given the better imagery used to create the 2018 shoreline, the margin of error for this time period is similar or smaller. For more information see the methods section and Appendix A in *Shifting Shores* (Beagle et al. 2015).

RESULTS

In this section, we report the general trends of lateral marsh edge change along Marin County's southeastern shoreline and San Pablo Bay, identifying which areas of the marsh edge have prograded, eroded, or remained relatively stable in the short- and long-term. We then provide examples of regions of the shoreline that are representative of trends and patterns of marsh edge change.

Though the marsh edge is always shifting, the time periods in question display a fairly dramatic reversal in trends of lateral shoreline movement. Between 1993 and 2010, 34% of the mapped marsh edge was prograding, especially around the mouths of creeks and along the Mare Island strip marsh. Between 2010 and 2018, 27% of the mapped marsh edge was eroding. In both time periods, approximately 60% of the mapped marsh edge was relatively stable (net lateral change within the error margins of the method), though the stable areas were not necessarily in the same places in both time periods.

Though the general trends have shifted, there are some consistencies across the 25-year period of study. For example, creek mouths continue to show evidence of progradation, most noticeably around the mouth of Novato Creek.

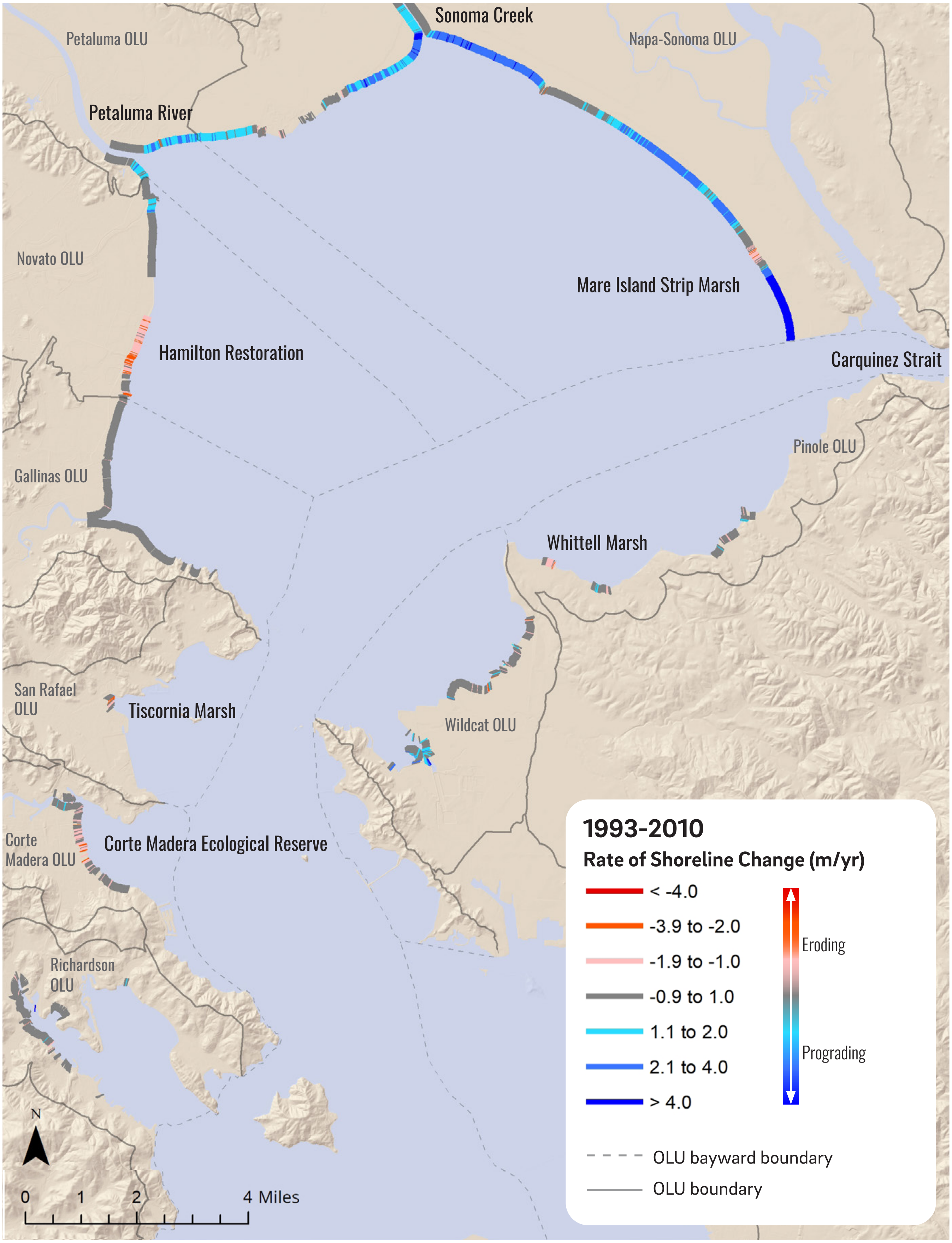


Figure 6. Shoreline transects showing rates of change from 1993-2010. Red transects are areas of the marsh shoreline that are eroding at very high rates. Blue transects are areas that are prograding at very high rates. Gray transects are areas that are neither eroding nor prograding (values within the margin of error of the method). Operational Landscape Units (OLUs) are connected geographic areas that share certain physical characteristics (OLUs are described in more detail on page 28).

Rates of marsh edge change: **1993-2010**

From 1993-2010, 34% of the mapped marsh edge was prograding into the Bay, and 8% was eroding (Figure 6 and Figure 7). For much of the mapped shoreline length (58%), the degree of lateral change falls within the error margins of the analysis, and is considered to be statistically unchanged (shown in gray; areas calculated to have a net rate of change of between -1 and +1 m/yr).

As reported in *Shifting Shores* (Beagle et al. 2015), the most rapid progradation of the marsh edge during this time period was at the southern tip of the Mare Island strip marsh (1-7 m/yr). There was also a large amount of progradation around the mouths of the Petaluma River (1-2 m/yr), Sonoma Creek (1-5 m/yr), and Wildcat Creek (1-5 m/yr). Areas experiencing marsh edge erosion included the north shoreline of Point Pinole at Whittell Marsh and the shoreline at the Hamilton restoration project in the Novato area (averaged 2 m/yr retreat).

New findings from the expanded study area indicate that several marsh edges along Marin County's southeastern shoreline showed signs of rapid erosion in this time period. Tiscornia Marsh in San Rafael eroded at an average rate of 0.8 m/yr for a total of 14 m over the 17-year period. The Corte Madera Ecological Reserve eroded at an average rate of 0.7 m/yr for a total of 12 m.

According to the methods used in this study, most of the marsh edges within Richardson Bay were relatively stable within this time period.

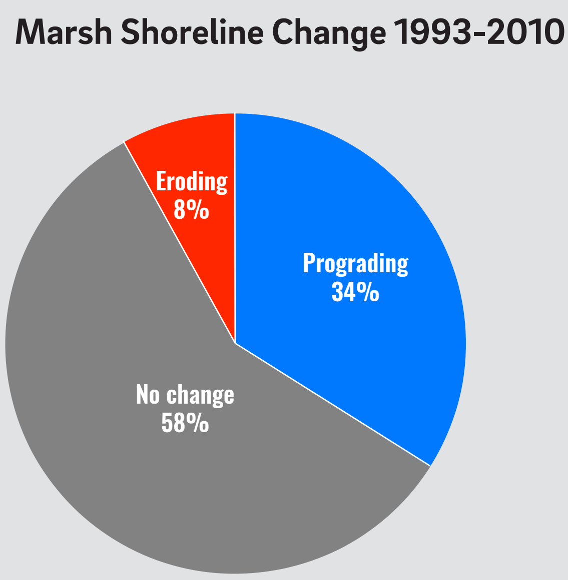


Figure 7. The proportion of the total mapped shoreline transects that were eroding, prograding, or not changing between 1993 and 2010. Transects categorized as "no change" had shoreline change rates that fell within the margin of error of the method (-1 to +1 m/yr).

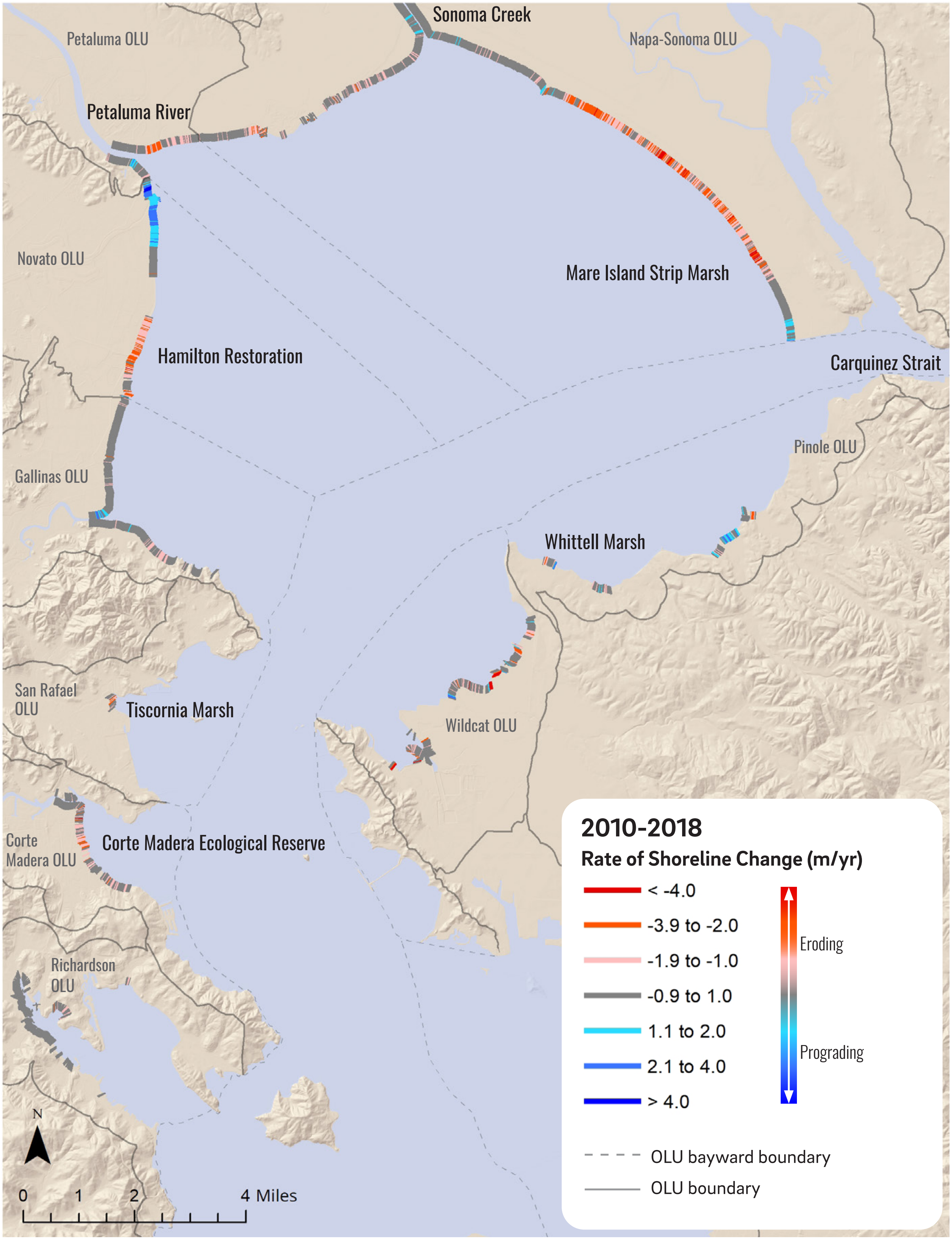


Figure 8. Shoreline transects showing rates of change for 2010-2018. Red transects are areas of the marsh shoreline that are eroding at very high rates. Blue transects are areas that are prograding at very high rates. Gray transects are areas that are neither eroding nor prograding (values within the margin of error of the method). Operational Landscape Units (OLUs) are connected geographic areas that share certain physical characteristics (OLUs are described in more detail on page 28).

Rates of marsh edge change: **2010-2018**

In a reversal from the earlier period, between 2010 and 2018 only 7% of the mapped marsh edge was prograding, while 27% showed evidence of eroding and 66% was unchanged (Figure 8 and Figure 9).

Reporting results counter-clockwise from Carquinez Strait: while most of the Mare Island strip marsh was prograding from 1993-2010, we observe a reversal of that trend from 2010-2018. The very southeastern edge of the marsh near Mare Island continues to prograde at 1-3 m/yr, while the rest of the marsh appears to be eroding at rates ranging from 2-6 m/yr. The marshes near the mouths of Sonoma Creek and the Petaluma River appear to be net static and slightly erosional in some places (1-4 m/yr), though the marshes near the mouth of Novato Creek have begun to prograde at rates varying from 1-4 m/yr.

In southeastern Marin, the Corte Madera Ecological Reserve and Tiscornia Marsh continued to erode at similar rates across the two time periods (1-3 m/yr). In Richardson Bay, shoreline trends from 1993-2010 were within the margin of error, but from 2010-2018 many of the marsh edges showed signs of more erosion. Overall, the findings are less conclusive than in San Pablo Bay, and field observations, continued remote measurements, or other expanded methods of measuring marsh edge change could be important.

Marsh Shoreline Change 2010-2018

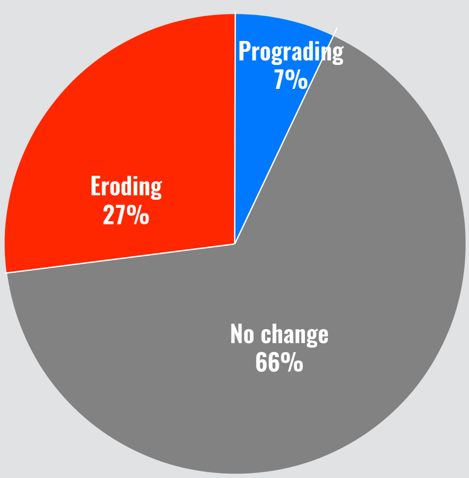


Figure 9. The proportion of the total mapped shoreline transects that are eroding, prograding , or not changing between 2010 and 2018. Transects categorized as "no change" had shoreline change rates that fell within the margin of error of the method (-1 to +1 m/yr).

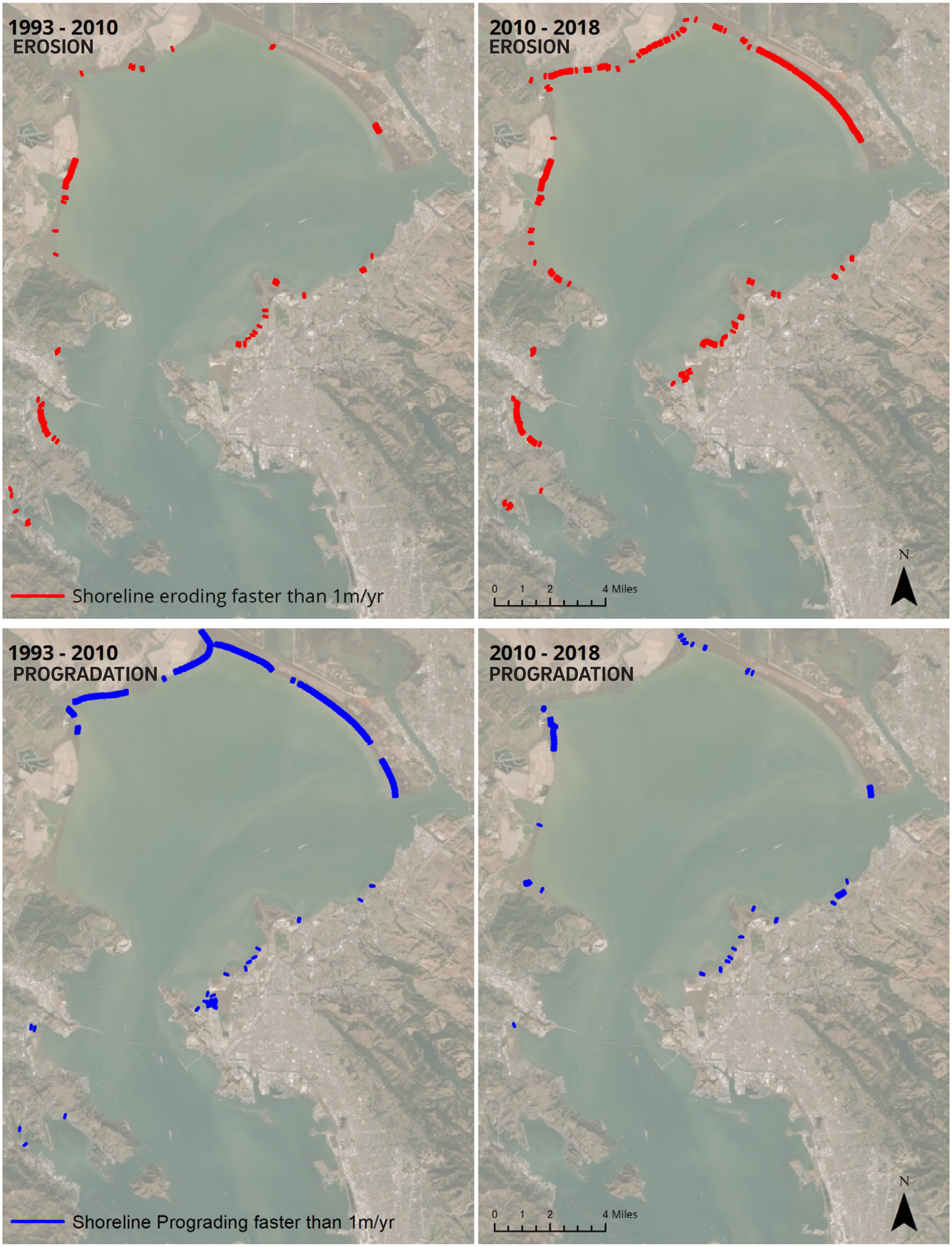


Figure 10. Comparison of eroding versus prograding transects across both time periods. The top two maps show regions of the shoreline that are eroding faster than 1 m/yr and the bottom two maps show regions of the shoreline that are prograding faster than 1 m/yr. The left two maps are for 1993-2010 and the right two maps are for 2010-2018.

A summary of overall change

The general direction of marsh edge movement over the two time periods can be seen in Figure 10 and Figure 11. The study area experienced a drastic increase in the proportion of total shoreline that was eroding over two time periods: from 8% (1993-2010) to 27% (2010-2018). The rates used to create these figures are calculated rather than measured rates; actual rates may vary within each time period. Change could have happened at a steady rate over the period or more quickly during a portion or portions of the period.

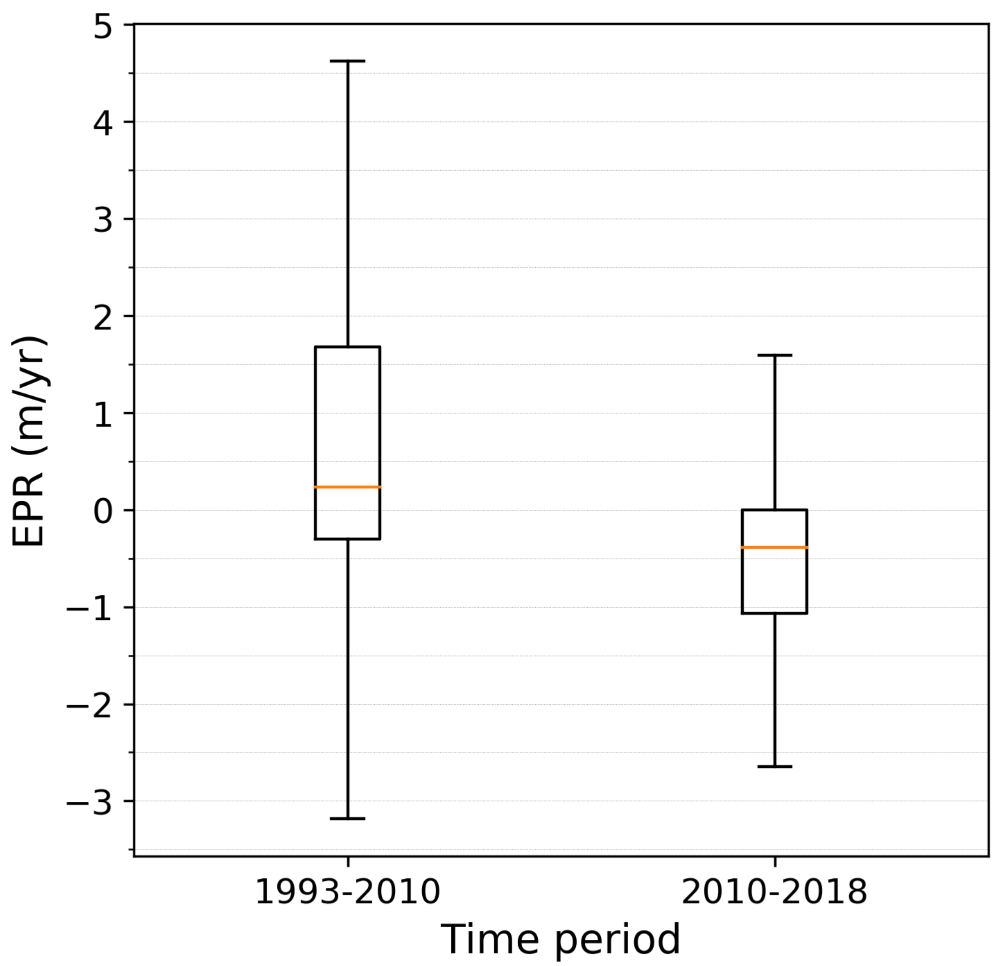


Figure 11. Shoreline change rates were more concentrated at the erosional end of the range in 2010-2018. Negative EPRs indicate erosion and positive progradation. While the median shoreline change rate was near zero in both periods, the range of rates observed decreased in 2010-2018 compared with 1993-2010. There were more transects in the negative (erosion) end of the range in 2010-2018 and more transects in positive (progradation) end of the range in 1993-2010.

Rates of marsh shoreline change by OLU

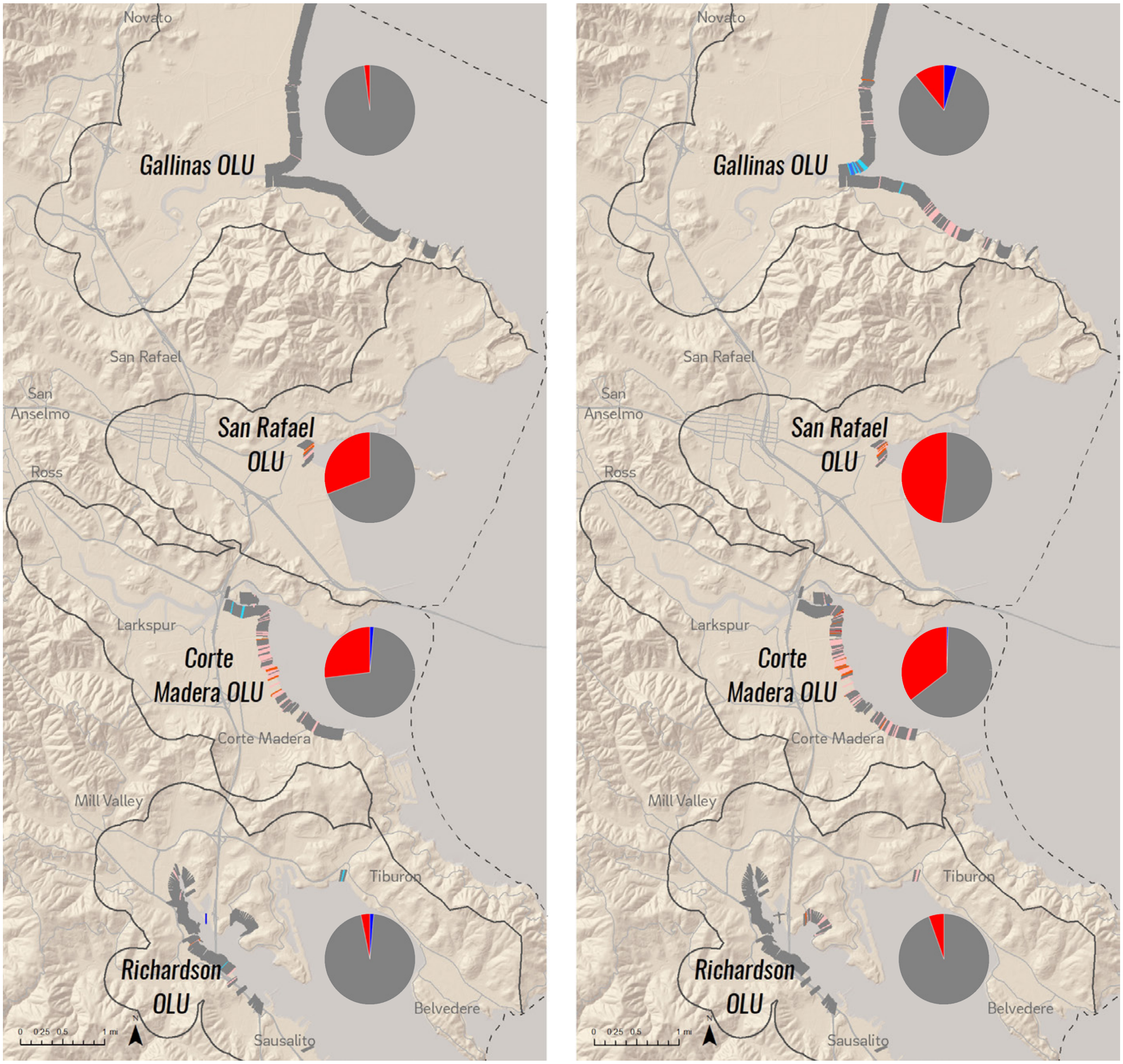
We also analyzed the data by geographic subset areas to consider landscape-scale patterns in shoreline change. Operational Landscape Units (OLUs) are "connected geographic areas sharing certain physical characteristics that would benefit from being managed as a unit to provide particular desired ecosystem functions and services." SF Bay OLUs were delineated in the SF Bay Shoreline Adaptation Atlas (SFEI and SPUR 2019). For each OLU, we ran a paired-sample t-test to evaluate whether there were significant differences in the mean EPR (meters of change per year) between the two time periods: 1993-2010 and 2010-2018 (Table 1). The mean EPR was significantly higher for 2010-2018 in the Novato and Pinole OLUs, and significantly lower in the Gallinas, Corte Madera, Wildcat, Petaluma, and Napa-Sonoma OLUs. There was no significant difference in mean EPR between the two time periods in the Richardson and San Rafael OLUs. Note that these analyses are based on calculated rather than measured rates. A summary of marsh edge change for each OLU in each of the two time periods is shown in Figures 12-14.

Table 1. Differences in rates of change at the OLU scale. Rows highlighted in blue (Novato and Pinole) indicate OLUs with significantly higher rates of change in 2010-2018 compared to 1993-2010 (i.e. shoreline was eroding, and now it is stable/prograding). White rows (Richardson and San Rafael) indicate no significant difference between the rates of change in the two time periods. Red rows (Gallinas to Napa-Sonoma) indicate that the mean EPR was significantly lower in 2010-2018 (ie. shoreline is eroding faster than it was). Negative EPRs indicate erosion and positive progradation. Results are reported to three significant figures here only to allow comparison; this does not indicate a higher degree of certainty. Asterisks (*) indicate signficance at a 95% confidence level (p <0.05).

OLU	N (number of transects)	Mean EPR 1993-2010 (m/yr)	Mean EPR 2010-2018 (m/yr)	Difference in means (m/yr)	Standard Deviation 1993-2010 (m/yr)	Standard Deviation 2010-2018 (m/yr)	t-statistic (paired t-test)	p-value
Novato	298	-0.35	0.06	0.41	1.11	1.92	-6.37	0.00*
Pinole	122	-0.25	0.03	0.29	0.69	1.25	-2.04	0.04*
Richardson	218	-0.16	-0.20	-0.03	0.63	0.36	0.65	0.52
San Rafael	26	-0.88	-1.01	-0.12	0.95	0.78	1.24	0.23
Gallinas	390	-0.09	-0.21	-0.12	0.37	0.71	2.59	0.01*
Corte Madera	219	-0.56	-0.77	-0.21	0.74	0.78	3.76	0.00*
Wildcat	310	0.17	-0.74	-0.91	0.94	1.46	8.83	0.00*
Petaluma	206	0.95	-0.69	-1.64	0.93	0.92	14.64	0.00*
Napa-Sonoma	1,230	1.93	-0.83	-2.76	1.71	1.21	52.6	0.00*

Rates of marsh shoreline change: ***Southeast Marin OLUs***

1993-2010 **2010-2018**



Maps: Rate of shoreline change (m/yr)

- < -4.0
- -3.9 to -2.0
- -1.9 to -1.0
- -0.9 to 1.0
- 1.1 to 2.0
- 2.1 to 4.0
- > 4.0

Eroding

Prograding

Pie charts: Proportion of transects eroding, prograding or no change

- Eroding
- No change*
- Prograding

*Between -1 and +1 m/yr (within the margin of error of the method)

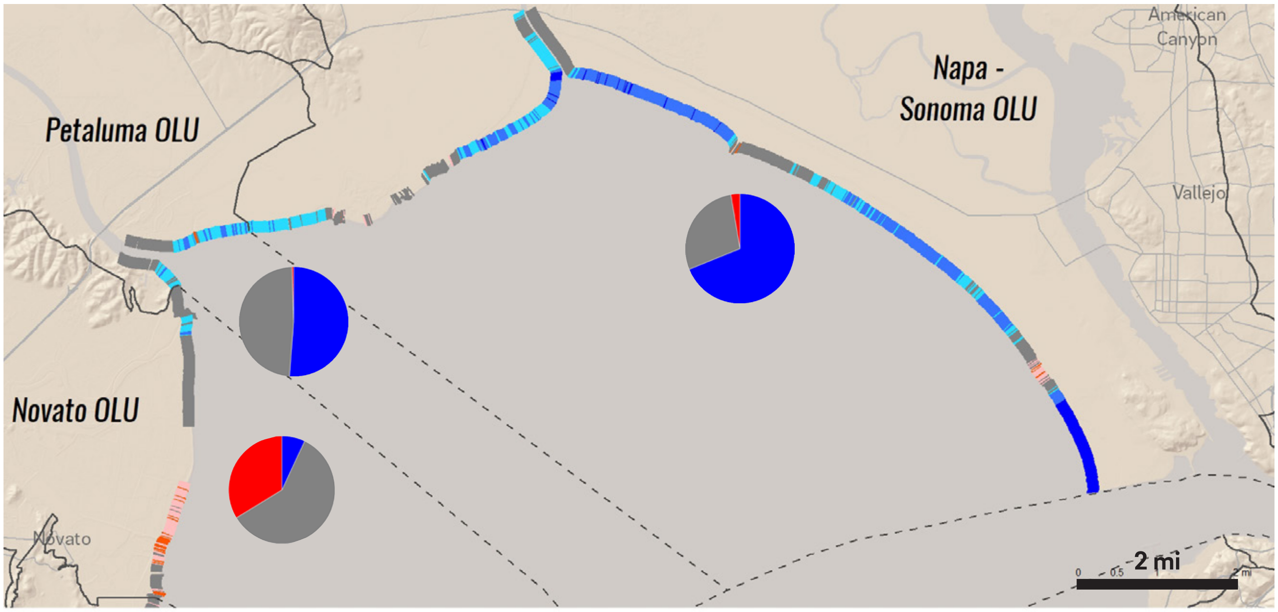
- - - OLU bayward boundary

—— OLU boundary

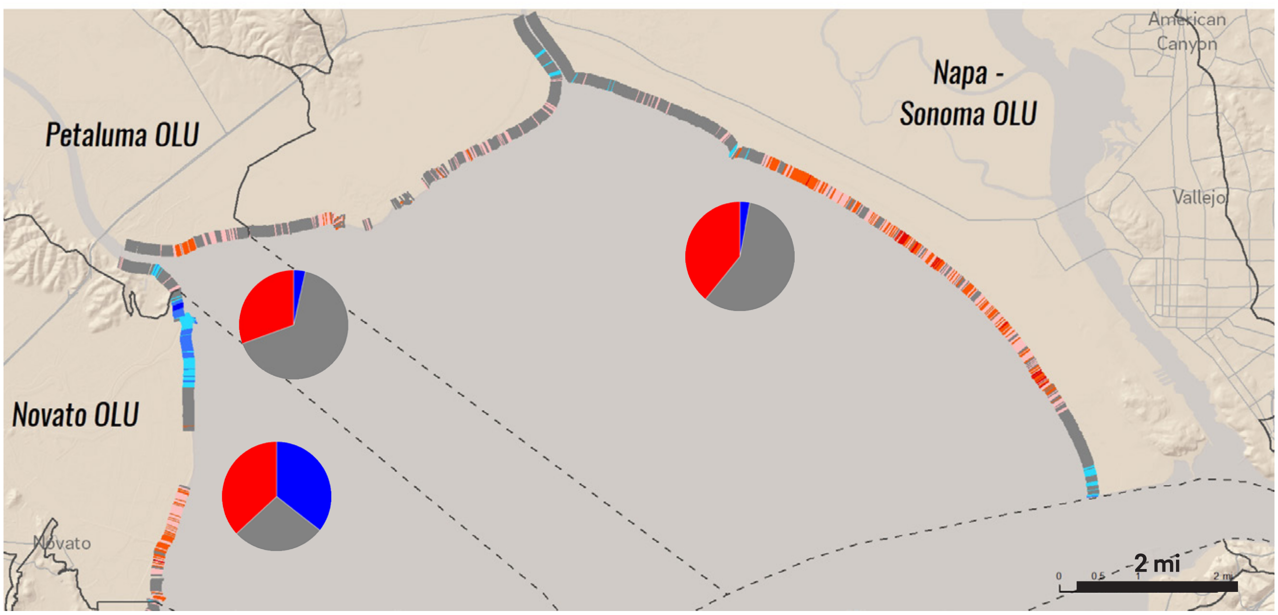
Figure 12. Shoreline change rates and proportion of transects eroding, prograding, or not changing, summarized for each southeast Marin County OLU.

Rates of marsh shoreline change: ***North Bay OLUs***

1993-2010



2010-2018



Maps: Rate of shoreline change (m/yr)

- < -4.0
- -3.9 to -2.0
- -1.9 to -1.0
- -0.9 to 1.0
- 1.1 to 2.0
- 2.1 to 4.0
- > 4.0

Eroding

Prograding

Pie charts: Proportion of transects eroding, prograding or no change

- Eroding
- No change*
- Prograding

*Between -1 and +1 m/yr
(within the margin of error of the method)

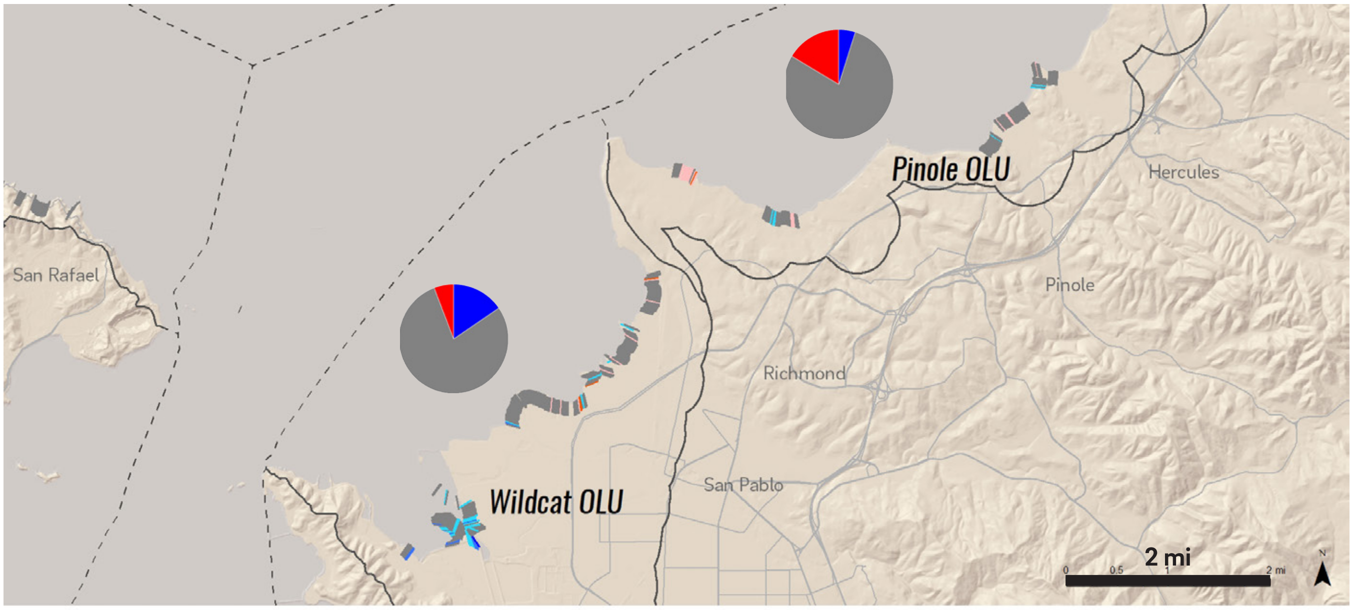
- - - OLU bayward boundary

—— OLU boundary

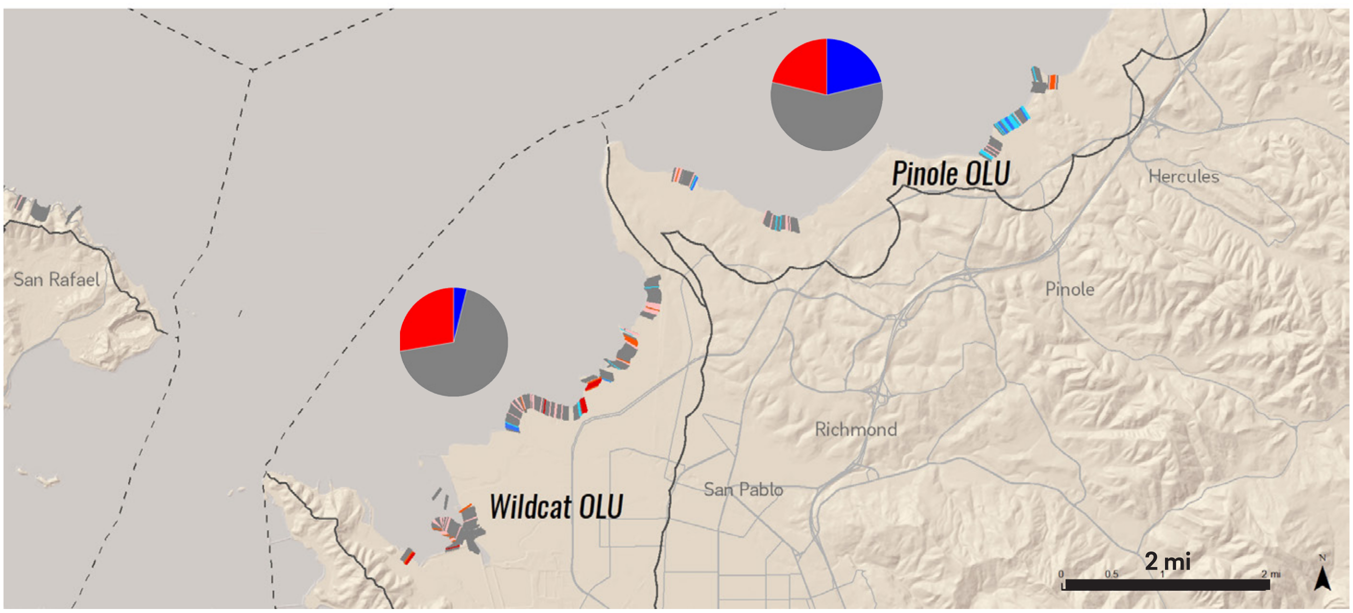
Figure 13. Shoreline change rates and proportion of transects eroding, prograding, or not changing, summarized for each North Bay OLU.

Rates of marsh shoreline change: ***West Contra Costa OLUs***

1993-2010



2010-2018



Maps: Rate of shoreline change (m/yr)

- < -4.0
- -3.9 to -2.0
- -1.9 to -1.0
- -0.9 to 1.0
- 1.1 to 2.0
- 2.1 to 4.0
- > 4.0

Eroding

Prograding

Pie charts: Proportion of transects eroding, prograding or no change

- Eroding
- No change*
- Prograding

*Between -1 and +1 m/yr
(within the margin of error of the method)

- - - OLU bayward boundary

—— OLU boundary

Figure 14. Shoreline change rates and proportion of transects eroding, prograding, or not changing, summarized for each West Contra Costa OLU.

PATTERNS AND EXAMPLES

In this section, we dive deeper into several examples that represent different types of directional change. While the overall trend was toward reduced progradation and increased erosion of marsh edges, the three sites explored in this section demonstrate the variation in marsh edge change patterns across the North and Central Bay. It should also be noted that this study captures three moments in time and compares them. Though the findings are consistent with empirical observations both in the field and using Google Earth, and anecdotal evidence about the direction of marsh edge movement, it is possible that these time steps are not representing a consistent trend. As we are working with averaged rather than measured rates, there could actually be faster rates of change occurring during shorter windows within the longer periods of record.

However, we find that some parts of the study area do show consistent erosion and net erosion over the two time periods. These include the marsh edge along the Novato shoreline near the Hamilton Wetlands Restoration site (Figure 15) and the Corte Madera marsh. Both areas show erosion across the 25-year study period. The cause of erosion in these locations likely varies across time and space, with possibilities including high fetch and large wind wave heights, ferry wakes, and eroding mudflats, which provide less wave protection to the marsh edge as they diminish in volume. The causes should be a priority for future study.

Progradation of the marsh edge seen from 1993-2010 has diminished between 2010 and 2018 in most parts of the study area. Expansion around mouths of major tributaries to the Bay (Napa River, Sonoma Creek, Petaluma River) has slowed both in extent and rate of progradation. The Mare Island strip marsh showed the fastest rates of progradation between 1993 and 2010, with rates up to 8 m/yr, but this has also slowed (Figure 16).

However, there is some stability along certain parts of the shoreline. China Camp (Figure 17), the mouth of Gallinas Creek, and McGinnis Marsh show no major measurable change in position or direction of movement in the 25-year period (all change within the margin of error of the method).

The next several pages explore some of these example areas in more detail.

CONSISTENT EROSION: Hamilton Wetlands

This stretch of shoreline, near the Hamilton Wetlands restoration site, has been eroding consistently over both time periods studied. From 1993-2010, the marsh edge eroded about 2 m/yr, with a net retreat of approximately 30 m. This trend continued between 2010 and 2018, with rates of erosion ranging from 1 to 3 m/yr. Over the 25-year total study period, this marsh edge has eroded approximately 40 m. If this rate of erosion continues, the fringing marsh will be completely eroded in the next 50-60 years.

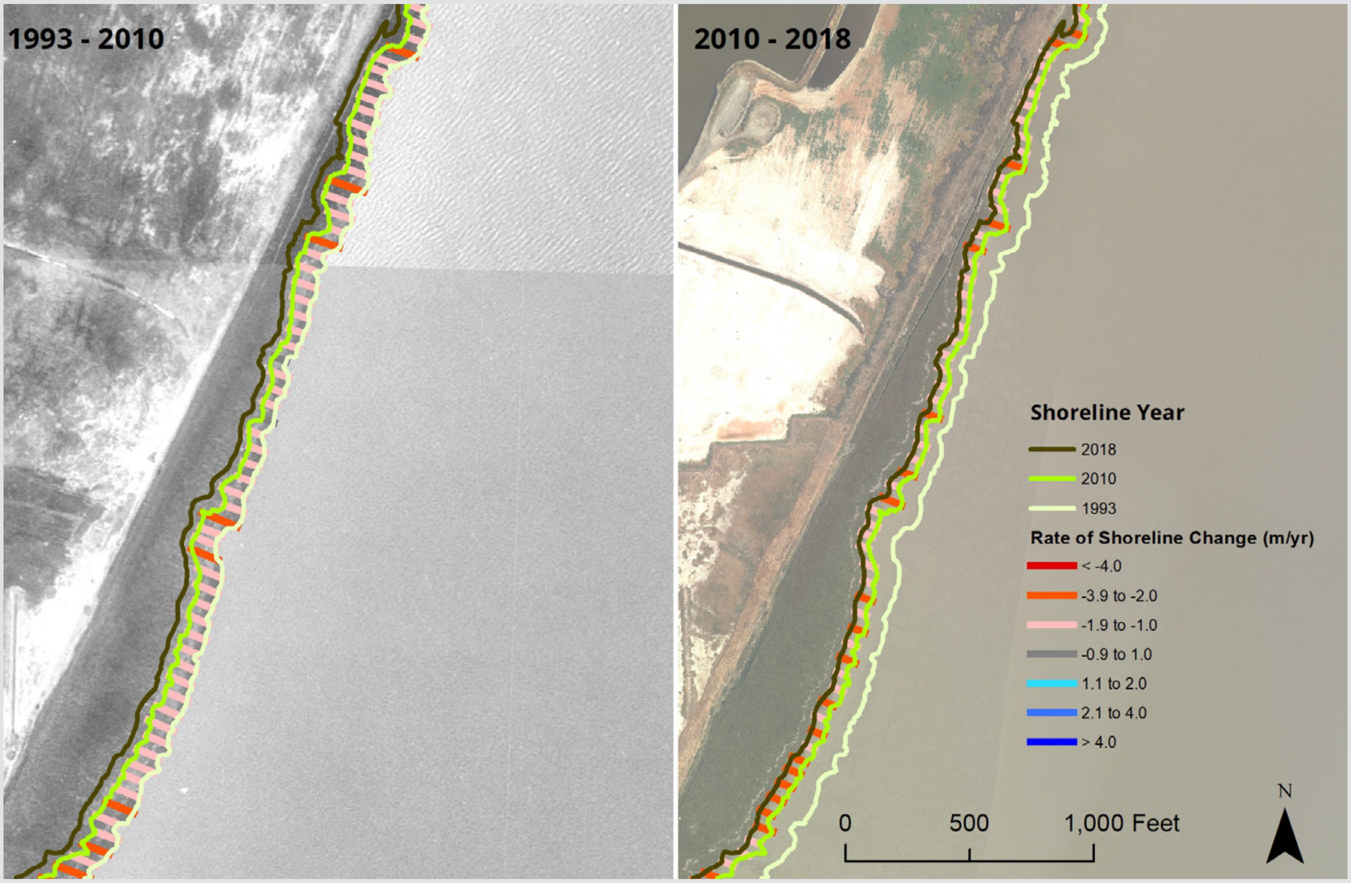


Figure 15. Shoreline change rates at the Hamilton Wetlands Restoration site.

EXPANSION SLOWING:
South Mare Island

This stretch of marsh at the southern tip of Mare Island prograded rapidly from 1993-2010 and remained relatively stable from 2010-2018. From 1993-2010, the marsh edge prograded about 5 m/yr, with a net progradation of about 85 m. This trend slowed between 2010 and 2018, with rates of progradation ranging from 0 to 2 m/yr, at an average of about 0.5 m/yr.

This location demonstrates the dynamic nature of the marsh edge and emphasizes the importance of regular monitoring to understand shifting conditions. From 1993-2018, the marsh edge prograded about 90 m, but 95% of the progradation occurred before 2010.

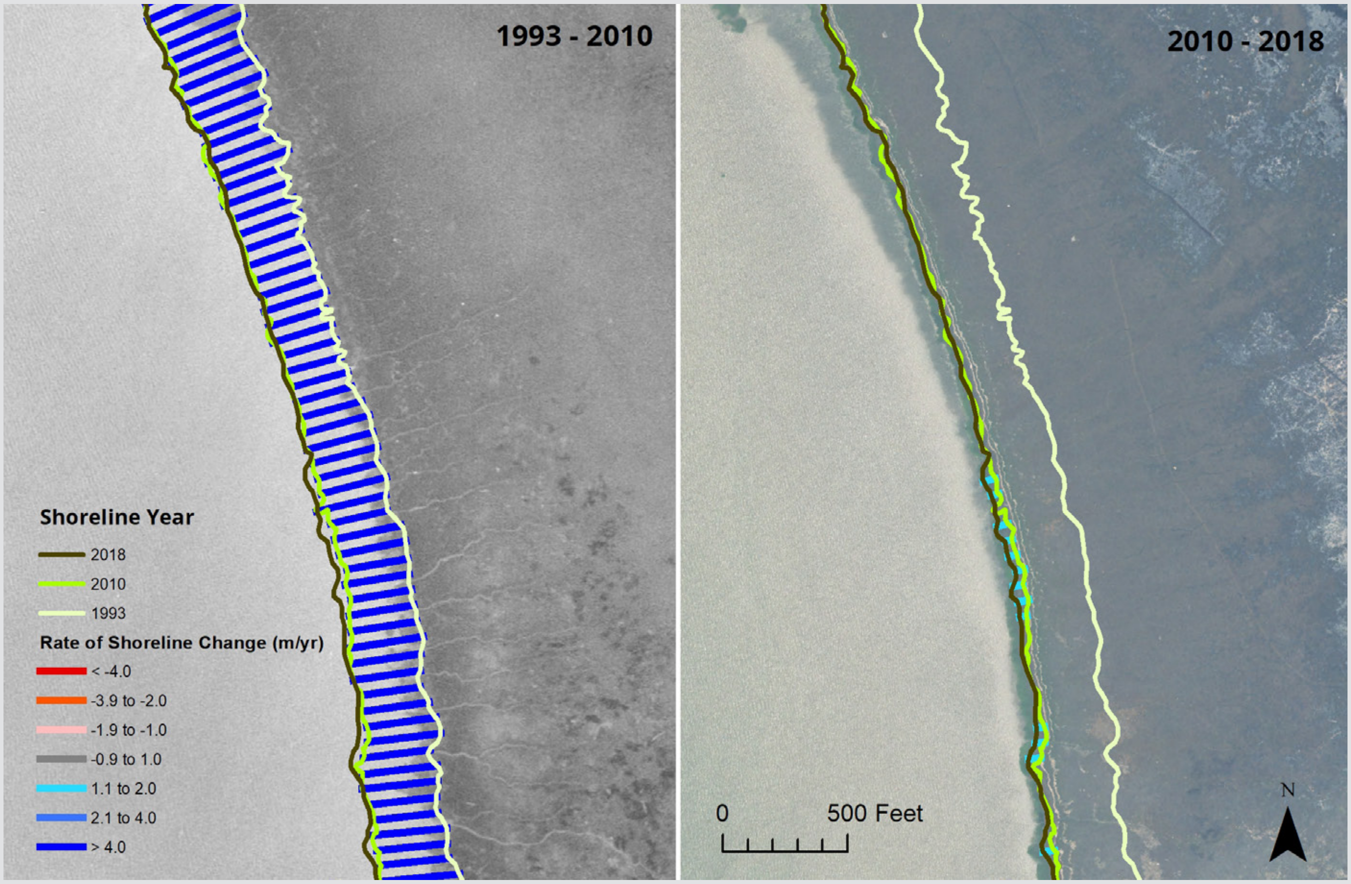


Figure 16. Shoreline change rates at South Mare Island.

CONTINUED STABILITY:
China Camp

The shoreline at China Camp marsh remained relatively stable throughout both time periods. The marsh edge prograded at an average rate of 0.4 m/yr from 1993-2010 and eroded at an average rate of 0.8 m/yr from 2010-2018. The shift toward a (slight) erosional trend matches the trend for the larger area. However, these migration rates are within the error margins of the study.

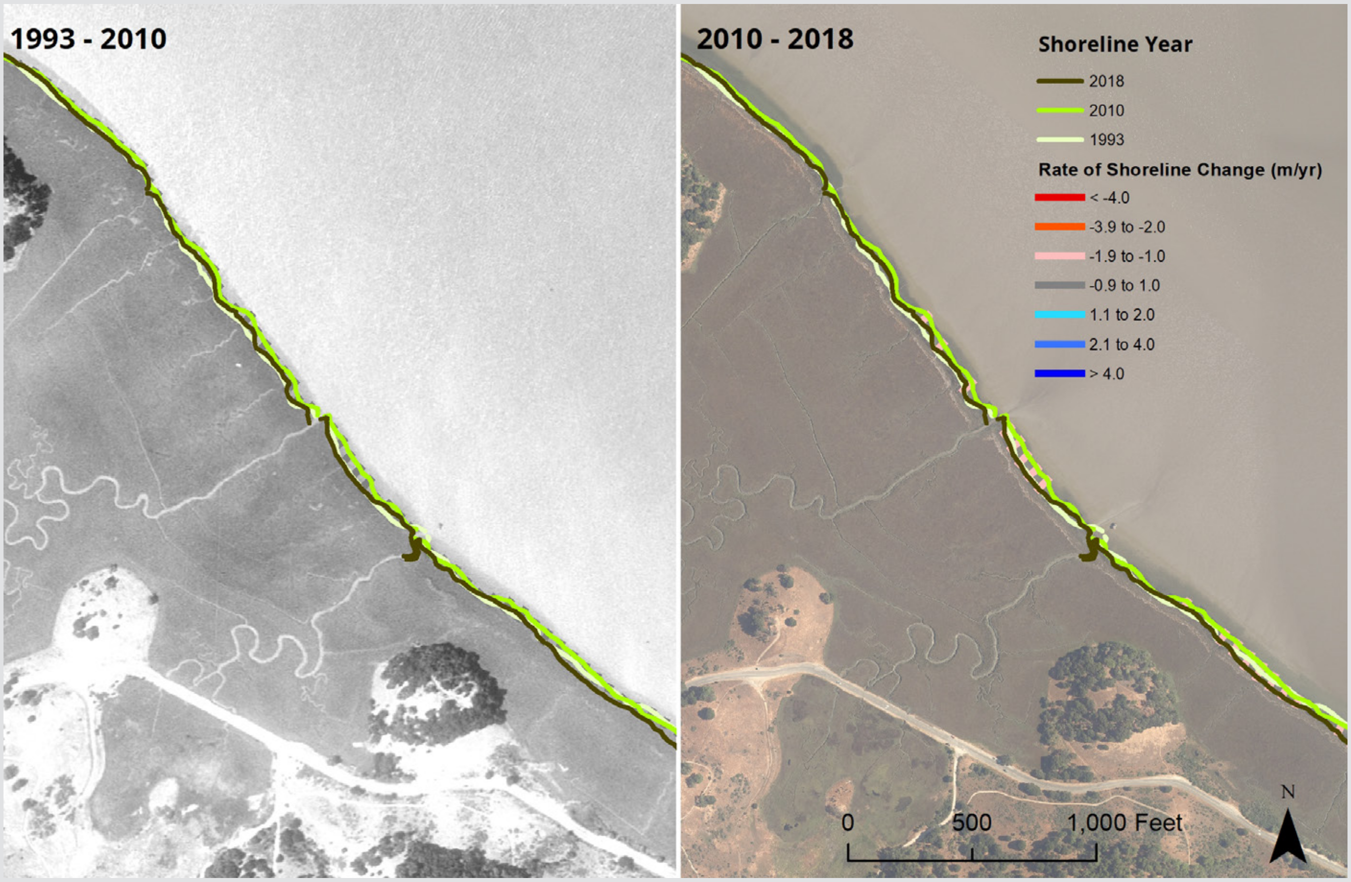


Figure 17. Shoreline change rates at China Camp.

USING UNOCCUPIED AERIAL SYSTEMS
to monitor shoreline change at Corte Madera Marsh

Corte Madera Marsh was diked and filled for pastureland in the early 1900s, then restored to tidal action in the 1970s. Where the outer levees have been breached or overtopped, the newer, unconsolidated dredge fill material inside has eroded much more quickly than older marsh sediment. This case study is a demonstration of a new technology that can be used to track the rapid changes in this dynamic landscape.

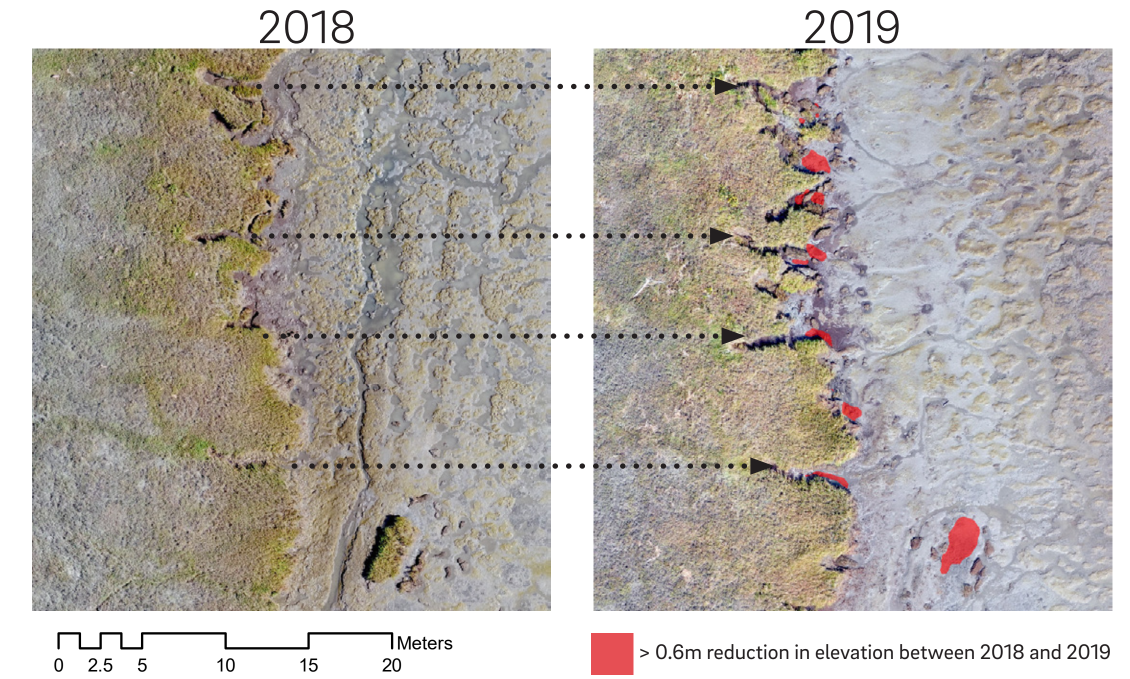
SFEI conducted two unoccupied aerial system (UAS) surveys over a roughly 80-acre area to investigate change along the marsh edge over a one-year timespan. The first survey occurred on July 17, 2018, during a -0.1 m low tide, using a Matrice 200 unoccupied aerial vehicle (UAV) with a 1" 20MP CMOS sensor. The second survey occurred on Sept. 4, 2019 during a 0.5 m low tide, using a Mavic 2 Pro UAS with a 1" 20MP Hasselblad sensor. Each survey was flown at 60 m elevation. Prior to each flight, 12 temporary ground control points (GCPs) were placed along levees, captured using a GPS unit, and retrieved. Surveys were conducted by an FAA-licensed UAS pilot with approval and monitoring from the CA Dept. of Fish and Wildlife (CDFW). Data from these surveys were then processed to produce approximately 1.3 cm orthomosaiced imagery, digital elevation models (DEMs), point clouds, and 3D models of the study area.

About 30,000 metric tons of sediment eroded from the marsh scarp from 2018-2019

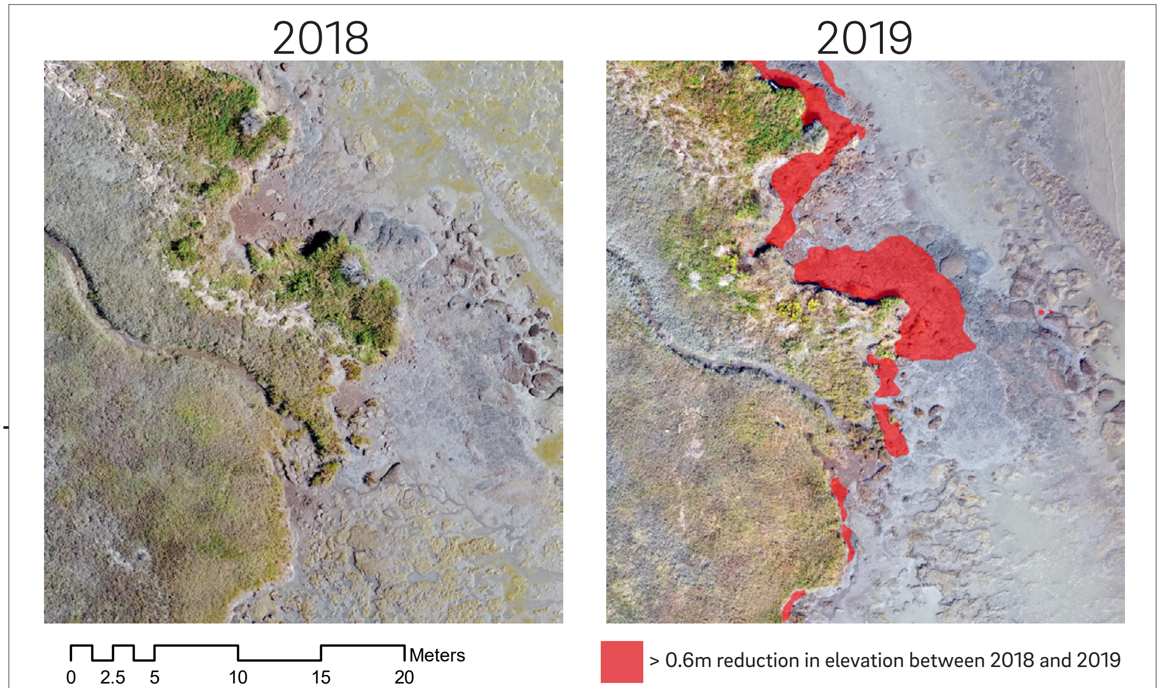
We used the two DEMs derived from the imagery collected in 2018 and 2019 to estimate change in volume along the marsh scarp over the one-year study period. We subtracted the 2019 DEM from the 2018 DEM to see the change in elevation. For areas within 10m of the 2018 shoreline, we extracted cells with a value greater than 0.6 m, a natural break in the histogram of elevation change values. We then calculated the volume reduction within these high-erosion areas only (areas marked in red). Therefore, this calculation provides an estimate of volume lost but does not represent the total change along the shoreline.

To convert from the calculated volume to mass of sediment lost, we used a sediment bulk density value of 462 kg/m^3. This value is derived from sediment core measurements taken at nearby Muzzi Marsh (Callaway et al. 2012).

Note: This volume estimation method would benefit from further refinement in future monitoring efforts. The lack of evenly distributed control points made aligning the DEMs from each year difficult and introduced error in elevation and volumetric change calculations.



Comparing images of the same site over time allows for a better understanding of the patterns of erosion at the marsh edge. Surge channels are deeper and more pronounced in the 2019 image.



Drone imagery reveals the extent of erosion of the remnant outboard levee at Corte Madera Marsh, with large blocks of marsh plain lost between 2018 and 2019.

Lessons learned: The small UAS we used are relatively quiet and CDFW did not observe any disturbance to wildlife, meaning UAS are a viable tool for acquiring high resolution imagery over sensitive habitats. There are limitations on the accuracy of the elevation products produced due to practical restrictions on placement of GCPs. Ideally GCPs would be evenly distributed, but that is difficult to achieve in a wetland setting. Improvements could be made by creating permanent GCPs that could be captured prior to the first flight and reoccupied for each subsequent survey. An RTK-enabled UAS and/or more costly LiDAR sensors would also help improve accuracy.

LESSONS and APPLICATIONS
from UAS monitoring at Greenwood and Brunini beaches

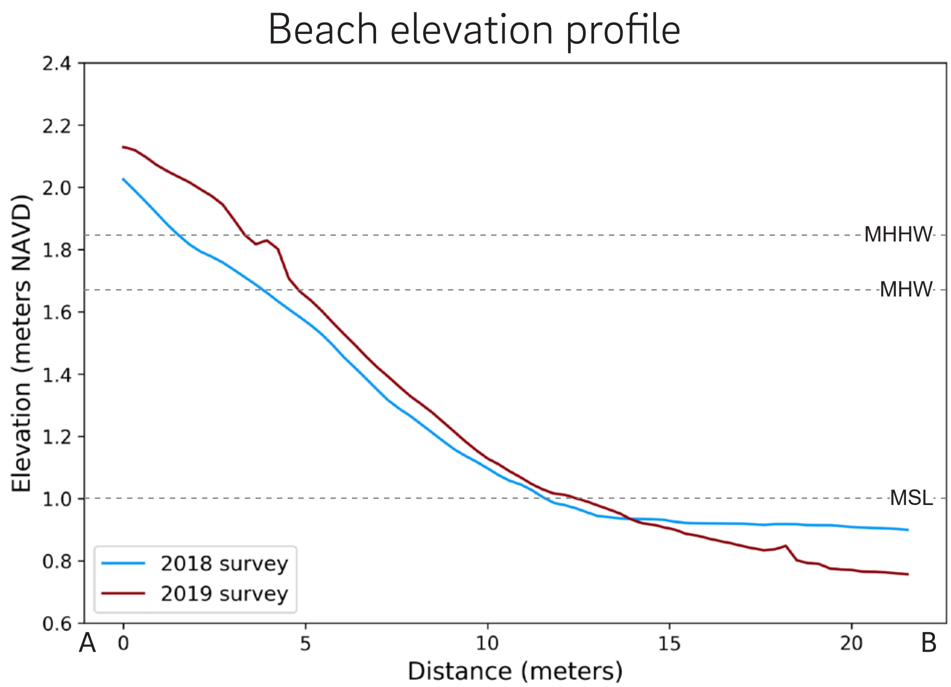
Marin County Public Works conducted an unoccupied aerial system (UAS) survey of Greenwood and Brunini beaches, Tiburon, CA, in September-October 2018 using survey grade LiDAR for higher elevation areas above the tide line and bathymetric surveying using single beam sonar for the subtidal areas. The elevation survey of the shoreline included roughly 30 acres of mudflat, beach, and adjacent upland edge.

SFEI conducted a repeat survey on November 22nd, 2019 during a 0.3 m low tide at 2:30pm, using a Mavic 2 Pro UAS with a 1" 20MP Hasselblad sensor. The flight was conducted at 60 m elevation to provide approximately 1.3 cm resolution orthoimagery. Prior to the flight, 12 temporary ground control points (GCPs) were placed along the shore edge to cover as much of the study area as was logistically feasible. These GCPs were surveyed using an Emlid Reach RS+ GPS unit. The survey was conducted by an FAA-licensed UAS pilot and permission for the survey and UAS flight was given by the Town of Tiburon. No wildlife disturbances were observed during the conducted surveys.

There are challenges when using this relatively new technology. Without permanent ground control points, it is difficult to compare data across surveys, even if the relative accuracy within each survey is high. Because of the variety in surface types and lack of access on mudflats, it is difficult to capture evenly distributed ground control points. Since mudflat elevation changes from year to year are likely to be small, any mismatch in the rectification process can cause warping of the DEM and make change analysis difficult. As with the Corte Madera Marsh survey described above, improvements to the accuracy of captured elevation data could be made by using permanent ground control points, an RTK enabled UAS or LiDAR sensors. Ground-truthing of mudflat, beach, and marsh elevation change using other field methods are critical to validate results from UAS-based analysis. Using the same survey and analysis protocols for similar tides should improve the comparison across surveys.

Some applications of UAS for shoreline change research include monitoring of:

- Elevation and volumetric change (see elevation profile on facing page and volumetric analysis for Corte Madera Marsh above)
- Changes in mudflat, beach, and marsh topography, surface roughness, and sediment movement patterns
- Plant characteristics: species, plant size, area, density, distribution (see upper right on facing page)
- Vegetation community shifts by season and between years
- Woody debris characteristics: distribution and density



Elevation data from repeated UAS surveys allows comparison of topographic change over time. The plot compares the 2018 and 2019 surveys. The 2019 survey shows a steepening of the profile with a buildup of material on the upper beach and a lowering of the mudflat. These are preliminary findings, given the data challenges reported on the previous page.

One application for long-term UAS monitoring could be tracking vegetation changes. High-resolution orthoimagery collected by UAS allows monitoring at the individual plant level, as demonstrated in the image below of four *Suaeda californica* planted as part of the New Life for Eroding Shorelines project. Especially in large study areas where access is difficult, UAS may help track changes in plant communities. Access to this type of data could allow early detection of invasive species or declining health of native plants, and perhaps trigger management actions.

DISCUSSION

Though the focus of this report was to document change over time using desktop methods, we briefly describe several factors that may help explain the changes observed over the two time periods. Further research is needed to pair the physical and ecological drivers of change (wind-wave energy and direction, sediment supply, vegetation, sea level rise) to the marsh edge change observed in this study. For example, a linear relationship has between wave energy and erosion rates has been demonstrated elsewhere (Leonardi et al. 2016), but we found no relationship between wave height (DHI 2011 and 2013) and EPR for either time period (R^2 = 0.1 for 1993-2010 and R^2 = 0.01 for 2010-2018). Other variables, such as sediment availability, wind direction, and fetch lengths may be greater drivers of erosion.

Conditions at the marsh edge are also governed by the extent, shape, and elevation of tidal mudflats, unique and valuable habitat areas that are flooded and exposed again each tidal cycle. Mudflats influence the size and energy of waves reaching the marsh and provide important sources of sediment for adjacent salt marshes (van der Wegen et al. 2017). Therefore, depositional or erosional environments for mudflats may affect the erosion or progradation patterns of the tidal marsh edges. More work is forthcoming and necessary to tie the evolution of mudflats to the changes observed along marsh edges.

Larger regional-scale dynamics, including weather patterns such as droughts and periods of wet weather, can also influence drivers of marsh edge change. Between 2012 and 2016, California experienced a record-breaking drought that is considered a harbinger of what may become "normal" as the climate continues to change (Ullrich et al. 2018). During droughts, there are fewer and smaller discharges to the Bay from local watersheds and the Delta. Smaller discharge events tend to mobilize less sediment, so there is less available and mobile suspended sediment to the Bay from contributing watersheds. However, smaller discharges can also result in lower average tides, and thus more resuspension of mudflat sediments by wind waves due to shallower water. The availability of suspended sediment in the water column can influence how much sediment is deposited onto the marsh during high tides, and could influence the potential of marshes to prograde. Smaller discharges could also result in a contraction of ebb deltas of creeks, exposing the adjacent marsh edge to more wave energy.

Aside from possible impacts of extended drought, there is evidence that suspended sediment concentrations have decreased in general throughout the Bay. Decadal-scale disruptions to sediment loads have caused both increases in sediment supply (development and other land use changes) and decreases (dams, water diversions and water infrastructure management that constrict sediment supply and delivery to the Bay) (Barnard et al. 2013). These changes have made sediment supply to the Bay highly variable over space and time. However, a net reduction in supply has impacted suspended sediment concentrations (SSC) in a measurable way (Schoellhamer 2011, Goals Project 2015).

Several questions remain: Do changes in bathymetry, precipitation regimes (e.g., droughts, El Niños/La Niñas), wind patterns, and overall sediment supply explain why marshes are eroding? What will the impacts of climate change and increasing rates of sea level rise be? How will marshes respond?

Changes to the shoreline are expected, especially with increased rates of sea level rise and changes to storm regimes and sediment supply. Erosion is a natural process, and tracking the direction, rate, and magnitude of shoreline change is critical for understanding how vulnerable the marsh edge is to impacts of climate change. Increased precipitation and atmospheric river events may increase sediment supply to the Bay through tributaries. Deeper water may lessen the shear stresses on the mudflats, but increase stress on the marsh scarps. The impacts of these changes on shoreline evolution are yet to be determined.

Lateral erosion is one of the primary drivers of tidal marsh habitat loss worldwide (Fagherrazi 2013) and this study shows it may become a major driver for the loss of marshes in the SF Estuary. The lack of datasets tracking long-term regional change continues to hamper our ability to manage the shoreline in a resilient way. Empirical observations of the entire Bay shoreline are critical to prioritizing and maintaining restoration and climate adaptation projects. Datasets like this one are also important to include in sea level rise flood models and marsh resiliency models and studies. The Wetlands Regional Monitoring Program (WRMP; a collaborative working to track conditions of mature and restored tidal marsh habitat in the SF Estuary) holds great promise for the natural resources of our region (WRMP 2020). This type of program will allow managers to pair robust monitoring with prioritization of “living shoreline” approaches such as restoration, creation, and nourishment of estuarine beaches that can slow erosion rates of marsh edges and increase resilience of our shorelines for both ecosystems and people as climate change intensifies.

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CHAPTER 3: A TECHNICAL INTRODUCTION TO BEACHES IN THE S.F. ESTUARY

The aim of this chapter is to help improve regional understanding of beach behavior and characteristics specific to the SF Estuary by highlighting the unique evolution, varied geographic settings, and distinct and complex ecology found among beaches in the estuary, as distinguished from open-coast beaches. Estuarine beaches hold high potential to be used as a multi-benefit, soft-shoreline stabilization tool. To that end, this chapter provides an introduction on geographic variation in SF Bay beaches, including a discussion of the variety of sediment types that characterize typical SF Estuary beaches and the range of wildlife benefits estuarine beaches provide for specific species, including shorebirds, small mammals, invertebrates, and native plants.

This work explores the premise that estuarine beaches could serve as a multi-benefit, ecosystem-based alternative to erosion control along engineered levees and armored shorelines. From a habitat perspective, coarse and composite beaches can provide breeding or foraging habitat for birds such as Forster's terns (*Sterna forsteri*), black-necked stilts (*Himantopus mexicanus*), American avocets (*Recurvirostra americana*), black oystercatchers (*Haematopus bachmani*), and other shorebirds. They can also provide unvegetated, high-tide roosts for shorebirds and high-tide refuge for marsh wildlife. Beaches provide spawning habitat for grunion (*Leuresthes tenuis*) and haul out spaces for harbor seals (*Phoca vitulina*; Goals Project 1999; SFEI and SPUR 2019).

From a shoreline protection standpoint, the practical applications for this assessment of SF Estuary beach dynamics are ultimately related to the environmental policy need to reduce or buffer the rate of shoreline retreat and wetland habitat loss without degrading or compounding damage to sensitive shoreline habitats by armoring shorelines with rock: the standard, default engineering approach to shoreline stabilization (Puget Sound, Johanessen et al. 2014). The tidal marsh/barrier beach interface–also classified globally as marsh-fringing barrier beach (Cooper et al. 2007, Pilkey et al. 2009)–is particularly relevant to the SF Estuary, where artificial bayfront levees that are expensive to maintain have provided the primary wave erosion protection for reclaimed (and now often tidally restored) wetlands.

Declining fine sediment supplies and sea level rise threaten to increase erosion of protective mudflats and increase wave erosion exposure to salt marsh edges and other SF Estuary shoreline types. When marsh edge erosion occurs, it often results in a positive feedback loop: the retreat of the marsh edge leads to more exposure across the fronting mudflats, which results in increased wave energy and dispersive transport, net loss of eroded, re-suspended fine sediment, and, ultimately, progressive marsh edge erosion (Schwimmer and Pizzuto, 2000; Mariotti and Fagherazzi 2013, Mariotti and Carr 2014, Fagherrazi et al. 2013). In contrast, beaches that form along the edge of a marsh (referred to here as marsh-fringing beaches) provide added protection from wave-induced erosion by attenuating waves before they reach the marsh edge. Beach-fringed marsh edges dominated by coarse sediments have especially high potential to buffer wave energy due to their larger pore volume and permeability. The rapid infiltration and energy loss of wave uprush (swash) volumes makes coarse beaches more prone to persist over time compared to the otherwise erosional behavior of fine-grained marsh and mudflat shores. Where salt marshes cannot migrate landward (due to "coastal squeeze" urban development) to compensate for edge loss, the restoration, creation, and nourishment of marsh-fringing beach edges could help reduce erosion rates along salt marsh edges while providing additional wildlife benefits.

As erosion intensifies along wave-exposed bay shorelines, wetland and shoreline managers in this region are left with few erosion control options that are compatible with restored wetland habitats and natural sediment transport during rapid estuarine submergence. One focus of this report is on estuarine beaches as potential models for the "soft" end of the living shoreline spectrum, within the natural range of coarse sediment sizes found in the region, and at sites that include interactions with backshore terrestrial and wetland vegetation. The wide national spectrum of "living shoreline" treatments, however, has included substantial armoring (immobile rock revetments, sills, rip-rap in soft sediment-dominated estuaries) at a scale that Pilkey et al. (2012) viewed as a potential threat to the estuarine ecosystems they are intended to protect.

Translating from the policy level to the project level, applications of estuarine beach nourishment as a regional method of sea level rise adaptation (Goals Project 2015) require design guidelines based on regionally specific information on variation in beach form, processes, coastal settings (backshore and nearshore frameworks of estuarine beaches), sediment size and supplies. These guidelines should also be based on lessons learned from the first generation of engineered or nourished beach pilot projects in eroding shoreline habitats of the SF Estuary (see Chapter 5). Beyond purely geomorphic and engineering considerations for estuarine beaches, the ecological relationships between beaches and estuarine wetlands, plants, and wildlife need to be properly integrated and prioritized as habitat goals alongside shoreline erosion prevention.

This chapter is organized as follows:

1. A discussion of the major differences between estuarine and open-coast beach processes and form
2. Descriptions of the typical SF Estuary beach types and accompanying shoreline processes
3. A description of the sediment types found on SF Estuary beaches
4. How wetlands and estuarine beaches are interconnected
5. The ecological benefits of estuarine beaches

For explanations of technical terms, refer to the glossary on pgs. *viii-ix.*

Estuarine low energy beaches

Estuarine beaches are one of the coastal settings of a low energy beach, a category that is distinct from typical ocean beaches in terms of wave climate, size, form, dynamics, and the relative influence of various beach processes. Low energy beaches are associated with bays, gulfs, sounds, and sheltered lagoons and estuaries where ocean swell influence is negligible and where limited open-water fetch (conventionally estimated at 25 km or less) restricts non-storm significant wave heights to less than 0.25 m. Significant wave heights of low energy beaches during strong onshore winds are typically less than 0.5 m (Jackson et al. 2002). Low energy beaches also are likely to differ from maritime (ocean) coasts in dynamic morphological responses to storm and fair-weather waves. Low energy beaches exhibit more persistent morphological features left over from storm events, in contrast with more rapid seasonal storm and post-storm recovery of maritime beach profiles. In the absence of long-period, low-steepness swell, onshore transport of sand transported offshore during storms is relatively slow, potentially delaying post-storm beach profile recovery (Goodfellow and Stephenson 2005, Jackson et al. 2002).

One of the outstanding contrasts between maritime and estuarine beaches is the prominent role of fine-grained, muddy low tide terraces like estuarine tidal flats. Estuarine beaches, like those of SF Bay, are fronted by wide low tide terraces composed of muddy intertidal flats with highly dissipative profiles. Cohesive fine silts and clays of estuarine low tide terraces can restrict onshore wave transport of larger sand or shell hash sediments embedded in muddy low tide terraces. Low energy beaches are exposed to variable wave approach by short-period wind-waves that undergo less refraction than swell, increasing the potential for longshore transport along open shorelines.

The intertidal zone of estuarine beach systems bordering tidal mudflats is therefore divided between narrow, steeply sloping upper foreshores with coarse-grained beachfaces (sand, shell hash, or gravel) and flat, broad finer-grained low tide terraces with smaller amounts of beach-sized sediments embedded in cohesive muds. This estuarine beach profile, typical of most SF Estuary beaches, represents the low end of the "low energy" beach spectrum, where incident wave energy is fully dissipated over mudflats at tide levels near mean sea level (MSL) and below (Figure 1).

Wave action is negligible at the estuarine beachface until tide levels submerge the fine-grained low tide terrace. Thus, the active estuarine beachface, where swash and backwash transport sand, shell

Figure 1. (Left to right) Typical examples of low energy estuarine beach profiles in SF Bay: a wide low tide terrace (muddy tidal flats) with a sharp boundary at the steeply sloping beachface at Roberts Landing, San Leandro (Long Beach); Whittell Marsh Beach mudflats below sand beachface; and mudflats attenuating waves near mid-tide at China Camp Beach, San Rafael.

hash, or gravel, is largely restricted to mid-high tidal elevation ranges. The abrupt edge between beach (swash/backwash of coarse sediment) and tidal flat (prevalent fine sediment) is visually conspicuous at most SF Estuary beaches at low tide, where the beach step (i.e., the lower edge of the beachface) terminates with a sharp line of coarser sand or gravel over cohesive mud, sandy mud, or other shelf material rather than a continuous beach profile (Figure 2).

In contrast, typical maritime beaches usually have broad surf zones and intertidal profiles dominated by beach-sized sediments where wave breaking and wave bores pass over the tidal cycle. The wide surf zone below the beachface of maritime beaches allows both cross-shore and alongshore transport by waves and currents at all tide stages. Ocean beach profiles may exhibit one or more intertidal or nearshore subtidal bars, where beach sediment can be transported and exchanged across the whole beach profile between storm and post-storm recovery phases (Davis and Fitzgerald 2004; Komar 1976, 1998). The nearshore subtidal "closure depth" concept by coastal engineers (i.e., the theoretical equilibrium beach profile depth beyond which beach sediment transport is negligible) for maritime beaches may not be applicable to most estuarine beach profiles with muddy low tide terraces, or it may have limited application to the landward limits of the low tide terrace, close to the beach step.

In the SF Estuary, most estuarine beaches are very narrow compared with maritime (ocean coast) beaches, with moderately steep or slightly concave-upward profiles on estuarine sand beaches and very steep profiles on shell hash and gravel estuarine beaches. The calm-weather backshore beach zone (i.e., the sparsely vegetated high tide beach above normal tides and wave runup) within the SF Estuary is typically very narrow (a few meters wide) compared with maritime beaches that are exposed to high ocean swell during winter storms (tens of meters wide). Maritime beaches typically have wide berms backed by substantial coastal dunes, bluffs, or cliffs. Maritime beaches are shaped in part by exposure to long-distance high swell, including storm waves, which can widen the beachface into a broad, dissipative profile or spread out the backshore with very extensive, high-energy bores (turbulent, broken waves) that form wide storm washover fans or flats. Estuarine beaches are primarily exposed to locally generated, steep, short-period wind-waves, with significant breaking wave heights normally less than 0.25 m (0.1-0.25 m; Jackson et al. 2002). Low wind-waves build relatively narrow, steep beachfaces (swash slopes) and beach berms (with flat-topped, backshore dry sand beach areas), often only a few meters to at most a few tens of meters wide. Where storm washovers do occur, they are associated with super-elevated high tides and short-period storm wave bores transporting sediments and coarse debris over the submerged barrier beach and backbarrier salt marshes.

Figure 2. The estuarine beach step has an abrupt change in grain size, between sand or gravel deposited by backwash at the toe of the beachface, to fine-grained tidal flats of the low tide terrace, sometimes mixed with beach sediment. Examples, from top to bottom: Rat Island Cove at Camp State Park (photographed in 2015); Foster City shell beach (photographed in 2010).

Estuarine beach planform and shoreline setting: swash-aligned and drift-aligned beaches

The relative stability of estuarine beaches depends on surrounding shoreline features that influence wave sheltering and exposure, wave approach direction, and longshore drift (Table 1). Small variations in shoreline settings modify local wave exposure and can have significant effects on beach morphology and dynamics. Irregular shoreline configurations caused by resistant rocky headlands or foreshore outcrops, armored bay fill, protruding erosional marsh peats, or shoreline orientation changes provide strong local controls on beach form and stability (Jackson and Nordstrom 1992, Phillips 1986).

One of the most fundamental influences of shoreline setting on beach form and dynamics is the effect of embayments and relatively resistant headlands. Embayments and headlands restrict wave approach, create pockets that effectively trap beach sediment, and provide obstacles to longshore drift within the embayment. Embayed beach planforms tend to adjust their orientation to the long-term average wave approach, wobbling or swiveling with drift caused by short-term variations in wave approach. Such embayed or "swash-aligned" beaches (Davies 1980) tend to develop smooth, concave-bayward (arcuate) to nearly straight planforms that are relatively symmetrical (or very gradually asymmetric alongshore) in the long-term. Swash-aligned "pocket" beaches within relatively narrow embayments can approach zero net long-term drift conditions, depending on the degree of wave sheltering and variability in wind-wave approach in estuarine settings. Swash-aligned beaches on maritime coasts are more influenced by wave refraction (bending) of long-period ocean swell, which tends to reduce the angle of oblique wave approach in the swash zone within embayments. In contrast, short-period, steep local wind-waves drive longshore drift of estuarine beaches. Local wind-waves tend to be variable in approach direction to the shore, and are less affected by wave refraction than long-period swell.

Open straight or convex shorelines with few obstacles to longshore drift result in more irregular and dynamic beach planforms, termed drift-aligned beaches (Davies 1980). The spectrum between swash-aligned, sheltered embayed beach settings and drift-aligned, unsheltered shorelines exposed to variable oblique wave approach is a fundamental distinction for assessment and planning of estuarine beaches. Irregular shoreline configurations common in San Francisco Bay, such as crenulate, eroding salt marsh edges, remnants of rocky eroded bay fill, bends or indentations in armored levees and revetments, (landings, pier footings, etc.) provide settings for small-scale swash-aligned pocket beaches even where large-scale embayments are absent. Large-scale, headland-controlled embayments defined by natural rocky shorelines and armored shorelines provide settings for potential swash-aligned fringing or pocket beaches. Because San Francisco Bay estuarine beaches are generally narrow and built by low wind-waves, even small shoreline drift obstacles like large driftwood, boat and dock wrecks, and old pilings, can establish small, local pocket beaches.

Table 1. Summary of physical controls of swash-aligned and drift-aligned beaches.

Physical controls	Swash-aligned beach	Drift-aligned beach
Predominant wave approach (after refraction)	Shore-parallel or low-angle; low variability	Oblique, variable from one or more directions
Shoreline configuration	Embayment, cove, pocket shore position	Straight or convex, smooth, exposed open shore
Shoreline position	Bayhead, cove head; sheltered or recessed	Bay side, headland, foreland
Headlands, outcrops, retention structures (groins), other alongshore obstructions	Present, sufficient to impede longshore transport over part or or whole beach planform	Absent or weak; unimpeded longshore transport

Natural examples of strongly swash-aligned San Francisco Bay reference beaches include natural headland-bound shorelines such as Keller Beach, Richmond, and China Camp Beach, San Rafael. Naturally formed swash-aligned beaches along artificially filled San Francisco Bay shorelines shown in profile view include Radio Beach, Oakland (Figures 3 and 4a), Marina Bay, Richmond (Figure 4b), and Starkweather Shoreline Park Beach, San Rafael (Figure 4c). Among the swash-aligned beaches within this study, long-term shoreline changes were too small, relative to variability of backshore beach width, to detect significant beach retreat or progradation trends. Swash-aligned beach planforms are typically either symmetrical or exhibit relatively stable gradients (gradual widening or tapering). In contrast, naturally formed drift-aligned beaches with irregular, dynamic planforms (Figure 5) include Whittell Marsh, Point Pinole (a), and Bair Island, Redwood City (b).

Figure 3. Radio Beach located in Emeryville near the Bay Bridge approach is an example of a naturally formed swash-aligned beach along an artificially filled shoreline in SF Estuary. A conceptual beach profile is superimposed to demonstrate features typical of a summer profile of Radio Beach as photographed during a field visit in 2018.

Figure 4. (Top half of page) Examples of stable swash-aligned beach planforms naturally formed in embayments between rock-armored artificial fill headlands, SF Bay. Examples include (a) Radio Beach, Oakland; (b) Marina Bay barrier tombolo (coarse sand), Richmond, showing shore-parallel wave crests along the beach, and oblique waves along the rock-armored “headlands”; and (c) Starkweather Shoreline Park Beach (medium sand), Francisco Boulevard, San Rafael. Images: Google Earth.

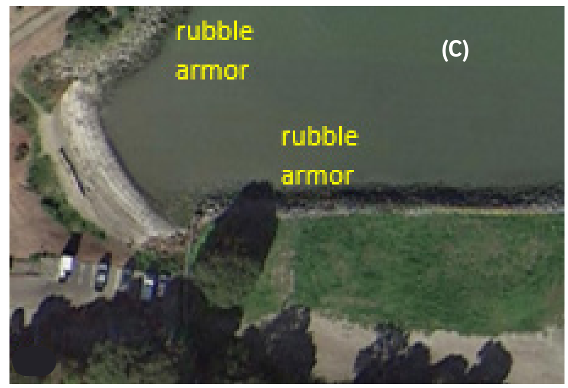


Figure 5. (Bottom half of page) Examples of complex, irregular drift-aligned beach shoreline morphology in SF Bay. Examples include (a) Whittell Marsh sand spit, Point Pinole, Richmond, San Pablo Bay, with a drifting swash bar complex on a wave-dominated ebb tidal delta. March 2018; and (b) Marsh-fringing shell hash barriers, spits, and forelands along a convex shoreline with variable orientation to wave approach, southwestern Bair Island, Redwood City, South SF Bay. Note locally reversing drift directions of overlapping relict spits within the shoreline reach in the shelter of the complex cuspate foreland. Both beach systems have apparent updrift (eroding headland) or nearshore (eroding shoals) sources of beach sediment. August 2018. Google Earth images.

POCKET AND FRINGING ESTUARINE BEACHES

Estuarine beaches in SF Bay occur in variable natural and artificial shoreline settings that strongly influence their form and dynamics. The most significant dichotomy in SF Bay beach settings is between embayed fringing and pocket beaches backed by upland cliffs, bluffs, or high artificial fills which have resistant headland or emergent foreshore features (rock outcrops, boulders, groins, or other barriers to longshore drift), and beaches associated with open irregular but non-resistant shorelines lacking headland controls (marsh and artificial levee or low bay fill shorelines).

Pocket beaches occur in relatively steep-sided coves or narrowly indented embayments, and are effectively closed littoral cell traps for beach sediment. Fringing beaches occupy shallower, more linear shorelines punctuated by relatively shorter headland features. Pocket estuarine beaches have inherently limited potential for significant long-term net longshore drift, despite potential seasonal fluctuation in drift. Fringing beaches with relatively less influence by headlands also have significant restriction of net long-term longshore drift. The signature planform of estuarine pocket beaches ranges from concave-bayward to nearly straight, and often symmetrical or gradually and regularly tapering in width alongshore.

Pocket and fringing beaches in San Francisco Bay are mostly limited to natural distribution along rocky or bluff shores with local supplies of sand and gravel sediment from seasonal or ephemeral creeks in gulches and valleys (e.g., San Rafael and Tiburon, Marin County; Point Molate, Richmond, Contra Costa County), bluff erosion (e.g., Point Pinole, Richmond, Contra Costa County) or erosion of landslides and earthflows (Tiburon, Marin County) (Figure 6). Pocket beaches also occur locally along urban shorelines with rip-rap, often forming in irregular shoreline indentations. The sediment supply of urban-edge pocket beaches often derives from decomposition and wave erosion of old concrete slabs, or erosion of old unconsolidated mixed rocky fill.

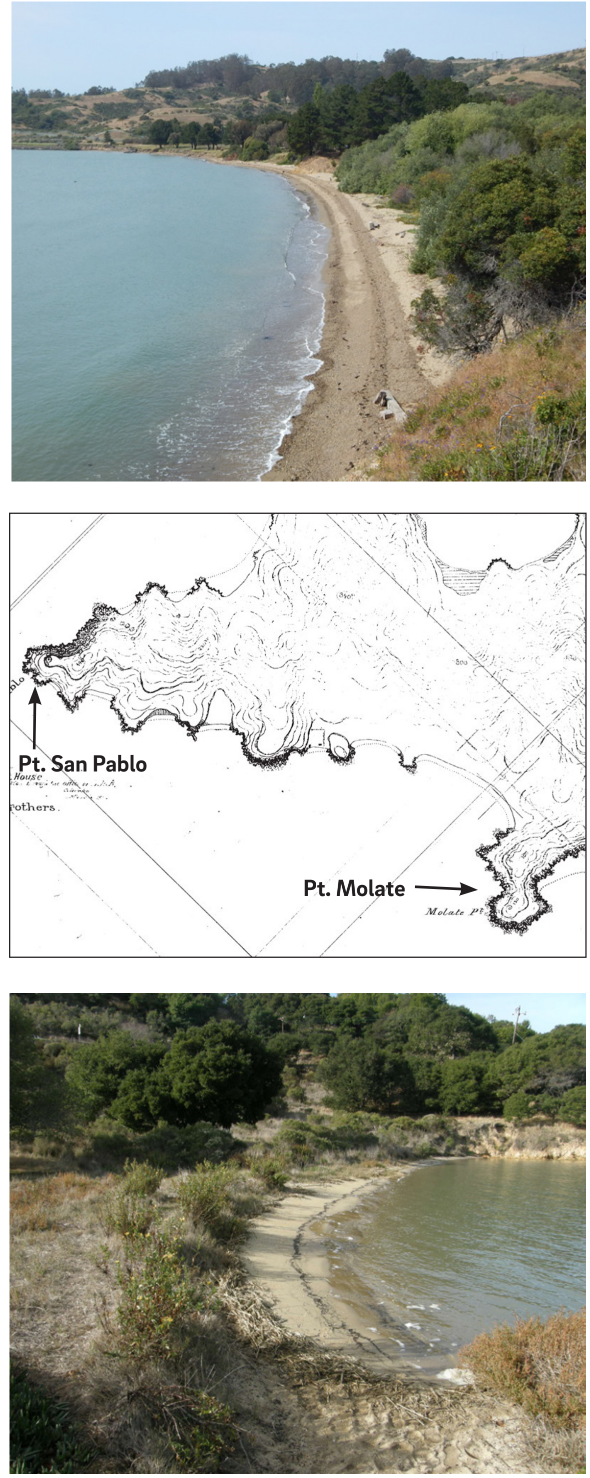


Figure 6. Pocket estuarine beaches embayed between headlands include barrier and fringing beaches along cliffed, rocky shores with coves or canyons. Examples (top to bottom): Point Molate Beach, Richmond in 2017, and 1853 (shown with multiple pocket barrier beaches prior to filling and development; U.S. Coast Survey T-561), and China Camp State Park, San Rafael (Rat Island Cove).

MARSH-FRINGING BARRIER BEACHES

In contrast with headland-bound pocket and fringing beaches, marsh-fringing barrier beaches (spits and island-like marsh fringing barriers) are perched over the outer edges of salt marsh platforms, and often exhibit highly variable planforms. Marsh-fringing barrier beaches are fetch-limited, low-energy beaches that develop along edges of tidal marshes within larger tidal lagoons, bays, or sounds, often in the shelter of maritime barrier islands of oceanic or gulf coasts (Pilkey et al. 2009, Cooper et al. 2007, Cleary et al. 1979). Historical and modern marsh-fringing barrier beaches of SF Bay fit this category, though they were not included in global inventories (Pilkey et al. 2009).

Marsh-fringing barriers form by overwash and beach ridge deposition at the outer edge of eroding salt marshes (Pilkey et al. 2009). They were originally described as "marsh bars" by Johnson (1919), who distinguished them from barrier beaches by their secondary origin in relation to the marshes they shelter. In contrast with classic barrier islands and spits, which form secondary backbarrier tidal marshes (wave-sheltered platforms of washover fans, abandoned inlet shoals, muds), marsh-fringing barrier beaches deposit along older, erosional marsh scarps (peaty mud outcrop) bay shorelines, and their sediment supply (sand and shell hash) may arise from erosion and sorting of coarser sediment from marshes and flats, as well as longshore drift or shoreward bar/shoal migration.

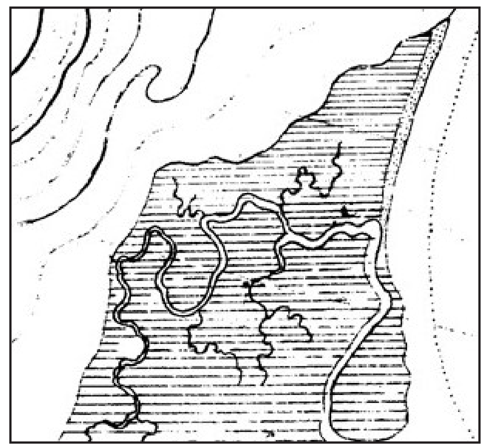
Marsh-fringing barrier shoreline configurations in the SF Estuary today can vary from smooth, arcuate (concave bayward) planforms to irregular and unstable planforms dominated by undulating forelands (large asymmetric beach protuberances, blunt or acute), irregular protuberances related to large driftwood or marsh peat outcrops (temporary, unstable functional headlands), or even drifting short spit recurves. Small pockets of marsh-fringing barriers in the SF Estuary can occur in shallow marsh embayments between eroding peaty mud outcrops or headlands of salt marsh, or they may occur as "wraparound" fringing barriers along convex marsh islands like southwestern Bair Island (Figure 7). Highly irregular, complex large spits–apparently including true "primary" barrier beaches as well as secondary marsh-fringing barriers–were characteristic features of historic mid-19th century tidal marsh shorelines of the Central Bay to South Bay (Oakland to San Lorenzo, San Mateo to Ravenswood), with fine details of beach and marsh forms represented in some early U.S. Coast Survey t-sheets. Map signatures of true barrier beaches within the early historical Oakland ("Brooklyn")-San Lorenzo marsh shoreline include wide beach ridges with multiple recurves extending over mudflats, enclosing distinct swales (wetlands). Historical marsh-fringing barrier beach

Figure 7. (Left to right) Marsh-fringing estuarine barrier beaches in South SF Bay include pocket barriers (bay levee, salt pond 4A Newark near Coyote Hills; 2014) and extensive "wrap-around" fringing barriers along the perimeter of convex marsh islands (southeast Bair Island, Redwood City; 2010).

signatures in 1850s San Francisco Bay T-sheets include very narrow beach ridges along salt marsh edges that were mapped with both hatching (marsh symbol) and stippling (sand symbol) overlapping, or in sequence alongshore within the same linear ridge (Figure 8).

The significance of marsh-fringing barrier beaches for evolution and conservation of salt marshes is twofold. First, bay beaches can act as an important, primary line of defense against storm wave erosion impacts and rising sea levels (Barnard et al. 2013b). Just as important, as marsh-fringing barriers retreat over their salt marshes, the high salt marsh vegetation colonizing temporarily stabilized beach ridges and associated overwash deposits can maintain "hotspots" of high plant species diversity (Elsey-Quirk et al. 2019), elevated beach-high salt marsh ecotone topography, and associated high tide refuge habitat during net shoreline erosion and retreat (Johnson 1919, Pilkey et al. 2009). Barrier beach washovers intergrade with high marsh plains at Long Beach, Roberts Landing, and correspond with silty washover terraces of high salt marsh at outer China Camp (Baye 2012), where marsh-fringing beaches no longer occur (Figure 9).

Figure 8. (Below, top to bottom) U.S. Coast Survey t-sheets display some estuarine beach and marsh edge shorelines as single features that grade between stippling (coarse sediment, beach) and hatching (salt marsh), or overlapped stippling and hatching, consistent with transitions between active bare beach sediment and vegetated beach ridges (marsh berms). (Top) T460N Sierra Point barrier beach, San Mateo County, 1857; (Bottom) T664, Ravenswood marsh shore south of shore locality labelled "Shellbank".



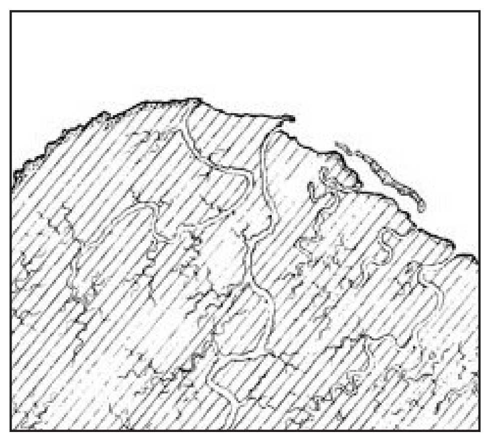


Figure 9. (Left) Sand washovers from estuarine beach to backbarrier salt marsh are deposited by storm wave action during extreme high tides at Long Beach, Roberts Landing, San Leandro (2015). Thin landward washover deposits (<15 cm thick) partially bury dominant salt marsh vegetation, which directly regenerates in spring.

The backshore zone of most SF Bay marsh-fringing barriers (above non-storm spring high tides) today supports mostly washover flats or fans with at most a thin veneer of wind-blown sand (minor incipient foredunes around tidal debris and beach or high marsh transition zone vegetation). Dune sand transport is limited by the narrow backshore and upper beachface of typical estuarine sand beach profiles. Low foredune ridges are uncommon and local today, but larger sand spits and barriers evident in 19th-century U.S. Coast Survey maps developed substantial dune ridges and coastal dune vegetation. This is confirmed by many herbarium records of Pacific coast dune plants from Alameda County shores that face dominant westerly onshore winds. Coarser sand beaches (Marin, North Richmond) and shell hash beaches (San Mateo to Palo Alto) are not associated with low backshore dunes.

Marsh-fringing barriers and true sand spits were the most extensive and widely distributed type of estuarine beach in San Francisco Bay prior to bayland reclamation, fill, and development. Marsh-fringing sand beaches and spits were typical features of the northern San Francisco-San Mateo embayments (Point San Bruno north to Black Point). Large and complex spits and marsh-fringing barriers extended intermittently along the East Bay from Fleming Point (near modern Aquatic Park, Berkeley) to the vicinity of San Lorenzo Creek (near modern Roberts Landing, San Leandro). Small, crescent-shaped pocket barrier beaches also occurred across the mouths of small coves (some enclosing lagoons, others marshes) and along the rocky cliff shorelines of Point Molate and Richardson Bay.

San Francisco Estuary beaches and sediment types

SF Estuary beaches vary geographically in terms of the relative importance of contrasting beach sediment types and sources. Sand beaches (and their provenance) are by far the most extensive type and the best studied (Barnard et al. 2013a), but regionally unique estuarine beaches composed of fossil oyster shell hash were historically extensive along the San Francisco Peninsula bay shores, and many still regenerate there today. Natural gravel beaches, mixed sand and gravel beaches, and even cobble beaches are more narrowly distributed along rocky cliff and bluff shorelines of Richmond and Marin, and (historically) southern San Francisco. These beach sediment types, and the dynamic beach forms they comprise, are summarized below.

ESTUARINE SAND BEACHES

Sand sources of estuarine beaches in the Central Bay are primarily associated with erosion of Pleistocene Merritt Sands of eastern Central Bay (Lawson 1914, Bonilla 1971, Barnard et al. 2013b) and Colma Formation deposits of the San Francisco Peninsula. Merritt Sands are composed of well-sorted paleodune sand, with some raised beach deposits. These were originally derived from Sierran glacial outwash, then reworked by waves and wind when the antecedent San Francisco Bay lowland was a marine embayment (Witter et al. 2006). Colma Formation on the San Francisco Peninsula (Bonilla 1971) has been described as marine, estuarine, and fluvial unconsolidated fine-to-medium sand with some silt and clay. The stabilized paleodune sand hills of Oakland (oak woodland and grassland vegetation, soils) formed wave-exposed sand bluffs along the bay edges of Oakland and Alameda (Figure 10), supplying pre-sorted medium beach sand to form barrier spits. Seasonal and ephemeral streams in gulches and valleys draining Colma and Merritt deposits also transported sand to bay shores, supplying beach sediment to longshore drift processes (e.g., mid-19th century South Oakland, Alameda, Bay Farm Island). Dredging and sandy dredge spoil deposition in the industrial era also mobilized buried Merritt paleodune sand, making it available for wave erosion and transport onshore and alongshore. Similarly, bay fill along the San Francisco Peninsula and Oakland delivered Pleistocene sands to the modern bayshore in places, adding to sands transported by stream channels and flood control channels to the Bay (Figure 11).

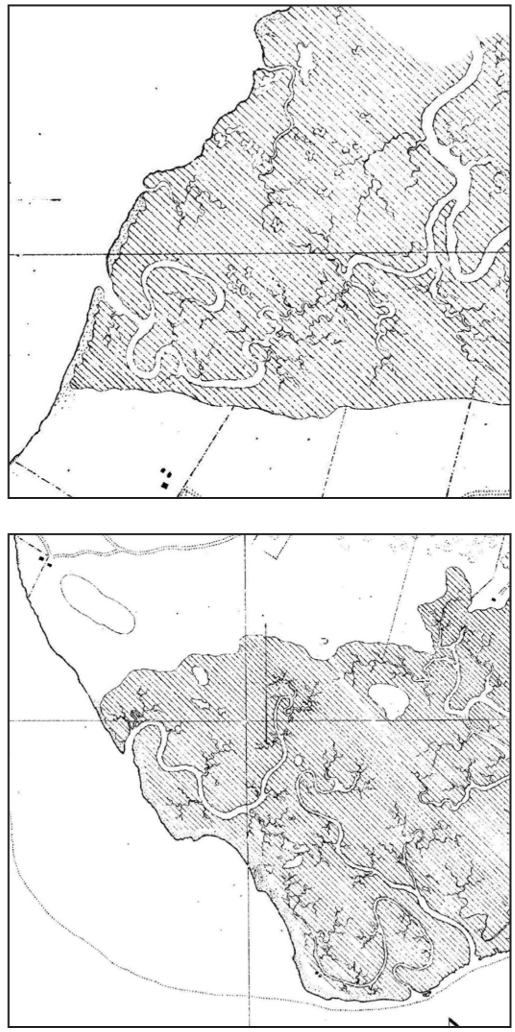


Figure 10. (Top to bottom) Historical bluff erosion of Oakland sand hills supplied sand to adjacent barrier beaches (spits) through longshore drift north and south of San Antonio Point. USCS T-sheets T592 (1856).

Additional sand sources for San Francisco Bay estuarine beaches are associated with stream deltas that reach the bay tidal flats, or reached historical tidal marshes, delivering local watershed sediment from ridges. An outstanding regional example is San Lorenzo Creek (flood control channel), which contains coarse to medium sand extending far into Central Bay tidal flats, forming a delta platform capped with multiple sand bar forms and patterns rare or absent elsewhere in the Bay, and associated with intermediate beaches (emergent swash bars) and stabilized sandy salt marsh berms (Figure 12).

Figure 11. (Above) Modern Bay fill erosion and flood control channels deliver Pleistocene beach sand to the modern bay shore, forming new beaches and low dunes at India Basin's south shore, San Francisco. (2006)

Smaller creeks around the Central Bay also delivered sand to deltas in bay flats that were reworked into historical and modern estuarine beaches. Examples include unnamed pocket barrier beaches of pre-reclamation Richardson Bay. Greenwood and Brunini (sand) beaches in Tiburon, for example, are modern sand beaches associated with an active delta (flood control channel mouth) in the low tide terrace, at the approximate location of an historical natural barrier beach. Erosion of sand-bearing cliffs and bluffs also supplies estuarine beach sand locally, often in association with alluvial fans in adjacent gulches. This delivers relatively coarser sand, often mixed with gravel, than erosion from eroded paleodunes. Examples of estuarine beaches with bluff, cliff, and alluvial fan sand sources include China Camp Beach, adjacent pocket barrier beaches (Rat Island Cove), unnamed historical beaches along Richardson Bay, and beaches of Point Molate, Point San Pablo, and Point Pinole in Richmond.

Figure 12. (Below) The ebb delta of the San Lorenzo Creek flood control channel forms a mud and sand low tide terrace, with multiple sand bars and shoals, adjacent to Long Beach, Roberts Landing, San Leandro.

ESTUARINE SHELL HASH BEACHES

Extensive, large oyster shell hash beach ridges and spits are a shoreline type unique to San Francisco Bay on the Pacific North American coast. Historically, massive oyster shell hash beaches were the prevailing beach type along the San Francisco Peninsula bayshore south of San Francisco, from San Mateo (Guano Island) to Ravenswood (Palo Alto). Remarkable and extensive spits, barriers, and marsh-fringing barriers in San Francisco Bay were composed of native oyster (*Ostrea lurida*) shell hash (shells and disintegrating shell flakes). They formed a "white glistening" barrier beach and bar chain of discontinuous beaches extending for about 12 miles or more south from San Mateo (Townsend 1893). The shell hash deposition rate was reportedly massive along the San Mateo bayshore "shellbanks" in the late 19th century, described as a "constantly increasing deposit of shells that covers everything alongshore and forms bars extending into the bay" (Townsend 1893).

Equivalent or nearly identical large oyster shell hash beach ridges, spits, and complex cuspate or scrolled (highly recurved) forelands develop today along the Foster City shoreline to Belmont Slough mouth and along most of southern Bair Island and Bird Island. The most complex shell hash beach forms on Bair Island are associated with evolution of shell deltas (mouths of breached, beach-dammed tidal marsh channels) reshaped by longshore drift and wave action as strongly recurved, oblique, offset flying spits like those of the Caspian and Black Seas (Zenkovich 1967) (Figure 13). Topographic and tidal drainage pattern signatures of vegetated shell hash berms (stabilized beaches) are evident along eroded mid-19th century salt marsh edges of the U.S. Coast Survey t-sheets covering these localities (Figure 14, pg. 62).

Oyster shell hash is a mixture of wave-abraded Olympia oyster shells and partially disintegrated shell flakes. Olympia oyster shells are eroded from extensive exposures of mid-Holocene (fossil) shell-rich mud deposits by wave and current action. Abundant Olympia oyster shell deposits in bay mud are remnants of past Holocene climates associated with low bay turbidity and high salinity, at lower sea levels than today. These shell-rich muds are probably associated with oyster-dominated strata of California Indian shell mounds (middens) of the East Bay (Nelson 1906, Gifford 1917). The abundant oyster shell mud deposits are relict mid-late Holocene legacies, with the last phase of oyster abundance ending relatively abruptly around 430 C.E., based on archaeological data (Milliken et al. 2007). This is consistent with evidence of a climatic shift of the Little Ice Age in San Francisco Bay (LIA I and LIA II) from 650 to 280 cal YBP (McGann 2008), with rapidly increased fine sediment accretion and tidal marsh expansion (Watson and Byrne 2013).

Figure 13. (Left to right) Complex shell barrier beach configurations at southeastern Bair Island, South SF Bay, as viewed from aerial imagery (courtesy of Google Earth) and during a field visit. Formations include free flying spits, recurved spits, and cuspate and looped spits, associated with episodic deltas and variable longshore drift.

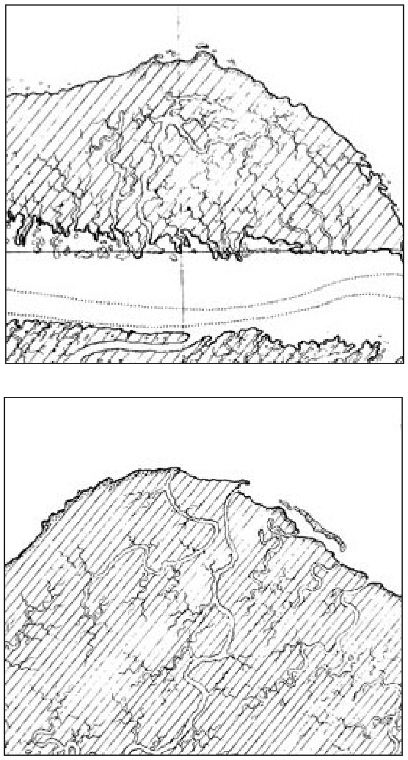


Figure 14. U.S. Coast Survey T-sheet 664 (1857) shows bay edge signatures of marsh-stabilized shell beaches: small spit forms marked with both stippling (coarse sediment) and hatching (marsh), bayward marsh with no tidal creeks, tidal creek drainage patterns away from the bay waves.

Low-density Olympia oyster shell hash is sorted by wave action, concentrated, and deposited in shallow subtidal bay and intertidal mudflats as variable bar forms, including relatively stationary and mobile submerged bars, intertidal swash bars, and transverse bars (Figure 15). Onshore shell hash transport along marsh edges or artificially armored shores today still generates highly dynamic, large estuarine beach ridges, spits, and cuspate forelands. The most extensive and largest shell hash beaches today occur along the Foster City and south Bair Island shorelines. Olympia oyster shell hash is physically dissimilar from heavy shells of introduced Pacific oysters (Crassostrea gigas) of mariculture operations.

Studies of beach morphology and dynamics of oyster shell hash beaches are scarce in the global coastal geomorphology literature, probably because of the geographic rarity of these beaches. Oyster shell hash beaches in some respects behave like gravel beaches (rapid infiltration of backwash, high, steep berm and beachfaces), and in some respects like sand beaches (rapid entrainment in turbulent backwash and wave-generated longshore currents). Low-density shell hash flakes, with discoid shape and high surface/volume ratio, have relatively low settling velocities compared with sand and gravel. They can be extensively transported in suspension by turbulent wave action, as well as in bed load (swash/backwash) during storm events. Natural SF Bay shell hash berms and bars can deposit very rapidly; transient swash bars at Bair Island can visibly form in minutes under the influence of boat wakes, or during short periods of high wind-wave action or tide heights (Figure 16). Significant shell hash beach accretion (progradation) alongshore can also be very rapid, occurring during single tidal cycles or single storm events.

The imbricate structure of overlapping disc-like shell hash enables it to develop very steep beachface slopes, like gravel beaches, but under the influence of relatively lower wave energy. Wave-cut scarps in shell hash ridges can persist as nearly vertical banks. Progradation of shell beach ridges (bayward accretion) often results a composite structure of closely spaced, steep, high berm crest series.

Older, stabilized shell hash beach ridges can undergo weak cementation and increase in resistance to erosion. Shell hash beach ridges are subject to rapid colonization by high salt marsh vegetation once active mobility of the surface is significantly reduced for a year or more (no significant winter storm wave action) and they are converted to high salt marsh berms (Figure 17).

The supply of oyster shell hash for beach accretion may be influenced by commercial oyster shell mining, permitted at rates up to 80,000 cubic yards/year (San Francisco Bay Conservation and Development Commission) under a subtidal lease area approximately 1,560 acres offshore from the Foster City-Bair Island shell beaches (California State Lands Commission 2011). Limited data are available on the distribution and abundance of shell and shell-rich mud shoals that supply beach sediment.

Figure 15. Oyster shell hash sorted by wave action from the shell-rich muddy low tide terrace and nearshore bay at Foster City forms bars and beaches (2010), and a close-up view of shell hash.

Figure 16. Rapid deposition of oyster shell hash bars during a falling tide leaves a descending series of multiple small swash bars. Bair Island SE, 2010.

Figure 17. Vegetative colonization and stabilization of estuarine shell beaches converts them to high salt marsh berms, an alternative state of estuarine beach ridges. Historical maps likely showed these features as part of marshes unless coarse beach sediment was exposed.

ESTUARINE GRAVEL BEACHES

Gravel beaches in SF Bay occur naturally along bay shores with erodible rocky cliffs or bluffs containing gravel-sized sediment (2-63 mm), or along artificial bay fill or armored shorelines where concrete or rocky fill disintegrates into gravel-sized sediment. Naturally well-sorted, nearly pure gravel beaches are uncommon in SF Bay compared with poorly sorted, mixed sand and gravel beaches with characteristics more similar to sand beaches (Jennings and Shulmeister 2002).

Composite sand and gravel beaches, characterized by a sandy beachface and a steep storm gravel berm in the backshore (Jennings and Shulmeister 2002) are rare, local, and seasonal in the SF Estuary, occurring at a few shoreline segments at Point Pinole, Richmond, and Tiburon (Figure 18). Mixed sand and gravel beaches and poorly sorted coarse sand beaches are common in pocket beaches along cliffed shores and canyon or valley mouths in Marin County (Richardson Bay, San Rafael Bay) and Richmond (Point Molate, Point San Pablo). Gravel beaches derived from erosion of artificial bay fills, armored shores, and old landings also occur in small shoreline pockets, around relatively resistant forelands and headlands, or at the mouths of flood control channels (Figure 19).

Gravel beaches and very coarse sand beaches develop steeper, wave-reflective beachfaces with higher crests than sand beaches (grain sizes smaller than about 1.5 mm). Gravel and very coarse sand beaches coarser than this threshold grain size have hydraulic conductivity exceeding 1 cm/second. Gravel and very coarse sand beaches exhibit rapid infiltration of swash and backwash in large pore spaces, resulting in asymmetry in the volume and energy of swash and backwash, favoring net onshore transport and steep beachfaces (Masselink and Li 2001). Mixed sand and gravel beaches, however, tend to have pore spaces filled with sand, and have hydraulic conductivity, swash/backwash processes and slopes more like those of sand beaches. The capacity of permeable gravel beaches to accrete vertically and maintain berm profiles even during storm wave action that typically erodes sand beaches makes them especially useful for erosion control objectives and coastal engineering design.

Figure 18. Composite estuarine gravel and sand beach profiles are rare in SF Bay. One publicly accessible example of a storm gravel berm above a sandy beachface occurs at the Richardson Bay Audubon Sanctuary in Tiburon, Marin County.

Figure 19. Estuarine gravel and mixed gravel-sand beaches are associated with natural erosional headland or depositional stream mouth sources of gravel, and with anthropogenic sources of gravelly sediments. Natural gravel beaches occur at Point Pinole, China Camp Beach (south end). Mixed sand-gravel beaches are widespread along the Tiburon cliffed coast, as at Paradise Beach. Anthropogenic "gravel" spits are formed from various materials (seaglass, ceramics, metal, asphalt, and concrete fragments) eroded from old landfills or bay fill, near Strawberry Creek at Eastshore State Park in West Berkeley.

ESTUARINE COBBLE BEACHES AND LAG SHORES

The rarest beach type in the SF Estuary is composed of the coarsest, least mobile beach sediments: cobbles, which are coarser than very coarse gravel (63-200 mm). In low wave energy shorelines like estuaries dominated by cohesive fine sediments, cobbles can behave much like boulders (over 200 mm), which embed in mud and form immobile lag armor deposits or veneers over mud, peaty mud, or muddy sand. Rounded cobbles roll and pivot under higher storm wave energy levels, and can form storm cobble berms like gravel berms. One of the only natural occurrences of rounded cobble beaches in the Estuary occurs at Point Pinole's western shoreline, where rounded cobbles locally erode out of bluffs (Figure 20). The lower foreshore of the cobble-dominated shoreline is a natural, immobile lag surface (cobbles embedded in peaty mud or basal bluff clays), and an upper foreshore cobble storm berm that is active during high tides and high wave action. Other cobble beaches in SF Bay are more like rocky shores, because angular, interlocking cobbles behave like rip-rap, exhibiting little erosion or deposition even under storm wave action. Estuarine beaches intermediate with rocky shores, composed of angular cobbles mixed with gravel from colluvium below cliffs and bluffs, occur on East and West Marin Island (San Rafael Bay), Red Rock Island, and scattered cliff-toe shorelines at Point Molate (Figure 21).

Figure 20. (Right) Estuarine cobble beaches and immobile beachface lag armor composed of rounded cobbles eroded from bluffs. Rounded cobbles pivot and roll, and are more readily transported by high wave action than angular, interlocking cobbles. Immobile cobble is covered with green algae, and embedded in bay mud, muddy sand, or remnants of old peaty marsh mud.

Figure 21. (Right) Two examples of fringing cobble and gravel estuarine beaches with angular cobble and gravel eroded from Franciscan sandstone and shale cliffs, and erosion of fill at Point Molate. Cobbles grade into small immobile boulder lag in the lower beachface (photographed in 2017).

Estuarine beach and wetland interactions

In the original Baylands Ecosystem Goals Project (Goals Project 1999) and its science update edition in 2015 (Goals Project 2015), beaches in SF Bay were treated as a discrete estuarine habitat category, like tidal marsh or mudflats. But just as tidal mudflats and marshes literally intergrade by ecological succession, or by dynamic physical erosion and depositional processes, estuarine beaches can also intergrade with marshes and mudflats, or exist as discrete shore landform types that are independent of tidal marsh-mudflat systems.

Natural estuarine beaches in SF Bay exhibit dynamic intermediate states between active beachfaces and berms with minimal perennial vegetation, to stabilized, vegetated beach ridges dominated by high salt marsh, beach/foredune, or intermediate (ecotone) vegetation gradients. Estuarine beach and salt marsh vegetation globally plays a major role in the formation and morphological evolution of low-energy estuarine beaches, including marsh-fringing barriers (Cooper et al. 2007, Pilkey et al. 2009). The classic New England geomorphic landform originally described as a "marsh bar" (Johnson 1919) is essentially a marsh-capped stabilized low-relief beach ridge (like a sandy chenier), or washover (Cleary et al. 1979). Thin washover deposits of beach sand, shell, or gravel over salt marsh edges (wave-eroded peaty mud platforms) occur under relatively low estuarine wave energy conditions, and maintain high marsh islands, or zones of high salt marsh above normal tidal elevations (Cleary et al. 1979). These can be "hotspots" (or refuges) of high salt marsh plant diversity where salt marshes are otherwise undergoing submergence and loss of diversity due to sea level rise (Elsey-Quirk 2019). Thus, estuarine beaches (including sandy or shell-rich washovers) are part of a spectrum of estuarine landforms bridging salt marsh and "pure" beach. This global relationship also applies to SF Bay marsh-fringing barriers and intermediate high marsh berms (Figure 22).

Figure 22. Intermediate estuarine beaches and tidal wetlands occur over a spectrum of washovers, beach ridges, and high salt marsh berms in different stages of erosion, deposition, and vegetation establishment, and are not always distinct. **(left)** A high salt marsh berm Pinole Creek (2006) is an emergent gently sloping ridge composed of interbedded sand, tidal litter, and coarse silt capped with tall gumplant and pickleweed vegetation, above mixed organic/mineral sand beachface resembling peat. **(right)**Stabilized shell beach ridges are similarly mantled with high salt marsh vegetation at Foster City (2010).

Estuarine beach processes also have significant indirect hydrological effects on salt marsh hydrology and aquatic or wetland habitats. Where beach ridges transgress across salt marsh platforms with tidal creeks, they can impound them (beach dams) and convert them to elongated non-tidal or spring-intertidal pools ("channel pans" of Yapp et al. 1917) (Figure 23). Estuarine spit recurves or barriers migrating over existing salt marsh platforms or high tide flats can vegetatively stabilize as high salt marsh berms and enclose poorly drained swales or shallow lagoons that become shallow pools, pans, or marsh habitats. Whole barrier beaches can enclose and impound salt marshes that become largely non-tidal, overwashed or stream-flooded brackish to hypersaline ponds (Figures 24 and 25). High beach crests of fringing beaches along valley or alluvial fan mouths can form backshore swales that become seasonal wetlands (Figure 26). Many of the diverse tidal marsh sub-habitats that are artificially designed in tidal marsh restoration projects by earthmoving to replicate natural features are equivalent to tidal marsh wetland features naturally generated by interactions with estuarine beach processes and landforms.

Figure 23. Estuarine sand and shell beach ridges can migrate over the mouths of tidal creeks or pools, and temporarily or permanently dam them, forming enlarged, broad to elongated pools or channel pans. Examples occur at SE Bair Island, and Whittell Marsh, Point Pinole.

Figure 24. Estuarine barrier beaches can impound small lagoons or saline pans in salt marshes, and in swales between beach and alluvial fan or canyon mouths in cliffed shorelines. Although not in the SF Estuary, Morro Bay in San Luis Obispo is shown here as an example.

Figure 25. Rat Island Cove within China Camp Sate Park,San Rafael, is a local example of an estuarine barrier beach with a lagoon behind it.

Figure 26. Estuarine beaches can impound freshwater runoff from alluvial fans or canyon streams, as well as tidal overtopping from storms, creating backshore fresh to brackish seasonal wetland swales. China Camp Beach, 2018.

Wildlife habitat relationships among estuarine beaches, erosional salt marshes, and artificial levees

Eroding salt marsh and levee edges and estuarine beaches are related as the first line of shoreline exposure and interaction with wind-waves and sea level rise. These shoreline types and their responses to changing sea levels and wind-wave climates also critically influence the distribution and abundance of wildlife habitats. Marsh edge erosion increases the area of unvegetated upper intertidal flats, exposing the eroded, consolidated marsh mud platform beneath tidal salt marsh, but it can also remove or degrade the limited high tide roost habitats of migratory shorebirds. Marsh submergence and edge erosion can also reduce the abundance of critical high tide refuge habitats: the cover and shelter provided by local tall vegetation canopies that remain emergent above extreme high tides that submerge the vegetation of tidal marsh plain. Estuarine beaches, controlled by the local supply of coarse sediment and shoreline setting, can mediate shoreline dynamics at eroding marsh and levee edges, and modify wildlife habitat interactions there.

Estuarine beaches and related transitional, intermediate landforms between sandy high salt marsh and estuarine beaches, can potentially play an important ecological management role by providing resilient, self-constructing, depositional supratidal habitats, such as high tide roost, foraging, and nesting habitats for shorebirds, and high tide refuge cover (tall perennial vegetation, coarse debris) for salt marsh wildlife including small mammals and rails. In local wind-wave climates that induce significant erosion of cohesive bay mud and marsh, sufficient supplies of coarse sediment can potentially maintain estuarine beach depositional processes that support local high tide roost and refuge habitats, and “hotspots” of species and habitat diversity.

Artificial bay mud levees and salt marsh platforms are composed of cohesive fine sediments (clay, silt) that are eroded by high waves generated during strong onshore winds. Levee and salt marsh scarps (wave-cut vertical cliffs) reflect wave energy and intensify turbulence, forming unstable profiles where fine sediment budgets deficits prevail. Their eroded fine sediments are resuspended and dispersed by tidal currents. Artificial levees generally do not spontaneously recover through natural processes after erosion events in estuary settings where adjacent mudflats are themselves erosional and wind-wave energy is high. Eroding salt marsh edges in the SF Estuary have exhibited a significant progressive net erosional trend for decades (see Chapter 2).

Artificial bay mud levees have largely replaced the equivalent natural, historical form and function of estuarine beaches: linear, partially unvegetated, high-albedo, topographically elevated ridges parallel to erosional marsh edges, raising topographic elevation thresholds for tidal and wave overtopping, located next to tidal mudflats and shallow open bay waters. Leveed bay shores occur today where widespread marsh-fringing barrier beaches historically established shorelines in the Central Bay.

For example, estuarine marsh-fringing barrier beaches can rebuild vertically during landward transgression over marsh platforms (beach “rollover”; Davis and FitzGerald 2004), maintaining beach-high marsh topographic gradients by wave deposition (overwash). Post-storm recovery of estuarine beach profiles occurs during calm-weather low wave activity, where beach sediment supplies are sufficient. Thus, two critical salt marsh wildlife habitats—partially barren, sparsely vegetated linear island-like habitats and high salt marsh vegetation canopies above normal high tides and wave runup elevations—may be maintained by interactions between estuarine beaches and salt marsh edges. Additional interactions between beaches, washovers, and salt marsh are provided by increased threshold elevations for trapping driftwood and coarse debris along the bay edge of salt marshes. Driftwood deposition provides local topographic heterogeneity, cover, and potential structural support for some species of native high salt marsh vegetation, enabling their shoots to clamber (climb) above extreme high tide water levels, enhancing potential high tide refuge habitats (see plants, below).

High tide shorebird roost habitats in the modern artificial diked bayland landscape are supplied in abundance by non-tidal seasonal wetlands and salt pond flats and bare levee road tops that are closed to frequent human disturbance (Takekawa et al. 2000). Along other coasts where estuarine beaches remain a significant shoreline habitat type, they provide significant high tide foraging or roost habitats where they are not subject to excessive human disturbance (Burger et al. 1996, 2004). Similarly, terns and plover species with high conservation priority in the SF Estuary commonly exploit artificial playa-like diked bayland, levee, and salt pond habitats, although they typically inhabit beach habitats range-wide (Ryan 2000, Feeney 2000). High tide refuge habitats in recently formed, young salt marshes are often provided by artificial levee edges, and remnants of former berms and other artificial fills that are difficult to maintain by traditional methods as sea level rises (Goals Project 2015).

The relationships between selected wildlife and plant guilds, marsh edge erosion, submergence, and estuarine beaches are summarized below.

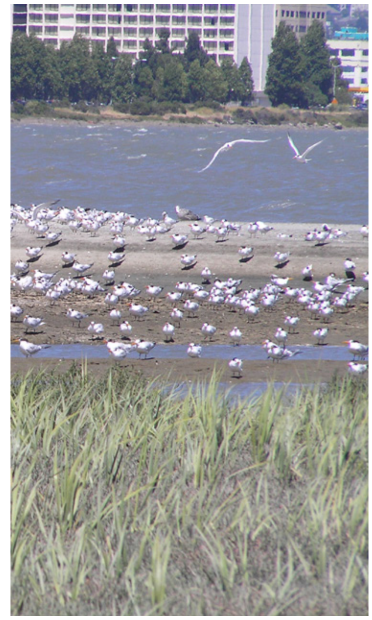
SHOREBIRD ESTUARINE HABITAT UNITS: LOW TIDE FORAGING, HIGH TIDE ROOSTING

As salt marshes retreat, the area of potential tidal flat foraging habitat for migratory shorebird increases. Shoreline erosion in the SF Estuary (marsh, artificial levee, beach) can also affect the distribution and linear extent of high tide roost habitats of shorebirds (unvegetated or sparsely vegetated flat areas emergent at high tide, including levee roads, salt ponds, salt pans, tidal debris wracks, and beaches), where they rest and conserve energy when productive tidal flats are submerged (Figure 27). Ecologically, tidal flat foraging habitats and associated high tide roost habitats of shorebirds are a functional unit (Luis et al. 2005). Shorebird use of intertidal flat foraging habitat can be limited by the distribution of high tide roost areas in San Francisco Bay (Takekawa et al. 2000) and globally (Rogers 2003, Rogers et al. 2006, Dias et al. 2006). Long-distance flights between tidal flat foraging habitats and high tide refuges are energetically expensive. Levee breaching or collapse due to wave erosion can cause extensive local loss of high tide shorebird roost habitats. Estuarine shoreline retreat and erosion can interact with human recreational disturbance of high tide shorebird habitats (Burger et al., 1997), reducing the availability of otherwise suitable high tide roosts along levees or beaches.

Figure 27. Shorebirds forage on productive muddy low tide terraces at low tide (top left: Roberts Landing low tide terrace below Long Beach), and move to high tide roosts (top right: Foster City beach; bottom: Crown Beach, Alameda), including high tide beaches with low disturbance from humans and dogs.

TERNS AND WESTERN SNOWY PLOVERS

On the Central California Coast outside SF Bay, tern species that occur in SF Bay (Caspian tern, *Sterna caspia*; Forster's tern, *S. forsteri*; Elegant tern, *Thalasseus elegans*; California least tern, *S. antillarum browni*) are associated with sand beach and washover flat habitats near open shallow estuarine and marine foraging habitats of bays and lagoons (Ryan 2000, Feeney 2000; Figure 28). Tern nesting areas are typically located near open water, usually along coastal beaches and estuaries. Similarly, western snowy plover (*Charadrius alexandrinus nivosus*) are primarily associated with beach and washover habitats on the maritime Central Coast, but inhabit artificial salt pond beds (playa-like saline seasonal wetland flats) in SF Bay. These are habitats with ample invertebrate prey, bare, high-albedo substrate, and sparse or absent vegetation. Historically, western snowy plovers were reported from locations of past estuarine beaches at Berkeley, Alameda, and Bay Farm Island, at the same time of early reports of common nesting and foraging in salt pond edges of Alvarado (Grinnell and Wythe 1927). Extensive estuarine sand and shell beach systems of Central SF Bay were eliminated by reclamation and fill for urban development and salt ponds in the 19th century, prior to regional scientific bird surveys (Grinnell and Wythe 1927).



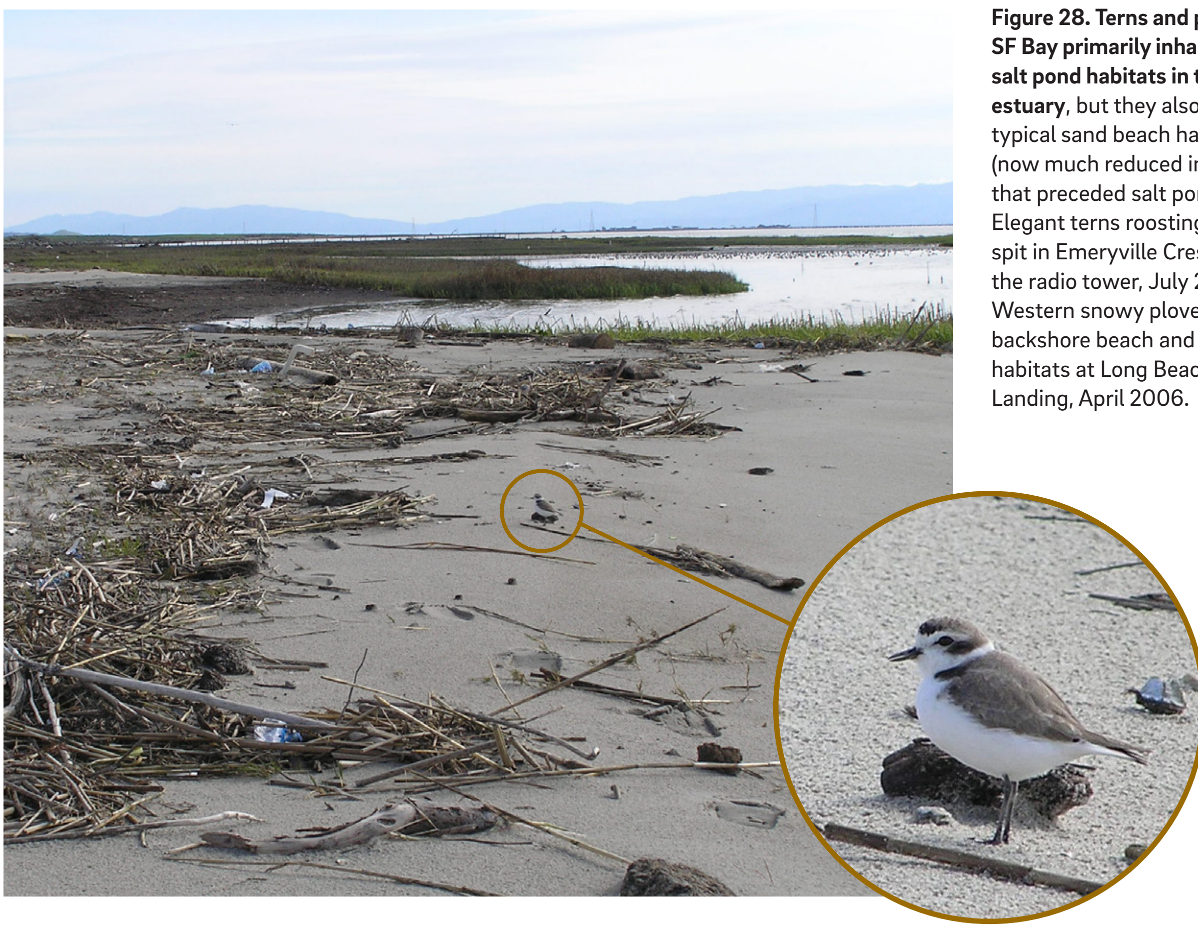


Figure 28. Terns and plovers in SF Bay primarily inhabit artificial salt pond habitats in the modern estuary, but they also utilize typical sand beach habitat types (now much reduced in extent) that preceded salt ponds. Above: Elegant terns roosting on a sand spit in Emeryville Crescent behind the radio tower, July 2006. Left: Western snowy plover forages in backshore beach and washover habitats at Long Beach, Roberts Landing, April 2006.

SMALL MAMMALS AND RAILS: EXTREME HIGH TIDE REFUGE HABITAT

Small mammals, including the endangered salt marsh harvest mouse (*Reithrodontomys raviventris*), are dependent on emergent cover providing refuge from extreme high tide flooding. High tide refuge for small salt marsh mammals is provided by taller vegetation and trapped tidal debris, and old song sparrow nests, that occur in the narrow band of tall high salt marsh along tidally well-drained salt marsh banks (Johnston 1956, 1957). The tall perennial vegetation canopies of gumplant (2-4 ft; Johnston 1956) and robust pickleweed are climbed by small mammals and used as local high tide refuge (cover) when extreme high tidal flooding submerges the vegetation canopy of salt marsh platforms (Hulst et al. 2001), or brackish tidal marshes (Smith et al. 2014). The endangered California Ridgway's rail (*Rallus obsoletus obsoletus*) is similarly dependent on high tide refuge cover to survive avian predation during marsh-submerging extreme high tides (Albertson and Evens 2000, Overton et al. 2015). Tall high marsh vegetation is also essential nesting and foraging habitat for endemic tidal marsh-dependent song sparrow subspecies (Marshall 1948, Johnston 1957).

Sea level rise and salt marsh bank erosion in the SF Estuary are likely to reduce the abundance of high tide refuge and high tide roost habitats as well as their structure and distribution pattern. Sea level rise rates that increase tidal submergence time of pickleweed can reduce plant height (Woo and Takekawa 2012) and eventually convert higher salt marsh zones to low marsh and unvegetated tidal habitats (Thorne et al. 2016). Acceleration of tidal marsh bank erosion along tidal creeks, due to increased tidal prism forced by sea level rise, may increase lateral erosion rates of tall high marsh vegetation. The erosional loss of high tide refuge habitat along salt marsh banks, coupled with accelerated sea level rise and increased storm high tide flooding impacts (Thorne et al. 2013) are likely to limit the availability of critical high tide refuge and roost habitats before tidal marshes are submerged to low marsh and mudflat.

ESTUARINE BEACH INVERTEBRATES

Estuarine beaches provide habitats for terrestrial and estuarine invertebrates, including rare species of tiger beetles, carrion-feeding and deadwood-feeding beetles, ground-nesting wasps and solitary bees. The marginal terrestrial (supratidal) sand and shell substrate habitats of estuarine marsh-fringing beaches allow specialist insect species, including important pollinators like native solitary bees, to inhabit tidal marsh landscapes at locations remote from uplands.

Maffei (2000) identified remnant localities of tiger beetle species (*Cicindela* spp.) in SF Bay diked habitats, including species with typical range-wide habitat preference for beaches and wet, sandy beach-like areas (*C. senilis*, *C. oregona*, *C. haemorrhagica*). *C. oregona* was last identified at Bay Farm Island, a historic beach locality, in 1996 (Maffei 2000; Figure 29). Remnant sand and shell beaches of SF Bay have apparently not been surveyed for tiger beetles in decades. *Cicidela* species occur along maritime beaches of the Central Coast, including sandy lagoon shores and washover flats (Abbott's Lagoon, Point Reyes; Manchester Beach State Park, Mendocino; W. Ericson, pers. comm. 2020).

Ground-nesting wasps and solitary bees opportunistically colonize supratidal beach and washover sands (and artificially deposited sandy sediments, such as dredge disposal sites) with sufficient trace silt content, providing sand grain cohesion sufficient to support small burrows. Ground-nesting wasps (*Bembix, Diadasia* spp.) and solitary bees (*Agapostemon, Anthophora, Bombus, Cerceris, Philanthus, Melissodes* spp.) are expected to colonize coherent sandy soils and sands above normal tides along the Central Coast, and occur in SF Bay terrestrial habitats.

Sand beaches and washovers with decaying driftwood and other detritus provide habitats for darkling beetles (Tenebrionedae), including *Eleodes, Coniotis, and Coelus* spp. Other beetles associated with sandy shores and detritus include carcass-feeding clown beetles (*Histeridae*; *Neopachylopus*, *Hypoccacus* spp.), carabid beetles (*Carabidae*), rove beetles (*Staphylinidae*), and weevils associated with sandy substrates and vegetation *(Curculionidae; Trigonoscuta* spp.). These beetle taxa are large potential prey items for western snowy plovers that also have range-wide habitat preference for sandy beach and washover habitats (Page et al. 2000).

The intertidal beachfaces (foreshores) of estuarine beaches accumulate high tide drift-lines of decaying organic wrack (tidal litter), composed of tidal marsh and riparian (watershed) vegetation detritus, macroalgae, woody debris fragments, and anthropogenic materials. The moist, warm, thick organic debris layers provide microhabitats for high densities of beach insects, isopods, and amphipods, including abundant Traskorchestia traskiana (Pacific beach hopper, present in SF Bay pickleweed marshes). Estuarine beach wrack deposits provide potentially significant macroalgal subsidies to shorebirds foraging during rising tides, as on maritime beaches.

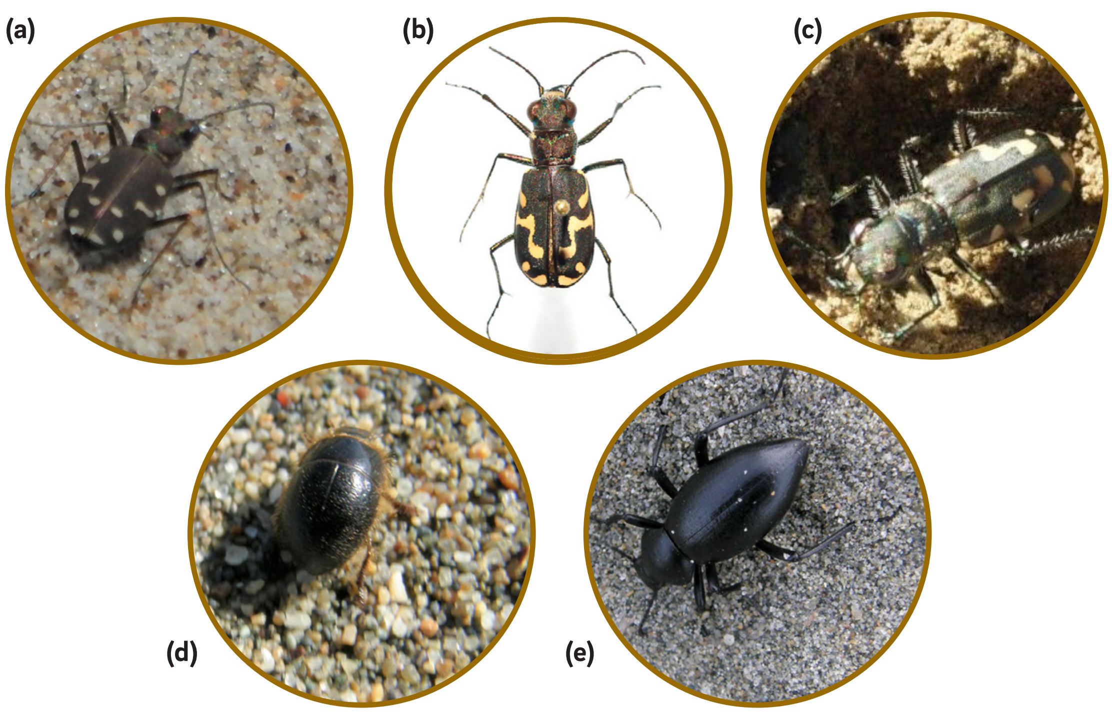


Figure 29. Estuarine sand beaches support uncommon to rare insects specialized for sand beach and sandy lagoon shore habitats, as well as generalist species of decaying wood, detritus, or carrion shoreline microhabitats. Rare insects in SF Bay beaches include three tiger beetle species ((a) *Cicindela oregona*, (b) *C. haemorrhagica*, (c) *C. senilis*) also found on the maritime coast. Sand-inhabiting darkling beetles include (d) *Coelus* spp., and (e) *Eleodes* spp.

PLANTS AND VEGETATION OF SAN FRANCISCO BAY ESTUARINE BEACHES, WASHOVERS, AND MARSH BERMS

Estuarine beaches and related sandy washover flats support two overlapping or intergrading vegetation types: sandy high salt marsh and beach/foredune. Estuarine beaches undergoing active erosion and deposition at supratidal elevation ranges maintain bare or wrack-dominated beach substrate, or sparse backshore vegetation mixed with wrack. Permanently or temporarily stabilized beaches (marsh berms) and washovers become extensively colonized with beach and foredune vegetation, or ecotones between beach and high sandy salt marsh. Vegetation stabilization is usually associated with prolonged periods of low storm intensity and frequency, such as during multi-year droughts.

SF Estuary beach flora today is composed of subsets of maritime and inland sandy riparian and alkali shore plant communities. They include pioneer beach and foredune species typical of maritime Central Coast beaches, including beach-bur (*Ambrosia chamissonis*), non-native sea rocket (*Cakile maritima*), and rarely beach wildrye (*Leymus mollis*) (Figure 30). A richer historical dune flora, now extirpated, formerly occurred along East Bay estuarine dunes, documented by interior SF Bay herbarium specimen localities of species now restricted to the maritime dune flora. These maritime beach species co-occur with widespread interior sandy shore and alkali flat pioneer plants, including western ragweed (*Ambrosia psilostachya*), alkali-wildrye (*Leymus triticoides*), cressa (*Cressa truxillensis*), poverty-weed (*Iva axillaris*; Figure 31) and some species that occur in both maritime and inland sandy shores like heliotrope (*Heliotropium curassavicum*).

These mixed maritime/inland sandy shore plant assemblages of supratidal zones on SF Bay estuarine beaches intergrade with robust forms of high salt marsh (spring high tide zone; Figure 31) including native dominant species like gumplant (*Grindelia stricta* var. *angustifolia*), saltgrass (*Distichlis spicata*), pickleweed (*Sarcocornia pacifica*), alkali-heath (*Frankenia salina*) and Jaumea (*Jaumea carnosa*). Common non-native pioneers from the high tidal marsh flora also occur in drift-lines and well-drained sandy washover gradients over salt marsh, including perennial pepperweed (*Lepidium latifolium*) and orach (*Atriplex prostrata*). Gumplant and pickleweed typically develop robust, tall phenotypes on well-drained stable low-relief beach ridges and washovers with deposits of organic wracks. Saltgrass and pickleweed also can slowly interact with structural support provided by woody debris, and develop clambering, elevated canopies (Figure 32, pg. 78). All these species exhibit significant tolerance to shallow, repeated burial by sand deposition, and provide sand-trapping roughness, like washover fans of barrier beach/salt marsh ecotones globally (Maun 1998).

Rare plant diversity is also associated with ecotones between sandy washovers and salt marshes. Historical collections of now-rare annual salt marsh plants like salt marsh bird's-beak (northern subspecies *Chloropyron maritimum* subsp. *palustre*), smooth goldfields (*Lasthenia glabrata* subsp. *glabrata*) and salt marsh ecotypes of owl's-clover (*Castilleja ambigua* subsp. *ambigua*) were associated with historical SF Bay beach localities (Baye 2000), and are still associated with old stabilized washover-salt marsh ecotones at Limantour Spit and Kent Island (Bolinas Lagoon) in maritime salt marshes of west Marin County (Figure 33). This pattern of plant

Figure 30. Native maritime foredune species also occur in the Central Bay's sand beaches, though infrequently and locally. (Left) Beach-bur (*Ambrosia chamissonis*) is widespread in Central Bay, but (right) beach wildrye (*Leymus mollis*; syn. *Elymus molllis*) is nearly extirpated in unmanaged sandy shores of the Bay.

Figure 31. Native beach plants of the SF Estuary include elements of alkali sandy inland habitats, including alkali (creeping) wildrye (*Leymus triticoides*), alkaliweed (*Cressa truxillensis*), and poverty-weed (*Iva axillaris*), all present at Point Pinole and Point Molate, Richmond beaches.

diversity “hotspots” on depositional sandy washover-high salt marsh ecotones corresponds with research on Atlantic coast tidal marshes that are prone to tidal marsh plant diversity loss due to sea level rise submergence (Elsey-Quirk et al. 2019).

An ecologically important rare plant, California sea-blite (*Suaeda californica*), was historically associated with high salt marsh and estuarine sand beach localities of Central SF Bay, and some South Bay peninsula salt marshes where shell hash beaches occurred (USFWS 2013, Baye 2006). This endangered plant was extirpated in SF Bay by the 1960s, but pilot reintroduction projects have re-established experimental research populations (San Francisco State University, Boyer Wetland Laboratory) in San Francisco, Marin, and Oakland. In Morro Bay, California sea-blite is a robust, salt-tolerant subshrub that colonizes sandy high salt marsh berms and scarps, dunes, sandy low shoreline bluffs, and estuarine beaches. It also has an adaptable, burial-tolerant mounding, spreading, or climbing growth habit that allows it to clamber over driftwood and low-branched trees and shrubs along shorelines, elevating its dense leafy canopy above highest tides and waves (Figure 34). Studies of interactions between structural support of woody debris and sea-blite growth habit have recently been conducted (K. Santos, San Francisco State University, in prep.), in context of high tide refuge habitat management. No research has been conducted on the sand burial tolerance or sand-trapping (foredune or marsh berm-building) capacity of California sea-blite.

Figure 32. Native high salt marsh plants like Pacific pickleweed (*Sarcocornia pacifica*) and saltgrass (*Distichlis spicata)* interact with structural support of driftwood and locally develop perched, climbing canopies elevated above high tides. China Camp Marsh, 2011.

Figure 33. Stabilized old sandy washovers grading into (or drowning into) high salt marsh provide species-rich sub-habitats (“hotspots” of high salt marsh plant diversity) on the Central Coast, including uncommon to rare annual salt marsh plants (smooth goldfields, *Lasthenia glabrata*; salt marsh owl’s-clover or Johnny-nip, *Castilleja ambigua*). These species and habitats are rare today in SF Bay, but remain extensive in this example from Limantour Estero, Point Reyes (2017).

Figure 34. California sea-blite *(Suaeda californica)* is a robust salt marsh subshrub that is adapted to high sandy salt marsh, estuarine beaches, and low sandy bluffs. It can readily develop climbing canopies high above the highest tides and wave action where support from driftwood, bluffs, or dead or living tree branches. San Francisco Bay is the type locality for the species, which survives as wild populations only in Morro Bay.

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CHAPTER 4: A REMOTE SENSING APPROACH TO EVALUATE BEACH CHANGE

Beaches in the SF Estuary provide valuable shoreline protection through wave attenuation, fulfill local habitat conservation objectives by providing breeding and foraging habitat for shorebirds, and provide high-tide refuge for marsh plants and wildlife. When appropriate management protocols (e.g. restricted access to areas with sensitive species) are put in place, estuarine beaches can also provide recreational spaces for people to site-see, birdwatch, and more. Estuarine beaches are dynamic and adaptive, shaped by sediment flows, wave conditions, currents, tidal cycles, and storm events. Although beaches front approximately 36 miles of the SF Estuary's shoreline (as analyzed using imagery from 2009-2015), these features were not generally considered throughout recent decades in shoreline planning and design (SFEI 2016). Compared to more hardened alternatives (e.g. rip rap), estuarine beaches may have lower whole-life costs due to their ability to adapt during storm events, reduce shoreline erosion by dampening wave heights, and provide multiple benefits to people and wildlife. While the extent and distribution of modern and historical SF Estuary beaches has been assessed (Goals Project 1999, Goals Project 2015, SFEI and SPUR 2019) and a general knowledge of estuarine beach dynamics has been established globally (Freire et al. 2013, Jackson et al. 2002, Komar 1976, others), relatively little research exists on the evolution of beaches and geomorphic drivers specific to the SF Estuary.

As the ecological benefits, adaptability, cost savings, and recreational opportunities of nature-based shorelines are becoming more widely recognized, beaches present a unique opportunity to attenuate waves along vulnerable shorelines while bringing back underrepresented native habitats. As such, a better understanding of the behavior of different types of beaches found in the SF Estuary is needed. How can empirical evidence and observations be used to inform and improve beach design for sea level rise adaptation? As a first step toward answering this question, this study applies remote sensing and field observations to analyze planform change in four estuarine beach sites over time, linking observations to beach types discussed in the literature. The findings can be used to improve and expand applied methods in remote sensing toward a more comprehensive study of beach morphology throughout the SF Estuary.

How others have measured beach change

Previous studies have looked at beach evolution in estuarine systems using various measuring, monitoring, and surveying methods. Sites for these studies range from artificially engineered beaches in the Tagus Estuary in Portugal (Freire et al. 2013; Andrade et al. 2006) to wave-dominated shorelines on the southeast coast of Australia (Vila-Concejo et al. 2011). Previous studies have also looked at the impact that various types of events or processes, ranging from artificial nourishment (Andrade et al. 2006; Jackson, et al. 2010) to natural sediment transport events (Nordstrom et al. 2003; Jackson and Nordstrom 1992) have on beach stability.

In the United States, a national assessment of shoreline change was conducted by Hapke et al. (2006) and improved upon by Hapke et al. (2011). Hapke et al. (2006) created a repeatable standardized method using historical t-sheets and modern maps (derived from LiDAR topographic surveys) to calculate short- and long-term coastal erosion and land loss for sandy beaches. However, this method focuses specifically on open-ocean coasts, so geomorphically diverse inland bays, including the SF Estuary, are not suitable sites for this method. Thus, there is a need to adapt this type of analysis to quantify beach shoreline change within the SF Estuary.

GIS and remote sensing are commonly used tools for efficiently analyzing large landscape changes. Improvements over the past 30 years in GIS and remote sensing technology have led to higher spatial and temporal resolution of satellite imagery and enhanced access to publicly available imagery and analytical software. Imagery from long-term satellite remote sensing projects, such as Landsat, can be georeferenced based on fixed or relatively unchanging points, and used to compare the same area at different moments in time. Landsat data from 1986 to 2000 was used to show the growth of the Ruvu river delta on the coast of Tanzania, including the development of subaqueous levees and offshore sandbars (Shaghude et al. 2010). Over a longer timescale, Mann & Westphal (2014) compared aerial photographs from the 1940s and images from 2005 to 2012 from the QuickBird and WorldView-1 satellites, using GIS tools to estimate and calculate rates of shoreline change on atolls in Papua New Guinea.

Various unsupervised classification algorithms have been applied to satellite imagery to identify morphological changes. Unsupervised classification is a GIS technique that clusters data into a user-defined number of classes based on spectral similarities. Teodoro et al. (2009), Pais-Barbosa et al. (2009), Sekovski et al. (2014), and Dewidar and Frihy (2010) use unsupervised classification to extract shorelines from satellite imagery and assess beach evolution over time. de Boer et al. (2019) create maps of beach area change across 130 African seaports, visualizing eroded and accreted areas relative to the baseline shoreline. These unsupervised classification techniques provide high enough spatial resolution to detect and identify specific coastal features and their morphology (Sekovski et al. 2014). Many studies also use field measurements of beach characteristics and/or accuracy assessments to validate their analysis (de Boer et al. 2019, Sekovski et al. 2014, Teodoro et al. 2009, Mann and Westphal 2014).

(Facing page, top) View of a pocket beach and tidal marsh located at Rat Island Cove in Marin County.

(Facing page, bottom) Pocket beach along the western shoreline of Point Pinole.

METHODS

In this chapter (Chapter 4), we use a combination of mapping and remote sensing techniques to assess beach change over time. In Chapter 5, we incorporate qualitative, seasonal, and event-linked (storm, post-storm) observations collected by coastal ecologist Peter Baye over 15 years to further understand beach characteristics.

To evaluate representative sites to analyze, the project team visited several beaches throughout the SF Estuary in October 2018. These included: Radio Beach (Oakland), Emery Cove beach (Emeryville), McNears Beach County Park (San Rafael), China Camp (San Rafael), Greenwood and Brunini beaches (Tiburon), Paradise Beach County Park (Tiburon), Seminary Drive beach (Mill Valley), Dutra beach (Marin), and beaches along the eastern and western shore of Point Pinole Regional Shoreline (Richmond). Additional site visits to the Foster City beach and Highway 80 Frontage beach occurred at different points in time. Six beach sites were then selected to represent a range of estuarine settings and sediment types found in the SF Estuary (Figure 1). Selected sites included Point Pinole Cobble Marsh beach (henceforth Cobble Marsh beach), Highway 80 Frontage beach, Long Beach, Foster City beach, Aramburu Island beach, and Pier 94 beach. Sites without established place names were given descriptive names for the purposes of this report. Dominant sediment types of beach sites ranged from coarse (cobble and gravel) to fine (medium sand), and included a regionally distinctive Pacific coast beach type comprised of fossilized Olympia oyster shell hash (Table 1). Other sites were engineered for habitat enhancement and comprised of a broad range of sediments from large cobbles to coarse sand to oyster shell hash.

Two of the selected beaches, Cobble Marsh beach and Highway 80 Frontage beach, are located between natural and artificial headlands, respectively. In contrast, Foster City beach and Long Beach are located along exposed stretches of the shoreline. Using a combination of observational and professional knowledge of the sites, and several spatial variables (e.g., wind-wave patterns, geology, topobathymetry), we hypothesize that these beaches fall into two types; Cobble Marsh beach and Highway 80 Frontage beach are bayhead/pocket beaches and Foster City beach and Long Beach are spit/fringing beaches. Additionally, we suggest that the engineered sites fall into a separate category referred to in this report as 'project beaches,' as they represent a novel beach type. Project beaches include Pier 94 beach and Aramburu Island beach. Project beaches were not included in the remote sensing analysis described in Chapter 4 (for more information on project beaches, see Chapter 5).

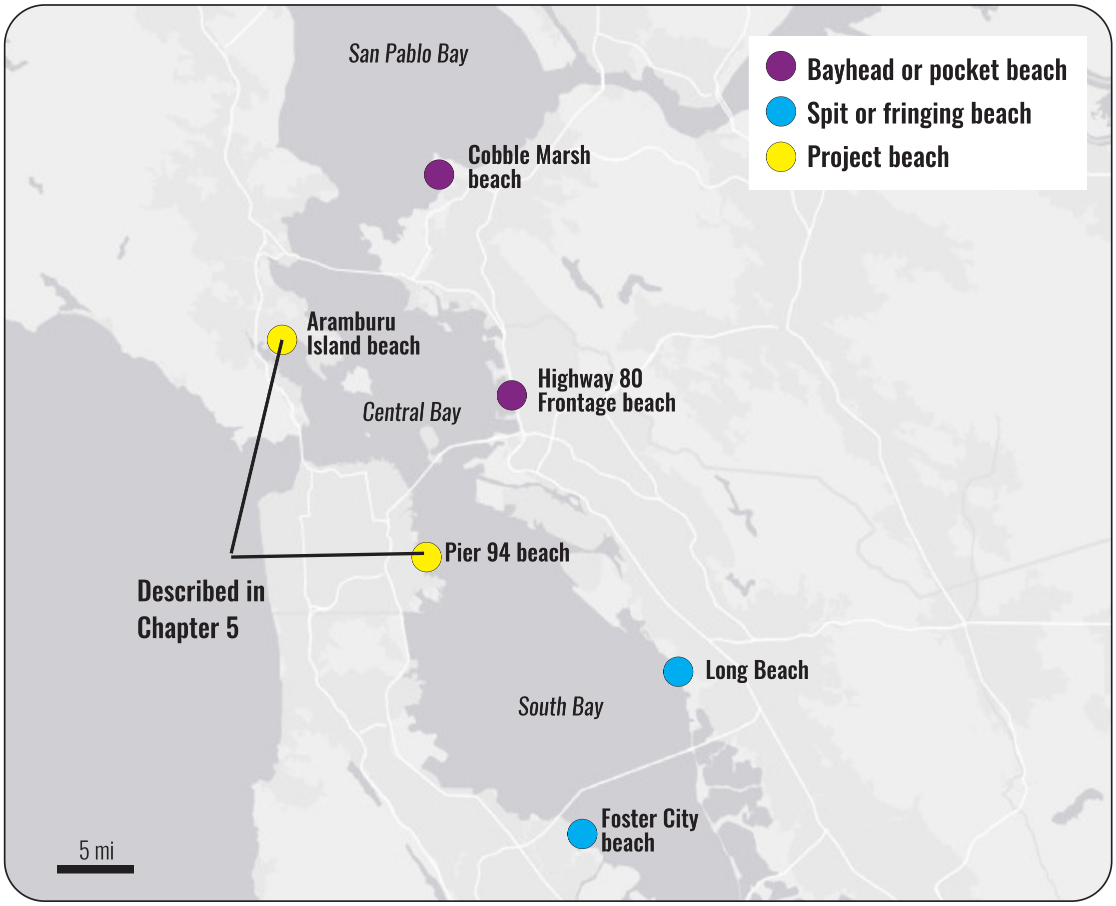


Figure 1. Six beach sites were categorized into three types to evaluate estuarine beach morphologies throughout the SF Estuary.

Table 1. Six beach sites categorized into three types were analyzed in this study using either remote sensing or repeat observations and surveys. Beach sites selected represent a range of sediment types and settings throughout the SF Estuary.

San Francisco Estuary beach types	Beach sites analyzed	Location	Change detection method	Sediment types
Spit or fringing beach	Foster City beach	Foster City, San Mateo County	Remote Sensing	Oyster shell hash
	Long Beach at Roberts Landing	San Leandro, Alameda County	Remote Sensing	Medium-coarse sand
Bayhead or pocket beach	Highway 80 Frontage beach	Frontage Road shoreline, Berkeley-Albany, Alameda County	Remote Sensing	Medium-coarse sand
	Cobble Marsh beach	Point Pinole, Contra Costa County	Remote Sensing	Coarse sand and gravel
Project beach	Pier 94 beach	San Francisco County	Repeat observations, Surveys	Mixed (concrete debris, coarse gravel and sand, and medium-coarse sand)
	Aramburu Island beach	Marin County	Repeat observations, Surveys	Mixed (cobbles, medium-coarse sand, gravel, oyster shell hash)

Remote sensing of beach change over time

We used satellite imagery to visualize and quantify changes in beach area, location, and position over time for four beach sites. Time periods analyzed for each site ranged from 9 to 17 years between 2002 and 2018, with most time steps one or two years apart but in some cases spanning several years. Based on a professional understanding of physical processes and geomorphic settings within the SF Estuary, we selected sites that fell into two categories: (1) bayhead or pocket beaches, which we expected to experience little to no change in beach area, location, and position, and (2) spits or fringing beaches, which we expected to experience larger and more frequent changes in beach area, location, and position. Remote sensing is ideal for this type of analysis because of the high temporal resolution of publicly available imagery.

The four beaches we analyzed are located in Central San Francisco Bay (Foster City beach, Long Beach at the mouth of the San Leandro Creek, and Highway 80 Frontage beach in Emeryville) and San Pablo Bay (Cobble Marsh beach on the western side of Point Pinole Regional Shoreline). A series of 1-meter resolution RGB images recorded during low tide was obtained for each beach location using Google Earth (Google Earth V 9.0). The presence of exposed mudflats in the imagery and the transition from coarse beach material to mudflat were used to determine if an image was taken at low tide. In addition to filtering for imagery taken at low tide, other considerations included minimal cloud cover, clarity of features (i.e. grainy images were excluded), and ease of image stitching. Imagery downloaded from Google Earth included sufficient extent to locate permanent features that persisted in all time steps analyzed to ensure accuracy during georeferencing. Due to data limitations resulting from the presence of cloud cover, georeferencing issues, and the need for low-tide imagery, the number of images that met these requirements ranged from five to ten images per site analyzed.

Unsupervised classification was performed in ArcGIS (ArcMap 10.7) to detect and map the extent of beach at each site for each time step. Satellite imagery was clipped to reduce computation time before unsupervised classification was performed (Figure 2a). Using the IsoClassification tool, pixels were separated into a user-defined number of classes based on nearest neighbor and Euclidean distance algorithms (Figure 2b). Because the optimal number of classes to detect the beach in each image is unknown, multiple iterations were needed to sufficiently segment the beach. Initial classifications were made using ten classes (clusters). Results were then compared against the original RGB imagery to determine if more or fewer classes were needed to delineate the beach. To isolate the beach, imagery was reclassified into two distinct classes, 'beach' and 'not beach' (Figure 2c).

Since the unsupervised classification was based on differences in spectral signatures (i.e. pixel color) there were instances in which dry beach, wet beach, and adjacent mudflats characterized by fine, wet sediment had very similar signatures. In lieu of field data, a simple random sampling method (Accuracy Assessment Points tool) was used to assess accuracy of unsupervised classifications. This involved randomly creating 100 points using the Create Random Points tool, half of which were in the area classified as 'beach' and half of which were in the area classified as 'not beach.' Each point was then assigned a class based on visual inspection of the corresponding RGB imagery (i.e. virtual ground truthing). The virtually ground-truthed pixels were compared against the corresponding pixels from the unsupervised classification using the Confusion Matrix tool in ArcMap, which reports an accuracy percentage and a corresponding percentage of uncertainty (Sekovski et al. 2014). For lower-quality images with more noise, we expected to see lower accuracy assessment scores that reflected more instances of spectral confusion between beach and adjacent land cover types. Although the Confusion Matrix tool cannot improve the accuracy of an unsupervised classification, it can help assess how well a beach was detected and caveat the results. Accuracy assessments were performed on the imagery corresponding to the first and last time steps for each beach site analyzed. Since the image quality generally improved over time with technological advances, we applied an average of the accuracy assessment results of the first and last time steps to the remaining time steps to approximate the range of uncertainty. Accuracies above 85% are commonly cited in the literature as acceptable results from unsupervised classifications (e.g., Jansen et al. 2008, Wulder et al. 2006, Thomlinson et al. 1999).

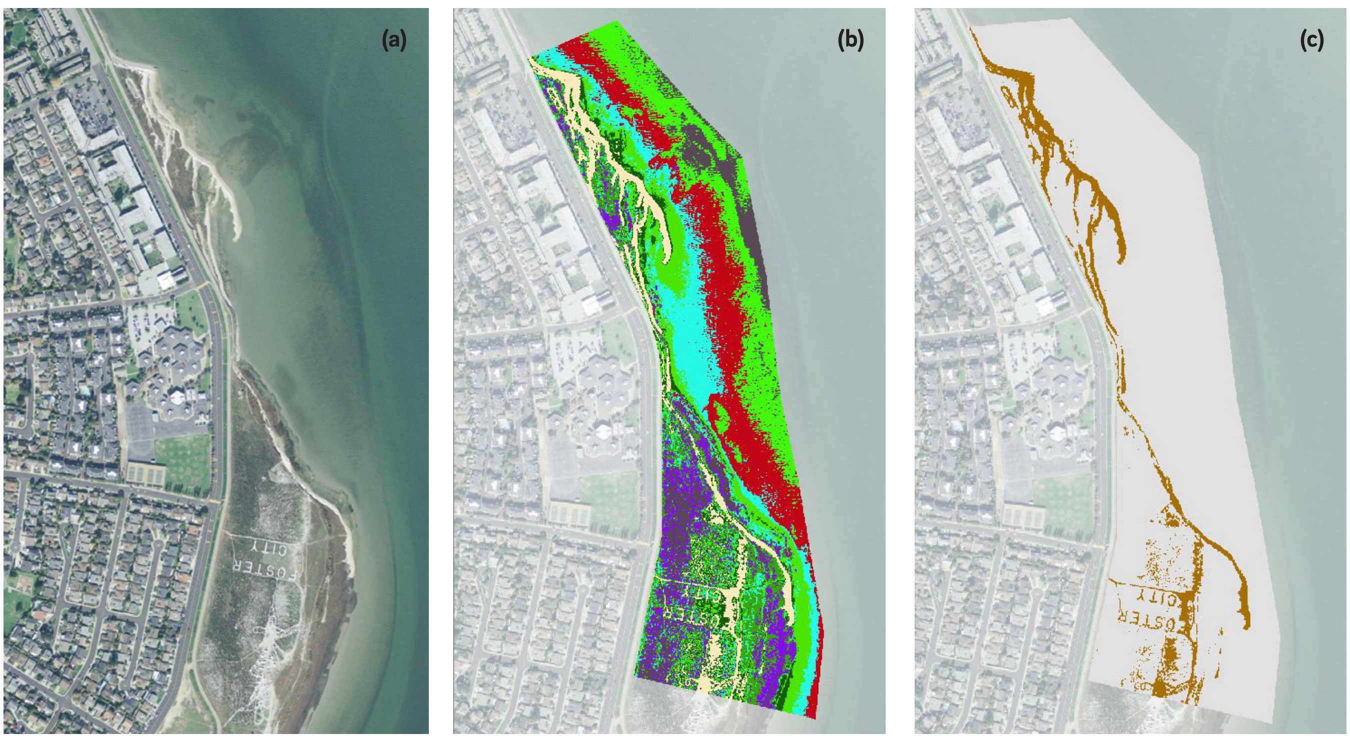
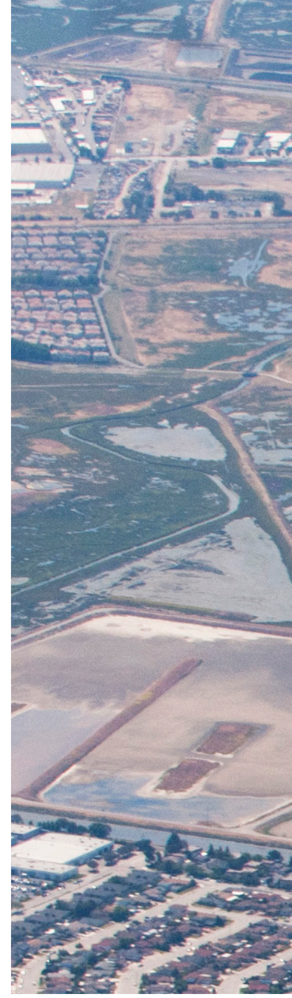


Figure 2. (Left to right) Unsupervised classification of RGB satellite imagery from August 2008. The beach at Foster City was distinguished from surrounding land covers through a combination of visual interpretation of aerial imagery (left) and adjusting the number of pixel classes in the unsupervised classification (middle) until a final beach classification could be reached (right, as shown in brown).


RESULTS

This section summarizes results from the unsupervised classifications of four of the six beach case studies, as described in the previous section. For results of the remaining two beach case studies categorized as project beaches, which employed qualitative, seasonal, and event-linked (storm, post-storm) observations, see Chapter 5.

The four beach sites that were analyzed using unsupervised classification were broken into two categories: spits/fringing beaches and bayhead/pocket beaches. For each case study, we provide a brief site description of broad historical change over time as interpreted by examining publicly available historical maps (e.g. ca. 1800 t-sheets courtesy of NOAA) and aerial imagery (courtesy of Google Earth). We then report findings from the remote sensing analysis. Descriptions of the two beach categories (spits/fringing beaches and bayhead/pocket beaches) are largely drawn from over 15 years of observation by ecologist Peter Baye, in addition to technical information from the literature. Site descriptions include a summary of on-the-ground observations from field visits in 2018 that provide a finer-scale understanding of beach composition, such as grain size of beach material, vegetation, and other considerations.

Results of the remote sensing analysis are summarized in three parts for each time step: (1) the size of the beach mapped; (2) the observed change between time steps; and (3) the measured and estimated uncertainty of mapped beach pixels. Pixels classified as beach are overlaid on corresponding base imagery for the time periods analyzed. The shifts in beach location between time steps highlight the observed patterns in beach change over time.

We observed noticeable and measurable differences in beach behavior between bayhead/pocket beaches and spits/fringing beaches. We saw changes in beach orientation, size, shoreline shape and location for spits and fringing beaches. For bayhead and pocket beaches, we found very little variation.

(Top left) Ice plant grows along the rip rap berm of the Highway 80 Frontage beach (looking north from the Bay Trail).

(Top right) A southward-facing aerial photograph of Long Beach from 2011 shows cuspate features along the beach's southern end. (Photo by D. Coetzee, CC BY 2.0)

(Bottom) View looking south of the oyster shell-hash dominated beach located along Foster City's shoreline (in 2018).

Spits and fringing beaches

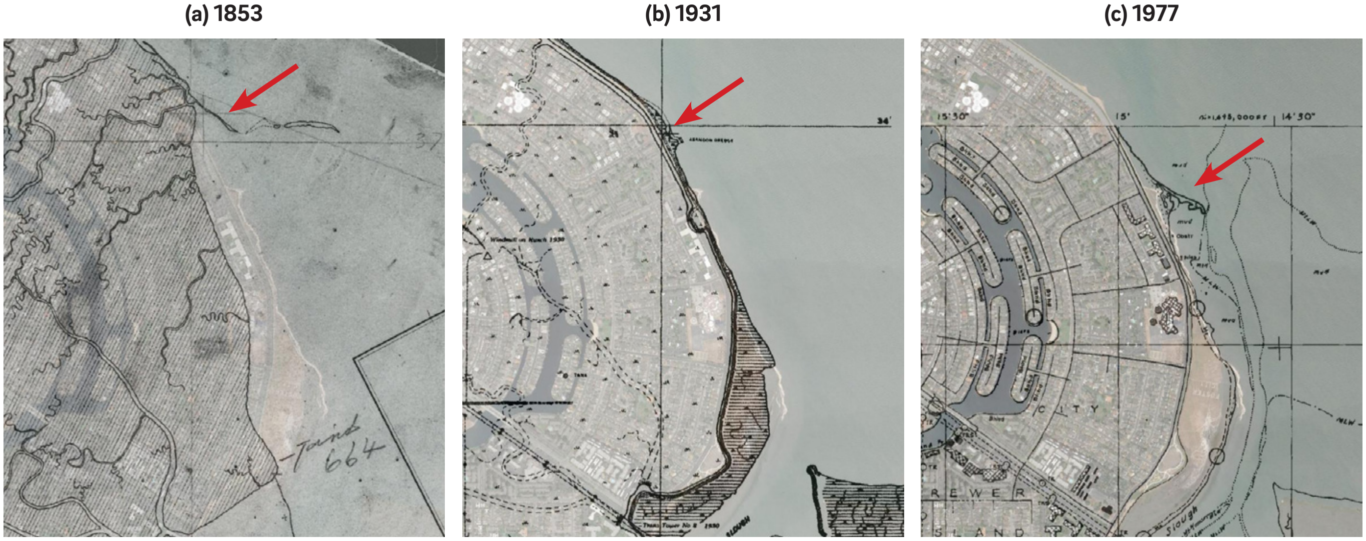
Spits and fringing beaches form naturally within the SF Estuary through a combination of wind, wave, and tidal action. A spit—an expanse of beach material that extends into the Bay and is joined to the shoreline at one end (Lobeck 1939)—forms where the shoreline changes orientation and longshore drift continues to move material along the beach. These beach types often occur in areas with low-lying coastal topography, high sediment accumulation, and wind-wave action that transports and deposits sediment along the shore, also known as a drift-aligned orientation (Griggs 2010). Secondary forces acting on a spit (e.g., secondary winds, wave refraction) can shape the end of the beach into a hook or, if occurring in multiple directions, a series of flying spits detached from the landward edge of the beach. Spits can build up over time and act as fringing or barrier beaches by breaking up wave energy and sheltering the shorelines behind them, allowing for tidal flats or marshes to form (Evans 1942). For more information on spits and fringing beaches, see Chapter 3.

FOSTER CITY BEACH

Site description: The Foster City beach is a complex of spits and marsh-fringing barrier beach, found at the edge of a residential development built on a diked bayland and protected by flood control levees. A 10- to 15-meter-wide beach complex composed of nearly pure oyster shell hash ridges is located along the bay edge of Foster City's engineered flood control levee and fringing salt marshes. This particular beach complex is noteworthy for its relationship with historical oyster shell hash beach ridges and vegetated marsh berms that formed along the edges of tidal salt marshes located along this stretch of shoreline ca. 1850, as evidenced by historical t-sheets (Bache 1853; Figure 3a) and more recent historical maps (USAAC 1932; NOS 1981; Figures 3b and 3c).

At present, a prominent spit has formed where the shoreline changes orientation from northeast-facing to southeast-facing, near the mouth of Belmont Slough. A series of smaller flying spits protruding into the shallow open water have prograded as a series of compound recurved spits "welded" to the landward edge of the beach. The beachface contains oyster shell fragments and minor sand deposits. Bayward of the beachface are shell-rich tidal flats that comprise the low-tide terrace. Two to three visible relict beach ridges were observed during a field visit in 2018, as well

(a) 1853 (b) 1931 (c) 1977



as interbedded mudflats with thin beach/shell lenses that could indicate recent bar or beach ridge migration across soft, saturated muds. Bayward of the low-tide terrace within the intertidal and subtidal zones are long oyster shell hash bars ranging from oblique to transverse (nearly perpendicular to the shore) which have maintained stable northeast to southwest orientations and positions between 2003 to 2018. All but one of these oyster shell hash bars are detached from the beachface, located along the northern end of shoreline and south of the western landing of the Dumbarton Bridge.

(Left) Shell hash ridges observed during a 2018 field visit to the barrier beach found along Foster City's shoreline.

(Right) Mud/ silt deposits interbedded with shell lenses indicating migration of beaches over time along Foster City's shoreline. More study is necessary to date the ages of these deposits and reconstruct a longer history of beach change.

Figure 3. (Facing page, left to right): Historical maps overlaid onto 2019 aerial imagery of the beach along Foster City's shoreline show major changes in the surrounding landscape from tidal marsh and tidal flat habitat in 1853 to diked ranch land in 1931 to leveed residential and commercial developments in 1977 (Bache 1853; USAAC 1932; NOS 1981). One notable feature in the 1977 map is the prominant hook formation of the barrier beach, similar to the forms that appear in more recent decades as observed in the remote sensing analysis of Foster City beach (red arrows indicate the location of a spit or fringing beach formation).

Remote sensing results: We collected eight clear, cloud-free images for Foster City beach from 2003 to 2018 with yearly intervals between one to three years (Figures 4 and 5). From 2003 to 2007, Foster City is separated into two smaller beaches, then connects in 2008, as shown in Figure 5. From 2003 to 2007, multiple shell spits develop, then reconnect with the beach in 2007 to 2008. This may be a result of the prevailing wind direction, which is almost perpendicular to the beach, as well as wave refraction, which carries beach sediment south along the coast, connecting the two smaller beaches in 2011. By 2018, the beach starts to separate again. The triangular-shaped headland at the north of the beach acts as a barrier and protects the northern half of the beach from being eroded. As shell hash spits form off of this feature, shell hash is replenished and is transported down the shoreline.

Foster City beach appears to oscillate between periods of growth in area and loss in area. The average size of Foster City beach across all time steps is about 18,700 m^2 (4.6 ac), reaching its largest area in 2008 (27,100 m^2 or 6.7 ac) and its smallest area in 2011 (13,200 m^2 or 3.2 ac).

Accuracy assessment: Using unsupervised classification, approximately 90% and 92% of pixels were accurately classified as beach cover in the 2003 and 2018 imagery respectively when compared to known beach cover points in the corresponding RGB imagery (i.e., based on visual interpretation of 50 beach cover points and 50 non-beach cover points). This yielded uncertainty values of 10% for the 2003 imagery and 8% for the 2018 imagery. Since little to no cloud cover was visible across all eight images analyzed, an average of the measured error of 9% was applied for the remaining time steps (as indicated by the dashed error bars in Figure 4).

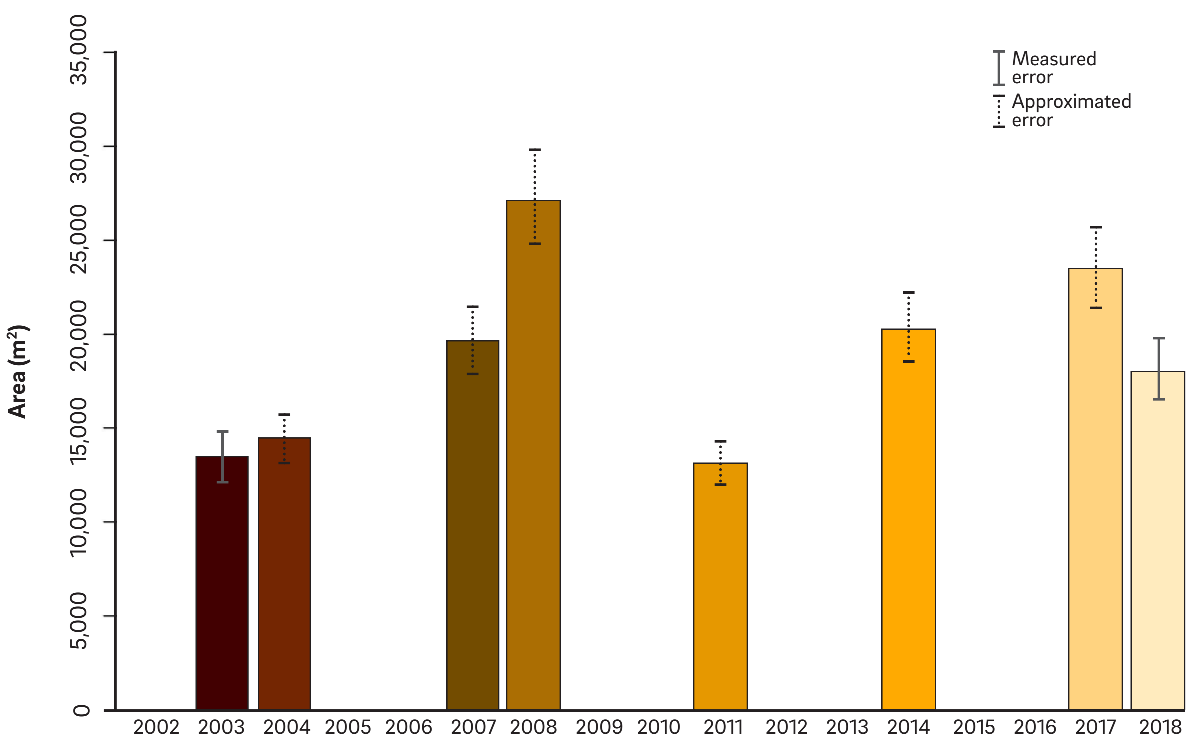


Figure 4. Change in beach area over time at Foster City beach. Of the eight time steps analyzed, the maximum area was reached in 2008 and the minimum area was reached three years later, in 2011. No data was obtained for 2002, 2005, 2006, 2009, 2010, 2012, 2013, 2015, nor 2016. The error bars on the oldest and most recent time steps reflect the corresponding uncertainty values, 10% and 8% respectively, based on the results of the accuracy assessments (i.e. measured error). Accuracy assessments were not performed for imagery corresponding to the remaining six time steps so an average of the measured error, 9%, was applied as indicated by the dashed error bars.

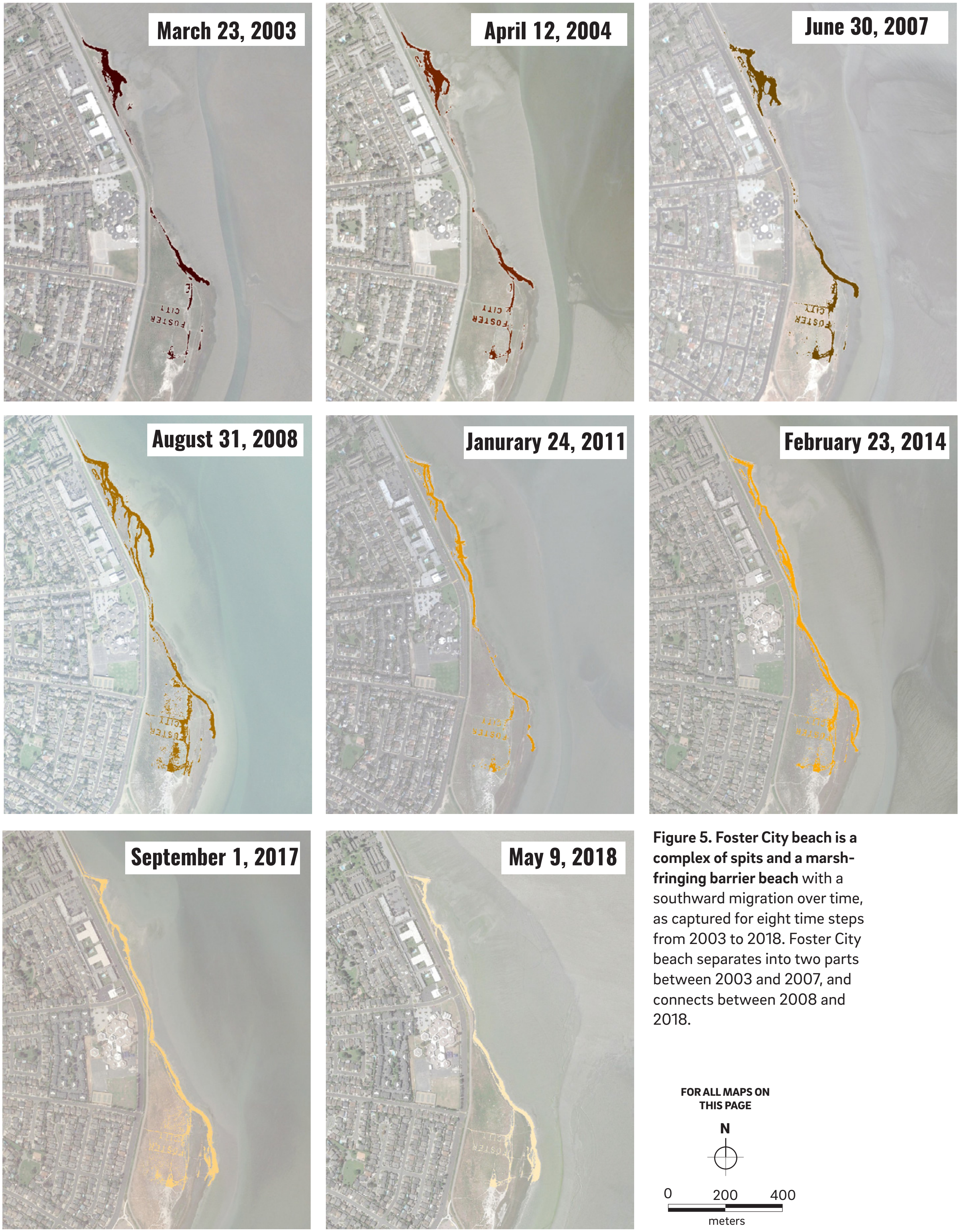
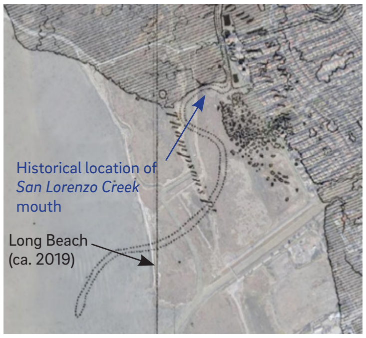


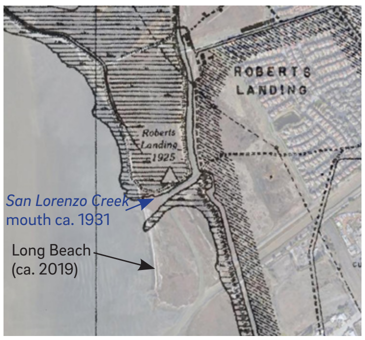
Figure 5. Foster City beach is a complex of spits and a marsh-fringing barrier beach with a southward migration over time, as captured for eight time steps from 2003 to 2018. Foster City beach separates into two parts between 2003 and 2007, and connects between 2008 and 2018.

LONG BEACH, ROBERTS LANDING

(a) 1857



(b) 1931



(a) 1993

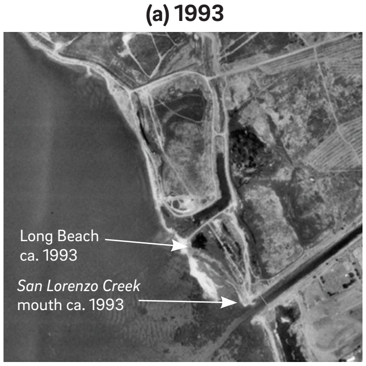


Figure 6. (Top to bottom) Historical maps overlaid onto 2019 aerial imagery from Google Earth and aerial imagery from 1993 of the Long Beach shoreline (Kerr 1857; USAAC 1933; Google Earth). The present-day shoreline at Long Beach was built out over time, and in the early 1960s the mouth of San Lorenzo Creek was rerouted for flood control slightly south of its original location as shown in the 1993 aerial imagery.

Site description: Long Beach (the local vernacular name) at Robert's Landing is one of the largest sand spits remaining in the SF Estuary. This marsh-fringing barrier beach is located along the City of San Leandro's southernmost shoreline. Long Beach fronts a ~50 to 150 m wide tidal salt marsh restored from historically diked baylands. Outcrops of peaty salt marsh muds, including abundant fossil driftwood, appear in the beachface and upper low tide terrace following major erosion events. The low tide terrace, connected to the ebb-delta of San Lorenzo Creek, is wide and well-developed in most low-tide aerial images of the site since the 1990s. Beach cusps occur where remnants of hybrid smooth cordgrass colonies, removed in the mid-2000s by California Coastal Conservancy's Invasive Spartina Program, form persistent topographic high points along the bayward edge of the beach. Small spits and swash bars (up to 0.4 m thick, with landward slipfaces and medium to coarse sand eroded from the San Lorenzo Creek delta) periodically form on the fluvial ebb tidal delta platform at the southern end of the beach at the creek (flood control channel) mouth.

The shoreline where Long Beach exists today was historically broad tidal flat that sheltered a large tidal slough draining San Lorenzo Creek and connecting to Robert's Landing, an important site for commerce and commercial transportation in the 19th and early 20th centuries (Grossinger and Brewster 2003; Figure 6a). The shoreline at the mouth of San Lorenzo Creek was built out over time through the diking of tidal habitats to create pastureland and support commercial and industrial activities at Robert's Landing (Figure 6b). In the early 1960s, the mouth of San Lorenzo Creek was rerouted for flood control slightly south of its original location as shown in the 1993 aerial (Figure 6c). The reduction of flows from the former channel alignment likely allowed beach material to deposit along the shoreline of the former creek mouth with fringing marsh forming behind the beach as a result, as observed in 1993 aerial imagery.

Remote sensing results: We collected ten images for Long Beach from 2002 to 2018. Most intervals ranged from one to two years, with the exception of a four-year interval from 2005 to 2009 (Figure 7). From 2002 to 2009, Long Beach appears to grow in length and width as beach material accumulates just north of the mouth of San Lorenzo Creek. After 2009, beach material appears to consolidate to form a line nearly parallel to the shore, with a marsh complex forming behind the southern half of the beach by 2018. It is unclear whether the beach is losing material and decreasing in volume or whether it is consolidating material and steepening over time.

The average size of Long Beach from 2002 to 2018 was approximately 19,600 m^2 (4.8 ac) (Figure 8). Long Beach reached its largest size in 2009 at 45,000 m^2 (11.1 ac) and decreased to its minimum size in 2013 at 7,100 m^2 (1.8 ac). Compared to all other time steps, Long Beach experienced the largest decrease in size between 2012 and 2013: approximately 21,100 m^2 (5.2 ac). Long Beach appears oscillated between periods of erosion and accretion throughout the entire time period.

Accuracy assessment: Using unsupervised classification, approximately 84% and 88% of pixels were accurately classified as beach cover in the 2002 and 2018 imagery respectively, when compared to known beach cover points in the corresponding RGB imagery. This yielded uncertainty values of 16% for the 2002 imagery and 12% for the 2018 imagery. Accuracy assessments were not performed for imagery corresponding to the remaining eight time steps. An average of the measured error of 14% was applied for the remaining time steps (as indicated by the dashed error bars in Figure 8). In comparison to other beach sites analyzed, the classification of Long Beach had the second lowest average accuracy score. Lower accuracies at Long Beach may have been due to an increased turbidity of surrounding water from wind-waves, as visible on the imagery, thus causing spectral confusion between beach and water pixels. Although these accuracies are slightly lower than at other sites, scores above 85% are generally acceptable (Thomlinson et al. 1999; Wulder et al. 2006; Jansen et al. 2008)

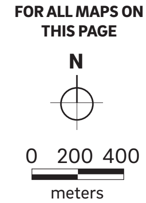
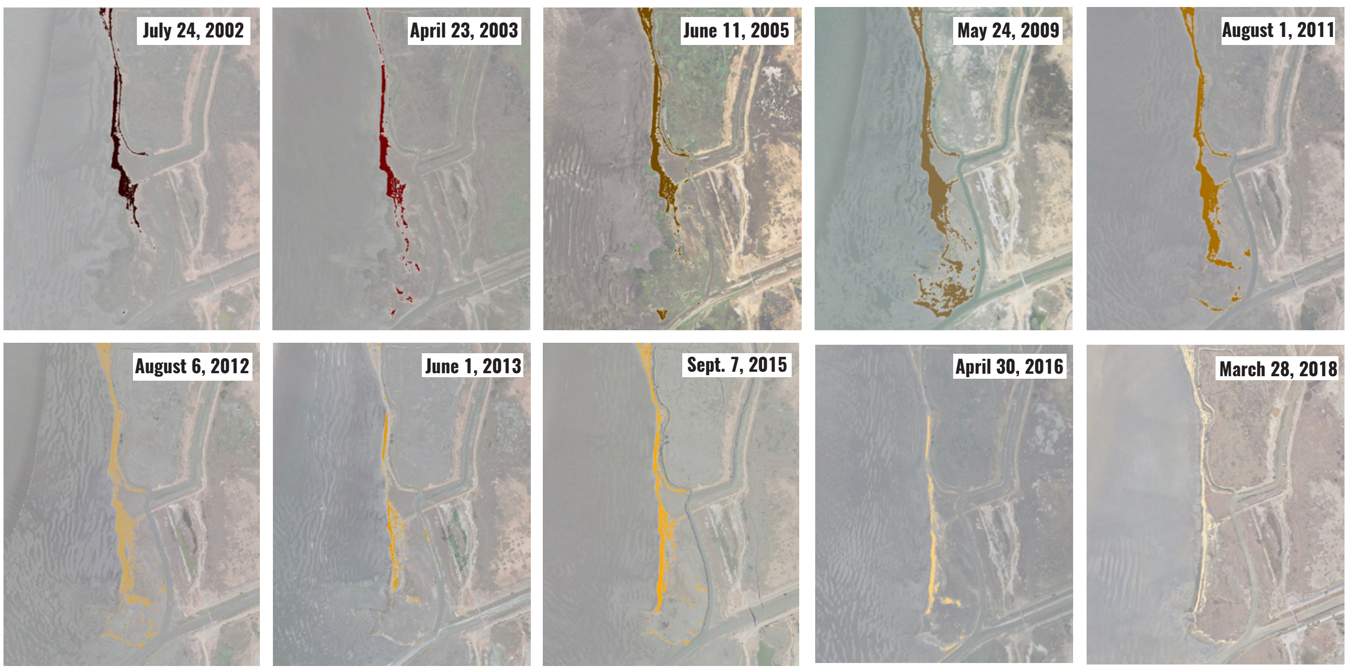


Figure 7. Long Beach fluctuates between periods of lengthening and shortening as observed over ten time steps from 2002 to 2018. Tidal marsh appears to form behind the beach over time.



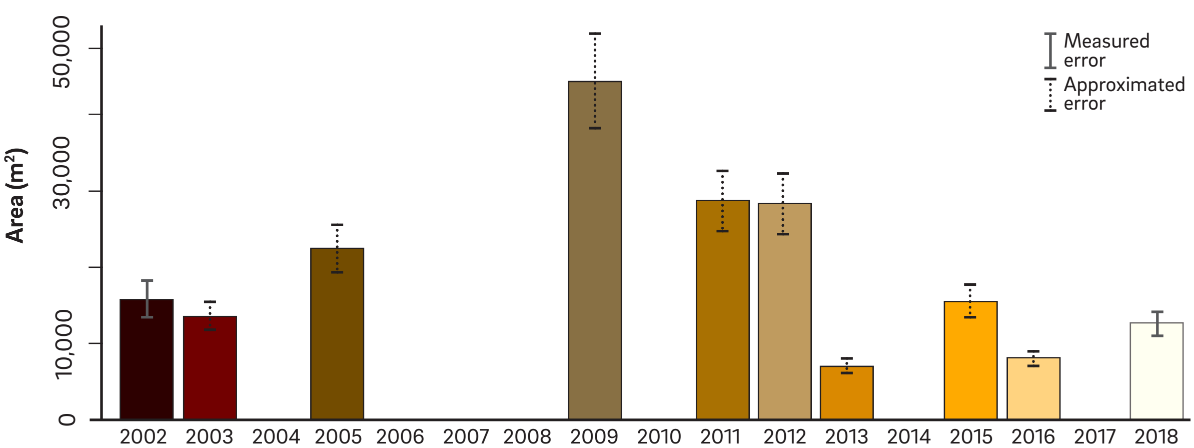


Figure 8. Change in beach area over time at Long Beach. Of the ten time steps analyzed, Long Beach reached its maximum size in 2009 and its minimum size four years later, in 2013. No data was obtained for 2004, 2006-2008, 2010, 2014, nor 2017. The error bars on the oldest and most recent time steps reflect the corresponding uncertainty values, 16% and 12% respectively, based on the results of the accuracy assessments (i.e. measured error). Accuracy assessments were not performed for the remaining eight time steps so an average of the measured error (14%) was applied, as indicated by dashed error bars.

Bayhead and pocket beaches

Bayhead and pocket beaches are formed by the deposition of sediment and other beach material between bayheads, coves, outcroppings or headlands (Lobeck 1939), and a wave approach perpendicular to the shore, also known as a swash-aligned orientation (Davidson-Arnott 2010).The headlands limit the extent of sediment exchange along the shoreline and reduce erosion due to waves and weather processes. The physical surroundings of bayhead and pocket beaches tend to make them very stable in size and orientation. If pocket beaches do move or change, they tend to oscillate within the embayment formed by the headlands rather than migrating along a shoreline. Because of this, bayhead and pocket beach material is not easily eroded and there is little lateral movement or transfer of material to the surrounding shorelines. The pocket beaches examined in this study include Highway 80 Frontage beach in Alameda County and Cobble Marsh beach in Point Pinole. For more information on bayhead and pocket beaches, see Chapter 3.

Figure 9. (Below, top to bottom) Historical t-sheets overlaid onto modern-day aerial imagery show the progression of developments along Berkeley's shoreline (denoted in the t-sheets in the thick black line below) (USCGS 1860; USCGS 1931; USCGS 1943).

(a) 1856

(b) 1931

(c) 1943

HIGHWAY 80 FRONTAGE BEACH

Site description: Highway 80 Frontage beach (Eastshore State Park) is located on a west-facing shoreline within an artificial deep tidal embayment between the Berkeley Marina and the Emeryville Marina. It lies between the south-facing Brickyard Cove beach (a deeply embayed pocket beach), and the small Point Emery artificial rocky fill peninsula, which also traps a small pocket beach. The rock-armored shoreline fill platform of the Ashby Avenue off-ramp (including the Bay Trail) acts as an artificial headland that locally obstructs longshore drift of beach sand. The shoreline where Highway 80 Frontage beach exists today was historically tidal flat habitat (Figure 9a). Between 1935 and 1937 the Works Progress Administration (WPA) built out the tidal flat shoreline to create Aquatic Park, one piece of the Berkeley Waterfront Project, and constructed tide gates to control the water level (USCGS 1943) (Figure 9b). The Bayshore Highway, constructed bayward of Aquatic Park, and Berkeley Marina were also constructed around this time period as part of the Berkeley Waterfront Project (Figure 9c), transforming the sediment dynamics along this stretch of shoreline.

The landward edge of Highway 80 Frontage beach is lined by a boulder revetment protecting the frontage road. The landward edge supports mats of iceplant that extend in some places to the beach. The fair-weather beach profile includes a variable flat berm top (maximum top width typically about 3-6 m, occasionally reaching nearly 15 m dry beach) that tapers nearly symmetrically at both ends to an intertidal beachface. During erosional post-storm phases, the intertidal beachface extends to the boulder revetment. The beach planform is nearly linear, or slightly arcuate bayward. Beach cusps are occasionally present in the berm and beachface. The beach sand is apparently derived from nearshore Merritt Sand deposits, possibly the same sources as the original historic Fleming Beach and other pre-reclamation 19th century sand beaches in the vicinity. The beach has a steep sand beachface above a narrow low tide terrace composed of muddy fine sand. The low tide terrace surface is rippled and supports eelgrass colonies.

Remote sensing results: We collected six images for Highway 80 Frontage beach from 2003 to 2018 with three or four years between each time steps (Figure 10). Based on the composite imagery, Highway 80 Frontage beach remains relatively stable across the

15-year period with no notable changes in beach location or position. The average size of Highway 80 Frontage beach across all time steps is 13,700 m^2 (3.4 ac). The beach reaches its largest area in 2003, though this is not necessarily notable as its area changes only slightly in every time step except 2003-2007 (Figure 11). Highway 80 Frontage beach decreases by about 5,700 m^2 (1.4 ac) by 2007, reaching an area of around 9,200 m^2 (2.3 ac), although it is not clear how the beach behaved between 2003 and 2007.

Accuracy assessment: Using unsupervised classification, approximately 78% and 82% of pixels were accurately classified as beach cover in the 2003 and 2018 imagery respectively when compared to known beach cover points in the corresponding RGB imagery. This yielded uncertainty values of 22% for the 2003 imagery and 18% for the 2018 imagery. Accuracy assessments were not performed for imagery corresponding to the remaining four time steps. An average of the measured error, 20%, was applied for the remaining time steps (as indicated by the dashed error bars in Figure 11). Highway 80 Frontage beach was the only beach that scored lower than the acceptable accuracy threshold (i.e. 85%; Thomlinson et al. 1999; Wulder et al. 2006; Jansen et al. 2008) for both time periods analyzed. This may result from the close spectral signatures of beach and mudflat. Since Highway 80 Frontage beach scored so low, a sensitivity analysis on the impact of pixel class selection during the unsupervised classification is included on pg. 108 to explain how this manual step may impact overall beach change results.

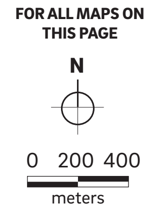


Figure 10. (Below) Highway 80 Frontage beach appears relatively unchanged across the the six time steps analyzed from 2003 to 2018.

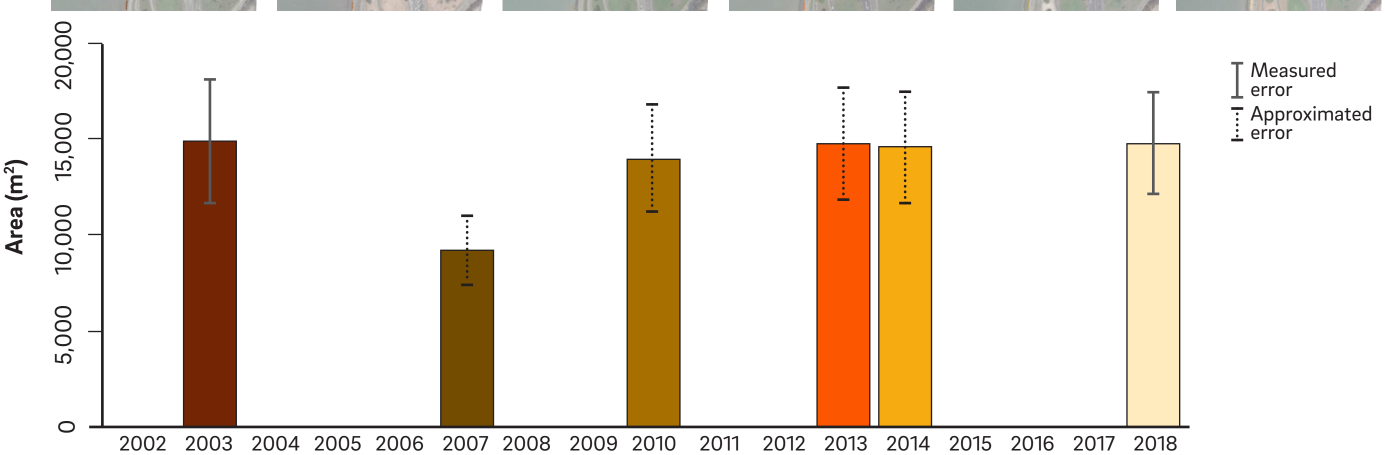


Figure 11. Change in beach area over time at Highway 80 Frontage beach. Across the six time steps analyzed, Highway 80 Frontage beach barely changed in size, hovering around 14,600 m^2 (3.6 ac), with the exception of 2007. No data was obtained for 2002, 2004-2006, 2008, 2009, 2011, 2012, 2015-2017. The error bars on the oldest and most recent time steps reflect the corresponding uncertainty values, 22% and 18% respectively, based on the results of the accuracy assessments (i.e. measured error). An approximated error of 20% was applied to the remaining time steps.

COBBLE MARSH BEACH

Site description: Cobble Marsh beach at Point Pinole Regional Shoreline is located between two large headlands: Point San Pablo and Point Pinole. These large headlands and smaller resistant promontories prevent the erosion of material along the stretch of shoreline where the beach is located. Cobble Marsh beach is characterized by a convex, recurved spit composed of conglomerate cobbles in eroding bluffs. There is a bluff toe and a cobble beachface, with a gravel berm formed by storm overwash and rollover in the backbarrier salt marsh.

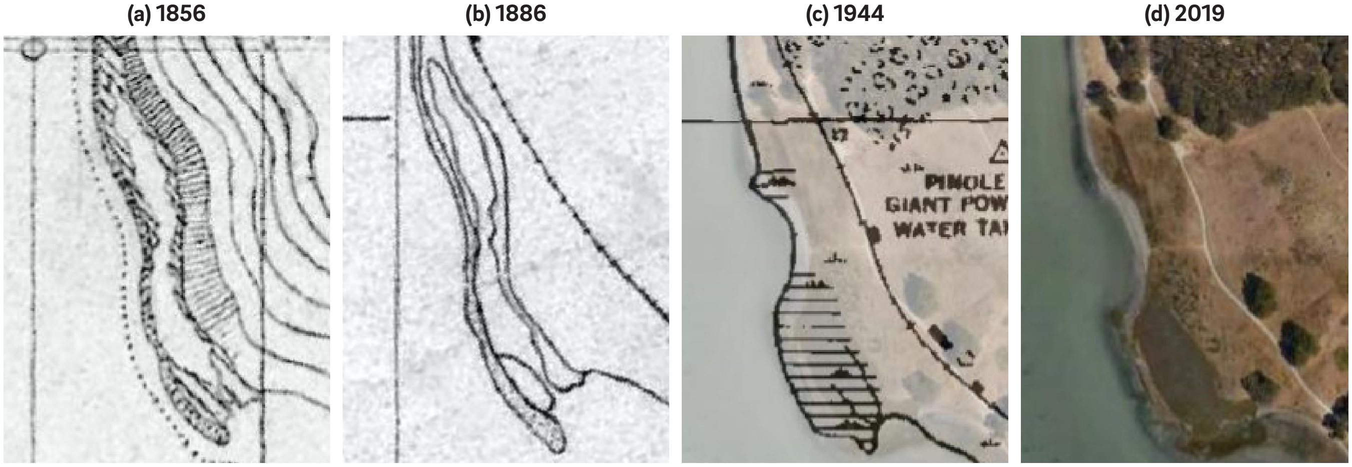
Unlike the other case studies analyzed, the stretch of shoreline at and around Cobble Beach has remained undeveloped since historical periods (ca. 1850); however, natural processes have reworked this stretch of shoreline over time, as evidenced by the historical t-sheets in Figure 12. Around the 1850s, this stretch of shoreline looked more like the spits or fringing beach type than a pocket beach (Figure 12a). There appears to have been a barrier beach in front of a narrow strip marsh and lagoon that remained intact in 1886, though the t-sheets are grainy (Bache 1856; Thorn and Rodgers 1886) (Figure 12b). Over time, the southern half of the barrier beach, marsh, and lagoon complex transitioned to more robust tidal marsh, with a smaller tidal marsh complex appearing at the northern edge of the present day Cobble Beach as shown underlaid the 1944 t-sheet below (USCGS 1949) (Figure 12c). The northern half of the complex appears to have retreated landward and formed the pocket beach seen today (Figure 12d). The small remnant marsh to the north of today's beach and the filled-in marsh to the south likely act as smaller resistant knobs that minimize the migration of beach materials off site. The erosion of the bluff at the back of the historical lagoon complex may have also contributed to the formation of the pocket beach, as bluff erosion would nourish the site with sediment while further carving out the "pocket" where the beach exists.

Remote sensing results: We collected five images for Cobble Marsh beach from 2005 to 2014. Most time intervals were 1-2 years, with a 5-year gap after 2008 (Figure 13). Cobble Marsh beach has not significantly changed in location, size, or shape. The composite imagery shows that the main part of the beach does not change significantly over time, though it expanded and retreated, or perhaps "wobbled," between 2007 and 2014.

Similarly to Highway 80 Frontage beach, Cobble Marsh beach is relatively stable with no significant changes in area, location, nor position. Of the time steps analyzed, Cobble Marsh beach is smallest in 2005 (4,300 m^2 or 1.0 ac) and largest in 2008 (7,500 m^2 or 1.9 ac) (Figure 14). The average size of Cobble Marsh beach across the time period is 5,900 m^2 (1.5 ac). The beach expands in area from 2005

Figure 12. (Below, left to right) Comparison of historical t-sheets to modern aerial imagery from Google Earth. Although the shoreline around the study area has remained undeveloped, a transition has occurred from a barrier beach-marsh-lagoon complex to a pocket beach updrift of a valley marsh complex (Bache 1856; Thorn and Rodgers 1886; USCGS 1949).

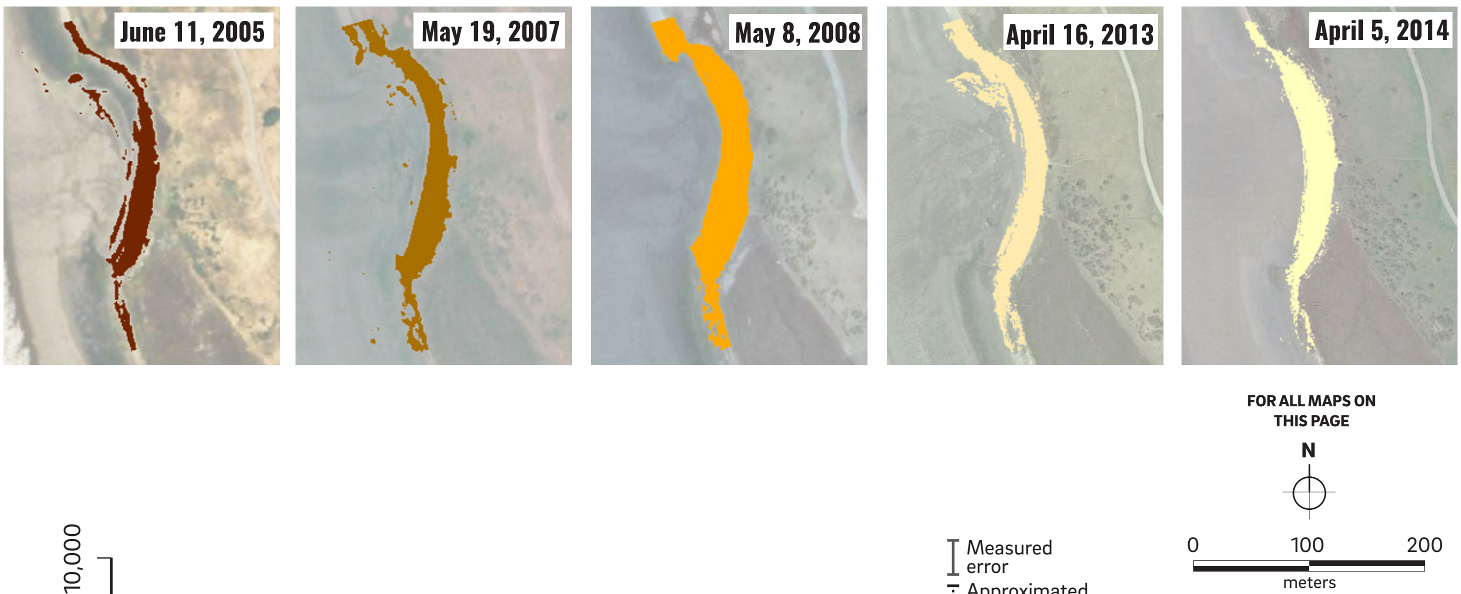
(a) 1856 **(b) 1886** **(c) 1944** **(d) 2019**



to 2008 and then shrinks between 2013 to 2014, but these changes are not very noticeable in the imagery.

Accuracy assessment: Using unsupervised classification, approximately 90% and 84% of pixels were accurately classified as beach cover in the 2005 and 2014 imagery respectively when compared to known beach cover points (i.e., visual interpretation of 50 beach cover points and 50 non-beach cover points) in the corresponding RGB imagery. This yielded uncertainty values of 10% for the 2005 imagery and 16% for the 2018 imagery. Accuracy assessments were not performed for imagery corresponding to the remaining three time steps due to time limitations. An average of the measured error of 13% was applied for the remaining time steps (as indicated by dashed error bars in Figure 14).

Figure 13. Cobble Marsh beach appears relatively unchanged across the five time steps analyzed from 2005 to 2014.



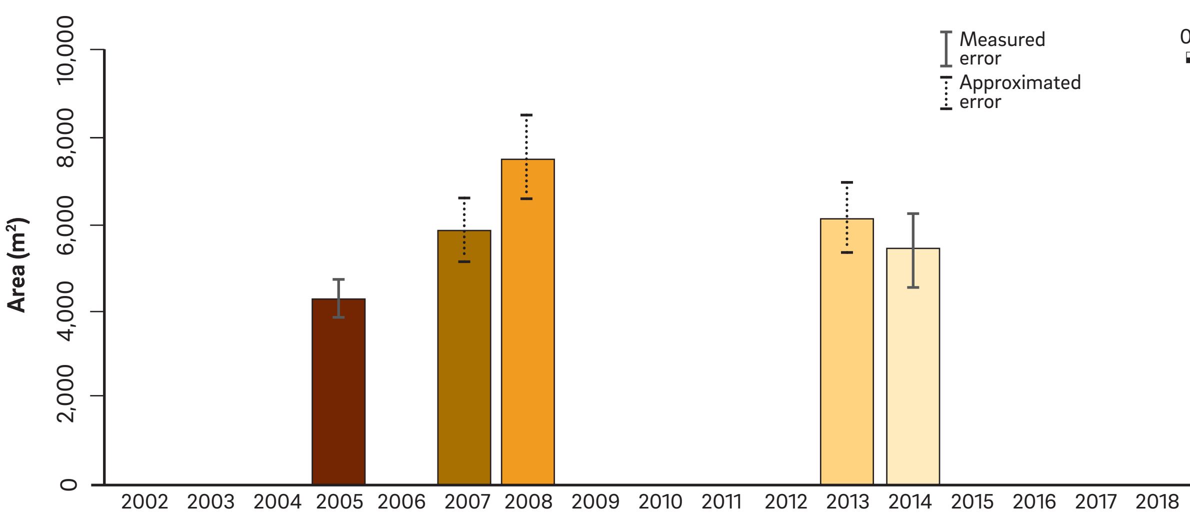


Figure 14. Change in beach area over time at Cobble Marsh beach. Of the five time steps analyzed, Cobble Marsh beach reached its minimum size in 2005 and its maximum size three years later in 2008. No data was obtained for 2002, 2003, 2004, 2006, 2009, 2010, 2011, 2012, 2015, 2016, 2017, and 2018. The error bars on the oldest and most recent time steps reflect the corresponding uncertainty values, 10% and 16% respectively, based on the results of the accuracy assessments (i.e. measured error). Accuracy assessments were not performed for imagery corresponding to the remaining four time steps so an average of the measured error (i.e. approximated error) of 13% was applied as indicated by dashed error bars.

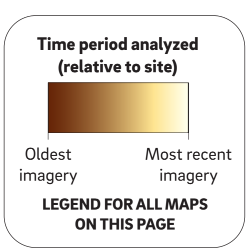
Comparison of change across beach sites

A side-by-side comparison of change in beach area over time and across the four sites highlights differences in the scale and geomorphic settings of the sites and the magnitude of planform change (Figure 15). However, data limitations constrain the degree to which interpretations can be made across sites, so more investigation is needed to validate the two beach types hypothesized in this report (i.e. bayhead/pocket beaches and spit/fringing beaches). Here, we discuss the calculated changes in beach size and shape. In the discussion section that follows, we analyze these results within the context of the two hypothesized beach types while underscoring the data gaps and limitations and providing ideas of ways to improve this analysis.

Long Beach had the largest observed change in beach area: approximately 37,000 m^2 (9.2 ac) across ten time steps between 2002 and 2018 (Figure 16a, b, and c). Of the time steps analyzed, Long Beach reached its maximum size in 2009 at approximately 45,000 m^2 (11.1 ac), and decreased to its minimum size, approximately 7,100 m^2 (1.8 ac), in 2013: an 84% loss in beach area in four years. Long Beach oscillated between gains and losses in beach area for the rest of the time period (3 time steps after 2013), but the magnitudes of those changes were much smaller (around 5,000-8,000 m^2 or 1.2-2.0 ac) compared to the changes observed between the years with the largest and smallest beach area (around 38,000 m^2 or 9.4 ac between 2009 and 2013). The composite image of beach area across all time steps analyzed (Figure 15) shows Long Beach experiencing a flattening of ridges and decreased edge sinuosity as the overall width decreases over time. The width of Long Beach appears to narrow between 2012-2018, and a marsh that was not present a decade or so before seems to have filled in behind Long Beach.

Foster City beach had the next largest magnitude of beach change, around 14,000 m^2 (3.5 ac) with about three years between its maximum and minimum size. Compared to Long Beach, Foster City beach exhibits a similar pattern of oscillation between periods of accretion and erosion as well as formation of spits and elongation of the overall beach over time. Additionally, sediment transport for both beaches appears to be disrupted by a creek channel or tidal slough, and both beaches coexist with tidal marsh complexes. The biggest differences between Foster City beach and Long Beach appear to be: (1) the overall magnitude of change for Foster City beach is smaller than Long Beach; and (2) there are distinct differences in the type of features

Figure 15. Composite images of change in beach area across all sites for each time step analyzed. Changes in the orientation and shape of beaches over time helps illuminate how beach behavior may differ with geomorphic setting, local wind-wave conditions, and other factors. The beaches with the most colors shown—Long Beach and Foster City beach—indicate more changes in orientation and distinct features compared to the beaches with very little color variation and thus change in orientation and features—Highway 80 Frontage beach and Cobble Marsh beach.



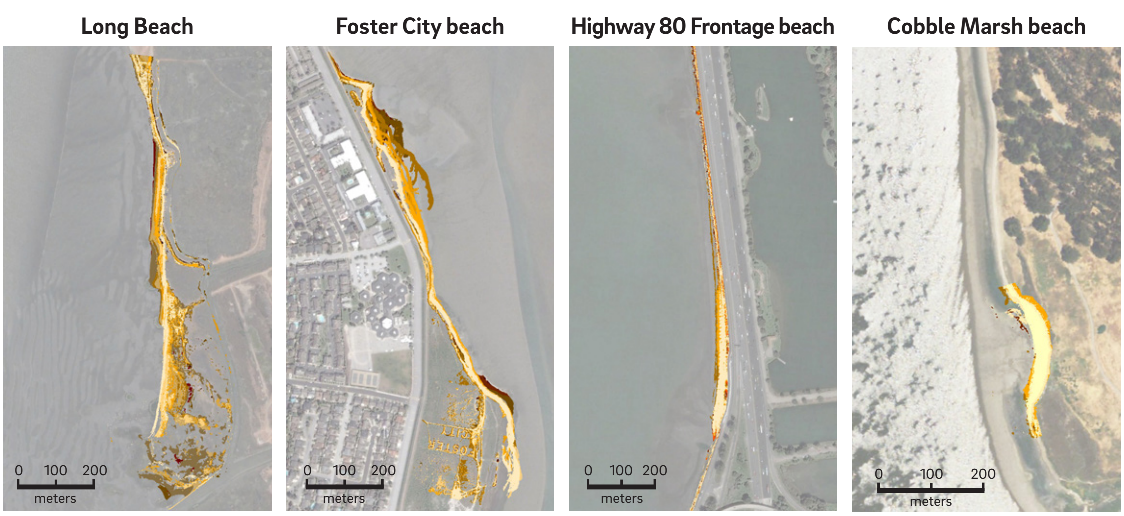
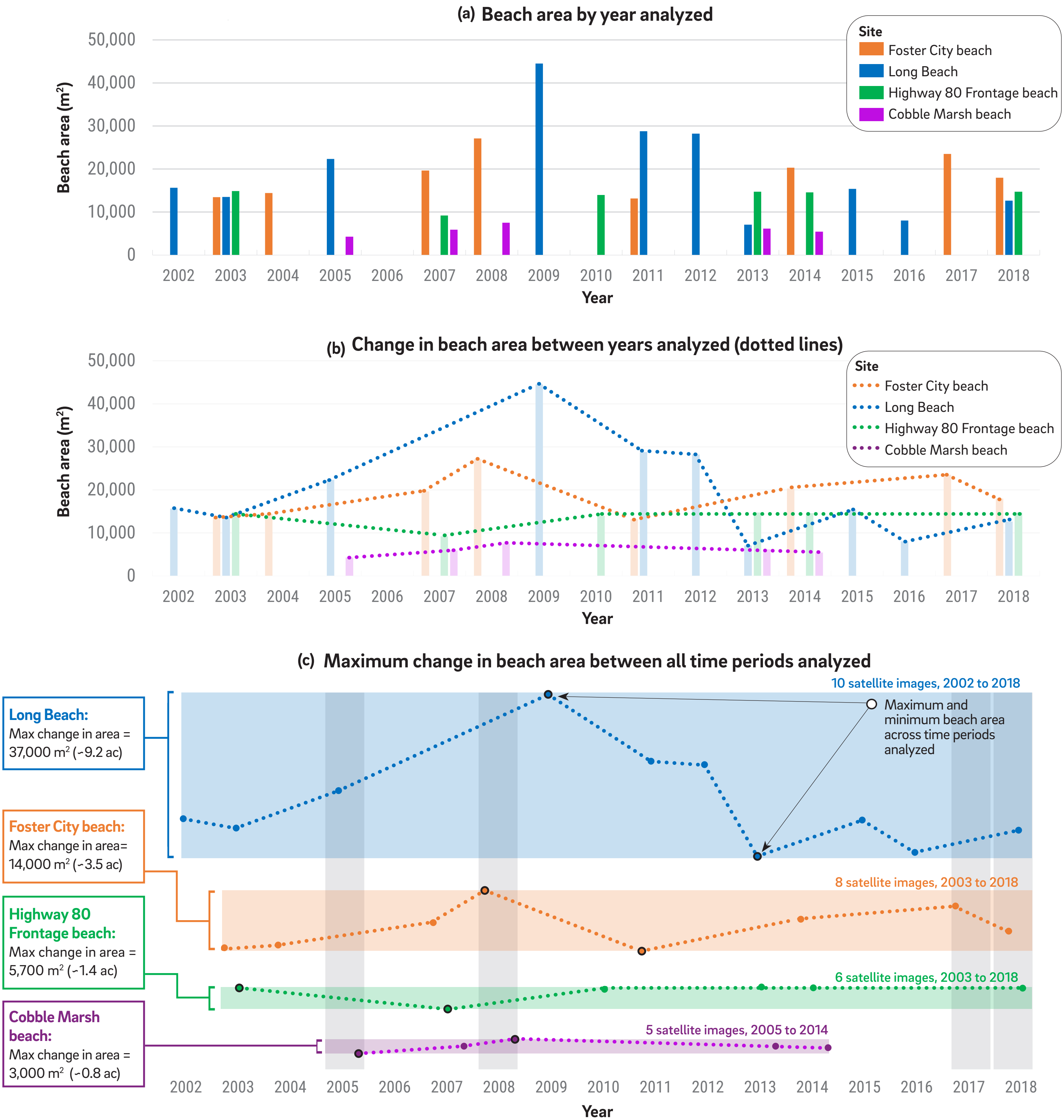


Figure 16. (a) Beach area by site as calculated using unsupervised classification of high-resolution satellite imagery captured at low tide. (b) Although time periods analyzed were not at regular intervals due to data limitations, the change in beach area over time (indicated by the dotted lines, colored by beach site) suggests there may be differences in the magnitude of beach change between bayhead/pocket beaches and spit/fringing beaches but more data at standardized time intervals is needed to support this hypothesis. (c) The magnitude of overall beach change varied between sites, with the largest change observed at Long Beach (~37,000 m^2 or ~9.2 ac across imagery that spanned 2002 to 2018) and the smallest change observed at Cobble Marsh (~3,000 m^2 or ~0.8 ac across imagery that spanned 2005 and 2014). Vertical gray bars denote years in which a major storm event occurred (see Table 3 for details on how major storm events were determined).



that dominate (i.e. flying and cuspate spits at Foster City beach compared to ebb delta tidal formations at Long Beach).

Highway 80 Frontage beach and Cobble Marsh beach experienced the least amount of change in beach area across time periods analyzed, around 5,700 m^2 (1.4 ac) and 3,000 m^2 (0.8 ac) respectively. While both beaches had a similar number of time steps (six time steps for Highway 80 Frontage beach and five time steps for Cobble Marsh beach), Highway 80 Frontage beach was analyzed across a 15-year period compared to a shorter 9-year period for Cobble Marsh beach. Of all the beaches analyzed, Cobble Marsh beach was the most data-limited. Highway 80 Frontage beach experienced nearly double the change in beach area that Cobble Marsh beach did, but it is notable how flat the rate of change is for both beaches compared to Long Beach and Foster City beach (Figure 16b and c). With the exception of one to two time steps, the beach areas generally stayed around 14,600 m^2 (3.6 ac) for Highway 80 Frontage beach and 5,800 m^2 (1.4 ac) for Cobble Marsh beach. Although the time between maximum and minimum areas is three to four years, nearly the same length of time observed at Long Beach and Foster City beach, the overall variation seems to be much lower for Highway 80 Frontage beach and Cobble Marsh beach. The planform of both Highway 80 Frontage beach and Cobble Marsh beach remained seemingly unchanged, unlike Foster City beach and Long Beach, which changed dramatically from year to year, shifting south along their shorelines.

DISCUSSION

Comparison of beach types

We hypothesized that over time, the two spit/fringing beaches, Foster City beach and Long Beach, would have the largest changes in area compared to the two bayhead/pocket beaches, Highway 80 Frontage beach and Cobble Marsh beach. The results described in the previous section generally support this hypothesis, but important limitations exist that necessitate additional analyses to confirm the differences between beach types.

Distinct changes in beach planform at nearly every time step analyzed for Foster City beach and Long Beach are apparent in the composite images (Figure 15). In comparison, the planforms of Highway 80 Frontage beach and Cobble Marsh beach were relatively unchanged across each time period analyzed. This aligns with the assumption that pocket beaches have a limited ability to transport sediment due to the presence of headlands. The magnitude and frequency of change in beach area relative to each type was also in line with our initial hypothesis, but more data is needed to statistically validate these observations. For example, while the same oscillation pattern between growth and shrinkage in beach area is apparent at Foster City beach and Long Beach, the magnitude of change is over 2.5 times larger at Long Beach than at Foster City beach. More data is needed to verify whether the short-term changes found here are representative, or if the magnitudes of change would increase over a longer timespan. Similarly, Highway 80 Frontage beach experienced two times the magnitude of beach change as Cobble Marsh beach, but the overall time period of study for Cobble Marsh beach was six years shorter than Highway 80 Frontage beach. Because the time steps are not analyzed at consistent intervals, it is difficult to know whether the differences observed between Highway 80 Frontage beach and Cobble Marsh beach would be accentuated or minimized with more data. However, the nearly unchanged planforms for both beaches suggest the differences between them would be minimized with more time steps and higher classification accuracy.

Looking at all four beaches, none of these variables alone can explain distinctions in beach behavior. Changes in planform, the time between major changes in area, and the overall magnitude of change all appear to be important to consider in combination to parse out similarities and differences between sites. Additionally, it is important to note that this assessment was limited in sample size, so a larger sample size (among other refinements) is needed to statistically verify the beach types hypothesized here.

Other comparison difficulties arise from the multi-year gaps between many time steps and the variability in time periods across sites. These inconsistencies lead to unknowns in how these beaches behave during the time steps and periods that could not be assessed. For example, Foster City beach gained about 7,500 m^2 (~1.9 ac) of beach area in roughly one year between 2007 and 2008. About three years later, in 2011, Foster City beach lost around 14,000 m^2 (3.5 ac) of beach. Beach area between 2008 and 2011 could have shifted gradually, or it could have changed drastically during one storm, but that is not captured here. Although aerial imagery could be used to flag major changes in planform observed between gaps in time steps, this may be less feasible in beaches with less planform variation, such as at Highway 80 Frontage beach and Cobble Marsh beach. For this reason, changes in beach area (i.e. a 2-dimensional assessment method) may not be the most effective metric for discerning beach types throughout the SF Estuary. Future studies should incorporate volumetric measures of beach change using field surveys, LiDAR or structure-from-motion data to further assess how beaches in the SF Estuary change over time, vary with setting, and whether their relative height and width is sufficient to provide specific ecological or physical functions such as attenuating waves or building high-tide refugia.

Comparison of the accuracy of unsupervised classifications across sites

Eight of the 29 unsupervised classifications performed were assessed for accuracy. Two assessments were made for each beach site based on the unsupervised classification results of the first and last time steps analyzed. The results ranged from 78% to 92% accuracy with an overall average of 86% (Table 2). Although the average is just above the 85% cutoff commonly cited in the literature as acceptable for unsupervised classifications (e.g., Jansen et al. 2008, Wulder et al. 2006, Thomlinson et al. 1999), four classifications scored below this threshold: Long Beach (one time step; 2002), Highway 80 Frontage beach (both time steps; 2003, 2018), and Cobble Marsh beach (one time step; 2014).

One reason half of the classifications sampled scored so poorly may stem from the difficulty in discerning between the cover type of interest (beach) from adjacent habitats (mudflat and water, the latter of which may be more of an issue during highly turbid conditions). This could cause problems at many points in the analysis: (1) while running the unsupervised classification algorithm, due to spectral similarities between pixel signatures; (2) during the visual interpretation of 'beach/not beach' that guides the lumping and splitting between groups of pixels during unsupervised classification; (3) during the manual classification of the accuracy assessment points, which is based on visual interpretations of RGB-imagery. For example, at Highway 80 Frontage beach it was particularly challenging to distinguish the bayward extent of beach from the surrounding mudflats. Two attempts were made to capture the full beach extent for each time step analyzed, and a comparison between attempts demonstrates the high sensitivity of the overall beach areas calculated to judgment calls made during the unsupervised classification. Across the six time steps, the overall beach area varied between 3% and 30% between unsupervised classification attempts, with the average change approximately 20%. Additionally the accuracy assessment scores on the oldest and most recent time steps analyzed changed by 13% and 5% respectively. In the discussion that follows, we offer ideas on incorporating field collection data (i.e. ground truthing points) to help refine unsupervised classifications or to use as training pixels to perform supervised classifications and ultimately achieve better overall accuracy in future analyses.

Table 2. The overall accuracy of the oldest and most recent imagery for each beach site ranged from approximately 78 to 92%. Highway 80 Frontage beach had the lowest averaged accuracies and Foster City beach had the highest averaged accuracies.

Beach site	Year of imagery	Overall accuracy (%)	Overall uncertainty (%)	Average accuracy (%)	Average uncertainty (%)
Foster City beach	2003	90	10	91	9
	2018	92	8		
Long Beach	2002	84	16	86	14
	2018	88	12		
Highway 80 Frontage beach	2003	78	22	80	20
	2018	82	18		
Cobble Marsh beach	2005	90	10	87	13
	2014	84	16		

Data gaps, uncertainties, and next steps

There are several data gaps and areas of uncertainty that are important to acknowledge when interpreting these results. Major gaps in time steps and periods analyzed are due to limited availability of cloud-free, high-resolution satellite imagery collected during low tide. Although the availability of data meeting this criteria has increased substantially since the early 2000s and the resolution of publicly available imagery continues to improve, data limitations persist. Low-tide imagery was the primary limiting factor driving the data gaps. In some instances, even when low-tide imagery was available, resolution issues, cloud interference, or lack of distinguishable georeferencing points precluded the imagery from being used. More readily available low-tide satellite imagery would increase the chance of sufficient cloud-free imagery with discernible georeferencing features, helping to increase the number of time steps analyzed. The points in time captured by the images for each site analyzed provide clues on directional changes and trends, but they also may be indicative of anomalous years in recent history. A larger sample size of beach sites analyzed at a more regular and standardized intervals would help capture more inter-annual variability and trends across beach types that can be statistically supported.

Another challenge with the unsupervised classification method was accurately capturing the beach from surrounding mudflats because it required manual selection of classes of pixels. The boundary between the low-tide terrace of a beach and adjacent mudflat is difficult to distinguish on aerial imagery. Similarly, the spectral signature of these substrates may be similar and thus could easily be confused and lead to inaccuracies. Collecting GPS points of the lowest extent of the beach during low tide and then comparing that boundary with the most recent time period analyzed could help assess how well the unsupervised classification captures the full extent of a beach. Additionally, collecting 100 or more GPS points of known beach cover in the field to use as a training set to conduct supervised classification could also improve separation of pixels that correspond to beach from pixels that correspond to mudflat, water, or other adjacent land cover types.

The remote sensing method used here simplifies the complexities of physical processes acting on a particular beach. These types of observations lack the three-dimensional elevation change that takes place seasonally and inter-annually along the beach profile (i.e. summer profiles vs. winter profiles, build up of the beach berm), as well as the change in substrate over time and space (i.e. erosion and distribution of different sized materials across the beach profile). Unmanned aerial vehicles (UAVs, or drones) can be helpful in collecting tidally-controlled high resolution aerial imagery, as well as elevation data using structure-from-motion technology. These efforts would ideally be cheaper than repeat transect surveys, but do not replace on-the-ground field interpretation of changes over time. Learning how to combine these different methods to accurately capture beach evolution is an area of ongoing interest that would help increase understanding of beach morphology in the SF Estuary.

Another challenge was integrating analysis of beach change with an understanding of wave conditions driven by major storm events. Ideally beach change detection would occur immediately before and after a storm event, but due to data limitations described previously, establishing how storm events impacted each beach was difficult to assess (Figure 17). There is also the added challenge of distilling the type of storm event that could have the largest impact on beach evolution and the possibility that the type of storm event associated with the most significant beach change could vary by site conditions and/or beach type.

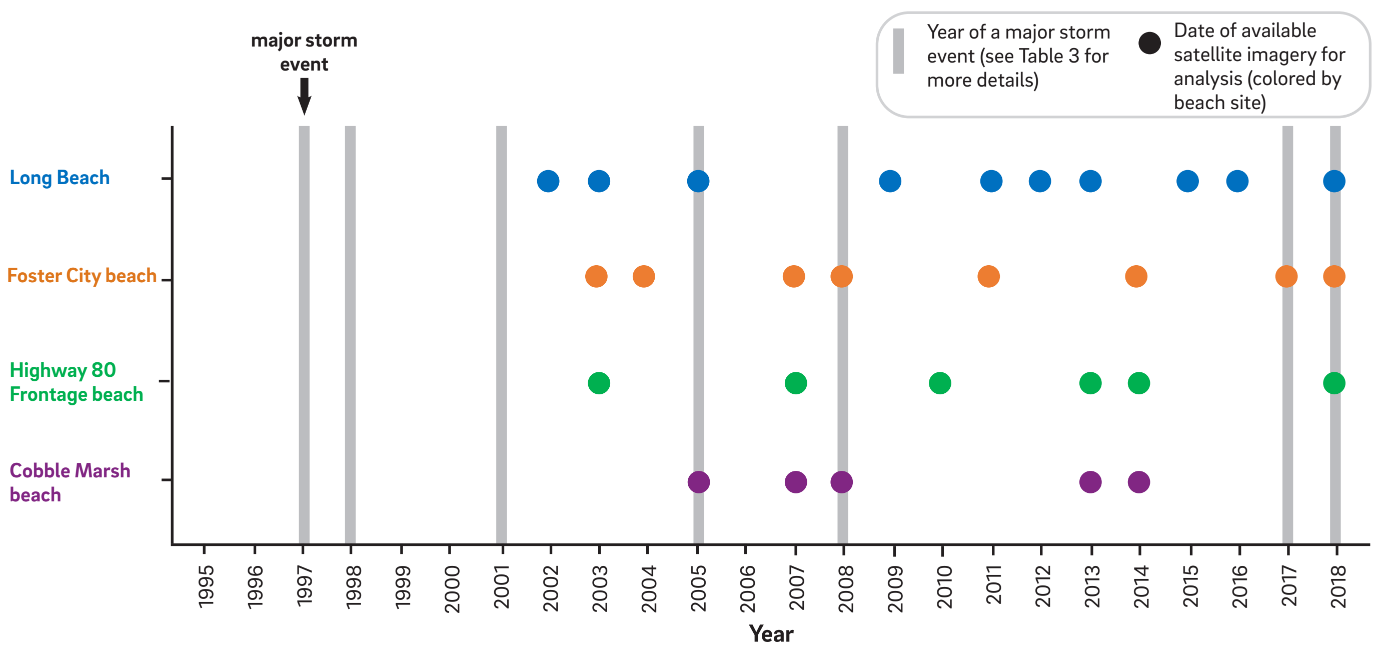


Figure 17. Time periods of beach imagery analyzed (colored dots) compared to the timing of major storm events (thick gray lines). The ideal time periods to analyze beach area are immediately before and after a major storm event; however, this was not possible for most beach sites due to data limitations as highlighted in the above graph. Major storm events include wet years (i.e. 1998, 2005 and 2017) and other types of events (e.g., coastal flood, heavy rain, high wind) as detailed in Table 3 (NOAA 2020).

Table 3. Storm event defintions as defined by the NOAA Storm Event database. Event types listed below were used as inputs to NOAA's Storm Events database to identify the years of major storm events in the Bay Area (NOAA 2020).

Storm event type	Definition (adapted from NOAA 2020)
Coastal flood	Flooding of coastal areas due to the vertical rise above normal water level caused by strong, persistent onshore wind, high astronomical ride, and/or low atmospheric pressure that results in damage, erosion, flooding, fatalities or injuries. Coastal areas are defined as portions of the coastal land zones adjacent to waters, bays and estuaries of the oceans.
Winter storm	A winter weather event that has more than one significant hazard: heavy snow and blowing snow, snow and ice, snow and sleet, sleet and ice, snow, sleet, ice.
Flood	Any high flow, overflow, or inundation by water of a normally dry area caused by an increased water level. This includes urban and small stem flooding that occurs in poorly drained or low lying areas, river flooding.
Flash flood	A rapid rise of water into a normally dry area beginning within minutes to multiple hours of the causative event (e.g. intense rainfall, dam failure, ice jam). Ongoing flooding can intensify to shorter flash floods when intense rainfall results in surges of rising flood waters.
Heavy rain	An unusually large amount of rain that does not cause a flash flood or flood event, but causes damage.
High wind	Sustained non-convective winds of 35 knots (40 mph) or greater lasting for one hour or longer, or gusts of 50 knots (58 mph) or greater for any duration.
Heavy snow	Snow accumulation meeting or exceeding locally or regionally defined 12 and/or 24 hour warning criteria. Accumulation depths range from 4-8 inches in 12 hours, and 6-10 inches in 24 hours.

A missing component in this report is an analysis of the sediment sources and grain sizes at each of the sample beaches. Understanding the mechanisms by which shell hash is replenished at the Foster City beach, for example, would be critical for honing design of a new longshore or fringing beach project. Similarly, understanding the interactions between the patterns observed in the aerial imagery and sediment supply could improve adaptive management protocols, especially in anticipation of shifting sediment dynamics with climate change. For example, at Long Beach, understanding how the ebb delta at the mouth of San Lorenzo Creek changed during this period would be important for linking sediment dynamics to beach changes. Additionally, localized information about the amount and type of sediment needed for beach construction, enhancement, or restoration would help improve beach design and resilience over time.

Additional considerations to improve change detection and assessment of estuarine beaches more broadly include:

- Expansion of beach types to include all naturally occurring types in the SF Estuary as observed on historical t-sheets in addition to novel types more recently created
- Analysis of beach change with respect to wind-wave height, direction, and energy, shoreline orientation, and geographic setting
- Consideration of site history and potential impacts on beach evolution
- Analysis of change in beach volume and profiles to better understand the evolution of beach

features (e.g., crests, berms, low-tide terrace) over time and how volumetric changes link to the types of ecosystem services and infrastructure protections possible within a particular setting or beach type. This could be assessed using field surveys, LiDAR, or structure-from-motion surveys using unmanned aerial vehicles (i.e. drones)

- A more robust assessment of the connection between the types of major storm events and morphological changes observed at various types of beaches in the SF Estuary
- Morphodynamic modeling of estuarine beaches specific to the SF Estuary to better understand how sea level rise and changes in sediment supply and precipitation patterns will impact beach evolution
- Investigation of how designed beaches may be useful in helping buffer shoreline erosion or providing high-tide refugia as the climate changes
- Further assessment on how to translate observations of beach behavior to beach management approaches and design standards

This effort increases our regional understanding of estuarine beach shorelines and offers an approach to monitor and compare beaches over time and across settings. The use of unsupervised classification of satellite imagery to assess changes in beach planform and area is a useful method to begin to categorize these estuarine beaches. Findings from this study indicate that beaches confined in bayheads or pockets may change less in area over a 15-year period, while beaches in unconfined drift-aligned settings tend to be more dynamic: shifting, expanding, and retreating.

The takeaways discussed in this report are a first step to eventually honing guidelines for appropriate conceptual design and implementation of beach projects specific to the SF Estuary as part of a multi-benefit, ecosystem-based approach for sea level rise adaptation. Future study of more estuarine beach types and how beaches integrate with marsh systems will help build a more comprehensive understanding of these dynamic baylands, especially with respect to the efficacy of marsh-beach shorelines in dampening the impacts of sea level rise while benefiting wildlife, plants, and people alike.

The next section of this report describes lessons learned from two beach construction projects: Aramburu Island in Richardson Bay and Pier 94 in San Francisco. With relatively few examples of beach construction projects in the SF Estuary and a regional desire to quickly implement adaptation and restoration projects, lessons learned provide critical paths forward to advance the field of practice.

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CHAPTER 5: LESSONS LEARNED FROM SF ESTUARY BEACH HABITAT PILOT PROJECTS

Bay beach pilot restoration projects in Central SF Bay urban wildlife habitats

The applied "lessons learned" about estuarine beach restoration from this report are based on comparisons between two shoreline enhancement pilot (demonstration) projects that reconstructed bay beach habitats, and analysis of natural and semi-natural reference beaches in San Francisco Bay (Chapter 3). The two pilot bay beach projects, Pier 94 San Francisco beach enhancement, and the Aramburu Island Shoreline Protection and Enhancement Project, were not beach nourishment or construction projects per se, but overall wetland and shoreline habitat enhancement projects primarily aimed at wildlife objectives. Each had supplemental beach construction components, either added later than the original project (Pier 94), or integrated in the original design (Aramburu Island). Both projects sites were subject to excessive shoreline erosion in locations where sensitive wildlife habitats were high priorities for conservation and management, incompatible with conventional engineered shoreline armoring (rip-rap). These pilot projects may be treated as ecological "restoration" in the broad sense of reconstructing modern functional equivalents of natural, historical estuarine beach habitats, including physical processes, vegetation, and landforms, but in artificial urban fill shoreline settings near historical shoreline locations that are long gone.

Previously, beach nourishment projects in San Francisco Bay were coastal engineering designs for artificial beach creation, with primary objectives for erosion and flooding protection of developed urban shorelines, and to provide large recreational beach parks with wide, high dry beach areas. Crown Beach, Alameda (East Bay Regional Parks) was a hydraulic dredge beach nourishment project with a scale (2.5 miles) and oversize backshore beach fill design. Oversized beach designs are those constructed larger than natural equilibrium beach berm size for the local wave climate and grain size, allowing for erosional loss and long project life; Nordstrom 2000, Dean 2002). The oversize beach design of Crown Beach was comparable with beach nourishment projects of the outer coast in Southern California (California Department of Boating and Waterways 2002), rather than restoration of natural estuarine beach form and size range for San Francisco Bay. In contrast, Pier 94 and Aramburu Island pilot beach projects were expressly aimed instead at reconstructing ("restoring", broad-sense) naturalistic equivalents of regional San Francisco Bay estuarine beach types to provide a balance of some erosion control/shoreline stabilization functions, and restored shoreline habitat for native wildlife and plants, compatible with wildlife sanctuary and public park land uses (recreational access with wildlife viewing). These integrated objectives followed from the Goals Project (1999), and anticipated the integrated urban estuarine sea level rise adaptation approach of SFEI/SPUR's Adaptation Atlas (Beagle et al. 2015).

PIER 94 PORT OF SAN FRANCISCO BAY BEACH PILOT PROJECT BACKGROUND

Pier 94 beach construction was performed in January 2006 as a minor permit modification to remediate and enhance a small eroding shoreline tidal wetland enhancement project within industrial urban Port of San Francisco lands next to a sand refining facility. The project implementation immediately followed a major coastal storm erosion event that severely impacted the Pier 94 shoreline. Pier 94 beach nourishment was an unprecedented, limited opportunity project that had no budget for stand-alone monitoring or research.

Pier 94 shoreline sand and gravel placement was designed to establish a small outer shore gravelly barrier beach to increase erosion protection of salt marsh vegetation, and to establish an inner sand shore beach and transition zone for native vegetation, including the first pilot test planting of a founder population of California sea-blite (*Suaeda californica*) in San Francisco Bay (Chapter 3). The rudimentary design of the sand and gravel beach enhancement was to place an approximate 2 ft thickness of bay sand refinery "screenings" (non-commercial sand, shell, gravel waste from sand refining for concrete mixes) above Mean High Water along the wave-eroded outer (bay) and inner (landward edge) shorelines of Pier 94 tidal wetlands. Less than 2000 cubic yards of Bay sand and gravel was placed using small ground-based equipment (bobcat) transporting beach sediment from the adjacent industrial Port sand refining site. The sand and gravel were left to be reworked by storm waves and high tides in fall and winter, to form naturalistic beaches over the artificial fill platform of the site, composed of old concrete rubble, rock, and other non-soil fills.

Pier 94 beaches were constructed at two distinct shoreline positions, with two sediment types. The exposed, outer shoreline of the north basin was a rocky (concrete debris) upper intertidal fill platform with a steep nearshore slope to subtidal bay, with no wave attenuation over a low tide terrace. The beach fill on the northern outer shoreline was a (1-) 2 ft thick deposit of coarse gravel and sand from the sand refinery on site, placed along the upper intertidal crest of the outer fill platform, which was perched over deep (subtidal) bay, with no low tide terrace below the rocky shoreface. The steep shoreline platform exposed the wave-scoured, rocky fill shore to long fetch and deep water, with potential high wind-wave energy from the east and southeast (storm wave approach). The remainder of the constructed beaches were medium-coarse sand fringes along the landward, sheltered interior shoreline, bordering restored tidal salt marsh, flats and pools (pans) with relatively sparse vegetation. The southwest corner of the southern basin formed a closed cove head or pocket beach above fringing salt marsh dominated by pickleweed, saltgrass, and alkali-heath.

Figure 1. Pier 94 San Francisco. Modified from Port of San Francisco Pier 94 wetland enhancement monitoring report (2010)

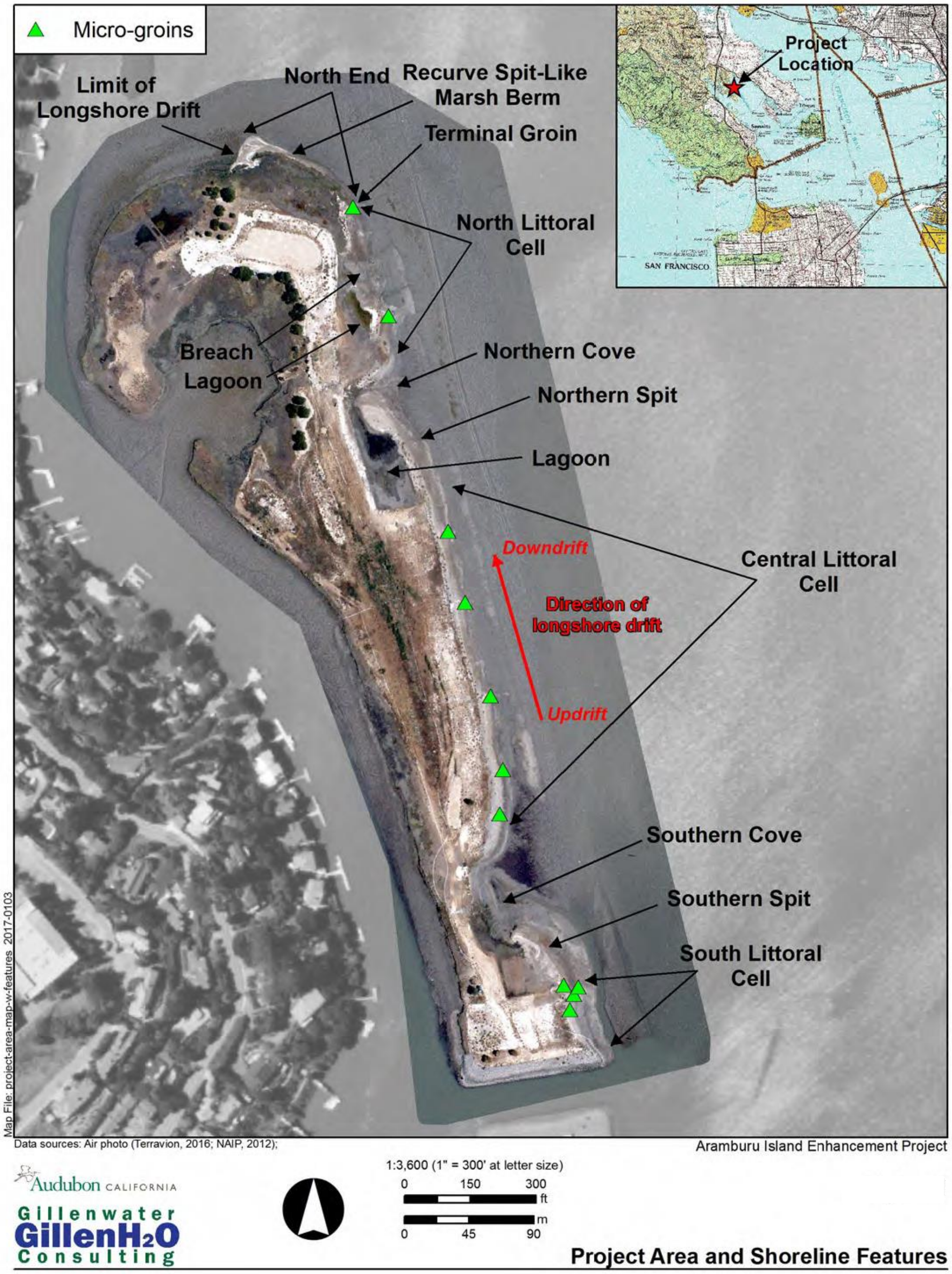

Figure 2. Aramburu Island and vicinity, Richardson Bay. (from Gillenwater and Baye 2016)

ARAMBURU ISLAND SHORELINE HABITAT ENHANCEMENT PROJECT BACKGROUND

Aramburu Island beach construction was a planned major component of an overall stand-alone habitat enhancement plan for a strongly erosional 17-acre derelict artificial fill island in Richardson Bay, located within Marin County Park lands and the Richardson Bay Audubon Sanctuary (Wetlands and Water Resources 2010). Aramburu Island beach construction was described in the final 5- year monitoring report (Gillenwater and Baye 2016), and summarized here. The rocky fill of the island formed a retreating, unstable, eroded wave-cut scarp and bench on the southeast facing shore, exposed to long-fetch wave action from San Francisco Bay. The island's bay shoreline was oriented nearly at right angles to the crests of prevailing waves from the south in Richardson Bay. Strongly oblique wave approach at the shore maximized potential for longshore drift of beach sediment, which was indicated by small gravel sand spits supplied by erosion of the island. The low intertidal island platform was a lag surface of remnant rock fragments (angular cobbles and boulders) in the old eroded fill. The wave climate was estimated from fetch (open-water distances in relation to wind speed and direction), and the observed patterns and sizes of beach-sized sediments transported in the existing eroded shoreline. No baseline local wave data were available, and none were collected to calibrate local wind-wave energy during the storm and non-storm seasons.

In 2011, the eroded vertical island scarp was graded to a gently sloping ramp on which beach sediments were placed between mean sea level (mudflat edge) up to high tide line. Two coves and a navigation channel formed wave-exposed, erosion-prone headlands (compacted earthen fill) in the shoreline. These were treated with mechanically graded layers of river cobbles, about 1-3 cobbles thick. The central and north shorelines were covered with a thick (approximately 2 ft) layer of mixed medium-coarse sand, gravel, and oyster shell hash. Log and small boulder groins were installed at intervals along the shoreline to locally impede longshore drift of beach sand, shell, and gravel in the upper foreshore and berm. The mixed-sediment type beach designs were based on topographic surveys, wave and wind climate, and sediment analysis of San Francisco Bay reference beaches (Foster City shell beaches, Brisbane gravel beach, Pier 94 San Francisco sand and gravel beach, adjacent Richardson Bay Audubon Sanctuary sand beaches, and Radio Beach (sand) at the Oakland Bay Bridge toll plaza; Wetlands and Water Resources 2010, Leventhal 2010), representing each dominant beach sediment type present in San Francisco Bay.

Both Pier 94 and Aramburu pilot project shorelines were exposed to multiple major episodes of high winter tides and storm wave action following sediment placement. Series of winter storms with high wave action and high tides caused abrupt, punctuated changes in beach erosion, onshore beach migration, and longshore drift. Although extreme storms were clearly a dominant influence on persistent beach changes, no monitoring or real-time storm event observations or data were collected for either project. Storm wave events are generally major persistent influences on estuarine beach morphology (Jackson et al. 2002). Post-storm site visits were made opportunistically each year, particularly in early post-storm beach profile recovery stages, and in fair-weather conditions with more advanced post-storm recovery of beach profiles. Annual summer beach surveys for project performance and permit compliance were performed at Aramburu Island beach transects for five years. Annual summer surveys, however, did not capture important intra-annual, seasonal or storm/post-storm recovery dynamics of Aramburu beaches. No long-term or interdisciplinary physical-ecological monitoring for either project has been available to guide the planning and development of the next generation of post-pilot bay beach projects in San Francisco Bay.

To date, there has been no retrospective assessment of the evolution of Pier 94's crudely nourished bay beaches. The final five-year monitoring plan for Aramburu Island beaches (Gillenwater and Baye 2016), and prior annual monitoring reports, did include a brief overview of long-term beach evolution (patterns and processes), and wildlife relationships, along with brief recommendations for the future management of the project. The focus of this retrospective assessment of both projects is to re-consider selected aspects of the long-term development, of both projects in context with one another and new analysis of reference beach systems. The emphasis of this review is on findings that are most relevant to planning and design of the next generation of restored estuarine beaches in the region.

OVERVIEW OF PILOT PROJECT BEACH EVOLUTION

Large-scale, long-term patterns of beach evolution at Pier 94 and Aramburu Island are summarized below to provide context for aspects of patterns and processes discussed in detail, and to highlight aspects of development similar between them. Following coarse sand and gravel placement, Pier 94 outer barrier beaches were rapidly and completely reworked by winter high tides and strong wave action, forming natural beach ridge morphology within two months. High wave energy events consolidated berms to a single linear barrier beach that migrated landward into the lagoon behind it, with a distinct slipface (steep angle of repose) along the lagoon edge. Landward transgression of the barrier occurred in pulses driven by strong storm wave and high tide events.

The outer Pier 94 barrier beach developed spit recurves indicating progradation and drift towards the northeast shore of the site (Mission Creek basin). The north shore developed a series of discontinuous berms with tidal and washover passes between them, partially colonized by high salt marsh vegetation. The seaward beachface retreated over the rocky fill platform, and the berms migrated progressively landward over the salt marsh and flats. In contrast, the interior fringing beaches, sheltered from breaking bay waves (exposed only to re-formed wind-waves attenuated across the interior flats and marsh), developed narrow beachfaces encroached by salt marsh vegetation from below, and beach and upland (mostly weedy) vegetation from above the high tide line. The interior fringing beach high tide lines gradually retreated landward and narrowed progressively over years, as more sand from the beachface became trapped in accreting salt marsh vegetation below. The interior fringing beaches became mostly vegetated, stabilized high salt marsh ecotones, in extremely low wave energy environments.


Figure 3. Severe storm wave erosion of the interior north shore of Pier 94 occurred during the New Years 2006 storms (immediately prior to beach nourishment) in the absence significant wave-sheltering by outer barrier beaches. January 6, 2006.

Figure 4. Pre-project shoreline conditions at the south shore of Pier 94 (left, January 5 2006), and post-grading beach sediment nourishment (right; January 26 2006), adding to pre-existing sand and gravel derived from local erosion, and occasional runoff from the adjacent sand import offloading facility.

Figure 5. Pier 94 north shore sand and gravel barrier beach evolution. The outer northeast-facing linear gravel barrier beach (2008) migrated landward into the lagoon and became a diffuse, discontinuous gravel beach veneer by 2017. Sand and gravel drifted west as the outer barrier declined, and consolidated an enlarged western barrier beach that welded with the backshore by 2017.

Figure 6. Rapid wave-reworking of coarse beach sediments occurred along the outer northern shore of Pier 94 during the first winter after beach sediment nourishment. Multiple recurved spits at open breaches and inlets (arrow), and relict recurves where tidal passes were aggraded and closed, indicate rapid longshore drift, predominantly to the northwest. February and March 2006.

Figure 7. Landward transgression of outer gravel-dominated barrier beaches across sheltered salt marsh and pool habitats occurred extensively at the north end of Pier 94 within 5 years after beach nourishment. The main barrier beach flattened during periods of rapid transgression and significant storm wave activity, but the landform persisted as a marsh-sheltering feature that impounded salt marsh pools used by wading birds, dabbling ducks, and shorebirds. March 2012.

Figure 8. Landward transgression of outer gravel-dominated barrier beaches into shallow lagoons of Pier 94 (north shore) continued through 2018, as decomposed concrete gravel contributed to beach sediment supply. Impoundment of perched upper intertidal lagoons continued despite coarsening and flattening of the east-facing segment of the barrier, and continued drift of gravel and coarse sand towards the northwest shore. April 2018.

Figure 9. Late stage development of barrier beaches facing Mission Creek basin at the north end of the north shore of Pier 94 in April 2018. Formerly discontinuous sand and gravel berms enlarged and consolidated due to longshore drift from the degenerating outer barriers. The distal (west, downdrift) end of the barrier welded to the mainland at this stage, as it also migrated shoreward.

ASSESSMENT OF PILOT PROJECT ESTUARINE BEACH EVOLUTION, PATTERNS, AND PROCESSES:

Lessons learned about constructed bay beach geomorphic features and processes

SWASH-ALIGNED AND DRIFT-ALIGNED LOCAL BEACH PLAN FORM AND SHORELINE CONFIGURATION

The local shoreline configuration of natural or constructed pilot project beaches had a fundamental influence on their dynamics, especially in relation to longshore transport processes, as they generally have on estuarine beach erosion and accretion processes (Jackson and Nordstrom 1992, Phillips 1986; see Chapter 3, this report).

Within the constructed Pier 94 beach complex, the sheltered interior south shore effectively formed a pocket beach within the salt marsh. This "dead end" for longshore transport remained relatively stable in plan form from 2006 to 2018, even as it became encroached by salt marsh at the toe of the beachface. In contrast, the outer barrier beaches of Pier 94 north shore, and all of the outer Aramburu Island beaches, are drift-aligned in orientation (Chapter 3, this report): they are exposed to strongly oblique or highly variable wave approach most of the time, and lack significant headland or other sheltering. In contrast, all of the drift-aligned beaches in this study exhibited relatively large changes in shoreline position and configuration relative to their initial dimensions.

Only local, internal impediments to longshore drift, such as constructed "micro-groins" caused local trapping of drifting beach sediment, and allow small-scale stable reorientation of internal "pocket" beach wedges to face prevailing wave approach (Figure 10). "Micro-groin" was the project term for log and boulder "outcrops" in the Central cell Aramburu shoreline that extended only across the anticipated width of the beachface, but did not extend beyond to the low tide terrace. The backshore crest of the micro-groins were about a foot above maximum expected wave runup elevation. Micro-groins trapped small gravel and shell pocket beach segments that faced southeast, deviating from the main beach orientation parallel with the island shoreline (Fig 5.10). Relatively slow swash-driven transport of gravel also restricted the rate of net longshore drift in the gravel storm berm at the landward end of the beach profile. The outer Pier 94 beach ridges and spits have been highly dynamic (unstable in size, configuration, and location) since they began to evolve after coarse sediment placement in 2006.

Figure 10. Short groins ("micro-groins", or drift-sills of embedded, pinned logs and boulders) along the Central littoral cell of Aramburu Island trap updrift accretion wedges of coarse sediment that prograde seaward, a characteristic of drift-aligned beaches (A-C). Downdrift sides of groins either remain stable or exhibit erosion where drift of beach sediment is obstructed locally. When gravel beach profiles retreated landward over time, beach accretion wedges on the updrift side of groins reorient to face dominant wave approach (D), in contrast with the strongly oblique orientation of the main beach axis relative to wave approach.

Where natural or artificial headlands can restrict longshore drift of mobile, unstable bay beaches, they can evolve from dynamic drift-aligned to relatively more stable swash-aligned orientations. At Aramburu Island, the Central cell cove (intertidal lagoon/salt marsh flats) evolved and reoriented from a drift-aligned, east-facing migrating (prograding alongshore) sand spit within a tidal inlet following beach nourishment in 2012, to a southeast-facing pocket beach after the cove (aggraded ebb tidal delta) filled with drifted sand by 2018 (Figure 11).

Figure 11. Aramburu Island, central shore cove, evolution from drift-aligned spit towards swash-aligned pocket beach. (a) Newly nourished sand spit at south end of cove in 2012, oriented southeast-northwest (dashed yellow line). Cobble beach headland faces southwest at the north end of the cove. (b) Sand spit progradation in 2018 (following strong net sand drift 2012-2018) fills in the cove, and a new sand beach reoriented southwest-northeast (dashed yellow line) forms in the pocket along the former cobble beach headland, facing prevailing wave approach from the southeast, refracted within the cove. Images: Google Earth.

Both Pier 94 and Aramburu project sites were predominantly drift-aligned beach settings, with small internal shoreline segments that had potential for swash-aligned, stable pocket beaches. The higher potential stability of swash-aligned, embayed bay beaches is a primarily consequence of the shoreline framework, location and coastal setting, more than an internal engineering design feature. Bay beach design to maximize relatively stable swash-aligned shoreline orientation can be achieved by site selection and beach fit within the local shoreline setting (within or between sheltering shoreline features like small headlands). Alternatively, limited internal small-scale swash-aligned beach features can be engineered by breaking up open drift-aligned beaches to a series of smaller swash-aligned littoral cells, or nested small pocket beaches. This can be achieved by closely spaced "micro-groins" or equivalent drift-sills that impede unrestricted longshore drift of beach sediment, but do not prevent bypassing altogether. (Figure 12). The spacing of micro-groins is related to beach width and variability in wave approach.

Figure 12. Short backshore groins ("micro-groins" or drift-sills; yellow circles), constructed from decay-resistant logs and boulders, provide persistent local obstructions to longshore drift of beach gravels, causing subtle beach protuberances and updrift beach accumulation wedges at intervals along the shoreline. Relatively stable storm gravel beach ridge positions between micro-groins are ecologically indicated by patchy growth of perennial high salt marsh vegetation along their crests.

In the absence of artificial or natural swash-aligned beach controls, long-term maintenance of drift-aligned beaches must presume either maintenance re-nourishment at intervals, construction of sacrificial updrift "feeder beaches" (drift-exposed beach nourishment sites; Johannessen et al. 2014) or erodible unconsolidated headlands with beach grain size range sediments, to balance long-term beach sediment budgets for drift-aligned beaches. Cyclic small-scale feeder beach nourishment is a phased project approach that is compatible with adaptive management and impact minimization, as an alternative to "full build" beach nourishment projects with oversize beach designs allowing for erosion. The relative costs of phased nourishment (adaptive management) versus single-construction beach projects is likely to depend on site-specific opportunities and constraints, long-term funding, and environmental sensitivity (see design and constructability discussion, below).

WAVE REWORKING AND SORTING OF IMPORTED BEACH SEDIMENT AFTER PLACEMENT

Beach nourishment projects in both open ocean coasts and estuaries sometimes construct design berms with oversized dimensions to maximize project life and erosion protection (Nordstrom 2000, Jackson et al. 2010). Environmental impacts of oversize design beaches are avoided if placed beach sediment is rapidly and completely reworked by wave action that erodes and re-deposits it in the form of natural berms or beachfaces. Timing of bay beach sediment placement prior to or during the high winter solstice tides and storm wave season resulted in very rapid reworking of all "profile nourishment" sediments (placement of mobile beach sand, shell hash, and gravel across the entire constructed intertidal and wave runup profile) at all outer beach locations at Pier 94 (Fig. 13) and Aramburu Island (Fig 5.14). Only interior, marsh-sheltered sand beach nourishment locations at western Pier 94 shorelines retained original graded sand and gravel placed above normal tide and wave runup elevations. The relatively wave-sheltered, stable interior Pier 94 shoreline beach sand fills were not rapidly reworked by waves, and so were rapidly converted to vegetated beach and high salt marsh habitats (Chapter 3, this report).

At Aramburu Island, artificially graded beach topography and vehicle tracks were largely eliminated by wave reworking within 2 months of late summer 2011 construction, and complete wave-reworking and redeposition of natural beach ridge landforms occurred by winter solstice tides in December 2011. Natural beach dimensions, morphology and shoreline patterns evolved rapidly and completely because of seasonal timing of placement prior to high tides and waves, and by filling beach sediment volumes approximating, but not significantly exceeding, predicted equilibrium beach profile geometry.

Figure 13. Rapid wave reworking of poorly sorted sand, gravel, and shell sediment (dredged bay sand, non-commercial screenings from sand refining) at Pier 94 north shore, Port of San Francisco. (A) Pre-project shore platform composed of decomposing concrete rubble and debris (lag armor), with patchy high salt marsh vegetation, January 6, 2006. (B) Nourished beach sediment placed by small ground-based equipment (bobcat), January 23, 2006. (C) Multiple natural gravel and sand beach ridge landforms deposited after winter storm wave reworking of placed sediment; minor residual of vehicle tracks. February 6, 2006. (D) Complete reworking of coarse beach sediment to single gravel storm berm by November 16, 2006.

Figure 14. Rapid complete wave-reworking of coarse beach sediment placed at Aramburu Island, central shoreline. (A-B) Engineered placement of all beach sediment (cobble, gravel, sand and shell hash) across the upper intertidal profile, August 2011. (C) High tides and waves overtopped new beach fills, concentrating lighter oyster shell hash in newly wave-deposited beachfaces and berm tops with natural morphology. Most original graded surfaces and fills are eliminated within 2 months; minor vehicle tracks persist. October 4, 2011. (D) Micro-groins rapidly develop updrift/downdrift asymmetry due to updrift accretion of gravel and shell hash, eliminating original beach fill grading and vehicle track patterns. December 22, 2011.

IMMOBILE COBBLE LAG BEACHFACE AND COBBLE BERMS

The most erosion-resistant beach feature at Aramburu Island in the long term was the relatively immobile cobble beachface and shore platform. The cobble "beach" features were in effect surface exposures of lag armor surfaces. Cobble lag beachfaces remained mostly immobile, and armored the beach platform where they occurred at the most wave-exposed headland locations, and shores adjacent to deeper water. The erosion-resistance effect of cobble veneers was similar to that of the irregular, angular cobble lag surface of the original island fill, but the habitat structure of rounded cobble embedded in finer sediment differed from angular rock. Cobble lag surfaces supported unexpected substantial foraging by small shorebirds when emergent at low tide (see ecological processes and habitats, below).

Slight movement of cobble occurred in the upper beachface of cobble beach headlands during extreme storms, where cobbles were able to pivot and roll on top of other cobbles. This contrasted with the stable interlocking of angular cobbles (like rip-rap). Most surface-exposed cobbles became embedded in bay mud or sandy bay mud, which was cohesive and increased the immobility of cobble surfaces (Gillenwater and Baye 2016). Embedded cobbles behaved similarly to cobble lag armor surfaces that formed below eroding cobble and gravel-laden bluff sediments at western Point Pinole. Upper beach cobbles at Aramburu Island behaved more like storm cobble berms at Point Pinole, which appear to be slightly mobile only during extreme storms. Cobble lag beachfaces at Aramburu were mostly buried by lighter gravel storm beach ridges and shell hash ridges, and were exposed as active shore surfaces only where more mobile gravel, sand, and shell were eroded, or where they were not placed (headlands). The primary utility of cobble lag surfaces in bay beach restoration may be as an underlying, basal surface armor that is normally buried by more mobile coarse sediments.

Figure 15. The southern cobble beach, adjacent to a dredged channel at the south end of Aramburu Island, has remained a stable profile from 2011 to the last survey in 2016, while the other beach types (gravel, sand, shell) have undergone landward transgression and alongshore progradation. Photo: July 5, 2016

Figure 16. Cobble beach veneers stabilized the storm wave-exposed headland at the south end of the Central cell, Aramburu Island. Left, Sept 9, 2013; right, July 5, 2016. Mobile gravels were transported landward by storm wave action during this period, leaving the cobble berm as the dominant erosion-resistant surface.

MOBILE BEACH SEDIMENT SIZES, TYPES, AND DYNAMIC RESPONSES TO HIGH WAVES AND EROSION EVENTS

Gravel, sand, and shell hash were mobile beach sediments in both storm and fair-weather wave action at Aramburu Island, in contrast with cobble that behaved mostly as a lag surface. Aramburu was constructed with all three main San Francisco Bay beach sediment types and grain size ranges together in the same system, to detect long-term differences in rates and patterns of beach processes affecting them in the same local wave environment. Mobile sediment types and sizes differed significantly in terms of both long-term and short-term resistance to shoreline erosion, and resilience (post-storm recovery from erosion) at Aramburu Island, where gravel, coarse and medium sand, and oyster shell hash were placed together in the same littoral cells.

Shell hash composed of flat, lightweight (calcium carbonate) fragments of native (fossil) oyster was commercially mined from South San Francisco Bay muds, and incorporated in two littoral cells. Low settling velocities and high surface area of the light carbonate shell hash appeared to enhance suspension in turbulent swash, wave bores, and currents. Shell hash was rapidly mobilized during initial periods of constructive wave action, and dominated the initial beach berm, washovers, and beachface surfaces for months in fall 2011-winter 2012. During subsequent storm erosion events, shell hash was also and rapidly eroded from the beachface transported down-drift long distances during storm events, where it deposited with a conspicuous white carbonate shell hash veneer at the beach surface. Eroded shell hash was also apparently transported in suspension cross-shore (landward overwash, bayward suspension plumes) during storms. Shell hash appeared mixed in nearshore mudflats (low tide terrace) bayward of placement locations during the first winter and later. Beachfaces that were initially dominated by shell hash were winnowed into sand or gravel-sand swash slopes following storm wave action. Shell hash deposits at the top of gravel storm berms, at the limit of wave runup, either formed imbricate (inter-layered, horizontal) firm surfaces, or were mixed interstitially in gravel berms.

Following shell placement in 2011-2012, shell hash was the most mobile, least erosion-resistant beach sediment type in littoral cells that were subject to strong longshore drift and intermittent high wave energy. Shell hash exhibited the greatest long-distance transport alongshore at the highest rates. Shell hash therefore provided little or no significant in-place resilience for beach profile recovery, except in micro-groin beach pockets. Oyster shell hash, therefore, would be most suitable as a component of beach fabric in swash-aligned beaches (confined littoral transport cells) with low to moderate wave energy and erosion rates, such as pocket beaches, sheltered crenulate marsh scarps, and bay-head beaches.

Gravel beach erosion and deposition during storm wave conditions exhibited very different patterns and rates compared with both sand (including coarse sand) and shell hash at both Aramburu and Pier 94. As predicted from studies of open sea coast gravel beach processes and forms (Jennings and Shulmeister 2002, Buscombe and Masselink 2006), gravel transport was onshore (landward) and resulted in deposition of high-crested, steep storm gravel berms during high tide and high wave events. No bayward cross-shore transport of gravel was observed at any locations except where longshore transport also occurred at the down-drift ends of spits. Storms with high wave runup were essentially constructive rather than erosional events for gravel beaches at Aramburu and Pier 94, but rollover – gradual net landward transgression (displacement) of the steep, narrow gravel berm profile – was confirmed by repeat beach transects at Aramburu (Gillenwater and Baye 201). Gravel beach berms and beachfaces were primarily constructive rather than erosional, and persisted for over 8 years at Aramburu Island, especially where they interacted with obstacles to longshore transport (micro-groins). This pattern and process is consistent with widespread gravel bay beach accretion during storms in Puget Sound, where wave energy ranges higher than San Francisco Bay (Finlayson 2006, Johannessen et al. 2014).

At Pier 94, where relatively deep water occurs bayward of the outer gravel barrier beach, major storm events drove gravel berms onshore as washovers across tidal marsh flats, and spread berms into relatively thin, wide gravel veneers over the rubble shore platform. Washover sedimentation is a significant mechanism for maintenance of high salt marsh gradients in marsh-fringing barrier beach settings (Elsey-Quirk et al. 2019, Cleary et al. 1979; see Chapter 3, this report). The nourished bay gravels mixed with eroded, decomposing concrete rubble fragments, and supplied the alongshore growth of spit-like berms that welded to the main landward shoreline at the north end. Gravel berm barrier beaches eroded at this highly exposed artificial port fill shoreline, but their residual structure and functions still provide sheltering of the landward salt marsh, flats, pools, and interior sand beach shoreline, as well as high tide shorebird roost habitat, after 15 years, with no supplemental nourishment or maintenance (see ecological and wildlife habitat discussion below).

Sand in mixed gravel and sand profiles exposed to storm waves at Aramburu Island was second only to shell hash in erodibility and rapid transport. Sand beachfaces rapidly flattened and widened during storms on drift-aligned beaches, forming temporary dissipative storm profiles. Sand was subject to rapid alongshore transport during storm events, bypassing short groins during turbulent high wave energy conditions conducive to suspended transport in backwash, bores, and currents. Sand beachfaces were depleted by updrift erosion in the Central cell at Aramburu Island, while concomitant sand spit progradation (alongshore and bayward beach accretion) occurred downdrift. Sand profile depletion resulted in exposure of gravel beachfaces, and some minor exposure of outcropping cobble or shore platform earthen fill.

These local pilot beach project results suggest that gravel or mixed gravel beaches would provide greater shoreline erosion resilience in drift-aligned and exposed, higher energy shorelines of San Francisco Bay, compared with sand and shell hash alone. Sand and shell hash beach sediments would be more likely to have adequate residence times and persistent profiles in either sheltered low energy and swash-aligned settings (pocket, embayed, or impeded longshore transport shores) or in groin-partitioned shore segments with moderate wave energy.

BEACH CREST ELEVATION RANGE

Gravel beach crest elevations increased after storm wave and high tide events at Aramburu Island, and persisted as relict storm ridges during fair weather. Wave-deposited gravel berm crests approached the elevation range of non-engineered bay levees in adjacent baylands (Gillenwater and Baye 2016), even as ridges migrated slowly landward. Aramburu gravel beach crest elevations ranged between the high tide line elevation (HTL; approximately 7.0 ft NAVD88) to 8.11 ft NAVD88, close to the extreme high water (EHW; 8.5 ft NAVD88). Lower beach crest elevation ranges (5.12-5.8 ft NAVD88) occurred where recurved spit-ridges of sand and shell hash were deposited by refracted waves at the north end of the island, where they vegetatively stabilized as high pickleweed marsh berms. Coarser grain sizes and exposure to greater wave height were associated with highest beach crest elevations (Fig. 17).

Coarse gravel bay beach ridges, in context of San Francisco Estuary wetland landscapes dominated by artificial bay mud levees, are analogous with self-constructing levees made of granular, mobile, permeable substrate, which gradually retreat with the shoreline and rise with wave height and sea level. Their high elevation range and positive accretion feedback with wave runup restricted overtopping by high tides and wave action at Aramburu Island. In this aspect, and in combination with the wave attenuation capacity of their beachfaces (Buscombe and Masselink 2006), they provide similar restrictions to tidal flooding as bay mud levees, but with potential for substantial self-maintenance (breach self-sealing due to coarse swash bar deposition) and elevation self-adjustment with sea levels and wave heights, depending on gravel sediment supply.

Figure 17. Gravel storm berm crest elevations are raised by storm wave runup during extreme high tides, and leave persistent relict high ridges that rise about 1 ft in relief (near or over 8 ft NAVD88) above adjacent landward supratidal lowland flats. August 2015.

Mixed sand and gravel beach ridges at Aramburu Island persisted at the Central cell sand spit, where their crest elevations also approached and slightly exceeded 8 ft NAVD88 by 2016 (Gillenwater and Baye 2016). Aramburu gravel and mixed sand/gravel berms rapidly developed within five years, forming vegetated beach ridges, similar to resilient vegetated mixed coarse sand and gravel washover beach ridges naturally formed in San Francisco Bay (Figure 18) with supratidal elevation ranges maintained by constructive rather than erosional storm wave runup.

Figure 18. Barrier beach ecotone between terrestrial beach/dune and high salt marsh vegetation traps coarse sand and raises backshore topographic elevations slightly above the adjacent unvegetated beach. Marina Bay, Richmond, 2005. Nearly identical vegetation and topography exists today.

ESTUARINE BEACH RIDGE SCALE AND DIMENSIONS

The self-construction of beach ridges by wave action at both Pier 94 and Aramburu Island ensured that the dimensions of resulting beach landforms were naturally scaled with local wave processes over years. The volume of beach sediment placement across the upper intertidal shoreface platform was approximately estimated from the range of variability of modern reference beaches dimensions from the Central Bay and South Bay, and from selected historic U.S. Coast Survey T-sheets of San Francisco Bay representing detailed beach landforms with distinct backshore and foreshore (beachface) zones above tidal flats. Modern reference beach dimensions represented the full range of sediment types applied to Aramburu Island. The approximate fit of the beach sediment prism over the graded, initial shore platform (ramp profile) ensured a low risk that over-sized berms or persistent eroded scarps would remain after beach sediment placement, which have adverse impacts to geomorphic functions, wildlife and esthetics in some beach nourishment projects (Nordstrom 2000, Jackson *et al.* 2010, Dallas *et al.* 2012). Estuarine beaches of San Francisco Bay are significantly smaller than open Pacific coast maritime beaches with direct (W-facing) or refracted swell (S-facing) influence. Non-storm backshore beach widths of coarse to medium sand beaches in San Francisco Bay are typically in a range of 1 - 5 m wide, in contrast with artificially oversized, engineered bay beaches such as Crown Beach, Alameda which ranges up to 30 m wide -- larger than some Southern California open coast beaches with artificial nourishment (California Department of Boating and Waterways 2002).

CROSS-SHORE TRANSPORT OF GRAVEL, SHELL, AND SAND

Artificially nourished Aramburu Island beaches exhibited important differences in patterns of cross-shore transport of different beach sediment types and sizes. Gravel sediments clearly exhibited swash zone transport only onshore in the beachface and beach crest and top, with no surface indicators of significant bayward transport to the low tide terrace. Gravel berms migrated onshore (landward) short distances over the backshore terrestrial flats during storm and high tide events, but no bayward transport of gravel was evident even after storms: small gravel was limited to the beach step, but was not detected anywhere in the low tide terrace after storms. This long-term observation of net onshore gravel transport is consistent with gravel beaches in both low-energy and open coast beaches globally (Buscombe and Masselink 2006).

In contrast, sand and shell hash sediments were found mixed with bay mud below the beachface, in low tide terrace mudflats, beyond their original placement locations and below the beachface step, following storms (Fig 5.19). This indicates offshore transport beyond the swash zone during high wave energy events with turbulent backwash and suspended transport (Gillenwater and Baye 2016). Mixed sand and shell hash in muds near the beachface were found in calm wave conditions during post-storm beach recovery phases. Constructive fair-weather wave action at times apparently winnowed beach sand and shell out of mixed muds on the low tide terrace, and transported them onshore to the beachface. This minor process was indicated by the presence of fine sand in asymmetric onshore-oriented oscillatory ripples on flats below the beachface, and rapid post-storm accretion of sand in the beachface where no updrift beachface sand occurred.

Sorting and onshore transport of sand and shell from the low tide terrace's mixed sediments (trapping or storing offshore storm-transported beach sediment) was likely limited to brief tidal stages where water depths reached thresholds when oscillatory sand ripples were active. The low tide terrace may have been a significant long-term sink for offshore-transported storm losses of shell hash, trapped in cohesive fine muds, with insufficient fair-weather wave energy to sort them and transport them back onshore at rates sufficient for beachface accretion (Fig. 19). In contrast, at natural shell hash beaches in the South Bay (Foster City, Bair Island), extensive shell-rich muds nearshore are exposed to long fetch and higher wave energy that forms mobile shell hash bars and shoals that can at times weld with the shoreline (Chapter 3).

Cross-shore transport of sand from fine muds in estuarine low tide terraces was not expected to be a significant beach profile recovery process (Jackson and Nordstrom 1992, Jackson et al. 2002). The long-term coarsening and erosion of Central cell beach reaches (loss of sand, dominance of gravel across the beach profile) indicates that cross-shore transport of sand and shell did not maintain equilibrium profiles where strong net longshore drift prevailed.

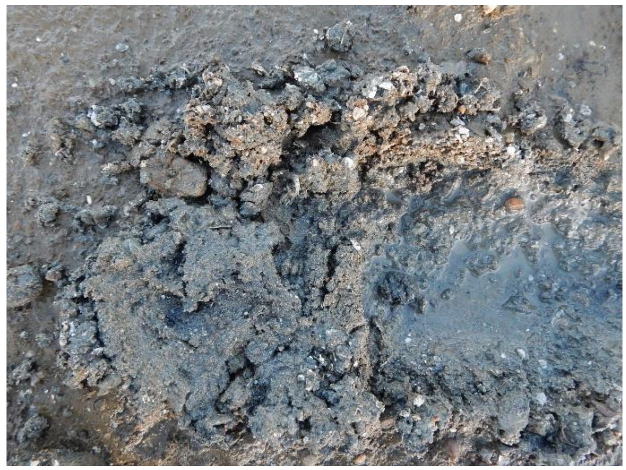

Figure 19. The low tide terrace below the beachface of Aramburu Island, central cell, contained significant fractions of shell hash and sand within a mud matrix. Sand and shell was apparently transported seaward of the beachface during storms, and minor onshore transport contributed to partial post-storm recovery of sand beach profiles. Coarsening (sand depletion) of the beach profiles occurred progressively as longshore drift occurred. July 25, 2016

LONGSHORE DRIFT AND TRANSPORT OF GRAVEL, SHELL, AND SAND

Gravel, sand, and shell hash exhibited major differences in rates of longshore transport at Aramburu Island nourished beaches. Differential transport rates were evident in the timing and sequence of spit sediment types during progradation down-drift during long-term beach evolution over years. Lightweight shell hash, despite large particle size (diameter) similar to gravel, was subject to rapid initial downdrift transport and beach ridge progradation during the first winter after nourishment. (Figure 20).

Figure 20. Shell hash was the first sediment type to appear downdrift of placement locations, in terminal spits and swash bars rapidly migrating down-drift immediately after placement in fall 2011 at Aramburu Island, preceding sand spit accretion by over a year. (A) Central cell cove spit, proximal end, December 2011. (B). North cell, south end, December 2011.

Subsequent years, progradation of sand beach ridge recurves dominated the down-drift end of the Central cell spit, and the north end of the island, after abundant shell hash was depleted updrift (Figure 21). Relatively minor proportions of beachface gravel appeared in down-drift recurved beachfaces by 2014, but sand remained the dominant sediment type at the down-drift end of the littoral cells in which they occurred (through 2019). Gravel drift was slow, and was primarily retained within the field of short micro-groins, and the proximal ends of spits. The high retention of gravel within the short groins was consistent with their profile position in narrow estuarine beach profiles, restricted to the uppermost foreshore and berm crests. Gravel was mobilized and removed from the proximal (south) end of the southern cell during the first year after placement (2011), drifting north to the adjacent cove, where it persisted in the landward-migrating gravel berms and spits, through 2019. Cobble movement down-drift was negligible or failed to occur, even during the most intensive storm wave action.

Figure 21. Longshore drift of sand, modified by wave refraction around the recurved spit during high tides, rapidly formed a recurved, prograded spit within the shallow intertidal cove of Aramburu Island's central cell. Spit progradation initiated in less than three years after beach nourishment. Aug 5, 2015

TRANSIENT BEACH FEATURES

Numerous minor but locally significant temporary beach features developed over short time-scales at Aramburu Island and Pier 94. They may be significant enough for focused monitoring, which would be required because their evolution is episodic or circumstantial.

Scarps. Short-term sand beach erosion can result in temporary wave-cut cliffs (scarps) in the upper beachface or berm profile during partial erosion of backshore sand berms, before the whole profile flattens to a gentle, dissipative beachface in response to storm wave energy. Scarps also can form in semi-coherent imbricate shell hash berms, but are weakly developed in loose gravel berms. Persistent beach scarps have been a concern for some beach nourishment projects with non-equilibrium constructed berm profiles (oversized, graded beach berms). Beach scarps have been rare and highly ephemeral (mostly absent) in the self-constructed beach morphology of Pier 94 and Aramburu Island bay beach projects (Figure 22).

Beach scarps are uncommon to rare features in San Francisco Bay reference beaches as well. Beach scarps are characteristic of “dry beach nourishment” methods of constructing design berms at or above wave runup elevations (Nordstrom 2000, California Department of Boating and Waterways 2002), out of equilibrium with prevailing beachface slopes and wave energy. Excessively high persistent beach scarps in design berm profiles can have adverse impacts for wildlife and beach esthetics (Dallas *et al.* 2012), but these appear have been avoided at the bay beach pilot project sites, where profile nourishment and complete reworking of placed sediments by wave action was essential to design.

Figure 22. One of the only storm erosion phases of Aramburu beaches resulting in minor, transient beach scarps (arrows) occurred along recently prograded sand and shell berms at the Central shore sand spit in February, 2014 (A-B). Scarp heights were generally less than 30 cm and did not persist by March 2014, following overwash that smoothed the scarped berm profile (C-D).

Gullies (terrestrial runoff). Rapid lowland runoff from adjacent terrestrial flats or drainages can result in intensive local gully erosion from the back of the beach profile during storms that also cause bayward shoreline erosion. The magnitude of beach gully erosion may locally exceed that of storm wave erosion. Local interaction between gully runoff erosion and wave erosion may intensify wave erosion impacts on the beach. Gully erosion may also cause local beach sediment fan deposition and widening of the beachface, which can locally increase dissipation of breaking waves. Coarse beach crests that rise above the adjacent lowland terrestrial elevations may cause pooling (ponding) of runoff, which can be released abruptly like lagoon breaching and channel erosion. Gully erosion of beaches back-to-front was observed multiple times at both Pier 94 and Aramburu Island central cell, adjacent to drainage swales and topographic lows bordering impermeable or low-permeability flats (Fig. 23). Where fringing beaches are artificially constructed, backshore (storm terrestrial runoff and overwash) drainage topography behind the beach crest should be incorporated in designs to steer gully formation.

Figure 23. Locally significant gully erosion of beach due to runoff adjacent to Pier 94, south shore beach, in the spring after fall beach nourishment. Persistent locations of beach gully erosion due to drainage patterns of adjacent lowland flats. Sediment fans of beach sand are trapped in the marsh below gullies, nourishing marsh and eroding beach. March 2006 (upper row), January 2008 (lower row).

Swash bars. Variations in wave heights during descending neap tide series, or even during single tides, can result in a staircase series of small swash bars on the beachface (Fig 5.24). During rising spring tide series, onshore-migrating small swash bars may be part of beach accretion processes. They can migrate across beachfaces and weld with the backshore and consolidate into more persistent and substantial seasonal berm features. These minor berms may provide important increased beach sediment reserves released during high energy erosion events. They may also have some ecological significance by trapping macroalgae or other organic debris in concentrated lines, either at their seaward crests, or in the minor trough depressions behind them. Intertidal drift-lines of filamentous or membranous algae provide moisture and organic matter substrates for beach invertebrates (trophic support for wildlife).

Figure 24. Small shell hash swash bars form over periods of wind-waves as brief as minutes or hours, temporarily descending in series at lower levels of the beachface during ebbing tides, and consolidating by wave action during rising tides. Aramburu Island, October and December 2011.

Beach steps. At Aramburu Island, sharply defined beach steps, with abrupt junctures between backwash-deposited sand and gravel, and muddy low tide terrace flats, were maintained along beach profiles over 11 years observed (Fig 5.25). These are markers of beach sediment transport, useful features for assessing the estuarine beach equivalent of "closure depth" typical of ocean beach nourishment projects. No low tide terrace sand bars or sand wave features (rare in San Francisco Bay, as at Long Beach, San Lorenzo Creek Delta) were observed at Aramburu Island, though small ephemeral asymmetric oscillatory ripples of fine to medium sand were occasionally observed below the beachface step. Low tide sand and gravel bars were precluded at the steep subtidal artificial fill platform of Pier 94.

Figure 25. Beach steps at the junction (arrow) between muddy low tide terrace and beachface maintain a knife-edge boundary between coarse and fine sediment, maintained by backwash and rolling of sand and gravel. Aramburu central shoreline, April 16, 2013, Feb 4 2016.

Back-beach pool and lagoon impoundments. Steep, high-crested coarse sand and mixed gravel beach ridges (berms) can act as small-scale barrier beaches that impound perched lagoon-like backshore pools at upper intertidal elevation ranges, where mud or sand flats are enclosed behind the berms, and flood during spring high tides (Figure 26). Such minor barrier and perched lagoon flats have repeatedly formed at the north cell of Aramburu Island, with no engineering or design. They are subject to unstable tidal inlet breaching and closure during high wave energy or high tide events, like natural analogs at Rat Island Cove beach's nontidal lagoon at China Camp, San Rafael (Fig 5.27 and Chapter 3, this report). These are potentially significant shorebird, waterfowl, and wading bird habitats (See wildlife habitat discussion below)

Figure 26. Mixed sand and gravel berms impound a wide, shallow perched (supratidal, above Mean Higher High Water) lagoon with a tidally choked inlet, providing restricted ebb drainage only during highest spring tides at Aramburu Island north cell, March 7, 2014. The large pool (spring-intertidal lagoon) is flooded during periods of heavy runoff or spring high tides, and drains or evaporates during dry neap tide series. Similar back-beach impoundments of freshwater runoff occur at the south end of China Camp Beach in wet winters (Chapter 3).

Figure 27. Natural and artificially formed beach-dammed partially tidal lagoons perched at or above Mean Higher High Water, San Francisco Bay. (A) Rat Island Cove beach, China Camp State Park, impounds a hypersaline non-tidal pan (shallow lagoon) flooded by tidal overtopping of the beach and freshwater inflows from the stream valley it occupies. This small backbarrier lagoon is closely analogous with smaller back-beach pools impounded by beach ridges. April 2008. (B) The artificially nourished gravel and sand barrier beaches at Pier 94, north end, enclose a shallow high tide lagoon with choked ebb drainage. April 26, 2018.

Minor eolian features: foredunes and deflation lags. Because most persistent beach profiles at Aramburu Island were gravel-dominated, no incipient or well-developed foredunes developed except at the Central cove sand spit recurve platform. The topographic high of the beach profile was the berm crest, however (Gillenwater and Baye 2016), and microtopographic dune accretion veneers under beach vegetation were insignificant. The lack of significant foredune accretion was likely due to the very small sand fetch of the beachface and backshore, and the orientation of the shoreline (offshore to dominant dry W and NW winds). At Pier 94, beach orientations were also offshore to dominant westerly winds, and beach deflation zones available to supply eolian sand were even narrower, and constrained by high salt marsh vegetation or gravel lag surfaces.

Artificially constructed or nourished bay beaches with medium to fine sand (susceptible to wind transport), oriented onshore to westerly winds, may develop potential significant low (circa 0.5-1.0 m) foredunes where beachfaces or dry sand backshores are wide enough to supply sand. Examples of low foredune terraces or ridges at San Francisco Bay beaches include Swimmer's Beach, Angel Island; Whittell Marsh beach, Point Pinole; and Radio Beach, Oakland. Of these, few are dominated by native beach or dune vegetation. As recently as the 1970s Long Beach (San Leandro) supported low foredunes up to about 1 m high. Long Beach currently is a washover terrace with ephemeral low dune mounds. Coarse sand beaches, such as Marina Bay beach (Fig. 18) do not form true eolian dunes, but backshore vegetation can similarly trap storm overwash sediment, like vegetated foredunes.

ECOLOGICAL PROCESSES AND HABITAT EVOLUTION OF BAY BEACH PILOT PROJECTS

LARGE WOODY DEBRIS DEPOSITION

Large woody debris embedded in beaches is an important wave-damping, erosion-buffering component Puget Sound shorelines (Johannessen *et al.* 2014, Finlayson 2006), but natural supplies of riparian woody debris are deficient in modern San Francisco Bay. The urbanized San Francisco Bay shoreline and its tributary streams generate large amounts of tidal litter from natural and anthropogenic sources, and bay beaches, as inherently depositional shorelines, trap significant volumes of both types. Though some natural large woody debris (tree trunks, limbs, and pieces) is deposited on bay beaches, the majority of large woody debris accumulations at Pier 94 Port of San Francisco and Aramburu Island are urban shoreline wood sources (artificial logs, pilings, cut lumber sections) often treated with wood (ecotoxic) preservatives (Fig. 28).

Placement of large woody debris in restored bay beaches may be necessary to replace ecosystem functions that are not well-represented in modern conditions, but are suggested by opportunistic wildlife use of large wood structures on constructed beaches (see beach and wildlife interactions, below). Large wood or natural driftwood added to beaches may need to be secured by embedding and pinning logs in place where beaches occur near potential navigation areas where hazards of floating debris may occur. Natural large woody debris deposition was insignificant at both Aramburu Island and Pier 94, reflecting deficient sources near these shoreline locations. Artificial log placement by embedding seasoned eucalyptus logs in bay mud underlying the beach (pressed into place by excavator buckets) during beach construction resulted in stable large wood (micro-groins) in wave-exposed beachfaces. These logs were later used by pelicans, herons, terns, and oystercatchers as roost sites (see wildlife interactions, below).

Figure 28. Large woody debris deposition on San Francisco Bay beaches is often dominated by storm deposits of driftwood from nearby urban port or other developed shoreline sources, including treated logs and pilings contaminated by preservatives (creosote, copper compounds). Pier 94 San Francisco, 2011-2019.

BACKBARRIER WETLAND EVOLUTION: SALT MARSH, PAN AND PERCHED LAGOON ENCLOSURE

One of the indirect wetland habitat-forming beach evolution processes observed at both Aramburu Island and Pier 94 was the spontaneous, unmanaged enclosure and partial impoundment of shallow pool, pan, mudflats, and related lagoon-like wetland and aquatic habitats behind barrier beaches. Backbarrier lagoons and pools are impounded (beach-dammed) during landward transgression beach ridges or spits with unstable upper intertidal inlets, outlets or breaches, which choke with coarse sediment, restrict ebb drainage, and impound runoff or extreme high tide flooding. Like gullying from impounded back-beach runoff or wave overtopping, this is a broadly predictable process that is likely to occur where low, poorly drained lowland or upper intertidal flat topography lies behind nourished beaches. Beach-damming of perched supratidal or upper intertidal backbarrier wetlands is a highly dynamic and annually variable process, however, so it is difficult to manage or precisely predict at any particular location. Beach-damming of lagoon-like habitats, such as tidal marsh pools, also is likely to occur where strong wave refraction can cause recurved spits to loop back completely and enclose swales or pools with obstructed drainage outlets. Shallow lagoon, pool, and pan habitats at Aramburu Island north cell (Figures 5.29, 5.30), and Pier 94 north shore, support invertebrate and small fish prey bases that provide foraging habitat for herons and egrets (spring-intertidal lagoons, pools), avocets, black-necked stilts (saline to hypersaline non-tidal pools), yellowlegs, plovers, willets, and sandpiper species (shallow submerged to emergent saturated mud).

Figure 29. Unstable, landward-migrating sand and gravel berms on the high flats of Aramburu Island north shore (A, B) and south shore (C-D) impound variable, inherently unstable saline pools and shallow lagoon habitats (non-tidal or tidally choked below highest tides) up to a foot deep, and up to nearly 0.25 acres in area. Swash bars and spits choke tidal inlets that restrict ebb drainage (arrows, C-D). A-B, July 2014. C-D, Nov 2018.

Figure 30. Recurved sand and shell spits can form high salt marsh berms that enclose salt marsh pools. Sand spit recurves loop back to enclose and impound salt marsh swales, where vegetation drowns out to form pools (pans) (A-B, Aug 22 2016). Sand accretion initially plugs the outlet of the tidal marsh swale during weak tides. The plug stabilized vegetatively by pickleweed, resulting in persistent pool habitat. Two recurves and pools formed within new salt marsh formed by progaded sand spits at the north salt marsh end of the island, down-drift beyond the beach enhancement shore (C - May 2018, D - Nov 2018).

BEACH AND VEGETATION INTERACTIONS

Natural estuarine beaches in San Francisco Bay exhibit dynamic intermediate states between active beachfaces and berm with minimal perennial vegetation, to stabilized, vegetated beach ridges dominated by high salt marsh, beach/foredune, or intermediate (ecotone) vegetation gradients (Chapter 3). The rapid formation and vegetative stabilization of large estuarine swash bars and beach ridges occurred at Aramburu Island within 3-4 years (Figures 5.30-5.32). The beaches formed at Pier 94 and Aramburu Island exhibited rapid ecological succession from estuarine beach to high salt marshes, even in shoreline segments with no active vegetation management.

Perhaps one of the most important long-term observations from these two pilot projects is that estuarine beaches can rapidly evolve into high salt marsh berms, as they do in sandy backbarrier lagoons of the outer coast. This indicates that salt marsh restoration and estuarine beach restoration processes are not essentially distinct, and the landforms and ecosystems they support intergrade. Beach nourishment and beach processes resulted in extremely rapid salt marsh progradation and vertical growth above Mean Higher High Water at the north end of Aramburu Island (Gillenwater and Baye 2016), suggesting the feasibility of regional applications for restoration of high salt marsh and high tide refuge berm habitats without direct construction.

Salt marsh berm accretion and progradation. The most dramatic example of rapid and unplanned salt marsh evolution from beach processes coupled with salt marsh processes occurred at the north end of Aramburu Island, beyond the project boundary. Rapid longshore drift of shell and sand from the initial beach nourishment of the north cell in 2012 produced a series of recurved beach ridges and short spits, initially deposited over pre-existing salt marsh vegetation (pickleweed, alkali-heath) on flat peaty muds. Partially buried salt marsh vegetation directly colonized and stabilized the new elevated sand and shell hash beach ridges, producing high marsh berms with thick dense cover about one foot above the original marsh plain elevation (Figure 31-32). Subsequent recurved beach ridges prograded bayward of the initial ones, and were directly colonized by pickleweed at wave runup deposition elevation ranges above Mean Higher High Water. The erosion of the north cell nourished beaches resulted in significant salt marsh accretion and marsh shoreline progradation, most of it as high salt marsh berms with emergent cover during highest spring tides, and related enclosure and impoundment of salt marsh pools (Figure 30). The high marsh berms were used as high tide roosts by long-legged shorebirds, including willets (Figure 32). In this case, beach-salt marsh succession was progressive and stable, because new outer marsh-capped beach ridges sheltered older ones from wave energy.

Figure 31. Initial beach progradation at the edge of salt marsh along the north end of Aramburu Island downdrift of beach nourishment areas, December 2012 (A, post-construction drift) and April 2013 (B, ongoing drift), along pre-project salt marsh erosion scarps. Sand was deposited both on top of salt marsh (pickleweed) vegetation landward of the previously erosional marsh edge, and bayward of the marsh, on mudflats.

Figure 32. Recurved, prograded beach ridges at the north end of Aramburu Island, deposited in 2012-2013 vegetatively stabilized and fully converted to high pickleweed salt marsh berms by summer 2015, producing tall pickleweed cover perched above the adjacent salt marsh plain. This local high marsh canopy is intermittently used as a high tide roost for long legged shorebirds (willet, pictured) when the marsh, mudflats, and beachface are flooded.

Transgressive high marsh berms and beachfaces. The crests of gravel and sand beaches at Aramburu Island central shore were colonized by high salt marsh ecotone plant species previously established on the site, as well as species locally reintroduced from source populations in the Central Bay. Alkali-heath (*Frankenia salina*), saltgrass (*Distichlis spicata*), Pacific pickleweed (*Sarcocornia pacifica*) and western ragweed (*Ambrosia psilostachya*) are the most common high salt marsh transition zone species that dominated mixed gravel and sand storm berms, establishing and spreading both along their crests and in the upper beachfaces during calm periods. The clonal below-ground shoots and roots of these species persisted in erosional upper beachfaces (outcropping in the shoreline) during and after episodes of storm wave-driven beach retreat. Clonal spread from the berm and from the low-lying seasonal wetland flats behind the berm maintained dominant high salt marsh as the berm profiles retreated landward. This process of vegetated high marsh berm self-maintenance during beach retreat is analogous with beach-foredune retreat in response to sea level rise (Davidson-Arnott 2005).

Figure 33. High salt marsh vegetation, spontaneously established, dominates landward-retreating mixed gravel, shell, and sand beach ridges at Aramburu Island, central cell. Patchiness of colonies varies with age (time of colonization) and disturbance (frequency and intensity of winter storm overwash. Left: patchy young coalescing colonies of pickleweed and alkali-heath near the high tide line, Aug 2015. Right: relatively continuous stands of western ragweed on a well-drained gravel ridge, June 2019.

Beachface and low tide terrace salt marsh. Along very low energy estuarine beaches, salt marsh vegetation can colonize, spread, and stabilize over the entire beach profile during prolonged low wave energy periods, converting it to stable sandy high salt marsh ecotone. Estuarine beach ridges that undergo succession to salt marsh berms persist unless or until beach processes are reactivated by storm wave erosion. The low tide terrace can support tidal salt marsh vegetation that traps cross-shore transport of sand down the beachface by backwash. Salt marsh vegetation at the beachface toe and low tide terrace inhibits return onshore transport of sand by waves because of sheltering under roughness of vegetation canopies, and binding of sand by roots (Fig. 34). During periods of low storm activity, beachfaces can rapidly narrow as vegetation creeps over it from above and below, converting low-energy fringing beach to salt marsh ecotone (Fig. 35). This occurred along the interior sand beach shorelines of Pier 94 (both north and south basins): a narrow residual strip of beachface was maintained primarily by human trampling disturbance paths by 2017.

Figure 34. The south shore of Pier 94 a month after construction (left, Feb- 2006) and after initial planting with the endangered estuarine beach/salt marsh shrub, California sea-blite in March (Sept 2006), exhibiting a full beach profile above a low tide terrace fringed with pickleweed salt marsh (Fig 36).

Figure 35. By winter 2008, the Pier 94 south shore beach profile (left) is narrowed to a sandy beachface as fringing salt marsh from the low tide terrace edge encroaches it from below, and high salt marsh and transition zone vegetation dominate the high tide line and above. By fall 2013, pickleweed salt marsh dominates the former beachface, stabilizing it and eliminating swash processes that define the beach.

Figure 36. Pier 94 south shore beach remained stabilized as a salt marsh ecotone for over a decade, with a narrow residual beachface maintained by wrack smothering of vegetation and human foot trails (trampling disturbance) in the wrack zone. April 2018.

Beach and Foredune vegetation. Beach and foredune plant species assemblages within San Francisco Bay vary geographically, and commonly include wide-dispersing species such as *Ambrosia chamissonis* (widespread), *A. psilostachya,* and local populations of *Leymus (Elymus)* spp. (*L. mollis, L. triticoides, L.* x *gouldii*), and *Atriplex leucophylla* (Chapter 3, this report). Foredune vegetation within the San Francisco Estuary is limited by dispersal of infrequent and small source populations, and by very low rates of onshore wind-blown sand transport. The narrow backshores and beachfaces (dry sand deflation zones supplying dune sand) of San Francisco Bay beaches support very low rate on onshore eolian sand transport, even where they face dominant westerly winds. Coarser-grained sand beaches, or those with significant mixtures of shell or gravel, are prone to form deflation lag surfaces which strongly restrict foredune growth. Episodic beach erosion and retreat during storms also limits growth of foredunes. Negligible eolian sand accretion occurred at Pier 94 after nearly 15 years, and no low dunes have formed even temporarily at Aramburu Island since 2011.

Persistent populations of native beach and dune vegetation were established at Aramburu Island by vegetative transplanting (perennial clonal species: *L. mollis, A. psilostachya*), direct seeding (*A. leucophylla*), and natural dispersal and colonization (*A. chamissonis*). Populations of reintroduced *A. psilostachya* spread extensively and persisted at Pier 94 (interior shoreline), but reintroduced populations of *L. mollis* were mistakenly removed (misidentified by weed crews). *L. mollis* at Aramburu Island was surprisingly adaptable to gravel and gravel-sand beach substrates. Many bay beaches with narrow, low foredunes are subject to invasion and local dominance by iceplant (*Carpobrotus edulis*), pepperweed (*Lepidium latifolium*), especially where seed source and vegetative fragment source populations are nearby.

California sea-blite, *Suaeda californica*. The pilot beach nourishment project at Pier 94 was originally aimed at testing feasibility of providing suitable habitat for a founder population of the native endangered salt marsh/beach ecotone shrub, California sea-blite (Baye 2006). Reintroduced sea-blite colonies in San Francisco Bay have exhibited multiple ecological interactions with estuarine beaches. The majority of original (March 2006) transplants at Pier 94 have survived to 2019, despite shallow beach sediment thickness and underlying substrate composed of concrete rubble fill. The planted founder population in the high tide line produced variable abundance of viable seed in the nourished beach, and recruited a few seedlings that transitioned to reproductive adults, at both Pier 94 and Pier 98 (Heron's Head Park), San Francisco.

Sea-blite has adapted to slow rates of beach retreat at Pier 94 and at another reintroduced population at Emeryville, Alameda County (Eastshore State Park, East Bay Regional Parks), but it has succumbed to rapid erosion as well. Under slow rates of beach retreat in San Francisco Bay beach reintroduction sites, sea-blite has migrated landward in pace with washover deposits by layering (clonal spread by adventitious rooting of buried prostrate shoots). It has also adjusted to slow, low-intensity beachface erosion seaward of plants, where live main shoots are not eroded, but drape into the lowered beachface and become buried by moist sand during post-storm beach profile recovery, which also promotes layering. Intensive, rapid beach erosion below main seminal root systems, however, can uproot and destroy plants that have not developed layered clonal sectors landward. Rapid beach retreat during storms destroyed robust, large young sea-blite transplants at the north shore of Pier 94 in 2018 (Fig. 38). At Emeryville, some well-established, landward-layered sea-blite clones survived 2018 beach erosion of the original seminal root systems at the transplant locations from 2008. The ability of sea-blite colonies to adapt to beach erosion may depend on the magnitude of short-term beach erosion rates, and the landward extent of the colony that has undergone burial and layering.

Figure 37. California sea-blite regenerates below a relict wave-cut scarp (dashed yellow line) by layering (adventitious root growth on buried stems) and regrowth in beach sand accreted after profile recovery following a storm erosion event, south shore Pier 94, April 2018.

California sea-blite itself may have erosion-buffering and sand-trapping influence on estuarine beaches, but this attribute has not been studied. Storm erosion of the southern interior Pier 94 beach shoreline caused erosion gaps along the flanks of large, dense sea-blite colonies in 2018, but less erosion under the dense, rough canopies themselves. (Figure 37-38). Like high salt marsh berms (Figure 32), shrubby, tall sea-blite colonies on estuarine beaches may also provide resilient high tide refuge habitat for wildlife, especially where otherwise semi-prostrate canopies are raised by clambering over drift-wood, as at the south end of Pier 94 (Figure 39 and Chapter 3, this report)

Figure 38. Intensive winter storm wave action in winter 2019 reactivated local beach profile gaps in continuously stabilized high salt marsh at the south shore of Pier 94. Erosion and beach sand mobilization occurred where salt marsh vegetation was undermined and blown out between stands of more stable and erosion-resilient large patches of California sea-blite. Feb 2019.

Figure 39. Estuarine beach colonies of California sea-blite can potentially provide elevated high tide canopies acting as high tide refuge cover for salt marsh wildlife, especially where they clamber over drift-wood. Pier 94 south, April 2018.

BEACH AND WILDLIFE INTERACTIONS

Shorebirds. Richardson Bay Audubon Sanctuary monitored bird use of the island before and after beach nourishment. They reported a 220% increase in shorebird abundance at high tides, 130% increase in shorebird use at low tide, and 115% increase in shorebird richness at both high and low tides compared to pre-construction conditions. Increases in bird species richness and abundance were greater than at control reference sites monitored. (Richardson Bay Audubon Sanctuary, unpublished data).

Qualitative predictions of shorebird use of restored beach habitats during planning phases of Aramburu Island shoreline enhancement presumed that sand beachfaces would provide more foraging and roosting habitat than the smaller intertidal cobble and gravel beach areas, because of greater invertebrate prey and diatom film availability. Sand beachfaces and berms did attract and support terns (elegant, Caspian, Forster's), plovers (black-bellied, semi-palmated, and at least one western snowy plover), and diverse sandpiper species. Sandpipers (including least, western, and dunlin), however, often concentrated in cryptic flocks in emergent cobble and cobble-boulder headlands during high tides, masked by heterogeneous, rough microtopographic cover of cobbles (Figure 40). They also foraged in congested flocks within small cobble-dominated emergent intertidal areas during lower tides, when they apparently foraged in high densities among moist interstitial finer sediments. Similar use of cobble lag beachfaces by shorebirds (willets), where cobbles are embedded in muddy peats, occurs at western Point Pinole. More investigations of habitat use and partitioning among different beach types, intertidal elevation ranges, and tidal stages is needed to clarify beach habitat objectives and designs aimed at enhancing shorebird habitat.

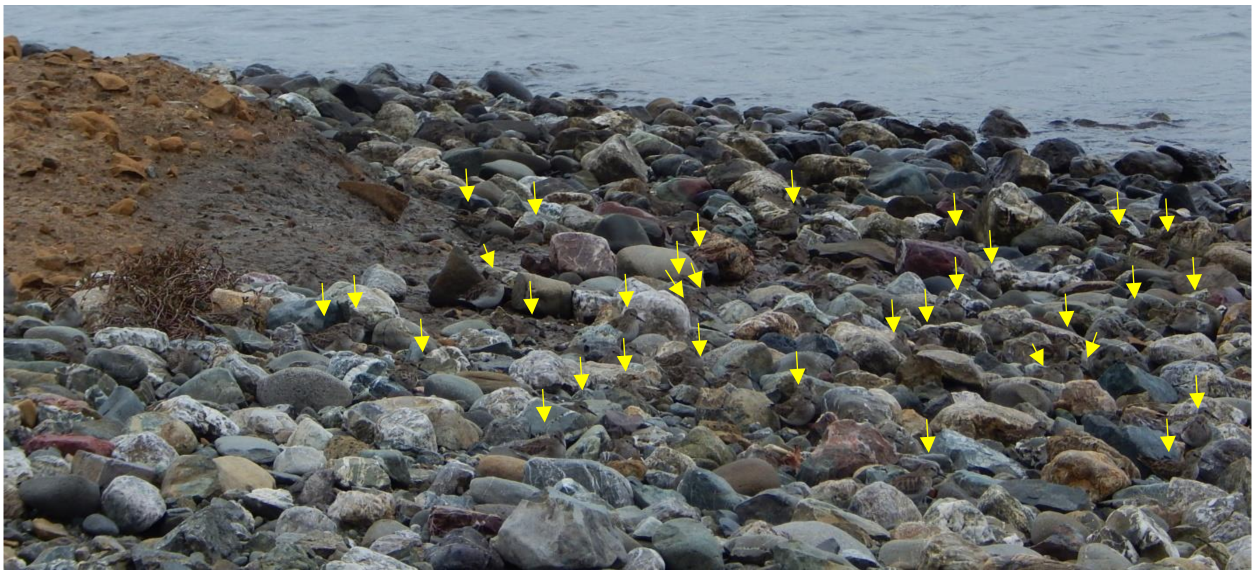

Figure 40. Rounded boulders and cobbles with interstitial mud, sand, and gravel provide cover (cryptic background) and accessible foraging habitat for sandpipers, which appear to frequent the habitat more than homogeneous sand or small gravel beachfaces and angular cobble/boulder shorelines nearby. At least 33 least sandpipers are partially hidden by cobbles and boulders in this view from of a small area the south-facing North cell headland at the cove.

Oystercatchers were present on the island prior to beach nourishment. Oystercatchers foraged and rested on rocky shoreline habitats in 2009-2011 (and during project construction), including the erosional rocky intertidal (angular cobble) flats, and the boulder revetment along the marina channel. No oystercatcher nesting was recorded on the island until 2014, when successful nesting occurred on the gravel storm beach ridge of the central cell, at a site-faithful location near foraging habitat and log groins that the mated adults apparently used for predator vigilance posts. Nesting of oystercatchers on the gravel beach has been ongoing. Successful oystercatcher breeding was is an unanticipated habitat use of the cobble and gravel beach and groins. Large woody debris (log) groins were used as roosts by Great Blue Herons, terns, and small shorebirds (Fig. 42), in addition to beachfaces and berms.

Figure 41. Oystercatchers were present on Aramburu Island prior to the beach project, foraging or resting on rocky artificial shorelines and rip-rap (A-B; 2009), but with no known nesting on the island. Following gravel beach nourishment, an oystercatcher pair nested on the beach, with site-faithful ongoing successful nesting over multiple years. The nesting pair used large wood log groins near the beach nest site during nest vigilance (C, July 5, 2016; D, June 26, 2019).

Figure 42. Great blue herons roost on logs embedded in the cobble beach at Aramburu Island's south shore. November 2018. Sandpipers (western, least) and a Forster's tern rest on embedded beach logs, Sept 2013.

Seal haul-outs. One of the original experimental habitat goals of the Aramburu Island project was to test whether beach reconstruction on the island could restore use of a former established harbor seal (*Phoca vitulina*) haul-out site that had been abandoned on the island. The island setting, and adjacent to a subtidal channel (escape route) was presumed to be as important a component of haul-out site selection by seals as the typical habitat type itself (sand or cobble beach with a ramp profile). Harbor seals continued to forage seasonally in the adjacent tidal channel during herring season, but no seal haul-out use of beaches on the island was resumed following beach nourishment.

PROJECT PLANNING AND IMPLEMENTATION

The 10-year retrospective on the Aramburu Island shoreline enhancement and monitoring provided an opportunity to review the relationship between project planning, funding, design, and outcomes. Outstanding aspects of these relationships, and their relevance to future planning, funding, objectives, designs, and regulation of comparable estuarine beach creation or nourishment projects within the San Francisco Estuary are discussed below.

COMPATIBLE AND FEASIBLE BAY BEACH SEDIMENT SOURCES

Beach nourishment project feasibility in San Francisco Bay depends on availability of well-matched suitable sediment types, grain sizes, and volumes for a project site, compatibly with sediment delivery, project construction, after permitting and funding. The logistics for matching volumes, schedule, and availability of compatible beach sediment between sources and project sites is challenging. Many suitable beach sediment sources are only intermittently or occasionally available, and need to be coordinated with either synchronized project-to-project transfers, or temporary stockpile holding sites.

Dredging project sand sources. High quality, well-sorted medium beach sand (clean, with few fines) are periodically dredged on a scale of >20 thousand cubic yards downdrift from the Crissy Field Beach littoral cell, at the City of San Francisco's marina entrance shoal. Dredging is normally performed with a clamshell dredge and barge, making land-based transfer to trucks difficult for beach restoration projects; relatively low-cost offshore disposal of sand at authorized unconfined dredge disposal sites makes policy-supported "beneficial re-use" options like sand beach restoration difficult in terms of cost as well as schedule and logistics.

Commercial in-bay sand and shell hash mining. The large-scale commercial lease mining of San Francisco Estuary shoal and high-energy tidal channel sands (poorly sorted coarse sand, shell, small gravel, suitable for beach restoration) is conducted under permit from the State Lands Commission. The bay sand mining industry has land-based refining operations at Pier 94, Port of San Francisco. Concrete industry demand for coarse refined bay sand makes it expensive and difficult to obtain for other uses. Bay sand refining, however, also generates waste "screenings" of clean bay shell and gravel unsuitable for concrete or fill. Sand refining screenings are highly suitable for coarse beach nourishment, such as Pier 94 outer beach nourishment and Aramburu Island. Commercial dredge mining of fossil oyster shell hash occurs in shell-rich muds and shell bars offshore of Foster City. Shell hash was been purchased for experimental beach nourishment at Aramburu Island.

Commercial aggregate mining. Sand and gravel mining of North Coast rivers and streams can also supply either raw (unrefined, unsorted) or sorted river-run gravels, sands, and cobbles from the same or similar geologic formations in the Bay Area. River cobble and gravel from the Russian River were obtained for Aramburu Island. The large demand for sand and gravel in the concrete industry has also supported a larger sand and gravel import facility at the Port of San Francisco, from remote aggregate sources such as British Columbia.

Stream and flood control channel sediments. Local Bay Area watersheds also generate poorly sorted beach-sized coarse sediments deposited in aggraded flood control channel bars that must be excavated to maintain flood control channel conveyance capacity. Flood control districts and local department of public works often remove creek and flood channel sediments, including coarse beach-suitable sediments, and dispose of them at landfills or other upland disposal or fill sites of convenience or low cost. Advance identification and coordination of potential sources of suitable local fluvial bar sediments for beach nourishment has so far not been performed in San Francisco Bay, although it has been proposed as a policy aspiration (Goals Project 2015), with untested feasibility. Typically, coarse fluvial sediment bars also contain minor but significant fine muds. Muds (clay and silt) in sand and gravel pore spaces are cohesive, and alter permeability (swash infiltration rates, capacity) of beachfaces, which affects their slope and erodibility. Beach-sized coarse sediments contaminated with fines must be placed intertidally so that waves rework and sort out suitable coarse fractions, and disperse suspended fines (in turbidity plumes). Direct placement of mud-containing beach sediments in the (supratidal) backshore beach results in cohesive sandy loam soil conditions that are conducive to terrestrial weed invasions, rather than beach vegetation.

SITE SELECTION AND FEASIBILITY OF ESTUARINE BEACHES

Most of the major feasibility factors for nourishment of San Francisco Bay beaches relate to site location and setting. Design considerations for nourished beaches are subordinate to site location and setting. The most fundamental aspects of beach stability and dynamic responses to storms and chronic fair-weather wave action depend on the local shoreline configuration, nearshore profile (depth gradient), orientation to dominant wind-wave approach, and the distribution of headlands, outcrops, or functionally equivalent wave shelter objects and obstacles to longshore drift. Where potential project sites are highly exposed to unsheltered wind-waves from multiple directions, constructed drift-obstacles (groins, micro-groins, or other groin-like structures; drift-sills) need to be incorporated in the beach plan form where mobile sediments are placed. Access routes for land-based equipment to transport and discharge beach sediment, or placement of pipelines for hydraulic placement of beach sediment slurries, must evaluated for feasibility before beach nourishment designs and specifications are developed. Preliminary feasibility assessments of different beach sediment types should be evaluated by complementary analytic and empirical methods, including wave modeling, beach slope/grain size analysis, and surveys of nearby reference beaches with similar wave exposure and variable grain size distribution.

DESIGN AND CONSTRUCTABILITY CONSIDERATIONS AND LESSONS LEARNED FOR THE ARAMBURU PROJECT

The Aramburu Pilot Beach Restoration Project (the "Project") raised some challenging aspects of the design, bidding, construction and post-construction monitoring phases of the project that are potentially applicable to other estuarine beach construction projects in the San Francisco Bay Area.

1. **Design and Preparation of Plans and Specifications for Construction**

Project funding constraints for basic baseline data needed for beach design can be significant, and require adaptation. The shoreline components of the Aramburu Island habitat enhancement project were funded by oil spill mitigation fines that limited the extent of hydrodynamic modeling and baseline data collection for design, such as local wave climate analysis. Therefore, the engineering design basis was based primarily on the following elements:

- Beach profile (elevation transect) surveys of multiple San Francisco Bay reference beaches during the non-storm season, to assess the regional variability of estuarine beach slope, beach crest elevations, grain size distribution, and beach dimensions, in relation to fetch distances (open-water wind-wave propagation pathways) and limited available wind rose data. These were interpreted and compared with on-site geomorphic features..
- The design basis used a self-organization design approach that allowed the natural wind-wave processes to sort, transport, rework, and deposit heterogeneous beach sediments over annual and seasonal cycles of storm and post-storm recovery of beach profile change.. This beach profile nourishment approach differs from engineered design of an artificial beach berm to specified dimensions and elevations (Dean 2002; Nordstrom 2000). Profile nourishment requires estimation of beach sediment volume, based on equilibrium beach berm dimensions and slopes, for a given grain size distribution, based on a range of reference beaches. In the Aramburu shoreline design, the profile included a relatively immobile (predicted) cobble veneer, and mobile sand, shell hash, and gravel corresponding with grain sizes observed on the pre-project shoreline.
- Empirical estimates of wave heights based on fetch , limited wind rose data, nearshore bathymetry and intertidal profiles.
- Simple one-dimensional analytical calculations using grain size and wave relationships (Lorang 1997, 2002), applying limited cross-section surveys and grain size sampling from selected bay beach reference sites
- Review of constructed beach designs from low energy coasts and large glacial lakes, including Pacific Northwest and Montana.

(a) *Limitations of Site-Specific Wave Climate Data.* The Aramburu project did estimate wave heights based on wind-wave fetch, so beach design was limited by a lack of long-term local wave climate data, including winter storm and summer thermal breeze conditions. No local wind-wave data in relation to tides were available to perform hydrodynamic modeling for design. No post-construction wave monitoring was available to correlate with beach profile changes performed semi-annually. Beach profile data were collected for performance monitoring according to a schedule set by permit conditions and budget, rather than storm/post-storm recovery dynamics over seasons. Thus, beach elevation transects and profile changes were difficult to interpret in relation to physical drivers of beach processes, and interactions with placed beach sediments.., With local pre-project and post-construction, ongoing wave monitoring, beach profile changes and sediment size sorting characteristics could be analyzed, and used to interpret results and provide quantitative, locally calibrated design criteria for San Francisco Bay beaches.

(b) *Additional Reference Site Data* - Certainly, a lesson learned is that While a limited set of reference beach profiles provided a preliminary estimate of geographic variation in static beach dimensions, slopes, and crest elevation ranges from a single season, more detailed San Francisco Bay beach reference site analysis and larger sample sizeswould be required to make robust and replicable bay beach designs that account for estuarine beach dynamics, especially responses to major storm events, and the pace and pattern of post-storm beach recovery. The Aramburu shoreline the design basis report included surveys and grain size sampling of reference beaches, but did not include hindcast wave modeling and/or sediment tracer studies that would advance beach engineering design and reduce uncertainty about dynamic variability. .

(c) *Contractor Selection Requirements* - The project prepared detailed plans and specifications that contained specific language for experience and expertise in the construction of natural restoration projects. These specific experience and expertise requirements were critically important for the successful implementation of the project design. The conventional low bidder project may risk under-performance, failure due to excessive change orders, or issues of construction contractors being unable or unwilling to collaborate closely with the design team for continuity and accurate interpretation and implementation of specifications. Restoration projects utilizing a self-organization approach requires a contractor experienced in working with the design team engineers and geomorphologist to fine-tune the design to the exact local conditions in the field. This is necessary because estuarine beach nourishment and construction design approach that cannot be pre-drawn in sufficient detail for all reaches of the shoreline. Therefore, the ability of the contractor to work with the design team during construction is key to success and any bid document needs to emphasize this in final selection. Some public agencies have low bidder requirements that make this approach difficult if not impossible, and as such a different bidding entity should be identified for optimum project success.

2. **Management of Longshore Drift**

Aramburu Island is particularly vulnerable to longshore drift due to strongly oblique dominant wave approach in relation to shoreline orientation. A major design element for the project was the ability to restrict rates of longshore drift to the north by construction of short shore-normal "micro-groins"(drift-sills comprising short composite log, brushwood, and boulder structures about the same width as the beachface and backshore berm, but not extending below the beachface into the low tide terrace). The log and boulder components of the micro-groins were constructed by contractors, but the brushwood installation components of the micro-groins were deferred to post-construction phases, and were not completed before the storm season. The excessively permeable log structures lacking brushwood and vegetation interactions allowed rapid longshore drift of sand and shell to occur with the first severe storm season. Micro-groins did enable significant retention of gravel berms within the micro-groins, however. Complete construction of any needed groin-equivalent structures (micro-groins, drift-sills, driftwood, boulders, etc.) including brushwood or vegetative stabilization, should be ensured prior to the first winter storm season, and not phased or deferred after the first storm season.

The placement and spacing of drift structures such as the micro-groins was based on professional judgment based on observation of a small sample size of natural San Francisco Bay reference beaches exhibiting beach accretion patterns around large drift logs, where significant longshore drift processes were evident. Micro-groin design was not based on analytic criteria scaled to San Francisco Bay estuarine beaches or quantitative estimates of longshore drift rates in storm and non-storm conditions. Based on monitoring trends, it is likely that more closely spaced and longer micro-groins completely constructed and vegetatively stabilized early in development would have been more effective in slowing the rate of longshore drift, especially during storms. In addition, we suspect that increased loads of driftwood incorporated in the beach berm itself, distributed along shore between micro-groins, may have reduced rapid longshore drift during storms. Observations from other beach sites indicate that micro-topography from woody debris along the shoreline helps to restrain sediment by creating pockets of reduced transport in the upper swash zone of the beachface.

3. **Challenges with post-construction operation and management by non-profit organizations and volunteers**

In our experience, it is common for nonprofit organizations managing shoreline and habitat restoration projects to maximize participation of staff and networks of dedicated volunteers in aspects of project implementation. For this project, nonprofit staff and volunteers were directly engaged in post-construction completion of micro-groin brushwood components, and planting of beach vegetation to stabilize the landward (backshore) end of the micro-groins. Because of variable volunteer schedules and participation levels, this work was not completed before the first storm season, and efficacy of the micro-groins was compromised. In addition, staff turnover constrained continuity of on-the-ground site-specific experience needed for effective implementation of deferred post-construction "living shoreline" tasks.

Primary or exclusive reliance on volunteers to implement essential construction and Operation & Management work for essential vegetative or other "living shoreline" soft stabilization components is likely to carry substantial risks, despite the best intentions of dedicated volunteers and nonprofit organization staff. There are inherent issues with the ability of volunteers to accomplish some tasks meeting design specifications of time-sensitive soft shoreline stabilization techniques. We recommend that volunteer tasks be limited to those that cannot substantially impact project success.

Monitoring, maintenance, and timely implementation of adaptive management measures.

One issue common to all restoration projects is that lack of funding for maintenance, monitoring, and time-critical implementation of adaptive management measures. It is relatively easier to obtain funding for construction and preparation of monitoring and adaptive management plans to meet permit conditions. But it is much harder to obtain funding to implement monitoring, so that adaptive management decisions and implementation can be executed in effective real time-frames, as well as provide performance monitoring reports to regulatory agencies on schedule.

4. **Obtaining timely supply and delivery of suitable beach sediment**

Coordinating suitable beach sediment source availability, transport, placement and permits is a major challenge for estuarine beach construction or nourishment projects. There is limited availability of suitable beach-sized sediments (sand, shell hash, gravel, cobble). Matching beach sediment grain size distribution, mineralogy, and particle shape (e.g., rounded versus angular cobble) to local shoreline settings is difficult when opportunistic sediment "matching" depends on independent projects such as navigational dredging, or commercial in-bay sand and shell mining for purposes unrelated to bay beach nourishment. Sand and gravel mining of rivers in the region to supply aggregate for concrete (construction) industry sets up strong competition for estuarine beach projects. Imported aggregate or crushed quarry aggregate from outside the region generally does not provide optimal or even suitable sediment types for estuarine beach construction or nourishment.

For the Aramburu shoreline project elements, the following sediment sizes were specified and used:

- 10 to 25 mm (0.5 to 1 inch) waste gravels from in bay sand mining (placed 2011)
- Oyster shell from SF Bay site (placed 2011)
- ¾- to 6-inch mix of rounded gravels and cobbles (placed 2011)
- Medium sand for the foreshore, dredged from terminal shoals within a sand beach littoral cell within the Golden Gate (placed 2012)

Finding the required sediment sizes, especially the larger sizes, is a major challenge to implementing beaches as a viable living shoreline design approach. The size range from dredging in the Bay proper is not big enough for many locations and as such, it is likely that the larger size fractions will need to be imported into the Bay at significantly greater cost and GHG impacts from trucking. For the Aramburu Project, we were able to secure a supply or larger gravels and cobbles from an abandoned quarry at a reasonable price. But the large-scale implementation of beach type projects will greatly outstrip the available supply of reasonably priced sources, even regionally. A lesson to be learned for other projects of this type is to plan ahead and secure well in advance of the project bid advertisement. The costs for importation of cobbles and large gravels are substantial and may strain budgets to import enough sediment of the proper size to construct projects of this type. Marin is trying to work with a local quarry to assess if the more angular quarry rock can be modified at a reasonable cost to meet the desired shapes for beach construction.

5. **Marine-based work contrasts with land-based work**

Many shorelines have significant restrictions for access of earthmoving equipment, trucks, hydraulic pumps and pipelines, due to recreational, public access, or wildlife and habitat constraints. One more obvious characteristic of the Aramburu project is that because it is an island, much of the work involving sediment transport and placement required marine equipment and contractors. Similar equipment access and sediment delivery issues apply to estuarine beach construction or nourishment along remote marsh or levee shorelines bordering tidal flats, where load-bearing levee road access is insufficient or lacking altogether. There are far fewer marine based contractors then land based contractors and the equipment is much more specialized and more expensive. As such, it is a much smaller contracting community and the cost tend to be higher and because the community is so small, there is much more rivalry between companies.

The Aramburu construction management experience indicated the need to be aware of the difference and allow additional time to work with the various Marine-based contractors upfront, and not wait until the traditional bid advertisement to alert them. The other lesson learned is to make sure that the cost estimates, especially for grant funded projects, reflect the higher costs for this type of construction over traditional construction. For example, having to work around the tides to bring in sediment barges can greatly limit work hours and increase costs. This is probably atypical of most shoreline projects where there is usually a land access route to the shoreline but not always so awareness of the differences was a key lesson learned for this Project.

6. **Estuarine beach design approaches and regulatory policies and practices: interface with costs, impacts, and goals**

In the decade since the Aramburu shoreline project work was completed, there has been increased policy interest by Bay regulatory and resource agencies in "Living Shoreline" adaptations for shoreline erosion, sea level rise, and integrated public benefits of recreation and wildlife habitat (Goals Project 2015, SFEI 2019) Living Shoreline approaches can include a spectrum of shoreline treatments, including constructed beaches as a "soft" alternative to traditional hard (armored) shoreline "stabilization" goals, as well as an approach to "managed retreat" resilience goals based on accommodation of buffered, gradual shoreline erosion and retreat with reduced impact. a. Living Shoreline beach designs addressing multiple environmental management objectives (e.g. shoreline erosion control, habitat, and recreation), can range over the spectrum between "gray" (emphasis on stabilization with rock or artificial resistant materials) to “green” solutions (based on gradual shoreline retreat accommodation with subsidies of natural sediment and vegetation treatments, akin to ecological restoration; Pilkey et al. 2012).

Estuarine beach design concepts and engineering approaches can also reflect this spectrum, raising contrasts in compliance with regulatory policy over interpretation of minimized fill impacts. Regulatory policy considerations include habitat type conversion (e.g., tidal flat to coarse beach, low marsh to high marsh), and short-term or long-term trade-offs among fish and wildlife guilds in soft-sediment estuarine environmental settings. The Aramburu shoreline pilot project tested these regulatory policy considerations in a relatively low-stake environmental setting: a degraded, highly erosional artificial derelict rocky fill island (left over from pre-regulatory era of bay fill), surrounded by a natural tidal mudflat in a county open space park and wildlife sanctuary. Aramburu pilot project demonstrated the importance of shoreline setting in determining feasibility factors (longshore drift rates, wave exposure) and environmental impact sensitivity. But most potential project applications of estuarine beach construction or nourishment for sea level rise adaptation and habitat enhancement would occur in existing estuarine shore habitats with relatively high environmental stakes and potential for adverse impacts or trade-offs, but with comparable scarcity in local wave climate background data.

Estuarine beach designs emphasizing stabilization objectives in exposed, highly erosion-prone shorelines can include potentially significant artificial changes in sediment size, type and shoreline morphology, similar to rocky shorelines or rip-rap. Construction of large, relatively immobile artificial cobble terraces with gravel berms are “estuarine beach” designs that may be most highly effective at erosion control, equal or superior to rip-rap in meeting objectives for long-term shoreline stabilization. In contrast, naturalistic estuarine beach designs that approximate modern or historical local reference beach types and conditions (narrow sand, mixed sand and gravel, shell hash beaches), congruent with adjacent estuarine wetland habitats, are well-adapted to multiple objectives for habitat enhancement, recreation, at the cost of higher long-term maintenance (e.g., decadal cycles of beach sediment replenishment) and only partial erosion buffering (reduced shoreline erosion and retreat rates), rather than shoreline stabilization.

This spectrum is reflected by a decade of Aramburu shoreline dynamics. The cobble beachfaces remained relatively immobile and resisted erosion, and storm gravel berms, like rip-rap. Natural sand and shell sediments were more mobile, resulting in more dynamic shoreline interactions and habitats (marsh berm formation, spits with new shorebird and wetland habitats), but more inconsistent shoreline erosion protection during extreme storm events. Yet cobble beachfaces and gravel berms also supported unexpected new wildlife habitats, including oystercatcher nesting on the island shore, and least sandpiper foraging and roosting among cobbles. The expected and unexpected outcomes of Aramburu shoreline changes in the long-term indicate the need for long-term monitoring and adaptive management to test assumptions and hypotheses about estuarine beaches.

In shoreline restoration or erosion control designs, there are often trade-offs betweenhigher initial fill and habitat impact upfront (in terms of footprint area, rock size and associated higher capital costs) versus a smaller footprint, less habitat impacts to existing resources, and the possibility of phased, higher maintenance costs. Key element to this trade-off is the mobility (stability) of the larger sediment sizes (cobble and large gravel) compared with quarry rock rip-rap, and prevalent natural coarse sediment size range (sand and gravel). For shoreline enhancement projects emphasizing stabilization and erosion protection, a key question is whether intertidal fill volumes and footprints of “minimized” cobble terrace and gravel beaches equal or exceed those of traditional engineered rip-rap, and whether the differences between them in terms of habitat quality, stability (storm mobility), and recreational value are significantly different, either during extreme storm wave conditions and fair-weather conditions. These considerations must be weighed against costs and impacts of more natural sand and gravel beach nourishment with long-term decadal costs and impacts associated with low-level, cyclic nourishment (ongoing supplemental sediment placement). These regulatory policy considerations also relate to the practical realities of grant funding: it may be easier to obtain grant funding for a new stand-alone project, and harder to obtain funds for phased construction, maintenance and monitoring.

These trade-offs between shoreline stabilization and restoration design approaches for estuarine beaches is an active and ongoing conversation among designers and regulatory agencies today. The Aramburu project may provide lessons learned in terms of cobble mobility and avoidance of impacts to existing intertidal resources such as mudflats and rocky shore native oyster habitat.The mobility of placed sediments, the conversion of one habitat type such as mudflats to rocky intertidal needs to be considered by the permitting agencies in approving projects.

CONCLUSIONS AND RECOMMENDATIONS

Short-term and long-term results of Aramburu and Pier 94 bay beach pilot projects help refine assumptions for ecological and erosion control planning of future San Francisco Estuary shoreline projects, especially where wildlife, wetland management, and erosion control objectives need to be integrated compatibly. Some outstanding results and implications of pilot project outcomes, in context of reference beach studies, are summarized below.

1. COARSE ESTUARINE BEACHES AS ALTERNATIVES TO RIP-RAP AND LEVEES

1.1. **Coarse estuarine beaches as environmentally preferable functional equivalents of bay mud levees and berms in tidal wetland management**. Most of the restored tidal marshes in the Bay Area are located in the shelter of old bay front levees that depended on fringes of tidal marshes for protection against wave erosion. They were not originally engineered for long-term maintenance (dependent on short-reach excavation from adjacent borrow ditches to cap or repair levees), or to withstand wave erosion after outer fringing marshes eroded. Armoring legacy bay levees is one option to "hold the line" of late 19th or early 20th century shoreline positions as permanent wavebreaks for restored tidal marshes, while 21st century sea level rise accelerates. It represents a costly and uncertain engineering solution with doubtful ecological compatibility.

Coarse marsh-fringing barrier nourishment is a nature-based alternative to static armored shorelines to protect bay edges of restored tidal marshes. The outer shoreline of southwestern Bair Island is fringed with complex drift-aligned shell hash beach ridges and spits that provide a first line of defense to wind-wave attack of the salt marsh scarps on which they are perched or welded. This wave buffer function of fringing beaches depends on natural resupply (onshore migration of shell hash deposits) to balance sediment budgets with longshore drift. Similar artificial processes include "feeder beaches" (sacrificial beach sediment placement zones for wave erosion and longshore drift; Johannessen *et al.* 2014) updrift of target drift-aligned beaches. Marsh-fringing barrier beaches maintained by nourishment do not require engineered placement or grading of fill along their entire lengths to maintain erosion protection and supratidal elevation ranges. Wave runup instead maintains crest elevation ranges (of coarse beach sediment).

1.2. **Coarse estuarine beaches as environmentally preferable functional equivalents of shoreline armoring.**

The cobble beach segments at Aramburu Island (exposed cove headlands and south shore) functioned as lag armor surfaces rather than mobile beach sediments. Cobble embedded in bay mud was highly stable and resistant to the most extreme storm wave erosion events affecting the site, comparable with rip-rap in protection. The rounded, embedded cobbles with interstitial fine sediment, however, was accessible to shorebirds that otherwise forage in beaches and mudflat shorelines, and provided cryptic habitat. Cobble veneers combined with gravel berms and beachfaces above them provided the same level of shoreline protection, but with greater habitat diversity. Cobble veneers, berms, and terraces, alone or combined with gravel berms, may provide equivalent erosion protection with environmentally preferable habitat conditions for migratory or local breeding shorebird populations. They may also provide superior esthetic and recreational opportunities compared with riprap shorelines (angular quarry rock, boulder to cobble size), which are known to have adverse geomorphic and ecological impacts on many sandy beach ecosystems in California and globally (Dugan et al. 2008, Griggs 2005).

2. BEACHES AS COMPONENTS OF TIDAL SALT MARSH RESTORATION

Aramburu Island's north shore demonstrated very rapid high salt marsh evolution from prograding sand and shell marsh beach ridges. These included salt marsh berms with crests above local Mean Higher High Water, providing high tide refuge and roost habitats for shorebirds. The gravel beach ridges of Aramburu also underwent succession to high salt marsh vegetation during years of low storm activity. Pier 94 south shoreline also underwent long-term succession from bay beach to high salt marsh and transition zone habitat, with localized reactivation of beachfaces during storm erosion episodes. Retreat of marsh berm/beach face profile analogous with beach/foredune retreat. Salt marsh accretion to elevation ranges above Mean Higher High Water by tidal sedimentation processes is slow (decreasing rates with increasing relative elevation in the tidal frame), and prone to fall behind accelerating sea level rise rates where suspended fine sediment supplies are limited. In contrast, wave deposition of sand and shell occurs during elevated tides with higher wave runup, above still-water tide levels, and at rapid rates during brief episodes of high wave action. This process, followed by salt marsh vegetation establishment in post-storm conditions, is well-adapted to restoration of high salt marsh in high wave energy shorelines subject to sea level rise impacts. Management of high marsh sub-habitat restoration by indirect coarse sediment nourishment, at suitable rates and intervals, is alternative to constructed high marsh habitat features (berms) composed of fine muds along outer marsh shores. High marsh berms naturally deposit along wave-eroded salt marsh edges if coarse sediment is present. Granular bay mud placement (aggregates of dried bay mud, in particle size range of gravel) is another potential surrogate for placement of actual mineral gravel, sand, or shell.

Salt marshes dependent on legacies of old berms as high tide refuge for wildlife, or high tide shorebird roosts, can benefit from wave-maintained beachfaces and berms as high tide roost sites, and high salt marsh vegetation canopies providing elevated cover adjacent to salt marshes. Addition of driftwood to marsh-fringing estuarine beaches may further enhance potential cover directly and by interactions with climbing salt marsh subshrub canopies and debris trapping. Aspects of these functions are represented at Aramburu Island and Pier 94, as well as some of their reference beach sites.

3. WILDLIFE INTERACTIONS WITH ESTUARINE BEACHES

The unpublished shorebird surveys conducted by Richardson Bay Audubon Sanctuary at Aramburu Island before and after beach nourishment indicated increases in species richness and abundance (220% increase in shorebird abundance at high tides, and 130% increase in shorebird use at low tide; 115% increase in shorebird richness), and successful nesting by oystercatchers on new gravel beaches – a species that had previously only foraged on the island. It is difficult to conclude whether this result was dependent on the specific geographic context (island location around extensive mudflats) of Aramburu Island beach nourishment project, or whether it may represent potential wildlife responses of restored estuarine beaches with similar dimensions and levels of human disturbance. There are no regional studies of shorebird tidal movements or foraging and roosting patterns on shorelines with estuarine beaches, levees, and diked bayland flats. Shorebird use of open coast and estuarine beaches in California and other U.S. coastal regions is significant (Hubbard and Dugan 2003, Withers 2002, Burger et al. 1997, Burger and Niles 2012).

Opportunistic colonization of artificial sandy dredge disposal flats by federally listed least terns and western snowy plovers beyond their historic range in the San Francisco Estuary occurred in eastern Suisun Marsh (Wallace 2014), just as vagrant western snowy plover appeared at Aramburu Island nourished beaches. Large-scale, linear, high-albedo habitats like beaches and bare levee road tops are likely environmental cues for many shorebirds. Focused shorebird monitoring at natural reference beaches and artificially nourished estuarine beaches, including sampling in relation to tide stages and seasons (migration, breeding) is needed to assess the potential role of nourished estuarine beaches in providing regionally significant contributions to shorebird habitat as legacy levees deteriorate.

4. VEGETATION AS A GEOMORPHIC AND ECOLOGICAL AGENT IN ESTUARINE BEACH RESTORATION AND MANAGEMENT

The well-established global role of restored foredune and salt marsh vegetation in inhibiting shoreline erosion and trapping sediment (Gedan *et al.* 2011, Nordstrom 2008) is applicable also to the San Francisco Estuary, but Aramburu Island monitoring of high salt marsh-capped gravel berms is one of the only (unpublished) data-based regional examples of vegetated estuarine beaches influencing shoreline erosion. Burial tolerance and coarse sediment trapping capacity of San Francisco Estuary beach, foredune, and high salt marsh plants under local shoreline environmental conditions have yet to be studied. Estuarine beach nourishment projects, especially those coupled with salt marsh erosion protection (marsh-fringing barrier beach nourishment), provide important opportunities to apply and study mechanisms of interacting vegetation and geomorphic processes.

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CHAPTER 6: CONCLUSION

This report sheds light on several ongoing and historical patterns and processes acting on the beaches and marsh edges around the margin of the SF Estuary. Marsh edge and estuarine beach change have not been systematically studied estuary-wide and are important to understand, especially as the pace of nature-based adaptation to sea-level rise and other climate impacts quickens in the region. This report offers guidance for repeatable methods for measuring and monitoring these habitat features, provides context-setting background on their geomorphic and ecological significance, and reports on observations and lessons learned from two completed beach restoration projects.

Mapping and monitoring lateral changes in the position of the marsh edge is important because marsh retreat (as opposed to drowning) is widely cited as the primary mechanism of coastal wetland loss worldwide (Francalanci et al. 2011, Marani et al. 2011, Fagherazzi 2013). Sea level rise will likely exacerbate this phenomenon, causing continued shoreline erosion and increased shoreline vulnerability (Wigand et al. 2017).

Recent SF Estuary marsh edge erosion trends presented here are sobering and cautionary. Though the marsh edge is dynamic, the time periods explored in this report reveal a dramatic reversal in trends of lateral shoreline movement over the last 25 years. Between 1993 and 2010, more than 30% of the mapped marsh edge was prograding, and less than 10% was eroding. Between 2010 and 2018, just less than 30% of the mapped marsh edge showed evidence of erosion, and less than 10% was prograding. While these data are extrapolated rates (averages between two points in time), they are likely related to long term trends in regional weather patterns and sediment supply. They should continue to be tracked over time and considered as a critical component of adaptation project siting and design, as well as sea level rise modeling. Not measured here, but equally important, are the feedbacks and connections between mudflats and marsh morphology. Continued work on the changes in mudflat morphology is important for understanding marsh evolution.

The erosion extent and rates presented here imply a time-sensitive window for intervention and action. The region must consider ways to prioritize restoration and adaptation of sensitive and critical habitats, taking into account their vulnerability to downshifting or drowning, their ability to transgress with sea level rise, and their vulnerability to lateral erosion. In some locations, such as the fringing marsh near the Hamilton Wetland restoration project, continued marsh edge erosion, if not managed, will result in the complete loss of fringing marshes in the next several decades.

Estuarine beaches are a softer living shoreline approach that can slow rates of erosion along marsh edges and provide dynamic vertical accretion zones (transgressive high marsh of washovers and marsh berms): valuable ecosystem services as marsh edges retreat. Beaches are not new or novel to the estuary, and were an integral historical component of tidal marsh ecosystems in the Central Bay and parts of the South Bay. Though they were widespread historically along the margins of the Estuary, they have been largely lost due to urban development, and were reduced to marginal habitat generations ago (as was *Suaeda californica,* for the same reasons).

Estuarine beaches are often associated with adjacent marshes. Marsh-fringing barrier beaches are a dynamic type of marsh edge, and historically were among the most widespread and extensive type of estuarine beach in SF Bay. They can be self-forming and self-maintaining depending on shoreline orientation, wave conditions, and, above all, coarse sediment supply. Estuarine beaches can also be an independent shoreline type used to provide erosion buffering along mainland shores, as at the Highway 80 Frontage Road beach. However, not all beaches are the same, and this work demonstrates the importance of understanding geomorphic setting, sediment type or substrate, wave climate, tidal regime, and associated trends in order to restore or enhance beaches to achieve desired goals.

Resilience for these types of beaches depends substantially on the rate of supply and shoreline location of suitable sediment grain sizes to nourish beach processes at marsh edges. For example, one component of a marsh-fringing beach is the dynamic marsh berm, formed by washover processes, which provides critical and limited high marsh habitat crucial for dependent salt marsh species. If enough coarse sediment supply is available, these features have the ability to adapt and maintain this elevation gradient as seas rise, at least in the near term.

As coarse sediment supplies to the Estuary from bluff erosion and local tributaries have largely been decoupled from the shoreline, there will be a more urgent need to match coarse sediment dredged from flood control channels with eroding marsh edge/beach projects on the margins of the Estuary. Building on the work of SediMatch (sedimatch.sfei.org) and ongoing sediment working groups, a regional program such as the Wetlands Regional Monitoring Program can integrate the priority locations for marsh erosion management with habitat objectives and sediment availability (WRMP 2020). Finally, as more marsh-fringing beach projects are implemented, monitoring of trends will enable the region to learn about effectiveness, longevity, permitting issues, whole-life costs, and physical and biological processes, ultimately improving this type of living shoreline adaptation strategy.

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