CONCEPTUAL DESIGNS FOR SEA LEVEL RISE ADAPTATION:

GREENWOOD AND BRUNINI BEACHES, TIBURON, RICHARDSON BAY, MARIN COUNTY, CALIFORNIA

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Executive Summary

Greenwood Beach and Brunini Beach, and Brunini Marsh, compose the bay shore south of "Blackie's Pasture", the local traditional name of a reclaimed, filled diked bayland managed as a public bayside park by the Town of Tiburon. The shoreline complex has evolved from early historical beaches between the Greenwood headlands and the Tiburon Peninsula at the head of northern Richardson Bay. The beach and salt marsh complex is directly related to the mouth of a flood control channel and intertidal delta extending over wide fine-grained tidal mud and sand flats. The main Greenwood beach has eroded and exposed underlying asphalt and concrete rubble from former bay fill. The beach and marsh are subject to long-term erosion driven in part by sea level rise and reduced sediment supply to the shore.

Traditional engineering approaches to address shoreline retreat and storm erosion typically involve armoring the shoreline to stabilize it against wave erosion, such as rip-rap or boulder revetments like those of the adjacent Tiburon Linear Park. Armoring of beaches to stabilize shorelines is incompatible with recreational, ecological and scenic beach park uses or values. As an alternative to armoring approaches to shoreline erosion, this conceptual design proposes incremental beach sediment nourishment, vegetation management, and beach sand-trapping sills to reduce shoreline erosion, attenuate wave energy across the beach profile, and increase retention and recirculation of both imported (nourished) and local watershed sand within beach zones. Sand beach nourishment, with supplemental addition of minor but important gravel and cobble components, is designed to integrate with vegetation management of salt marsh and beach habitats to enhance habitat quality, compatible with ongoing recreational use. This "soft" shoreline erosion management design avoids replacement of beach and salt marsh surfaces with rocky shores.

The conceptual design elements include vegetated groin-like drift-sills composed of cobble salt marsh, based on natural local San Francisco Estuary reference systems. The drift-sills provide a framework to increase retention of nourished mixed sand and gravel beach sediment, and reduce drift into the flood control channel. The design relies on natural wave transport processes acting on beach sediment, rather than engineered construction of a beach berm, to form natural beach profile. The proposed beach nourishment method is phased profile nourishment: sacrificial sand placement of mobile sand deposits in the upper intertidal zone, redistributed by waves. Beach re-nourishment would be phased incrementally over time, with deposition of small beach sand volumes to minimize impacts of each cycle. Beach nourishment design also incorporates existing salt marsh, which itself is sediment-nourished by local beach drift.

Erosional bluffs are proposed for set-backs to gentler slopes, and revegetation with native plant species assemblages that facilitate sand trapping and accretion, and buffering wave erosion impacts. Proposed beach and high salt marsh vegetation is adapted to recolonizing eroded shorelines and binding substrate (increasing erosion resistance). The vegetative stabilization design includes use of an endangered salt marsh/estuarine beach plant, California sea-blite, as a tool for enhanced shoreline resilience and habitat enhancement compatible with the recreational shoreline uses.

1.0 Introduction

This report provides a conceptual design for an integrated beach, salt marsh, and tidal flat shoreline adaptation and enhancement project at the shore south of Blackie's Pasture open space park in Tiburon, Marin County, California as part of the New Life for Eroding Shores project (Task 3) of San Francisco State University, Estuary and Ocean Center (Boyer Wetland Laboratory). The project was funded by Marin Community Foundation in 2017, and administered by the California Coastal Conservancy through the "Advancing Nature-Based Adaptation Solutions in Marin County" grant program. The project is aimed at adapting the semi-natural open space park shoreline to a suite of related climate change impacts (sea level rise, increased erosion, sediment deficits, storm impacts) that threaten to degrade the physical, ecological, and recreational values of the park in the long term. The overall need and purpose of the project are stated in the grant application was:

> …to address one of the most direct impacts of sea level rise on ecosystems in Marin County and San Francisco (SF) Bay – shoreline erosion and loss of tidal marsh habitat. It focuses on building natural shoreline systems and internal marsh features that emulate and reinforce the processes that can sustain high marsh habitats during accelerated sea level rise and tidal marsh retreat.

> We seek to test new nature-based methods for 1) establishing resilient and sustainable high [salt] marsh vegetation structure, and 2) beachface nourishment along wave-eroded marsh edges to slow erosion and trigger natural high marsh building processes. These methods are based on nearly extinct historical Marin salt marsh features: 1) connections to streams that delivered riparian woody debris to salt marshes and 2) gravel and sand beaches fringing the bay edges of many salt marshes. The methods proposed are alternatives to conventional coastal engineering stabilization methods that armor shorelines (rip-rap/rock slope protection, seawalls) at the expense of marsh habitat quality.

This report explores the physical and ecological basis of design, considering ecological and land use compatibility with "living shoreline" goals suitable for the estuarine shoreline setting of Richardson Bay (Goals Project 2015, SFEI and SPUR 2019) and San Francisco Estuary low-energy beach dynamics related to sensitive wetland environments. It builds upon the "New Life for Living Shorelines" technical memorandum that provided an atlas of bay beach shoreline types (SFEI and Baye 2020). The conceptual design is based in part on observed shoreline configurations and sediment transport processes that appear to support resilience of natural local beach reference systems. The conceptual design is also based in part on a local historical shoreline type at the project site – an estuarine barrier beach retreating over a back-barrier salt marsh during slow sea level rise of the late Holocene epoch.

The bay fill that established site's modern shoreline eliminated the naturally resilient historical beach and wetland ecosystem over a century ago. It cannot be, and is not proposed for restoration, but historical and modern reference systems provide a basis for "nature-based" conceptual designs to increase the resilience of the modified shoreline. The focus of the conceptual design is on augmenting beach sediment supply, and the shoreline's capacity to retain and recirculate coarse sediment. These integrated actions are expected to help compensate for sediment deficits caused by accelerated sea level rise and impacts of major coastal storms and droughts.

The level of design in this report is limited to conceptual design, considering the approximate scale, position, type, and quality of shoreline features, and the magnitude and frequency of coastal processes

that affect them. It places emphasis on an ecological and geomorphic basis of design derived from assessment of natural and artificially modified local Richardson Bay shoreline features, and their evolution over time. Although some consideration is given to rough approximate quantities of materials and construction methods, the conceptual design is primarily a framework to support development of subsequent preliminary and coastal engineering and restoration designs.

In the absence of established, standard place-names for the shoreline features in the vicinity of Blackie's Pasture, this report provisionally designates local beach and marsh place-names for purposes of this report. These names are adapted from the closest adjacent trails and roadways identified in the Town of Tiburon Bay Trail Gap Study (June 2012), as shown below. The predominantly sandy beach at the southwest end of the park, nearest the end of Greenwood Beach Road is "Greenwood Beach". The small eastern pocket sand beach adjacent to the northeast end of Brunini Way is "Brunini Beach", and the small salt marsh patch at the end of Brunini Way is "Brunini Marsh". Greenwood Beach is distinguished from the headland fringing beaches along private residential lots at the western end of Greenwood Beach Road.

1.1. Project Design Goals

The goals set for project design are interpreted from past and current regional San Francisco Estuary environmental goals (Goals Project 2015) in context of climate change adaptation needs in urban Marin bayland shorelines (SFEI and SPUR 2019), and local public park land uses of the City of Tiburon. The goals selected and the relative weight and emphasis of different goals shape the approach of shoreline adaptation design. Emphasis on "living shoreline" aspects of goals, esthetic and recreational values, and regional ecological restoration goals lead to design approaches.

1.2. Alternative Design Approaches for Shoreline Adaptation to Climate Change

A basic premise of living shoreline approach is that augmenting or replicating of natural ecosystems and processes is likely to minimize short-term and long-term ecological impacts compared with shoreline armoring or artificial coastal engineering. This approach is an adaptation of traditional landform and ecosystem restoration approaches, fortified to increase resilience to climate change impacts. Sediment nourishment (phased and implemented over multiple cycles) and modification of sediment transport controls (such as vegetation or nature-based topographic features) are a significant component of "living shoreline" approaches.

In contrast, emphasis on coastal engineering protection goals places more emphasis on resisting erosion processes and shoreline change, such as shoreline stabilization to protect high-value urban infrastructure against erosion impacts or land loss. Shoreline stabilization approaches may involve more conversion of habitat types or landforms to more erosion-resistant ones (armored, rocky or coarser sediment). Traditional coastal engineering approaches generally emphasize construction, relatively predictable design profiles and project life, with minimal maintenance and reliance on (relatively unpredictable) natural processes. Hybrid approaches to "soften" artificial coastal engineering structures (reduce impacts; incorporate mobile components or room for living features) are intermediate between the "gray" (armored, engineered) and "green" (mobile soft sediment, living vegetation or structures) ends of the "living shoreline" spectrum.

The "living shoreline" conceptual shoreline design in this report emphasizes compatible sediment nourishment (in-kind supplemental addition; replenishment of sediment volumes at rates to compensate for deficits of sediment in the same grain size range), and emulation of natural or naturalistic landforms and processes approximating the local and regional ecosystems, like ecological restoration. The approach is therefore essentially dynamic adaptive management design, reliant on integration of wetland evolution, beach evolution, and sediment supply and transport over time, rather than a single-event construction project with a target lifespan and design profile.

The conceptual design combines incremental, phased beach nourishment predicated on beach sediment matching, addition of compatible subordinate naturalistic shoreline components to increase resilience (set-back slopes, dynamic vegetative stabilization, artificial vegetated beach retention landforms, buried gravel storm berms), and conservation of beach-tidal salt marsh interactions. Repeated sand beach nourishment has been demonstrated by the U.S. Army Corps of Engineers and others to effectively overcome the effects of sea level rise on many Florida beaches (Houston 2017, 2019), without reliance on shoreline armoring. Shoreline advance produced by beach nourishment in Florida was determined to be eight times greater than the magnitude of shoreline recession caused by sea level rise from 1970-2017 (Houston 2017, 2019). Especially for relatively low-energy beaches (Jackson *et al*. 2002), beach nourishment based on profile nourishment – reliance on natural wave deposition of beaches rather than construction of artificially wide, high backshore berms (Jackson *et al*. 2010) - has high potential to be a feasible, low-impact "soft" shoreline engineering approach to erosion control and sea level rise adaptation (Stive *et al*. 1991).

An alternative approach is to replace the existing beach with a perched erosion-resistant beach system, a type of artificial beach design dating back to the 1960s (Moreno *et al*. 2018; Nordstrom 2000; Gonzales *et al*. 1999; Lorang 1991). It involves construction of a detached beach profile behind an erosion-

resistant sill, shelf or breakwater. At Greenwood Beach, an alternative design is based on an erosion-resistant cobble terrace placed over existing muddy sand tidal flats to retain sand and act as an intertidal sill or breakwater, designed to eliminate excess wave energy at the backshore for decades. This approach significantly increases wave energy tolerance and erosion resistance of a more predictable shoreline (Moreno *et al*. 2018), while retaining mixed sand and gravel beach features. The cobble-gravel terrace beach design alternative is developed by Marin County Flood Control in a related Coastal Conservancy grant (R. Leventhal, in prep. 2020)

2.0 Basis of Conceptual Design: Assessment of Coastal Environmental Setting and Project Site Conditions

The local estuarine beaches of northeastern Richardson Bay, including the existing Greenwood and Brunini Beaches and their natural historical antecedents, provide a frame of reference for their conceptual restoration design. The range of variability of local beaches (size, sediment texture, seasonal and annual dynamics), and their relationships with adjoining coastal landforms (e.g., salt marshes, deltas, cliffs, rock outcrops, shoreline armoring and fill) provides both environmental context and a basis for "nature-based" conceptual restoration designs, adapted to foreseeable land uses and near-future climate change.

2.1. Land use and setting. Greenwood and Brunini Beaches form the modern estuarine shoreline of a reclaimed, filled historical salt marsh at the northeast end of Richardson Bay, San Francisco Bay. The reclaimed marsh was previously (prior to 1966) used as a privately-owned horse pasture (Fletcher 2019). The beach occupies the head of a very shallow intertidal sub-embayment defined by the rocky Greenwood Beach Road headland (cliffed hillslope) to the west, and the Tiburon Linear Park shoreline of the Tiburon Peninsula (Figure 1). A wide tidal flat (section 2.2 below) extend south of the beach to the Mean Lower Low Water line. The terrestrial lowlands of the Pasture open space are artificial 20th century diked bayland fill approximately 10-12 ft in elevation, with nearly level to very gently sloping topography. A pedestrian bridge near the shoreline at the channel mouth connects access to the west and east side of the park. The City of Tiburon public land use of this open space is a recreational park. The park trail is connected to Tiburon Linear Park pedestrian/bicycle trail along the bay shore.

Figure 1. North Richardson Bay vicinity beaches from Richardson Bay Audubon Sanctuary, Greenwood Beach headland, Tiburon Linear Park boulder-armored shoreline. Google Earth image, June 2019.

2.2. **Local tidal flats and beaches of northeastern Richardson Bay** (Greenwood Beach Road headland shore). A series of small mixed sand and gravel fringing estuarine beaches extend discontinuously along the shoreline south of Greenwood Beach Road, below low rocky cliffs and rocky artificial fill west of Pasture open space, east to Brunini Way. Greenwood Beach and Brunini Beach occur at the extreme east end of this series, in a shallow embayment (Fig. 2). The headland beaches appear to overlie wave-cut benches below rocky cliffs, grading to narrow (40-80 ft wide) muddy low tide terraces. Most of the small pocket headland beaches are associated with low bedrock outcrops in the upper foreshore, acting as tombolos or groin-like sills that appear to restrict local longshore transport. The modern groin-like rock outcrop sills appear similar to the shoreline pattern of pocket beaches and outcrops represented in the 1851 T-sheet 433N (Fig. 3). These south-facing beaches have limited wind-wave fetch within east Richardson Bay: about 0.2 - 0.8-mile shallow water fetch oriented along prevailing SW winds, 2 mile fetch to the south, and a longer deep water fetch over 6 miles to the southeast to San Francisco, aligned with infrequent winter storm wind approach. The 100-year wave heights developed as part of the FEMA San Francisco Bay flood insurance mapping by bay wide hydrodynamic modeling and analysis of decades of Bay wave data are in the 1 to 1.9 ft range which is relatively low for a 100-year (0.1 AEP) wave event. The wide tidal flats at Greenwood Beach limit wave energy to the higher storm events. The available wave energy is sufficient to significantly erode the shoreline as shown in section 2.3.2 below.

The headland beaches are similar to the beaches below Lyford House at the Richardson Bay Audubon Sanctuary headquarters, west of the headland. These Sanctuary beaches (Fig. 4) were surveyed for grain size distribution and topography in 2010 to provide reference beach data for the design of Aramburu Island beaches (Wetlands and Water Resources 2010, Appendix H). Sanctuary Beach provides some local reference data for natural estuarine beach sediment size variation, slope, and size within northeast Richardson Bay. Most of the area beaches are composed of mixed medium to fine sand with varying

proportions of coarse sand and gravel. They often exhibit a thin layer of fine shell hash on the intertidal beachface, which appears as bright white patterned patches over darker gray wet sand in aerial photographs. Gravel (sandstone, shale) beaches and small gravel storm berms also occur on the Sanctuary headland, but no cobble beaches occur in this shallow sub-embayment of Richardson Bay. Beach widths (intertidal zone and narrow supratidal beach) vary between about 40-70 ft, with much seasonal and annual variation. Beach slopes of the Sanctuary Beach measured during calm non-storm periods were approximately 11:1, with crest elevations just over 8 ft NAVD 88 (WWR 2010). The mixed sand and gravel beach profile of Sanctuary Beach overlies muddy low tide terraces, mixed with minor amounts of sand and gravel.

Greenwood Beach Road Headland Shoreline

June 2019

3 A

3 B

Figure 3. Greenwood Beach Road headland beaches. A) Aerial view showing fringing mixed sand and gravel beaches segmented by groin-like bedrock outcrops and small rocky headlands. B) Similar 1851 shoreline configuration at slightly lower sea level stand, represented in U.S. Coast Survey T-sheet 433N (stippling indicates beachface), suggesting long-term relative stability of rock-bound beaches in plan form. C) detailed view showing groin-like rock outcrop sills oriented oblique to shore, with offset in the orientation of beach segments between them.

Richardson Bay Audubon Sanctary Beaches
June 2019

Figure 4. Richardson Bay Audubon Sanctuary Beaches. A) Aerial view of sandstone cliff and bluff with fringing mixed sand and gravel beaches, segmented by small rock headlands and foreshore outcrops, above narrow sandy mud low tide terrace. Google Earth image June 2019. B) persistent gravel storm berm above mixed sand and gravel beachface below Lyford House, June 2012.

2.3. **Greenwood and Brunini Beaches**. Greenwood and Brunini beaches (Fig. 5) differ from the neighboring headland beaches in some important aspects. They are associated with an artificially channelized flood control ditch delivering fluvial sediment to a intertidal delta and salt marsh bordering tidal flats up to 470 ft wide. Their bay-head position restricts potential net longshore drift. The beaches are both composed of mixed sand and gravel, with predominant medium sand near the beachface and backshore beach surface layers.

2.3.1. Greenwood Beach. The western Greenwood Beach is the larger of the two beaches bordering the flood control channel mouth. It was approximately 0.2 acres in 2019, extending from a rock-armored shoreline at the west end to the flood control channel. The beach was recently (2019) about 230 ft in length, varying among years depending on beach accretion and the relative extent of beach and salt marsh (see dynamics, below). The majority of the beach consists of an intertidal sloping beachface dominated at the surface by poorly sorted medium to fine sand mixed with gravel and coarse sand, often with a patterned veneer of fine shell hash. The beachface narrows to the west, ranging between about 14-30 ft wide. At the narrowest west end, the beachface thins to a sandy veneer over exposed lag surface of artificial rocky fill (concrete, asphalt, and angular quarried rock). At the east end of West Beach, near the channel, the beachface grades into an erosional remnant of wave-scoured intertidal salt marsh rootmats (peaty marsh soil outcrops) overlying coarser delta bar deposits.

The backshore (dry high tide) of Greenwood Beach is narrow, and varies in size among years. In 2019, it widened from about 1-5 ft wide at the west end, to a maximum of about 12-17 ft wide at the east end (measured from Google Earth imagery June 2019). The backshore beach grades into high saltgrass-pickleweed salt marsh patches, where sandy swash bars are deposited and become vegetatively

stabilized as low-relief sandy marsh berms (Fig. 7). These are remnants of a former large deltaic salt marsh on the west side of the channel mouth, which has been converted to beach by wave erosion and deposition (2.3, below). The back of Greenwood Beach is a low (3-5 ft) erosional bluff in artificial fill at the west end, declining to a sloping lowland near the channel mouth. Asphalt and concrete rubble outcrop in the eroded bluff toe of the Greenwood Beach in winter. A small gravel storm berm is occasionally exposed at the toe of the low bluff in artificial fill at the backshore. The calm-weather (spring-summer) backshore beach elevation range appears to be similar to the Sanctuary Beach, about 8 ft NAVD 88.

Greenwood Beach is more heavily used by the public for walking and dog exercise and water play area. Other uses are walking and bird watching. There is no formal trail to the West Beach. A social trail (trampled path) extends from the paved Bay Trail and bridge to the gently sloping east end of West Beach. No other infrastructure is known to exist at the West Beach.

2.3.2. Brunini Beach. The eastern Brunini Beach (Figures 5, 10) is a very small pocket beach (about 0.05-0.07 acres in 2018-2019) located in a gap between salt marsh and the armored fill bluff. It has recently (2019) been about 65 feet in length, varying among years with erosion or encroachment of the adjacent salt marsh. The backshore beach is variously vegetated with high salt marsh and beach vegetation (saltgrass, sea-rocket) and partially buried with wrack-lines (storm-drifted tule litter from Suisun/Delta marshes or local eelgrass and salt marsh litter). The beachface is relatively steep and narrow, only about 20 ft wide, terminating on the sandy mud low tide terrace. The beachface has become encroached by spread of low California cordgrass marsh near the toe of the beachface, offset at times by storm erosion. The boundary between salt marsh and beach is uneven and unstable. The long-term trend of the beach and marsh is uncertain, but marsh recovery after removal of hybrid non-native cordgrass may result in conversion of beach to marsh from the lower end of the profile upward.

Brunini Beach is a small pocket of unvegetated sand, shell hash, and minor gravel at the east end of the salt marsh east of the channel, bounded by the boulder-armored shoreline at the east end. A sandy terrace occurs behind the crest of the East Beach, representing vegetative stabilization of former prograded beach zones. The beach terrace is overwashed by winter storm high tides and waves depositing wrack.

Brunini Beach is less heavily used by the public for walking and dog exercise and water play area, but a small social trail from the bay trail to the East Beach appears to be used primarily for dog exercise and water play. Other uses are walking and bird watching. The paved Bay Trail (Brunini Way/Tiburon Linear Park trail connection) lies adjacent to the east end of Brunini Beach. No other infrastructure is known to exist at the East Beach.

2.3.4. Low Tide Terrace: Delta and Tidal flats

Below the intertidal beach profile is a wide low tide terrace and intertidal fluvial delta. The upper intertidal portion of the flood control channel delta (2.4, below) is a broadly and irregular fan-shaped, asymmetric mid-high pickleweed-dominated salt marsh, fringed with low cordgrass marsh. The upper salt marsh is formed in part by wave-deposited stratified fine sand, organic detritus (including marsh peat and vegetation particles, eelgrass and algal litter).

The intertidal flats below the beachface and salt marsh are not soft, unconsolidated mud, but firm, muddy sand (bearing weight of an adult) close inshore. The delta shoals (low-gradient convex lobes) and bars are also composed of firm muddy sand and gravel. A smaller peripheral freshwater drainage ditch discharges perennially (seep outflows) west of Pasture parkland; it exhibits a minor delta.

The mid-intertidal flats are often sandy at the surface and rippled during periods of high onshore winds, indicating potential shoreward transport of sand from the flats at times. During calm periods, the intertidal flats often exhibit a veneer of fine bay mud. An erosional artificial rubble lag surface of asphalt, concrete, and rock fragments outcrop at the west and east ends of the muddy sand low tide terrace. Eroded former salt marsh rootmats (peaty marsh muds) outcrop in the low tide terrace and lower beachface around the channel mouth.

Annual and inter-annual dynamics of the beach profiles have not been analyzed with repeated seasonal surveys. Qualitative annual changes observed during the last two decades (pers. observ.) include flattening and widening of dissipative intertidal beachface slopes during the winter storm season, with corresponding narrowing and lowering (or elimination of) the backshore sand berm. A narrow gravel storm berm often deposits (or becomes re-exposed) at the toe of the low West Beach bluff during winter sand beach erosional phases. The backshore beach (high tide dry beach) variably widens in spring-summer, but can remain narrow some years. Indicators of persistent erosional trends include perennial exposure of basal rubble layers in the low bluff.

Figure 5. Greenwood Beach features. A) overview of shoreline features. June 2019 Google Earth image. b – west beachface, winter erosion phase, February 2019. C) zonation of high tide (backshore) dry beach, wetted intertidal beachface, and rocky lag low tide terrace (exposed) above mid-intertidal mudflats (submerged), west beach, August 2018. E-F) -gravel storm berm at toe of low bluff above erosional winter beachface, February 2019 and Nov 2016. G) oscillatory wave ripples on fine sand and mud low tide terrace below beachface, west beach; bat ray foraging depressions. June 2012. Firm muddy fine sand, gleyed (anoxic, reduced) of low tide terrace bordering the intertidal delta; sediment bears weight of adults walking over flats. I-J) Shore-normal large asymmetric sand ripples on flats of low tide terrace/lower west side delta, February 2019, suggesting episodes of shoreward sand transport towards beach during energetic wave conditions.

2.4. Flood control channel, delta, and other potential sediment sources. The flood control channel provides a watershed sediment source to the shoreline that is sufficient to deposit substantial intertidal delta (0.75 ac). The delta is evident in all historical aerial images since the 1980s, and remained a conspicuous intertidal feature from on-site views during the last two decades. The delta includes multiple shifting distributary channels and variable bars and shoals composed of relatively firm muddy sand and coarser gravel (and minor amounts of small cobble) extending over the soft muddy low tide terrace (Fig. 6). The sand and gravel deposits in bars and shoals are evident following high precipitation and runoff in winter (Fig. 6 F-G), but they are often buried by finer estuarine sediment at the surface during the dry season. The drainage channel conveys storm runoff from the local watershed to the Bay, but is open to daily tidal flows (Fig. 6), but it has no significant freshwater discharge (or brackish tidal marsh gradients) during the dry season.

The flood channel has likely been a past significant local source of silt and sand for the relatively wider mudflats, the associated deltaic salt marsh patches flanking the mouth of the ditch, and Greenwood Beach. Adjacent to the mouth of the flood control channel are two asymmetric patches fringing tidal salt marsh (Fig. 7), apparently formed on past lobes of the channel mouth delta (Fig. 6): a smaller remnant west-side high salt marsh lobe currently reduced to approximately 0.23 acres (bayward of the low bluff), and a larger east-side salt marsh (low cordgrass marsh and high pickleweed-dominated marsh) about 0.31 acres.

The low bluffs west and east of the beaches are heavily armored by old boulder, concrete slab and rubble rip-rap, including asphalt rubble, placed prior to regulation of non-navigable bay waters (Fig. 8). These armored shorelines resist erosion and appear to contribute no significant sand to Greenwood and

Brunini beaches. Rock armoring continues along the entire Tiburon Linear Park shoreline. The low, non-armored fill bluff behind the beaches also contain significant amounts of buried rubble, and little sand-sized sediment. Prior to armoring, bluff and cliff erosion of sandstone-derived soils (including gulches and slope failures) east and south of the beaches may have contributed sand and gravel to the local littoral cell. Therefore, the intertidal delta of the flood channel mouth is likely a relatively important modern local source of sand and gravel sized sediment to the local littoral cell and is incorporated in the proposed project design.
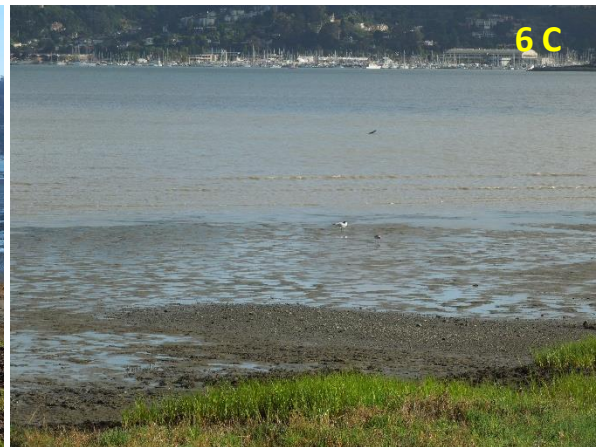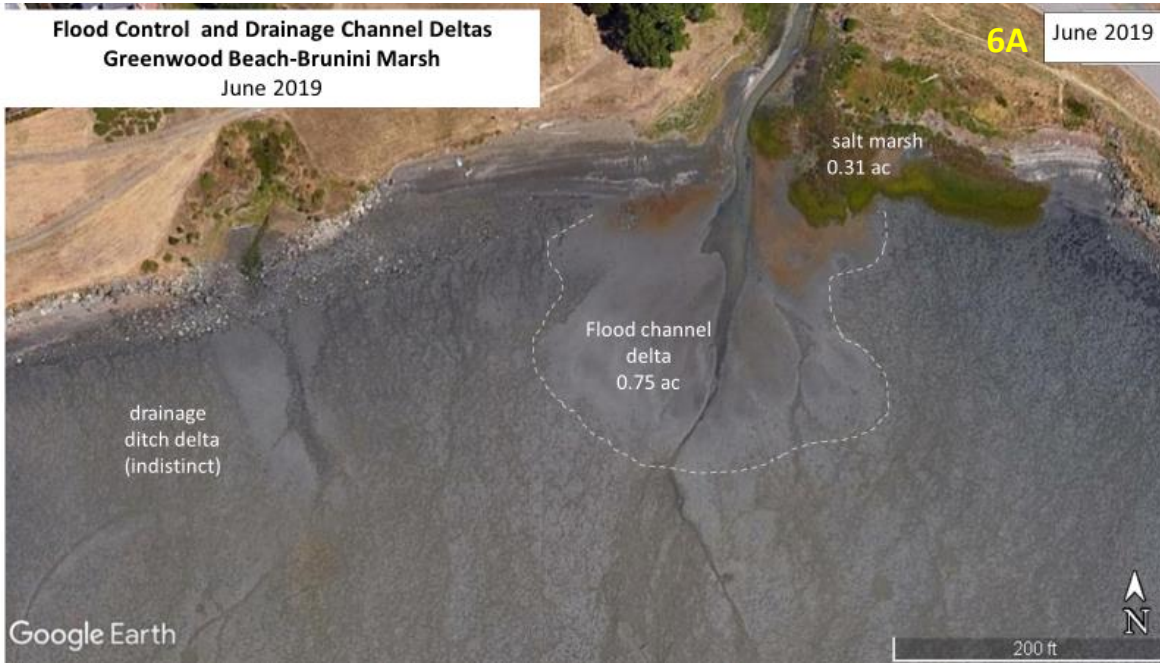
Figure 6. Delta of flood control channel (ditch) at Greenwood Beach, deposited on the low tide terrace A) aerial view, June 2019. Google Earth image. B) delta distributary channels, bars, and lateral lobes, February 2019. C) east lateral lobe of delta; persistent gravel and sand deposited over sandy mud by winter storm discharges, June 2012. D) flood control channel with fringing tidal salt marsh banks above pedestrian bridge, June 2012. E) Flood control channel mouth above intertidal delta at low tide, exposing cobble-boulder lag (sill), June 2012. F-G) active deposition of gravel and sand in upper delta shoal at mouth of flood control channel following rainfall, February 2019.

Figure 7. Deltaic fringing salt marsh flanking the flood control channel mouth, bordering beaches. A-B) Wave-deposited sand swash bars forming high marsh berms in pickleweed marsh, west marsh, during high tides and high wave action in November 2016 (B) and August 2017 (B). C) High tide transition zone (creeping wildrye dominant) and high salt marsh (pickleweed dominant, background), landward edge of east marsh. (D) east salt marsh at high tide, with emergent canopies of California cordgrass colonies and high pickleweed marsh, August 2017. E) wave-disturbed high salt marsh, east marsh, with patches of tule litter (from eastern SF Estuary), salt marsh dodder, alkali-heath, fat-hen, and pickleweed. F) East salt marsh substrate: wave-reworked sand (backshore beach progradation on delta platform) with decomposed tidal litter forming organic salt marsh upper soil horizon.

8 A

8 B

8 C

8 D

Tiburon Linear Park
North end
June 2019

8 E

Google Earth

300 ft

Figure 8. Shoreline rock and rubble armoring bordering Greenwood and Brunini Beaches. A) Concrete rubble, slabs, and rock armoring of low artificial fill bluff at west end of Greenwood Beach, above rubble intertidal lag surface, June 2012. B) Concrete rubble, slabs, and rock armoring of artificial fill bluff east of Brunini Beach to Tiburon Linear Park. C-D) extensive intertidal armoring of shoreline west of Greenwood Beach, bayward of residential lots, with large asphalt and concrete slabs. E) aerial view of continuously armored shoreline southeast of Brunini Beach (left), bayward of a wastewater treatment facility.

2.5 Recent shoreline evolution: beach, delta, salt marsh patterns and trends

The east half of Greenwood Beach has recently expanded from erosion of salt marsh formed on the platform of the western delta lobe. Salt marsh extended nearly half the length of the beach, from the channel mouth west, as recently as 2009 (Fig. 9). The deltaic native salt marsh developed prior to the modern beach, and expanded significantly during invasion of non-native hybrid cordgrass (*S. alterniflora* x *foliosa*) up to the late 2000s (Fig. 9). Hybrid cordgrass trapped and stabilized sand and mud until control was implemented by the California Coastal Conservancy's Invasive Spartina Project/Spartina Control Program over several years. Following eradication of the hybrid smooth cordgrass, the outer edge of the denuded sandy marsh sediment partially eroded from exposure to wave action, and released sand. The expansion of Greenwood Beach around 2012 and later corresponded with increasing erosion of the west salt marsh after removal of wave-damping hybrid cordgrass. A low sill of remnant cohesive peaty marsh mud, and a small area of sandy high salt marsh along the backshore, remained in 2019. The small remnant eroded high marsh appears to have reduced capacity for trapping and retention of beach sand transported by longshore drift towards the channel by westerly wind-waves. In 2009, the high salt marsh appeared to confine the beach's eastern extent.

Based on interpretation of available aerial imagery and intermittent ground observations, the recent long-term accretion and erosion patterns of Greenwood Beach appear to be related to long-term shoreline adjustment after eradication of marsh-stabilizing non-native hybrid cordgrass in the late 2000s, and variations in the growth of the intertidal delta. Greenwood Beach expansion corresponded with net erosion of sandy salt marsh sediments. Erosion of salt marsh increased unvegetated area available for wave transport of sand and beach accretion, and apparently released sand trapped by hybrid cordgrass marsh. Eradication of hybrid non-native cordgrass returned the shoreline to a condition similar to the 2002 aerial images showing extensive, wide sand beach and limited patches of salt marsh in the inner delta. The past and current contribution of the flood channel and delta to the beach sediment budget is has not been quantified, but appears to be significant based on morphological changes in beach, salt marsh, and unvegetated delta shoal and distributary channel patterns on the low tide terrace adjacent to beach and salt marsh.

Greenwood Beach
June 2019

9 A

BLACKIE'S PASTURE
ruderal grassland

High salt
marsh

Backshore beach

Low bluff

Intertidal beachface

Boulder
rip-rap

Relict peaty
marsh mud
outcrops

Flood
control
channel
mouth

Rubble lag foreshore
(concrete, asphalt, rock)

Google Earth
©2020 Google

delta lobe
(firm sandy mudflat)

N

100 ft

Greenwood Beach
October 2009

9 B

Backshore beach

Intertidal beachface

High salt
marsh

Rubble lag foreshore
(concrete, asphalt, rock)

Mudflat
(submerged)

Google Earth

N

100 ft

Figure 9. Greenwood Beach and marsh erosion patterns. A) aerial view Google Earth, June 2019, showing beachface extending continuously to the flood control channel mouth, and associated shoreline features. B) aerial view Google Earth, October 2009, showing the beach confined by a larger high salt marsh extending from the flood control channel mouth west across the east third of the beach. C-D) erosional scarp in artificial fill above the erosional beachface, west end, exposing horizons of earthen fill and mixed asphalt and concrete rubble, February 2019. E-F) wave-eroded relict hybrid cordgrass root mats (peaty fine sand and mud; residual deltaic marsh soils) outcrop and form low-relief sills at the east end of the west beach bordering the flood control channel, overlying poorly sorted, coarse gravel, sand and mud of the upper delta platform (F).
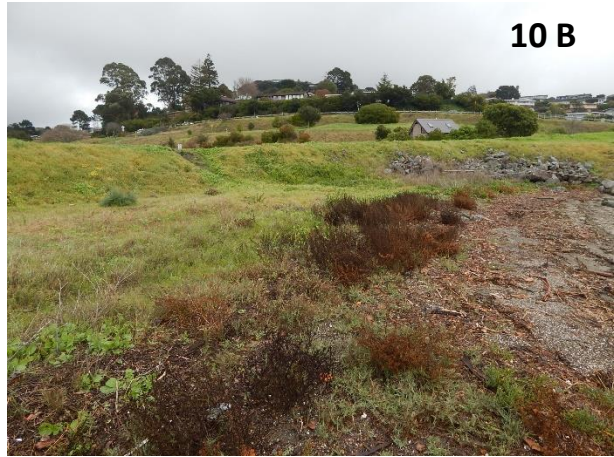
Figure 10. Brunini Beach, a pocket beach between salt marsh and boulder-armored bluff, November 2016. A) view to east, showing late fall beachface (shell, gravel sand) and high tide backshore zone with storm high tide drift-lines. B) Stabilized backshore beach terrace (past beach berm progradation, lowland terrestrial vegetation) landward of drift-lines, November 2016.

Greenwood Beach

Hybrid cordgrass colonization

May 2002

Greenwood Beach

Hybrid cordgrass colonization

Oct 2005

Figure 11. Hybrid cordgrass colonies establish within the prograding deltaic salt marsh of the Greenwood Beach-Brunini Marsh complex, 2002-2005.

Greenwood Beach-Brunini Marsh delta

May 2007

12 A

Google Earth

200 ft

Greenwood Beach-Brunini Marsh delta

July 2009

12 B

Google Earth

Image © 2020 Maxar Technologies

200 ft
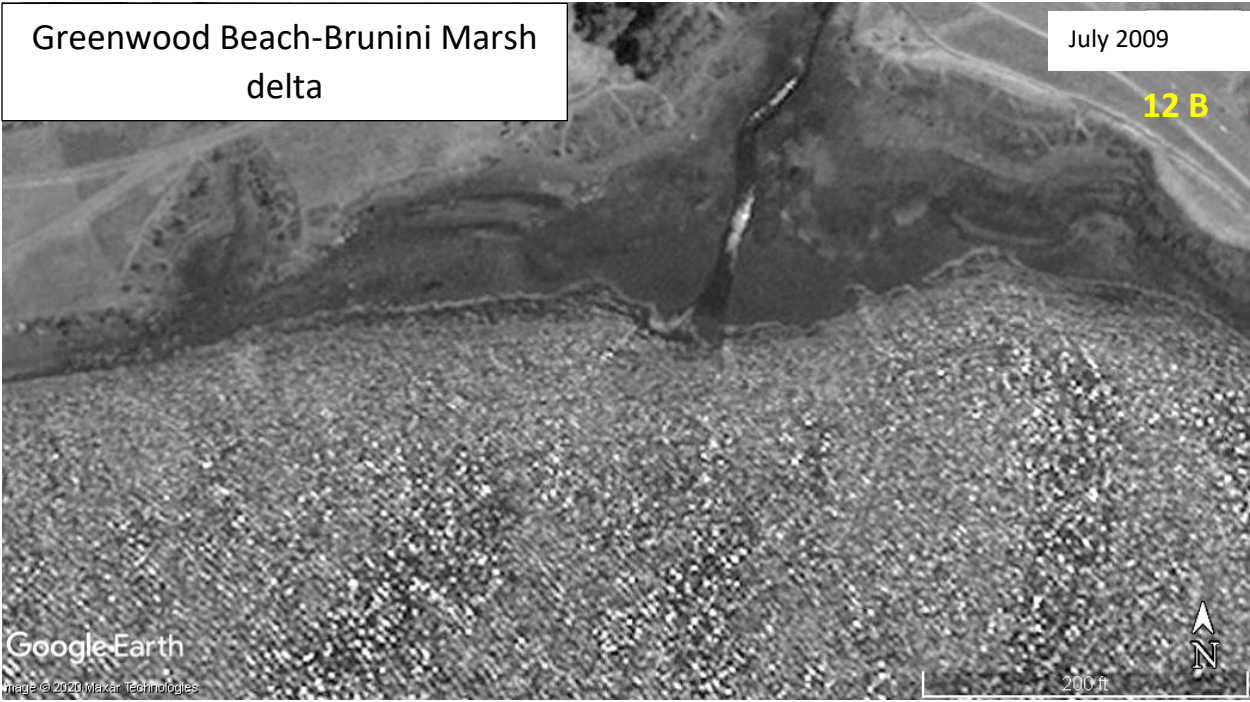
Greenwood Beach-Brunini Marsh delta

February 2011

12 C

Greenwood Beach-Brunini Marsh delta

May 2012

12 D

Greenwood Beach-Brunini Marsh delta

May 2017

12 E

Greenwood Beach-Brunini Marsh delta

June 2019

12 F
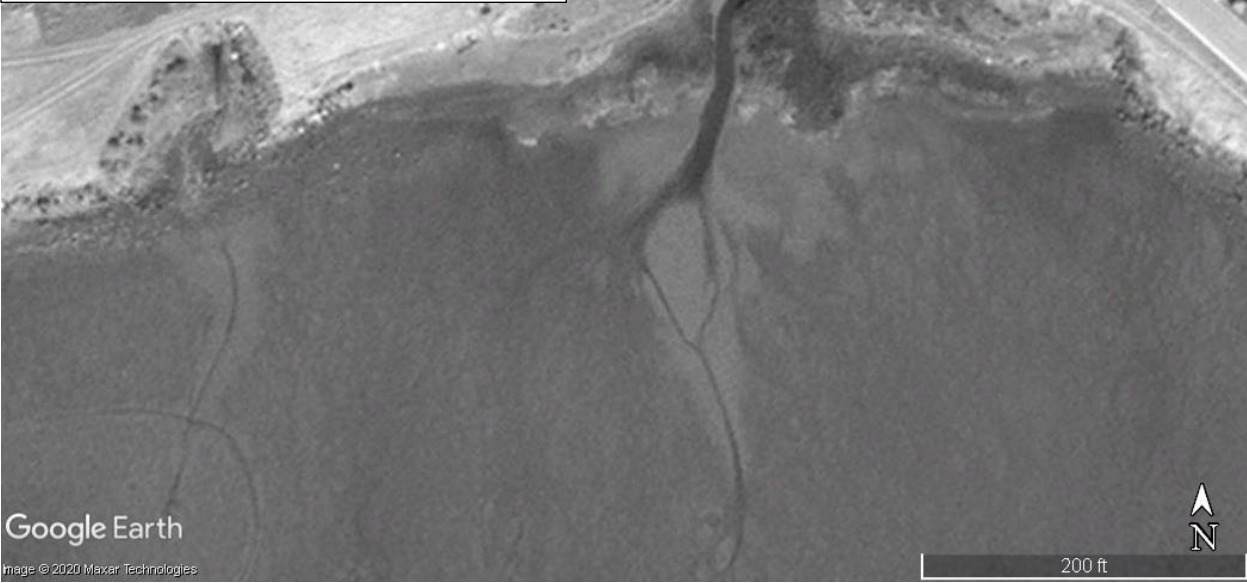
Figure 12. Salt marsh erosion and lateral beach expansion of the Greenwood Beach-Brunini Marsh delta complex from 2007-2019, corresponding with narrowing of the west beach and irregular change in the intertidal delta shoals and distributary channels of the flood control ditch/channel.

2.6. Historical Greenwood barrier beach and backbarrier salt marsh. The historic natural baylands of the site, prior to reclamation in the early 20th century, were shown in U.S. Coast Survey map T-334N, prepared in 1851. The shoreline shows a clearly delineated narrow supratidal (stippled) barrier beach with no tidal inlet, enclosing a non-tidal salt marsh with two shallow (hatched salt marsh symbol) pools or ponds. There are no defined marsh interior channels connecting either intermittent tidal inlets, or terrestrial streams or deltas from the drowned, marsh-filled valley above. The historical barrier beach extended east across the bay head, contacting the Greenwood Beach headland. The symmetrical (uniform width) beach was located above narrow intertidal flats. The supratidal barrier beach width was approximately three times the width of the narrow intertidal flats below them, similar to the proportions of the Richardson Bay Audubon Sanctuary beaches today.

The 1851 shoreline indicates that early historic Greenwood Beach was originally a distinct, relatively larger, wider barrier beach compared with its modern remnants. The barrier beach must have gradually retreated landward over backbarrier salt marsh during slow sea level rise of the late Holocene (Atwater *et al*. 1979, Malamud-Roam *et al*. 2006), but without a contemporary active stream mouth reaching the shoreline, delivering beach-size sediment to the littoral cell. This barrier beach system contrasts with the narrower cliff-toe pocket or fringing beaches shown in the 1851 T-sheet along NE Richardson Bay. It also contrasts with the modern beach surrounded by armored, stabilized shorelines, and a channelized connection to watershed sediment, terminating in an active intertidal delta, including the beach and fringing channel-mouth (delta) salt marsh. The 1851 barrier beach and backbarrier marsh appear to occupy a drowned (late Holocene transgression) lowland valley.
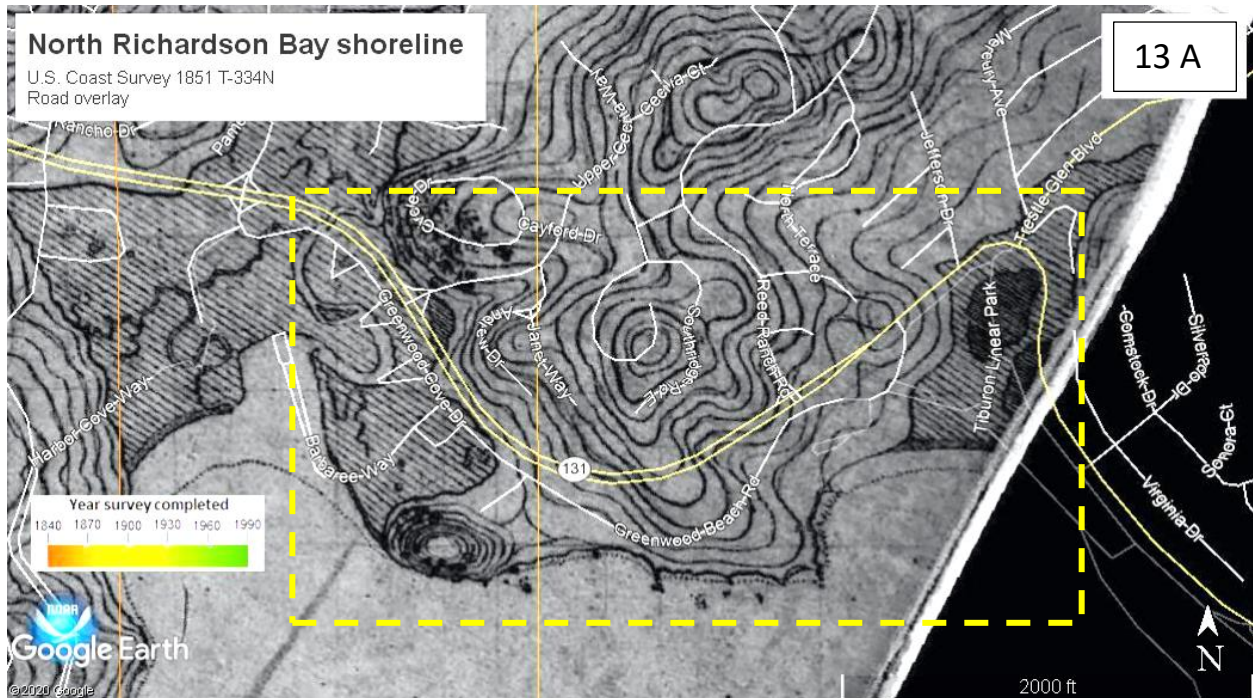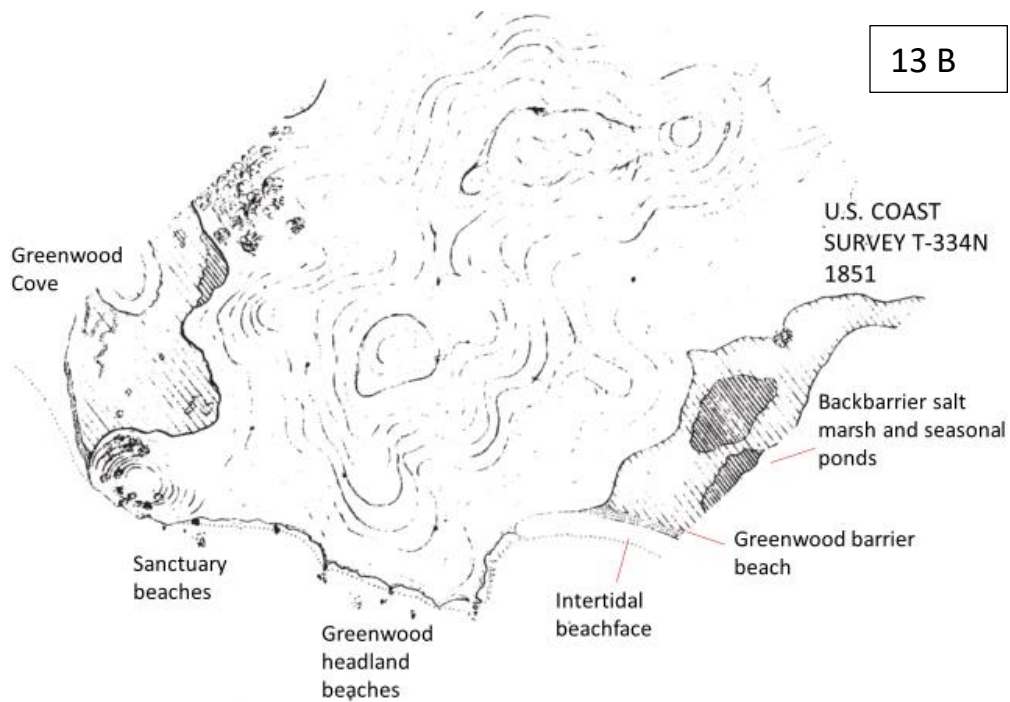
Figure 13. Historical Greenwood Beaches (U.S. Coast Survey T-334N, 1851) include a gravel spit extending north across Greenwood Cove, pocket headland beaches at modern locations, and a barrier beach and non-tidal salt marsh lacking channels occupying the lowland of modern Pasture open space areas. A) overlay of modern streets and shoreline on excerpt of T-334N (NOAA https://shoreline.noaa.gov/data/datasheets/t-sheets.html). B) annotated interpretation of coastal landforms of original T-334N in the site vicinity.

3.0 Objectives

The specific proposed objectives to inform beach restoration/enhancement design options include:

Geomorphic Resilience

- Significantly reduce beach and bluff wave erosion. Significantly reduce bluff instability and toe erosion risk (planning horizons near-term and long-term; options 10-20 yr, 20-50 yr, and 50+ yr).

- Increase the beach's capacity and rate of recovery following episodes of storm erosion.

- Restore mixed sand-gravel beach berm and beachface conditions (backshore summer berm width and annual variability) to pre-erosion, pre-hybrid Spartina conditions (circa 2002) to the greatest extent feasible

Land Use and Management

- Maintain and enhance safe year-round high tide beach access from east to west ends of Greenwood Beach. Minimize construction time or conditions that impair short-term beach access or recreational quality.

- Maintain and enhance Town of Tiburon public park and established recreational uses of the site. Minimize conflicts between public shore access, recreational use, and enhanced shoreline habitats. Enhance scenic, and other esthetic values of the shoreline for park visitors year-round.

- Minimize short-term and long-term ecological impacts related to construction and maintenance or adaptive management. Protect existing utilities, including the existing flood control channel (ditch) conveyance for stormwater discharge to the bay, and public trails.

- Spread costs of construction and maintenance over time; minimize short-term budget and cost burdens to landowner (City of Tiburon).

- Maintain and enhance (increase resilience to erosion; augment diversity and habitat quality) of existing salt marsh habitats.

- Increase long-term beach ecosystem resilience to direct indirect sea level rise impacts.

- Minimize impacts to the existing salt marsh habitats and experimental populations of endangered California sea-blite (*Suaeda californica*) established for research by San Francisco State University, Estuary and Ocean Science Center, Boyer Wetland Laboratory.

4.0 Greenwood and Brunini Beach conceptual design components

4.1. Layout and Integration of beach features

The overall conceptual layout of estuarine beach designs integrated with local salt marsh is illustrated as a sketch based on 2017-2018 baseline conditions, shown in Figure 14. The existing Greenwood Beach, and the smaller Brunini Beach are nourished with heterogeneous mixed sand and gravel in the intertidal beachface. Sediment texture would approximately match the existing proportions of beach grain sizes, which are predominantly medium to coarse sand. The proposed sand and gravel placed as part of this project would be reworked by wave action in fall and winter, mostly retained between low-relief vegetated and rocky topographic impediments to longshore drift that are artificially enlarged to form littoral sub-cells of locally impeded longshore transport. An additional small pocket beach is created next to the east beach, within a minor new pocket littoral cell defined by short, low boulder groins. Salt marshes are left intact to interact with increased volumes of mobile sand in the adjacent beaches.
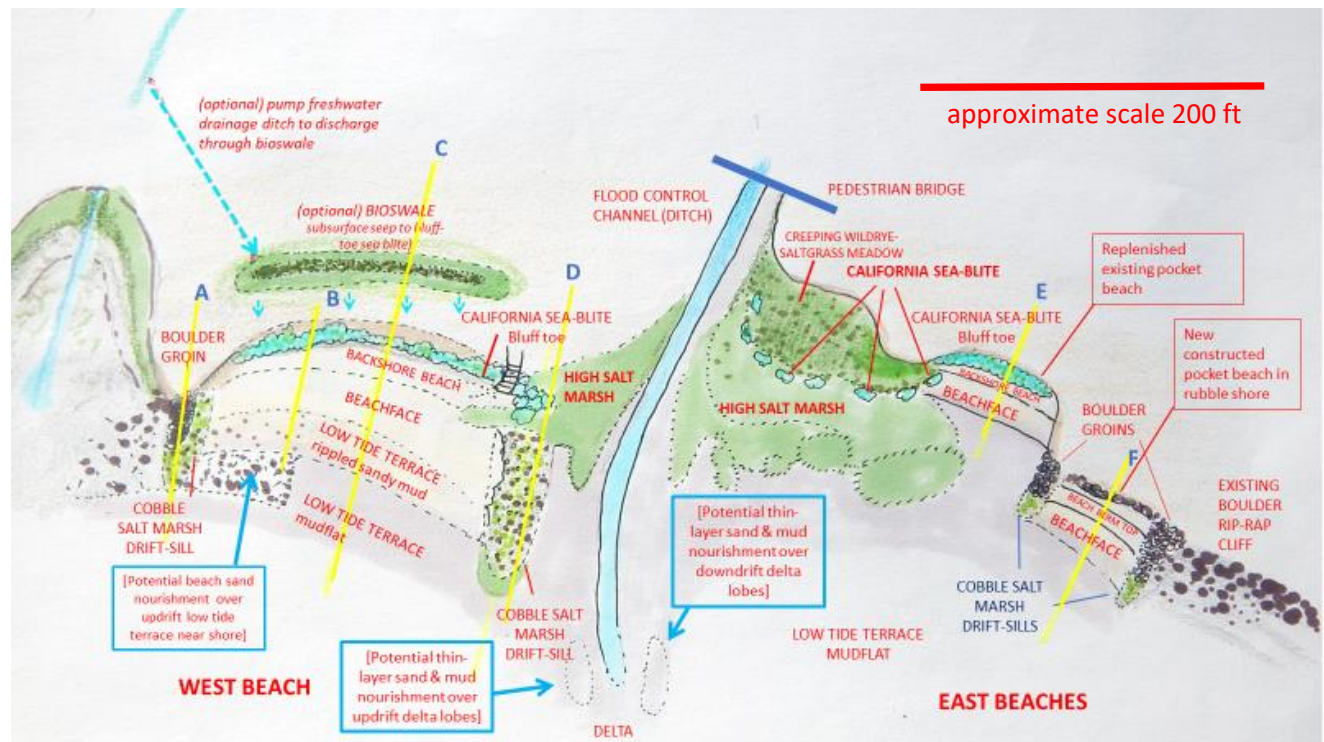
Figure 14. Overall conceptual layout of estuarine beach designs integrated with local salt marsh at Greenwood and Brunini Beaches. Scale approximate; based on 2017-2018 baseline conditions. See Figures 17-19below for sections.

4.2. Greenwood Beach. The proposed Greenwood Beach consists of a periodically nourished beach profile enclosed by low-relief, vegetated cobble salt marsh drift-sills. Cobble salt marsh drift-sills are "living shoreline" versions of beach groins for San Francisco Bay shorelines where beaches and salt marshes co-occur. They are semi-permeable, low-relief vegetated erosion-resistant cobble salt marsh with crests slightly above beach grade, acting as partial barriers to longshore drift. Their conceptual design and dynamics are described in Section 4.4.3 below. Some of the drift-sills merge with, expand, and protect existing high salt marsh. Some drift-sills merge with groins composed of small boulders and

large woody debris and logs, where rubble and rocky fill exists. At the back of the beach profile, near the toe of the bluff, a small existing gravel storm berm would be enlarged by localized deposition of coarse gravel in a narrow backshore zone about 4-6 ft wide. The gravel would be reworked by storm waves only, redeposited as a defined berm on the erosional, lower storm beach profile. The gravel storm berm would typically be buried by sand during phases of beach accretion in spring and summer, and re-exposed and activated during storm conditions, when it would intercept storm wave runup.

The backshore (above normal tide) zone of Greenwood Beach would be modified to increase wave energy dissipation by re-grading the near-vertical barren, reflective wave-cut low cliffs to a ramp-like bluff profile supporting perennial salt-tolerant creeping substrate-stabilizing native shoreline vegetation. The set-back bluff crest, gentler slopes, and vegetative stabilization (increased soil strength to resist erosion, canopy roughness to dissipate wave energy) would increase dynamic resilience of the bluff during shoreline retreat, erosion episodes, and post-storm recovery and recolonization phases. The ramp-like lower bluff slope at the shoreline would be vegetated with the native salt marsh/estuarine beach shrub, California sea-blite, which is expected to spread up the bluff as it does in many natural shoreline settings.

Sand beach nourishment would occur as profile nourishment: placement of sacrificial shallow deposit of unconsolidated sand across the active intertidal beachface, with relatively greater volume at the west (presumed net updrift) end of Greenwood beach, along the east side of the drift-sill. The western intertidal delta lobes (shoals of stratified sand, gravel and mud) themselves may be also be considered as potential locations of indirect sediment nourishment for both salt marsh and beaches. Past patterns of deltaic salt marsh and beach accretion suggest that aggraded delta shoals have supplied sand to the adjacent beaches and marshes. Hydraulic placement of heterogeneous sediment slurry over the natural storm-deposited delta shoals could supply a similar mix of silt, sand, and gravel to augment the local sediment budget, and increase wave energy dissipation over accreted intertidal flats.

Sand beach nourishment would likely be performed by mechanical placement by ground-based equipment accessing the shoreline from road-accessible uplands. Sand would likely be transported onshore or embedded in the low tide terrace. Silts would be resuspended, dispersed, and some would likely become incorporated in local mudflats or marshes. Flood control channel maintenance (removal of muddy sand or gravel bars) may be a source of sediment for hydraulic placement. An modified approach to mechanical placement of sand on the beach may include (a) hydraulic discharge of slurried sand or sand/gravel mixtures over the upper delta and beachface at low tide, forming sand splays (fans like small deltas), or (b) hydraulically redistributing mechanically placed sand mounds into washed sediment fans with a high-pressure firehose, using bay water pumped at mid-tide. Hydraulic placement of sediment to the delta (indirect beach nourishment) could be dispersive placement of mechanically placed sediment into the mouth of the flood control channel during periods of very high storm outflow, in small, incremental batches. This may be considered a component of dual beach profile nourishment of Greenwood Beach and salt marsh nourishment of Brunini Marsh.

4.3. Brunini Beach and Marsh. The small existing pocket Brunini Beach would also be nourished by mixed sand and gravel deposited in the beachface for reworking by waves. No storm gravel berm is proposed for the Brunini Beach, which is partially sheltered by the (currently) expanding salt marsh. The relict wave-cut scarp behind Brunini Beach has not been actively eroding in recent years, and is vegetated with weedy species that provide little bank stabilization. California sea-blite plantings at the

toe of the Brunini Beach bluff, set behind a more protected, prograded, nourished sand beach profile, are expected to provide increased bank stabilization over time. California sea-blite stands with enhanced wave-damping canopies (clambering vegetation supported by coarse driftwood or similar wood trellis support), backed by enlarged stands of coarse clonal perennial native grasses (creeping wildrye, *Leymus ×gouldii* and *L. triticoides*). Creeping wildrye is already established as large patches at the back of the Brunini marsh/beach terrace, and could be spread by transplanting and burying sod clumps in early winter. Expanded colonies of creeping wildrye at the back of the terrace, and California sea-blite and the beach and salt marsh, would together provide a broad gradient of vegetative roughness to trap overwash-deposited sand, and attenuate wave energy.

The deltaic salt marsh platform and sea-blite colonies of Brunini Beach and salt marsh would indirectly be nourished with sand drifting from the beach during storms, providing sediment for vertical accretion of sandy high salt marsh berms – an alternate state of low-gradient, low-energy estuarine beaches. Both beach and salt marsh accretion would be expected to increase after each episode of sand re-nourishment at Brunini Beach.

An additional small pocket beach, similar in size to the existing pocket East Beach, would be established over existing rubble and boulder upper intertidal shoreline. It would be enclosed by a composite groin and cobble salt marsh drift-sill, partially constructed by restructuring existing rubble to form a low boulder groin, and extending it bayward to near Mean Sea Level with a vegetated cobble salt marsh drift-sill.

The beach-salt marsh complex design is intrinsically dynamic and phased over time to balance beach and salt marsh sediment budgets with deficits caused by sea level rise and infrequent extreme erosion events.

4.4. "Living Shoreline" beach and salt marsh components supporting sand beach nourishment

The specific components of the overall conceptual shoreline design, aimed at modifying longshore drift and retention of sand within littoral cells, and resilience of backshore bluffs to storm wave erosion and sea level rise, are described in detail below.

4.4.1. Backshore Bluff slope

The existing bluffs at Greenwood Beach include a low, mostly bare wave-cut cliff (scarp) in artificial bay fill (Figures 8, 9)). The cliff is nearly vertical after storm wave erosion events, which expose asphalt and rubble fill at the toe. The bluff height depends on the variable sand-gravel backshore beach elevation and its erosion/accretion cycles, but it ranges up to nearly 5 feet. The near-vertical cliff face is mostly unvegetated because of recurrent wave erosion, but weedy herbaceous vegetation occurs sparsely. The bluff gradient flattens and lowers to the east, grading into a gentle slope with no scarp near the channel. The upper cliff is mostly consolidated subsoil fill. The substrate and extremely steep slope of the unstable bluff reflect storm waves, are not conducive to establishment of gentler slopes and roughness of perennial vegetation that could dissipate wave energy and increase bank stability, interacting with the replenished backshore beach profile.

The bluff at the East Beach is an inactive, relict scarp forming a predominantly vegetated steep slope, dominated by non-native weeds with low capacity for soil binding, erosion resistance, or slope stabilization. The substrate is also a mix of infertile, compacted subsoil and rubble fill.

The proposed treatment of the bluff is aimed at providing a gentler slope with substrate supporting perennial vegetation that is capable of dissipating wave energy and reducing wave runup by friction from a rough shoot canopy, and increasing bank strength with root systems, stabilized by native estuarine beach, high salt marsh, and bluff toe vegetation including saltgrass and California sea-blite. Reference system model for the design is provided by a low bluff (relict wave-cut scarp and slumps, naturally stabilized vegetatively) at Fairbanks Point, Morro Bay (Central Coast); natural San Francisco Bay analogs from Oakland, Alameda and San Francisco have been eliminated by urban expansion since the 19th century.

Figure 15. A low weakly consolidated coastal bay bluff (sandstone and Quaternary sandy dune and alluvium) above a west-facing estuarine beach at Fairbanks Point, Morro Bay, approximately 3-15 ft high, is vegetatively stabilized by California sea-blite and perennial high salt marsh vegetation including saltgrass and alkali-heath above a narrow low-energy fringing bay beach (2019). This is a model for vegetative stabilization of a low bluff above an estuarine low-energy beach at Greenwood Beach.

This may be performed by measures modified from the approach used at Aramburu Island shoreline enhancement (Wetlands and Water Resources 2010):

- Remove asphalt and other deleterious materials from the existing shoreline and dispose of at an appropriate facility. There is a lot of asphalt for example along the shoreline that should be removed from the shoreline. It is anticipated that some of the concrete can be reused along the shoreline but that some of the flatter slabs of concrete may need to be removed, broken up and recycled or potentially the more roundish concrete pieces may be able to be reused along the shoreline.
- Set back the bluff crest by grading the bluff scarp to a less steep more ramp-like profile (proposed as 3:1-5:1 h:v).
- Construct a storm cobble berm as an erosion resistant backstop in the event of shoreline erosion
- Backfill the graded ramp-like slope profile to provide a root zone, minimum 1 ft deep, composed of suitable substrate (sandy clay loam to sandy silt loam) to support transition zone (beach-terrestrial grassland) vegetation
- Actively revegetate the slope with selected native plant assemblages including salt-tolerant native clonal perennial grasses and subshrubs (bank stabilization, sediment trapping, and wave

dissipation functions), including California sea-blite, saltgrass, and creeping wildrye (see Vegetation, below).

Approximately match sediment size range to the existing beach system. Sediment quantities and sizes will be further refined during the next preliminary design phases of the project. For the Aramburu Island project, the quantities ranged from 2 to 3 cy/lf but these will need to be developed during the next project phase.

The cost for Aramburu was approximately $1,200 to $1,500 per linear foot but Greenwood Beach is expected to be significantly less, given the excellent access and that specialty marine equipment and contractors will not be needed.

Spoils (graded fill) from the ramp and set-back bluff crest grading could be spread as a topsoil layer in the zone between the set-back crest and the optional bioswale (see below). The topsoil should slope very gently landward to minimize gully and rill erosion at the ramp/bluff crest. This soil cap could be stabilized by plugs of perennial, slow-growing, trampling-tolerant, turf sod-forming native creeping wildrye (*Leymus triticoides*) and saltgrass (*Distichlis spicata*; see Vegetation, below), with a transitional fast-growing erosion-control seed mix of non-native annual ryegrass (*Festuca perenne*, syn. *Lolium perenne*), which is already abundantly established at the rough pasture/turfgrass of the park. The perennial creeping native components of the enhanced grassland would help regenerate soil-stabilizing vegetative cover and sod at the top of the bluff following future episodes of storm wave erosion. This process would operate in concert with vegetative recolonization by upslope-creeping high salt marsh vegetation at the bluff toe following erosion events.

Constructability of the Greenwood and Brunini Beach project is excellent, and much easier than at other beach projects such as Aramburu which as an island required marine transport which is much more costly. Site access is excellent, and there are large areas that could be used by the contractor for equipment and material storage within minimal impacts to park uses. There will be some impacts to public usage but overall, these are expected to be minimal. Construction feasibility and design will have to be reviewed and approved by the Town of Tiburon during future design and permitting phases of the project.

4.4.2 Bluff-top bioswale (optional)

A bluff-top swale is proposed as an optional feature to enhance the performance of the bluff vegetation stabilization functions (erosion resistance, wave dissipation) and improve water quality affected by runoff from the dog recreation activity of the park. The design is essentially similar to "bioswales" of urban runoff detention designs, but aimed in part at directing subsurface seepage towards the shoreline, in addition to water quality improvement.

The bioswale would be an inconspicuous gently sloped swale (side-slopes about 5:1 or less; maximum depth below average grade less than 1 ft) aligned parallel with the bluff crest, extending landward of most the length of the west beach, approximately 150 ft. The bioswale would be set back at a distance allowing for gradual retreat of the regraded ramp-like bluff, approximately 30-50 ft behind the bluff crest. The swale soil profile would be enhanced with added organic matter (composted wood fines) and stabilized with native turf-forming seasonal wet meadow vegetation (tolerant of seasonal dryness and saturation) including clustered field sedge and creeping wildrye (see Vegetation, below). Spoils from

bluff ramp regrading would be gently sloped towards landward towards the bioswale, minimizing rill or gully erosion from runoff at the bluff.

The swale would drain and intercept runoff from the field and collect it for slow infiltration and subsurface seepage towards the bluff. The infiltration of runoff through soil and root zone microbial activity would likely intercept nutrients by plant uptake and immobilization in organic matter. Increased seepage towards the bluff toe would likely enhance vigor and growth rate of California sea-blite and saltgrass, increasing both below-ground biomass and shoot canopy height and density that provide stabilization functions. Additional seepage and water quality improvements favorable for the beach and its water quality could be provided by pumping freshwater discharges from the peripheral ditch draining residential irrigation and shallow groundwater at the back of Pasture parkland into the swale. This ditch currently discharges residential runoff and landscaping seepage directly to the bay west of the beach.

4.4.3. Cobble salt marsh drift-sills and groins

Greenwood and Brunini beach planforms are consistent with a predominantly swash-aligned pocket or bay-head beach that traps beach sand in a confined littoral cell. Although wind-wave approach to the shore is variable, predominant wave direction appears to be perpendicular to the beach (wave crests nearly parallel to the shore most of the time). There is no indication of significant net longshore drift, such as long-term asymmetric beach erosion or accretion along the shoreline. Short-term longshore drift of beach sand, however, can occur even in pocket beaches with little or no net longshore drift. Short-term longshore drift rates may be significant during infrequent periods of high wind-waves with strongly oblique wave approach. The risk of significant short-term longshore drift may increase during non-equilibrium beach profile conditions when additional sand and gravel added to the shoreline during beach nourishment episodes. Some modification of shoreline structure to restrict longshore drift may therefore be needed in this project.

To increase predictability and retention of nourished sand and gravel within local beach compartments (littoral sub-cells) "nature-based" living shoreline obstacles to longshore drift functionally similar to groins, incorporated into the shoreline design. Site-adapted variations on beach groins and drift-sills are described below.

Longshore drift and beach groins

Engineered beach groins (groyne, British spelling) are shore-perpendicular hard structures (rock, wood) designed to obstruct or slow longshore drift of beach sand or gravel, and retain sufficient volumes of it it within a designated shoreline cell to maintain a necessary or desired profile of a nourished beach (Dean 2000) or modified semi-natural beach (Nordstrom 2000). Groins generally extend across the full beach profile, but may allow for bypassing (drift beyond the groin tip) when the groin-altered beach profile is sufficiently filled with sand or gravel. They are also used to restrict migration of channels or inlets, like larger jetties which are designed to maintain permanently open navigable tidal inlets. Alternative variations of groins may be partially permeable to drifting beach sediment. Poorly designed groins and beach sediment management can result in objectionable, harmful down-drift sediment deficits and erosion. Well-designed groins, combined with sound beach nourishment, can avoid typical adverse downdrift erosion impacts of groins on the southern California coast (Griggs *et al.* 2020).

Constructed small-scale groin-equivalent features designed to be relatively low (near beach crest elevation) and short (near beachface width) serve as partial longshore drift obstacles on low-energy Puget Sound beaches gravel and sand within rocky shore settings. They have been termed "drift-sills" to distinguish them from typical groin designs (Johannesen *et al*. 2014). Drift-sills are equivalent to "micro-groins" designed in San Francisco Bay at Aramburu Island's constructed estuarine beaches (Wetlands and Water Resources *et al*. 2010).

A modified version of drift-sills is proposed here for ecological compatibility with estuarine shoreline settings where beaches intergrade with or contact salt marsh habitats. The "cobble salt marsh drift-sill" is based on natural but uncommon occurrences of erosion-resistant cobble lag armored surfaces in salt marsh vegetation, as well as salt marsh accretion over or within cobble beach shores. The basic concept of this vegetated drift-sill is to create a local small-scale cobble salt marsh headland to provide inconspicuous groin functions, using a fortified, cobble-armored, salt marsh capable of accretion and erosion-resistance to storm wind-waves.

Natural analogs of cobble salt marsh as basis of conceptual design

Cobble salt marsh is a local estuarine shoreline habitat type intermediate between cobble beach, rocky shore, and tidal salt marsh. Classic type cobble salt marshes (vegetated low-energy cobble beaches) develop over rocky lag or depositional cobble shorelines along retreating, erosional glacial till headlands in New England (Bruno 2000, Kennedy and Bruno 1999, 2000). In the San Francisco Estuary, local salt marsh within cobble lag armored mudflats or along stabilized cobble beaches occur rarely, such as west Point Pinole (Richmond, Contra Costa County) and some rocky shores and cobble beaches along Richardson Bay and Marin Islands (Marin County). Local San Francisco Estuary examples are shown in Figure 16.

Figure 16. Cobble salt marsh in the San Francisco Estuary. A-B). Cobble low salt marsh dominated by California cordgrass emerging through a cobble lag surface over peaty salt marsh soil in early spring, West Point Pinole, 2010. C-D) High salt marsh dominated by dense saltgrass sod mats over cobble lag beach and rocky shore in spring (C) and winter (D), Seminary Drive shoreline, Richardson Bay. E). Rocky intertidal shore (boulder and cobble lag) west of Greenwood Beach, 2012.

Cobble salt marsh surfaces are armored by erosion-resistant, immobile cobbles embedded in either firm bay mud, peaty marsh soil, or a matrix of cobbles, sand and mud (buried cobble beach profiles). Some cobble salt marsh locations, such as Point Pinole, appear to be highly stable over historical time compared with other salt marsh and beach shoreline types (Beagle *et al*. 2020). Cobble salt marsh also has gentle slopes and vegetation canopy structure and roughness capable of trapping finer sediment (sand, mud) and damping wave energy, as well as rhizome mats capable of colonizing and stabilizing accreted sediment and raising substrate elevations above cobble surfaces. In this sense, cobble marsh groins are analogous with dynamic "living shoreline" features like vegetated foredunes over cores of buried cobble berms (Komar and Allen 2010), but in estuarine salt marsh and beach settings instead of maritime sand beach and dune systems.

Cobble marsh drift-sills are proposed as conceptual designs for Greenwood and Brunini Beaches to serve multiple purposes:

- Their basic groin-equivalent functions are to retain beach sand and gravel within target shoreline areas during episodes of short-term net longshore drift (oblique wind-wave approach), and minimize potential short-term or long-term drift of sand across the mouth of the tidal drainage ditch (delta), where it could seasonally restrict tidal flows and impair water quality in the park.
- Their main "living shoreline" functions are to provide dynamic potential vegetative sediment stabilization and accretion during depositional episodes (calm-weather wave deposition of silt, sand, and organic detritus), while providing storm erosion resistance when cobbles are exposed at the surface during winter storm wind-wave events. The cobble-stabilized rhizomatous high to low salt marsh vegetation (saltgrass, alkali-heath, Jaumea, California cordgrass) has potential to form sandy high salt marsh berms over the cobble-armored core structure, rising with sea level if beach sediment supply (which is also proposed for periodic nourishment) is sufficient.
- Their ecological "living shoreline" functions are to blend with natural dynamic beach and salt marsh interactions where they naturally occur, and historically occurred. Cobble marsh groins should enable all functions to coincide without sacrificing one habitat, structure, or function for others, thereby minimizing trade-offs between ecological and shoreline engineering objectives.

In addition to compatibility with ecological and coastal engineering objectives, cobble salt marsh drift-sills are proposed to be compatible with esthetic and recreational park uses: their vegetation and substrates would not be distinct from prior or adjacent shoreline areas, and their surfaces should provide safe shoreline access with adequate tolerance to light trampling that occurs in current conditions.
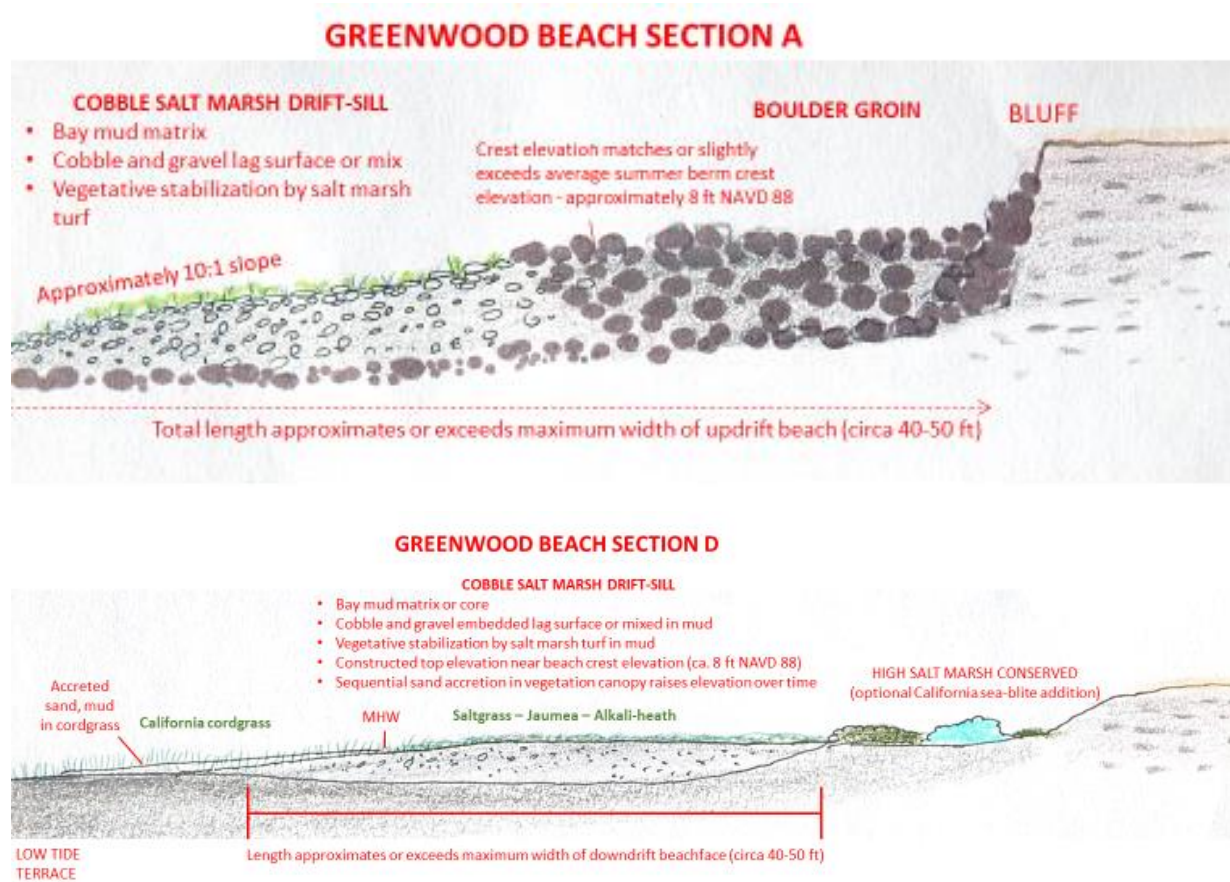
Cobble salt marsh drift-sill conceptual design options

Cobble salt marsh drift-sills are gently sloping, flat-topped vegetated berms composed of two layers: (a) a core of either bay mud or a matrix of bay mud, cobble, gravel and sand; (b) a surface veneer of closely spaced cobbles embedded in a matrix of interstitial bay mud, mixed with sod fragments (root/rhizome mat and embedded soil) containing viable clonal fragments of salt marsh vegetation. Vegetative sod fragments would be mixed with bay mud during in the veneer during construction while they are in dormant or quiescent (hardened, inactive) growth phases in fall, winter, or early spring. The rhizome bud bank of the embedded vegetative fragments in the bay mud matrix, within the upper 10-15 cm of the cobble veneer surface, are expected to emerge as shoots and spread roots and rhizomes in mud interstitial spaces, binding the cobbles during the first growing season after construction.

Plant species composition of the mud-cobble veneer would correspond with two (rough, approximate) tidal elevation zones: saltgrass, alkali-heath, and jaumea above Mean High Water, and cordgrass below Mean High Water. Clonal spread of each species, and sediment accretion, would adjust species distribution along the gradient. Temporary wind-wave stabilization of the exposed interstitial bay mud at the surface of the cobble salt marsh sill, immediately after construction and before vegetation establishes in the first growing season, may be provided by a very thin (2-3 cm) veneer of fine gravel.

Conceptual designs of two cobble salt marsh drift-sills for Greenwood Beach are shown in Figure 17. The western cobble salt marsh drift-sill merges with a boulder-cobble or log-boulder groin at the headland point (Section A), grading down to intertidal rubble lag. The eastern cobble salt marsh drift-sill (Section C) merges with a pre-existing sandy high salt marsh berm, and grades bayward into low tide terrace flats

(mixed gravel, sand, mud) of the delta. The approximate typical dimensions and composition of the cobble salt marsh drift-sills for Greenwood and Brunini Beaches are shown in Figure 18.

GREENWOOD BEACH SECTION A

COBBLE SALT MARSH DRIFT-SILL
- Bay mud matrix
- Cobble and gravel lag surface or mix
- Vegetative stabilization by salt marsh turf

BOULDER GROIN

BLUFF

Crest elevation matches or slightly exceeds average summer berm crest elevation - approximately 8 ft NAVD 88

Approximately 10:1 slope

Total length approximates or exceeds maximum width of updrift beach (circa 40-50 ft)

GREENWOOD BEACH SECTION D

COBBLE SALT MARSH DRIFT-SILL
- Bay mud matrix or core
- Cobble and gravel embedded lag surface or mixed in mud
- Vegetative stabilization by salt marsh turf in mud
- Constructed top elevation near beach crest elevation (ca. 8 ft NAVD 88)
- Sequential sand accretion in vegetation canopy raises elevation over time

HIGH SALT MARSH CONSERVED (optional California sea-blite addition)

Accreted sand, mud in cordgrass

California cordgrass

MHW

Saltgrass – Jaumea – Alkali-heath

LOW TIDE TERRACE

Length approximates or exceeds maximum width of downdrift beachface (circa 40-50 ft)

Figure 17. Conceptual illustration of composite cobble salt marsh drift-sills in the beach intertidal zone (beachface) and boulder groin (or log-boulder groin) in the backshore zone of Greenwood Beach. Sections are keyed to Figure 14. Section A = west end (boulder headland); Section D = east end (bordering high salt marsh and delta, channel)
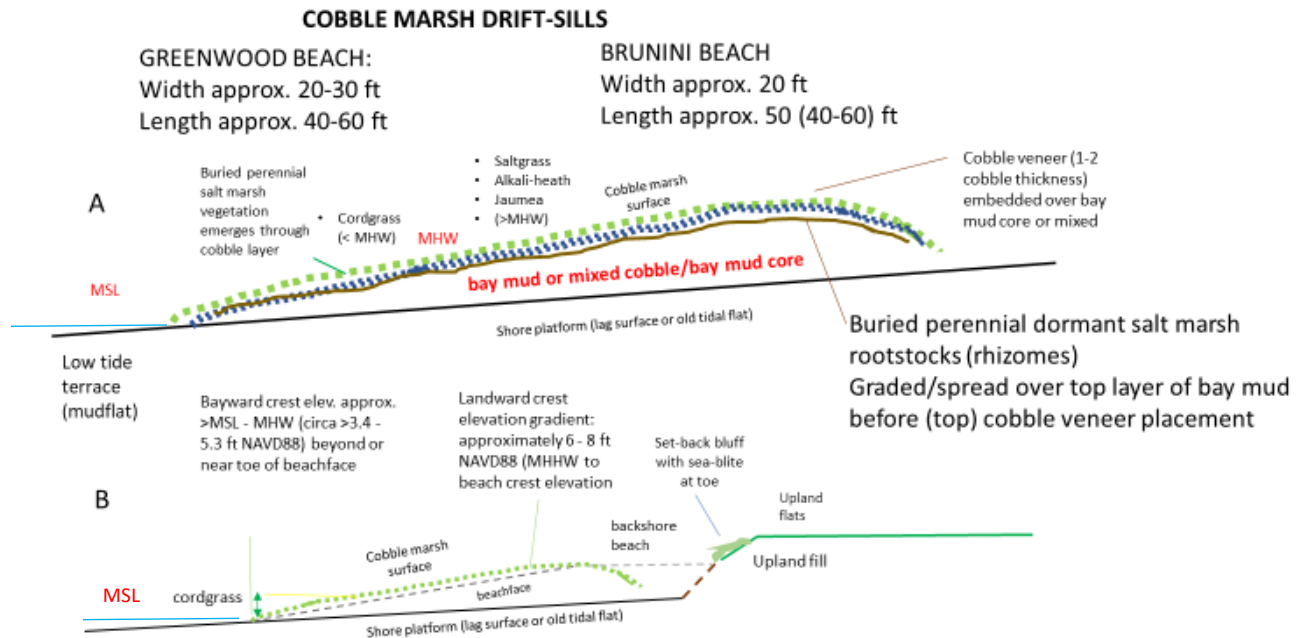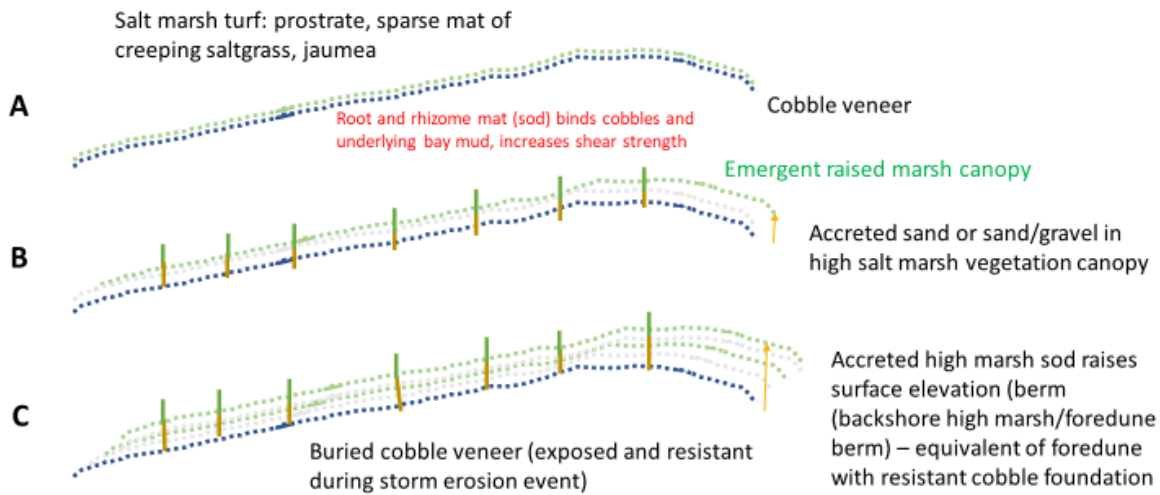
Figure 18. Schematic cross-sections of cobble marsh drift-sills fitted for A) Greenwood Beach and B) Brunini Beach.

The conceptual design options of a bay mud berm core, or a more fortified cobble-gravel-sand-mud core, may depend on the load-bearing capacity of the shore platform on which cobble marsh drift-sills are constructed. The higher bulk density of the cobble-filled core would require a firm shore platform (old, settled rocky bay fill or wave-cut bench in cliff or bluff). Lower bulk density of homogeneous bay mud may be more appropriate on poorly consolidated beach, bay mud or salt marsh platforms

The long axis of the constructed cobble marsh drift-sill would range in elevation from the beach crest to the bayward terminus of the sill, grading into the low tide terrace at or below the toe of the beachface. The shore-perpendicular long axis slope would approximate that of the beachface slope (near 1:10-1:11 at local reference beaches). Side-slopes of drift-sills, parallel to shore, would be mostly buried by the beachface in non-storm conditions, except near the crest. At construction, they would be no steeper than 1:3. The slopes and elevations of the drift sills would be dynamic during accretion and erosion phases of salt marsh and beach.

During net accretion phases, the vegetated surface of drift-sills would likely increase in crest elevation (high salt marsh up to wave runup elevation limit), broaden and widen, as shown in the sequence represented in Figure 19. Net accretion of vegetated drift-sills is most likely to occur in years following beach re-nourishment, or in years of low storm frequency and intensity, when beach sediment budgets are positive. During net erosion phases, their slopes may steepen, and re-exposure of the cobble-armored surface would lower crest elevations. Like cobble berm cores of artificial foredunes (Komar and Allan 2010), the actual surface of the cobble salt marsh drift-sill should be natural, self-constructed substrate and vegetation except during severe erosional and post-storm recovery phases.

Figure 19. Schematic diagram of sequential net accretion of sand and vegetation on cobble salt marsh drift-sill during depositional phases, cross-section view, landward end at right. A) Post-construction surface exposes cobble veneer (resistant lag surface) and initial rhizomatous vegetation growing in mud and sand of cobble interstices. B) Vegetation canopy traps wave-deposited beach sand and regenerates the shoot canopy at a raised position, as new roots and rhizomes bind the accreted sand layer. C). Multiple sequences of sand deposition, vegetation emergence and below-ground growth accrete a sandy root-mat of high to low salt marsh until extreme erosion events re-set the system at the original erosion-resistant surface.

Cobble salt marsh drift-sills are proposed along the margins of the tidal drainage channel, on delta lobes at the east end of the west beach, and at the opposite side of the channel (west end of the east shore). These banks exposed interbedded, poorly sorted and stratified gravels, sand, and mud associated with the delta lobes. The west side drift-sill would extend bayward from existing vegetated high salt marsh (sandy peaty marsh soil), across former salt marsh that has eroded. The east side drift-sill would extend bayward of high salt marsh adjacent to an existing patch of low cordgrass salt marsh. Drift-sills are proposed for construction in unvegetated tidal flats only, not in vegetated salt marsh.

Conceptual construction methods for cobble salt marsh drift-sills may include modification of the following components:

- Use of light, small equipment (such as bobcats) working from wood mats on relatively firm delta lobes extending from the shoreline.
- Sequential placement of firm, dry bay mud (drift-sill core), and an upper mantle of cover (cap) sediment composed of mixed cobble and wet, plastic to semi-fluid bay mud with embedded viable salt marsh sod fragments. Mixing of the sediments and sod pieces could be performed by rolling or double-handling the mixed stockpile of cover sediment. Bay mud could be wetted with fresh or salt water to achieve plastic, saturated consistency.
- Preparation of salt marsh sods by harvesting manually, or with a small excavator, from tidal salt marsh of artificial drainage ditches free from noxious invasive tidal marsh plants (e.g. Algerian sea-lavender, perennial pepperweed). Firm sods could be fragmented with a rototiller.

- Final surface treatment would include (a) very thin (1-3 cm) veneer of gravel to stabilize exposed interstitial mud at surface, washed over the constructed surface with a firehose pumping bay water from the ditch at any tide.

Cobble-boulder and log groins. Cobble salt marsh drift-sills could also be combined with cobble-boulder groins, or mixed boulder and coarse woody debris (log) groins, in higher estuarine wave energy shorelines where severe scour of salt marsh vegetation would be expected, and deposition of sand is unlikely or infrequent. The "micro-groins" designed for Aramburu Island, Richardson Bay (southwest of Greenwood Beach; Wetlands and Water Resources *et al.* 2010) were constructed from a mix of wave-immobile boulders, cobbles, and mobile gravel interstitial fill, combined with eucalyptus log sections embedded in bay mud (about ¼ length) and braced in place by wood stakes deeply embedded in compacted mud or fill.

The capacity for constructing cobble-boulder groins may depend on the presence of older compacted bay fill platforms capable of bearing the weight of boulders and cobbles without excessive settlement or mudwaves. Installation of large log and woody debris groins (lower bulk density than quarried rock) is an alternative for bay beach nourishment on unconsolidated, weak bay mud. Greenwood and Brunini Beaches appear to contain ample remnant, consolidated old 20th century rocky fill and gravelly delta deposits to provide firm ground for cobble-boulder groin segments in the backshore and upper intertidal zone.

Boulder-cobble groins, or boulder-cobble and log groins may be combined with cobble salt marsh drift-sills. The cobble salt marsh groin would extend over mid-intertidal portions of the groin profile, where maximum storm wave energy is lower than the upper beach profile. Cobble, boulder, and log groin components would cover the upper beach profile to the backshore on relatively steeper, wave-reflective shore profiles, where storm wave energy during highest tides may be most erosive. Steeper, rubble and boulder upper shoreline profiles occur at the extreme east and west ends of Greenwood and Brunini Beaches. Where boulder-cobble groins trap sand and become vegetated by saltgrass or California sea-blite, they may perform very similarly to cobble salt marsh drift-sills. The original design for Aramburu Island "micro-groins" anticipated vegetation spread and stabilization in the backshore, which in fact did occur locally in some groins.
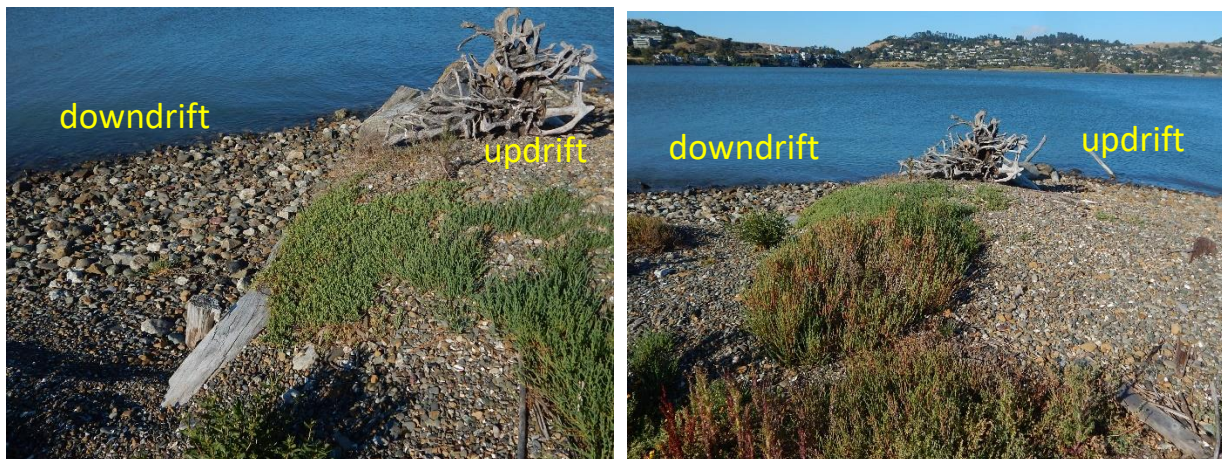
Figure 20. Log and boulder groins at Aramburu Island in June 2019, eight years after installation, are partially masked by perennial backshore vegetation (pickleweed, wester ragweed, jaumea) and gravel accumulated on the updrift side. Wood stake braces and boulders are exposed on the downdrift side.

Figure 21. Blue gum eucalyptus (*Eucalyptus globulus*) toppled by shoreline retreat in a west-facing bluff at Point Pinole was bucked (sectioned) into rootwads and log segments to reduce obstruction of public shore access. The interlocking, heavy decay-resistant logs generated a semi-natural groin that caused local trapping and progradation of mixed coarse gravel, sand, and shell beach berm. This is a partial reference system for nature-based log and boulder groins or drift-sills for beaches of the San Francisco Estuary.

4.5. Beach replenishment and enhancement features

4.5.1. Gravel storm berm augmentation

A small gravel storm berm exists at the toe of the existing bluff at the central reach of the West Beach. The west end of the beach lacks a gravel berm, and exposes asphalt and concrete rubble during winter storm erosion profile phases; the east end is sandy high salt marsh terrace. The gravel storm berm should be augmented as a minor, but geomorphically important subordinate component of the beach profile, and extended along the entire scarp toe. The augmented gravel berm would increase wave attenuation at the bluff toe during storm wave conditions at high tide. It would be constructed during erosional beach profile phases by directly placing a wedge of cobble and gravel along the base of the bluff, prior to scarp ramp grading. The size of cobble and gravel would likely range between that of the existing berm (usually buried below sand), and the small naturally deposited gravel storm berm across northern Richardson Bay at Aramburu Island, which was formed by wave action and sorting of artificially placed gravels on a veneer of cobbles.

The target size of the gravel storm berm would be based on the naturally deposited storm gravel berm (not the as-built condition) at Aramburu Island, central shoreline. This storm wave-built feature is a minor ridge or crest on top of the whole beach profile at Aramburu Island; its volume and dimensions are not comparable with the original whole-profile beach nourishment rate at Aramburu Island, which was on the order of 2-3 cubic yards/linear foot. The volume of cobble and gravel for the bluff-toe cobble storm berm at West Beach may be roughly estimated by the dimensions of the smaller Aramburu gravel berms of the south and south-central shoreline. This local reference system suggests that the volume of cobble and gravel needed for a small but augmented cobble and gravel storm berm would be on the order of 2-4 cubic feet per linear foot of shoreline, or a total gravel volume on the order of 400-500 cubic feet (about 15 cubic yard per truckload) for the West Beach.

### 4.5.2. Beach replenishment methods, materials, rates, and patterns

The sediment texture of Greenwood Beach has not been quantitatively analyzed, but its heterogeneous mixture of medium to coarse sand and gravel, with prevalence of medium sand near the beach surface during calm-weather conditions, is consistent with the textural analysis of Sanctuary Beaches used as reference for Aramburu Island shoreline enhancement (Wetlands and Water Resources et al. 2010). The heterogeneity of the existing mixed sand and gravel beach, and the demonstrated self-construction and sorting by waves at Aramburu Island beaches, provides indicators for the feasibility of profile nourishment (Nordstrom 2000): sacrificial placement of beach sediments in the zone of wave transport (in this case of a low energy beach above a tidal flat, the swash zone of the beachface) for subsequent reworking (redistribution by erosion and deposition. This approach presumes seasonal erosion and re-deposition of a berm and beachface, alternating with a dissipative, flatter winter storm erosion profile, rather than design of an equilibrium profile or constructed beach berm. The objective of profile nourishment design, therefore, would be a range of beach sediment volumes (Stive *et al*. 1991, Kana 1993) rather than a fixed beach form or profile target.

The volume of beach sediment placed in any interval could be opportunistic, following construction of sediment retention structures (groins, drift-sills) to make the shoreline receptive to multiple episodes of beach nourishment. Incremental "construction" (nourishment) of the beach would occur after authorization for fill (sediment) discharge are obtained for an appropriate multi-year permit (potentially

including a regional permit for small-scale, low-impact, low-volume local beach nourishment in Richardson Bay), as suitable sand and gravel supplies become available. Incremental, small volume episodes of beach profile nourishment (in units of 1-2 truckloads per year; ca. 15-30 cubic yards/year maximum) would minimize the magnitude and duration of disequilibrium beach conditions, or minor beach nuisances or hazards such as soft "sinking" sand or muddy sand. The rate of beach sediment delivery could be adjusted based on beach morphodynamic and profile response to added sand during the spring-summer accretion season. It could also be adjusted based on beach response to unpredictable extreme storm erosion events. Average dry (high tide, backshore) recent (2011-2018) summer beach widths in northern Richardson Bay and the north shore of the Tiburon Peninsula are approximately 10 feet, near the year-round average of 18.8 ft (J. Beagle, San Francisco Estuary Institute, 2020). A maximum beach sediment volume per year or decade would be established by engineering estimates for a maximum beach profile width (on the order of 40 ft wide backshore, 60 ft beachface), to avoid potential excessive short-term sediment loads. A reasonable range of beach sediment nourishment frequencies would be 2-6 year intervals, but may be considered for annual or decadal intervals based on shoreline response, ecological performance or impacts, or public park preferences.

Placement of sand and gravel may need a permanent ramp (dual purpose of public shore access and truck access) at the west end of West Beach, where rubble fill cliffs exist. Sacrificial placement of unstable sand and gravel updrift (west) of the active swash zone of the beachface in fall-winter would likely result in rapid natural wave reworking of the mobile sediment.

This approach to beach reconstruction through incremental, opportunistic profile nourishment implies that project construction is aimed primarily at grading of scarp/cliff profiles, ramps, and groins and drift-sills, prior to subsequent, phased beach sediment placement.

GREENWOOD BEACH SECTION B
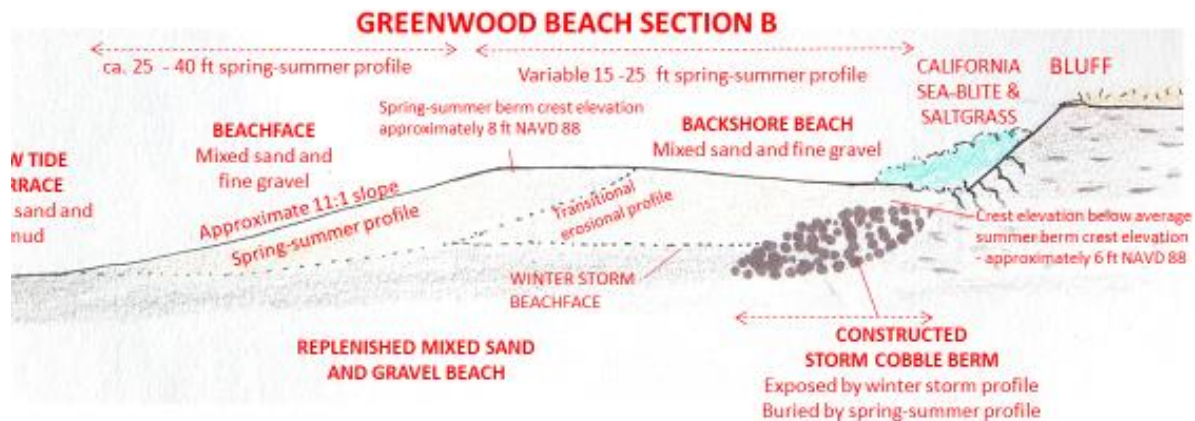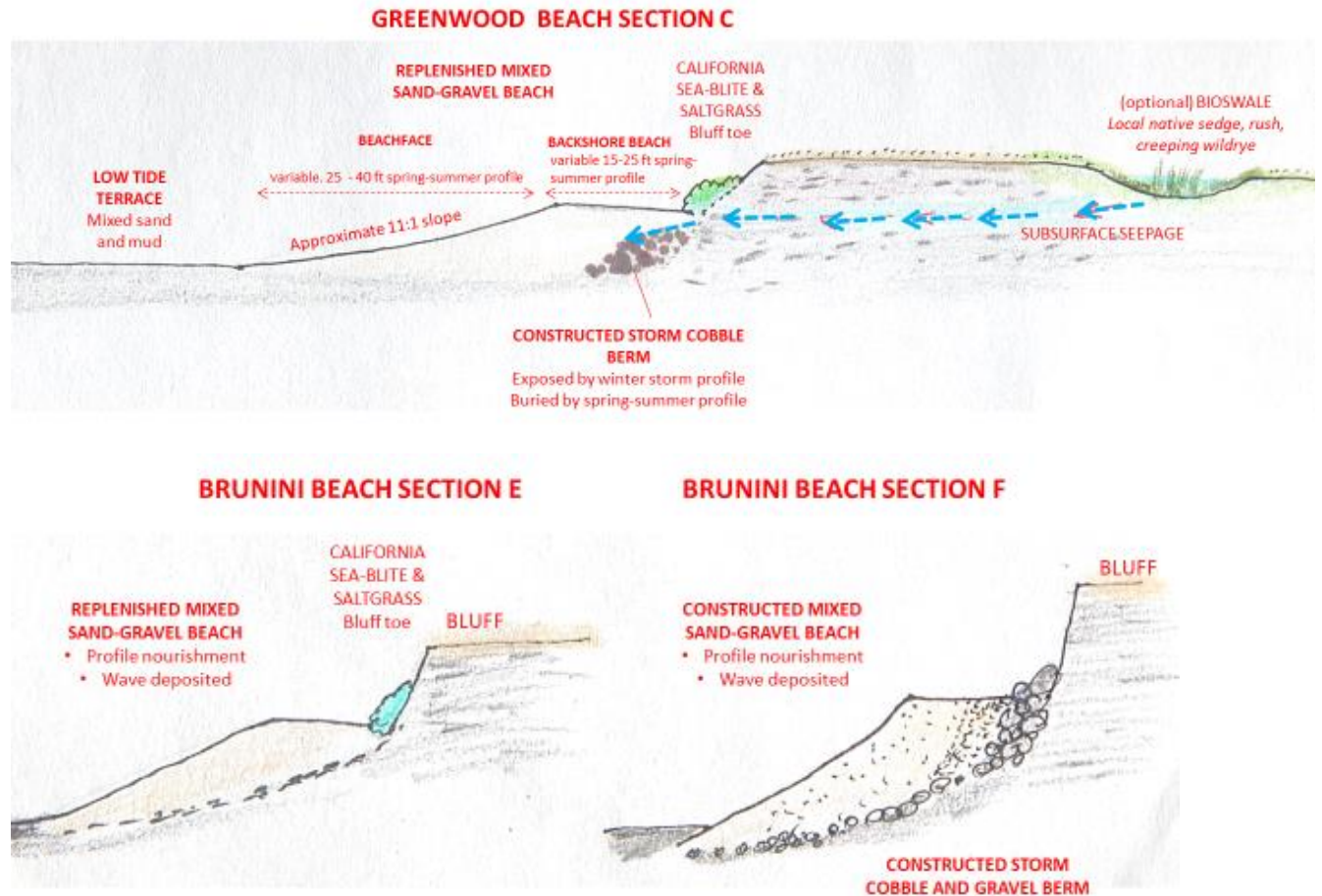
Figure 22. Conceptual cross-section views of nourished Greenwood and Brunini Beaches, interacting with related backshore (bluff, swale) feature and gravel/cobble storm berms. Sections are referenced to Figure 14.

4.6. Estuarine beach, bluff, and salt marsh vegetation

Native vegetation in San Francisco Estuary salt marshes, beaches and coastal bluffs are geomorphic agents that mediate significant erosion, stabilization, and accretion feedback processes, as well as provide biotic ecological functions such as habitat and trophic support. They are not merely esthetic park or wildlife amenities incidental to basic beach engineering design. Specific physiological and morphological traits of particular species are selectively exploited in the beach and marsh shoreline design. Prominent among relevant plant functional traits for these purposes are sand burial tolerance, sand trapping capacity, wave tolerance, clonal spread rates, root and rhizome shear strength, and salt tolerance. Key species are identified for incorporation in beach design features below.

Saltgrass (*Distichlis spicata*). Saltgrass is a mat-forming clonal perennial with a rhizomatous and stoloniferous growth form (rooting prostrate shoots above and below ground), well adapted to both sand and fine sediments ranging from saline to slightly brackish. It develops a dense sod with high shear strength that resists wave and current erosion from above surface. Growth can be rapid even in dry substrates, especially at elevated nutrient (nitrogen, N) levels associated with decaying N-rich organic matter. It regenerates after erosion primarily from vegetative clonal growth. Saltgrass also forms dense

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mats rooted in cobble lag shorelines. It is moderately tolerant of sand accretion at low, gradual rates, and can build low foredunes (vegetated beach terraces) up to about 2 ft high along estuarine and sheltered outer coast beaches (e.g., Doran Beach, Sonoma County; east Stinson Beach, Marin County; Alder Creek Beach, Mendocino County; Salinas River mouth, Monterey County). It should be incorporated as a dominant species in cobble salt marsh drift-sills (rhizome and sod fragments in near-surface interstitial fine sediment among cobbles), and in the backshore beach along the bluff toe (sod fragments transplanted in late winter). Saltgrass associates with Alkali-heath and California sea-blite in natural communities.

Alkali-heath (*Frankenia salina*) Alkali-heath is a broadleaf mat-forming clonal perennial (to subshrub) with both rhizomatous. It has higher tolerance to desiccation and salinity than saltgrass, and regenerates vegetatively after erosion of buried crowns and rhizome fragments. It is also well adapted to both sand and fine sediments ranging from hypersaline to slightly brackish. Like saltgrass, it tolerates gradual sand burial and can form low foredunes about 1-3 ft high on sheltered Central Coast beaches. Its low-growing shoot canopy can trap sand and induce gradual accretion of the high salt marsh transition zone where wave overwash or swash bar deposition occurs, so it is valuable not only for erosion resistance, but also for recolonization and recovery of eroded beach/salt marsh transition zones. It should also be incorporated as a co-dominant component of vegetation in cobble salt marsh drift-sills (rhizome and sod fragments in near-surface interstitial fine sediment among cobbles) in the upper intertidal zone, and in the backshore beach along the bluff toe (sod fragments transplanted in late winter). Alkali-heath associates with saltgrass and California sea-blite in natural communities.

Jaumea (*Jaumea carnosa*). Jaumea is a prostrate herbaceous clonal perennial halophyte native to high and mid-salt marsh zones. It also tolerates shallow, incremental sand burial, but has little capacity to trap sand and induce accretion because of its strongly prostrate shoot canopy. It should also be incorporated as a sub-dominant component of vegetation in cobble salt marsh drift-sills (rhizome and sod fragments in near-surface interstitial fine sediment among cobbles) in the upper intertidal zone. Jaumea associates with saltgrass, alkali-heath, and California sea-blite in natural communities.

Creeping wildrye (*Leymus triticoides* and L. X*gouldii*; syn. *Elymus*). The two creeping wildrye taxa (one parent, one natural hybrid) native to floodplains, valleys, riparian zones, and tidal marsh edges of the San Francisco Estuary are coarse, rhizomatous clonal perennial grasses. They tolerate flooding, soil saturation, and summer-arid soils of seasonal wetlands. They grow in a wide range of sediment and soil types ranging from clay loams to sands, alkali, brackish or nonsaline. The natural hybrid, Gould's wildrye, is taller and coarse in all aspects than the parent species creeping (or alkali) wildrye. Both form dense erosion-resistant, trampling-tolerant sods that are well-adapted to both erosion resistance and burial tolerance. Burial-tolerant stands of this perennial grass can trap wave-deposited sand and induce accretion of the high salt marsh transition zone. It readily recolonizes eroded shorelines by rhizome spread from backshore areas above erosion zones.

Creeping wildryes take several years to form a dense root/rhizome mat by below-ground spread from transplants, but once established, their sods provide firm, stable turfgrass cover for rough pasture or parkland use. They are superior vegetative stabilization tools for low coastal bluffs and scarps, as well as lowland valley grasslands. Local stands occur at the beach terrace of the east beach. They are highly recommended for resilient cover of park turfgrass, bioswales, and bluffs above California sea-blite. They

seldom establish from seed or seedling, but readily propagate with high survivorship from viable sod fragments rich in buds and rhizomes during dormancy.

California cordgrass (*Spartina foliosa*) California cordgrass is a clonal perennial salt marsh grass that grows at mid-intertidal elevations below nearly all other salt marsh plants. It tolerates gradual, low-level sediment burial by sand or silt, and is a dominant species of the low salt marsh zone, as well as the few examples of cobble salt marshes in the Bay region. It is propagated in the field by intact sod or rhizome fragments or vegetative plugs, planted within the top 2-4 inches below Mean High Water to the local lower elevation limit of observed reference colonies. It should be incorporated as sod fragments (harvested from local stands) manually transplanted in cobble salt marsh groins.

California sea-blite (*Suaeda californica*). California sea-blite has been experimentally re-introduced to Greenwood and Brunini Beach and salt marshes (within overall historic range in San Francisco and San Pablo Bay; no Marin records of the species are known). This federally listed endangered plant is a robust halophyte (salt-tolerant) sub-shrub that naturally grows on sandy lagoon and tidal salt marsh shorelines near the high tide line, as well as near the high tide shoreline along low sandy coastal bluffs or dunes. Historically it occurred only in Morro Bay and the San Francisco Estuary. California sea-blite can also colonize rip-rap and shell beaches with underlying sand and mud, and it can clamber over low branches of shrubs and trees, like a vine. It similarly can grow up low bluffs from shoreline colonies (above typical elevations of perennial Pacific pickleweed), and root in bluff substrate, so that the bluff is vegetatively stabilized. Sea-blite can be propagated by rooting cuttings of vegetative shoots, by layering (shallow burial of horizontal stems segments in moist sand), and by seed propagation. It has successfully established at Brunini Marsh in high salt marsh, but was susceptible to extreme storm wave erosion where fringing marsh or beach widths are too narrow to damp erosive wave energy.

California sea-blite is proposed for vegetative stabilization functions incorporated of the shoreline design at multiple locations (Fig. 14): the toe of the set-back regraded bluff at West Beach, above and behind the storm cobble-gravel berm; the back of the east shore high salt marsh; and along the bluff toe of East Beach. Sea-blite plantings combined with placement of large or small woody debris (small driftwood logs and limbs, brush) recommended to provide a framework (arbor/trellis) for clambering shoot canopies that may increase vegetative roughness. Sea-blite co-planted with saltgrass is likely to increase shoreline resilience to erosion, and speed recolonization and sand accretion after storm erosion events.

Additional species locally native and well-adapted to Marin bayshore beaches and high marshes include alkali-weed (*Cressa truxillensis*; Marin Islands cobble beaches), poverty-weed (*Iva axillaris*; Richardson Bay Audubon Sanctuary gravel beach, sandstone cliff, and bluff toe), and western ragweed (*Ambrosia psilostachya*; Aramburu Island and China Camp Beach) These would be suitable for late winter dormant-season translocation to the high salt marsh, bluff toe, and backshore beach at Greenwood and Brunini Beaches.

Local wet meadow sedges and rushes that are present in local (Tiburon, Mill Valley) tidal marsh edges and seasonally wet hillslope seeps and roadside ditches, suitable for inclusion in bioswales with weeks of soil saturation in winter. These include Baltic rush (*Juncus arcticus*), basket sedge (*Carex barbarae*) and clustered field sedge (*Carex praegracilis*).

5.0. Beach evolution and dynamics

The conceptual design of the restructured, nourished beaches of Greenwood and Brunini Beaches is to enhance and support ongoing natural processes of beach retreat (erosion phases) and recovery (accretion phases) by supplying compatible beach sediment and improved "living shoreline" retention structures that integrate with existing and historical tidal marsh and flats. The "Living Shoreline conceptual design aim is not to replace the existing mixed sand and gravel beach/wetland system with an engineered erosion-resistant rocky sill or shore platform. Instead, it aims to adjust local coarse sediment supplies to balance sediment deficits caused by sea level rise, and net beach sediment losses due to immobilization (offshore transport and loss to deeper tidal flats, incorporation in cohesive sediment deposits). Accordingly, there is no ideal engineered "design profile" beach to use as a performance standard, but instead a sequence of dynamic states that are expected to evolve in response to constructed features, sediment nourishment (placement) episodes, drought and flood cycles influencing fluvial sediment supply (delta deposition), storm erosion events, and long-term sea level rise. These dynamic responses are also cues for adaptive management actions to keep pace with external forcing of the beach system from beach processes, climate and meteorological events. They are described qualitatively here.

Post-construction wave reworking of sand and gravel. Shoreline profile nourishment is proposed for beach "self-construction" by waves during relatively high energy conditions in fall and winter, to ensure transport and complete reworking of imported heterogeneous (mixed sand and gravel) beach sediments. This approach was also used in the drift-aligned Aramburu Island shoreline enhancement project. There it resulted in rapid erosion of "sacrificially" placed upper intertidal beach sediment, and re-deposition of well-sorted, natural wave-built beach berms and beachfaces. The initial response of sacrificial beach sediment placed on the beachface (below spring high tide wave runup elevations) in fall and winter would likely be rapid widening (progradation) of the beachface, and some berm accretion during non-storm periods. Normal winter storms would likely rework the beachface to a flatter, wider profile, encroaching on the upper low tide terrace. The buried gravel storm berm may be exposed during and shortly after major storm erosion events.

In late winter/spring periods of calmer winds and lower (constructive) wave energy, the prograded beachface would slightly steepen, and a distinct berm crest and top (backshore or dry high tide beach) would prograde. The storm gravel berm would likely be buried by sand and fine gravel during spring-summer beach accretion phases. A wide berm top may be exposed to increased wind erosion in summer, with some thin eolian (dune) deposition in the high salt marsh at the east end of the west beach. Heterogeneous sand and gravel sediments would sort into gradients along the beachface, varying in relative abundance at the surface in response to variable wave action. Medium sand would likely be prevalent on the beachface and berm most of the year. Berm widths during post-storm recovery phases would likely significantly increase over pre-nourishment conditions, depending in part on the growth of the high salt marsh cobble groin elevation, and its capacity to trap beach sand near the upper limit of swash (wave uprush). Maximum backshore beach widths on the order of 40-50 ft (bluff toe to berm crest/upper beachface) would approximately equal most Richardson Bay beaches during beach full profile phases, but a typical berm width during spring and summer may be closer to 15-25 ft except for a few years immediately following beach nourishment cycles.

Storm erosion and post-storm recovery. Regardless of backshore beach progradation and beach width, extreme sustained storm erosion events (high tides and wind-waves over multiple tidal cycles) would likely flatten the mixed sand-gravel beachface to form a dissipative profile, and expose the gravel storm berm to storm wave action while the beachface elevation is low. The regraded ramp profile of the bluff may develop a low erosion scarp in extreme events, especially at higher sea level stands (including temporary high sea level anomalies) in the next two decades. Following extreme beach erosion events, beach-sized sand within the beachface and upper low tide terrace would undergo onshore (shoreward) transport during low wind-wave conditions, steepening and raising the beachface and berm crest as the berm progrades. The gravel storm berm would be partially or fully buried by sand during this phase. Over the growing season following erosion, saltgrass in the backshore would recolonize the toe of the bluff and back of the beach, and wave-scoured California sea-blite would regenerate gradually. Extreme erosion may leave vegetation gaps, however. Vegetative recovery of perennial vegetation would be increased by deposition of nutrient-rich, moisture-retaining deposits of decaying eelgrass and macroalgae. Lateral spread of perennial vegetation at rates of 2-4 ft/yr may be expected during post-storm recovery phases. Delay or incomplete recovery of post-storm beach profiles and vegetation would indicate a need for monitoring to reassess the timing and magnitude of the next expected maintenance cycle of beach nourishment, or potential need for supplemental replanting.

Drought and flood cycles affecting beach and salt marsh. The same major coastal storms that may cause high wind-wave erosion may also deliver extreme high precipitation and peak runoff flows that deliver coarse (beach-compatible) sediments to the delta on the low tide terrace, the likely long-term local source of sand and gravel for the beach and salt marsh in the modern era. Wave transport of accreted delta shoal sediment (erosion from delta lobes, gradual onshore transport to the beach and salt marsh) may temporarily increase beach and marsh sediment budgets after erosion events. Conversely, prolonged droughts and reduced delivery of coarse (and fine) sediment to local tidal flats around the delta may result in net trapping of mobile sand in high salt marsh vegetation, and reduced pools of mobile sand available for beach accretion. Although reduced storm activity during droughts may be associated with reduced beach erosion, post-storm recovery after "dry" wind-wave storms during droughts may result from drought-induced reduction in beach sediment supply. These relatively unpredictable internal variations in the local sediment budget (allocations among delta shoal/lobe, salt marsh, and beach compartments) should be considered during re-assessment of beach renourishment episodes. The total volume of potential beach sediment stored in all interacting sediment compartments of the shoreline system should be assessed, not just the beach sediment volume or beach profile.

Long-term erosion, drift, bluff retreat, and renourishment. Inevitably, unless the local fluvial supply of coarse sediment to the local shoreline significantly increases, sea level rise will itself induce beach sediment deficits and shoreline retreat. The beach and marsh shoreline system can adjust vertically and horizontally to sea level rise with a sufficient positive sediment budget and supply of coarse, beach-sized sediment needed for beach berm and high marsh berm accretion by wave action.

The rate at which beach sediment addition (nourishment) is designed can vary from single, large beach construction projects, or incremental, phased beach nourishment. Large, sudden artificial increases in the beach sediment budget can be caused by major, single-event beach nourishment projects that construct a "design berm" profile temporarily out of equilibrium with the shoreline (Nordstrom 2000, Dean 2000, Peterson *et al.* 2005). The ecological and geomorphic disequilibrium and disturbance of

single-event beach construction can be minimized by spreading beach profile nourishment episodes incrementally over time as relatively frequent, small low-impact sediment delivery cycles.

A sacrificial "feeder beach" nourishment placement zone (e.g., beachface adjacent to the western drift-sill, updrift west beach, or a designated lower beachface delivery zone on east beaches) can be designated for either direct mechanical placement of small truck-delivered beach sand/gravel sacrificial deposits, or for washing out (hydraulic dispersal by firehose) of truck-deposited sacrificial sand/gravel piles placed on the upper beach. Indicators or triggers for nourishment may include:

- net bluff retreat or reactivation of chronic scarp erosion;
- increased persistence time of erosional beach or salt marsh scarps;
- prolonged year-round exposure of gravel storm berms and buried old rubble lag surfaces;
- chronically narrow berm tops, or loss of beach berm profile year-round;
- persistently reduced estimated areas and volumes of beach and high salt marsh sediment

The feasibility of single-project large beach nourishment versus incremental "feeder beach" nourishment may depend on the availability of suitable matching beach sediment sources. If relatively small amounts of annual beach-size compatible sediment are available from flood control channel maintenance or stockpiles of sand (e.g. Port Sonoma), incremental "feeder beach" nourishment may be more feasible and lower impact. If only larger supplies are available from dredging projects requiring single "disposal"/beneficial re-use sites, larger nourishment projects may be more feasible.

There are limits of the ability of natural beach shoreline system to adjust to sea level rise through sediment nourishment, even though repeated cycles of beach nourishment have been demonstrated to be capable of overcompensating for recent sea level rise on highly vulnerable coasts, such as Florida (Houston 2017, 2019). The backshore space for a beach at Greenwood and Brunini Beaches is limited by its topography. Eventually, a rise in sea levels of perhaps 2 or 3 feet would eventually overstep the existing shoreline, and would drive even an artificially nourished beach onto the terrace behind it, like natural beaches migrating over low, gently sloping marine terraces. Nourished bay beaches do not stop sea level rise, but partly control shoreline position and buffer impacts of wave runup and erosion. Beaches have no influence on rising groundwater or backwater flooding that occurs with sea level rise, even if the nourished beach profile keeps pace with sea level rise. Managed retreat from public areas can provide additional room for adaptation and construction of levees or other barriers to sea level rise that can work in conjunction with living shoreline beach systems to provide sea level rise adaptation. Beach nourishment can buy valuable time for long-term adaptation measures that depend on managed retreat.

6.0 Steps towards preliminary design

Progression from conceptual to preliminary design for this alternative would include more detailed (10-30%) design estimates for materials, volumes, costs, construction feasibility, concerns of resource and regulatory agencies, identification of infrastructure conflicts, interests of local residents and the land manager/owner (Town of Tiburon), and ecological impact assessment.

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