FINAL

CONCEPTUAL DESIGNS FOR MARSH-FRINGING BEACH NOURISHMENT TO REDUCE WAVE EROSION OF MUZZI MARSH, CORTE MADERA ECOLOGICAL RESERVE, MARIN COUNTY, CALIFORNIA

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Task 3 Technical Memorandum for "New Life for Eroding Shorelines",
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Introduction

This memorandum provides a conceptual design for reducing wave erosion of Muzzi Marsh (Corte Madera Ecological Reserve, California Department of Fish and Wildlife [CDFW], Marin County, California) using estuarine beach nourishment methods. This approach to marsh scarp erosion management with beach nourishment falls within a spectrum of the "Living Shoreline" nature-based solutions that rely on artificial placement of natural materials (biological or mineral) to reduce erosion and increase resilience of dynamic shorelines. This memorandum is part of the New Life for Eroding Shorelines project (Task 3) of San Francisco State University, Estuary & 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 developing methods to reduce wave erosion of a salt marsh in ways that are compatible with habitat enhancement for two federal and state-listed endangered wildlife species, the salt marsh harvest mouse (*Reithrodontomys raviventris raviventris*) and California Ridgway's rail (*Rallus obsoletus obsoletus*). The overall need and purpose of the project are stated in the grant application:

> …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 explains the local geomorphic and ecological basis of design for "nature-based" shoreline engineering designs to reduce marsh edge wave erosion at Corte Madera Ecological Reserve, using regional analogs of salt marsh-fringing barrier beaches. The conceptual designs apply "living shoreline" goals for ecological compatibility with the Corte Madera Ecological Reserve (Goals Project 2015, SFEI and SPUR 2019) and San Francisco Estuary low- energy beach dynamics (Jackson *et al*. 2002; SFEI and Baye 2020) related to sensitive wetland habitats. It builds upon the "New Life for Living Shorelines" technical memorandum that reviewed bay beach shoreline types and processes that interact with wetland shorelines (SFEI and Baye 2020), and SFEI's atlas of regional shoreline adaptations for sea level rise based on operational landscape units (SFEI and SPUR 2019).

The proposed conceptual design itself is based in part on observed regional reference systems composed of marsh-fringing estuarine barrier beaches and their salt marsh platforms. Observations over decades suggest that salt marsh scarps fringed with sand or shell hash beaches are usually buffered from direct wind-wave attack, compared with nearby marsh scarps directly exposed to wind-wave action. The aim of the conceptual design is on providing a local supply of coarse beach sediment (sand, fine gravel) for waves to rework, deposit, and retain persistent marsh-fringing estuarine beaches, where waves otherwise would directly attack salt marsh scarps. In addition to providing beach sediment supply, the design aims at increasing the shoreline's capacity to trap, retain and recirculate coarse sediment along wave-eroded scarps, where they can also build high salt marsh berms perched behind the scarp, in addition to buffering wave attack on the scarp itself. These integrated actions are expected to help compensate for coarse and fine sediment deficits caused by trapping of bedload and suspended load of the Corte Madera Creek flood control channel (Schoellhamer *et al*. 2018) and other watersheds contributing to the local sediment budget. The wave attenuation processes associated with artificially nourished estuarine barrier beaches are intended to at least partially mitigate climate change impacts including interactions between accelerated sea level rise and increased severity or frequency of major coastal storms.

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 San Francisco Estuary estuarine beach-salt marsh complexes. 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 potential subsequent preliminary and coastal engineering and restoration designs and permitting.

2. Goals & Objectives

As the title of the memo suggests, the aim of the conceptual design is not to artificially stabilize the retreating shoreline (as with traditional shoreline armoring, or construction of cobble berms), but to reduce the rate of salt marsh scarp retreat caused by wave erosion and long-term sediment deficits (SFEI and Baye 2020, SFEI and SPUR 2019, Schoellhamer *et al.* 2018). This aim is aligned with overall goals to increase the resilience of the Corte Madera Ecological Reserve salt marsh to sea level rise, and especially its endangered wildlife habitats (salt marsh harvest mouse and California Ridgway's rail) that require well-distributed high salt marsh, high tide refugia, and tidal channel networks. The basic general goals for this conceptual design are derived from the New Life for Eroding Shore project Tasks 1 and 2 report on San Francisco Estuary marsh edge and beach change (SFEI and Baye 2020):

- Develop greater shoreline resilience in the face of climate change compatible with estuarine shoreline habitats;
- Incorporate estuarine beaches as components of tidal marsh restoration and management;
- Avoid impacts of traditional shoreline armoring (placement of rock rip-rap) and conversion of soft to hardened estuary shoreline types (estuarine marsh, mudflat or beach converted to rocky shore habitat).

The premise (testable hypothesis) of project goals is that marsh-fringing barrier beach types widespread in the Central and South San Francisco Bay can significantly buffer marsh edge erosion when they are sufficiently supplied with coarse sediment, compared with bare salt marsh scarps exposed to similar wave power (SFEI and Baye 2020). Marsh-fringing barrier beaches are small low- energy beaches that deposit along the edges of salt marshes of bays, lagoons or estuaries where beach sediment is available for transport by low-energy, fetch-limited wind-waves (Pilkey *et al.* 2009, Lewis *et al*. 2007). Their geomorphic evolution is primarily influenced by storm wind-waves and vegetation rather than fair-weather wave action (Jackson *et al*. 2002). Some smaller forms of marsh-fringing barriers are synonymous with “marsh bars” (barriers, berms) of Johnson (1919), which form secondarily along older erosional salt marsh edges. Marsh-fringing barriers are primarily mobile during storm wave events which drives overwash and landward migration. Their planform is often controlled by marsh peat outcrops acting as transient erosional headlands (Cooper *et al.* 2007). Goals of the project conceptual design also presume that beach nourishment in low-energy estuarine marsh-fringing beach settings is relatively more feasible and cost-effective than beach nourishment of high energy ocean beaches (Cooper *et al*. 2007).

Primary design objectives specific to the Muzzi Marsh project site build on previous sea level rise adaptation approaches that considered coarse beach nourishment to reduce marsh edge erosion (broad-sense “stabilization” with coarse beach sediment; BCDC and ESA 2013; SFEI and SPUR 2019). Objectives in this conceptual design do not cover the functions of other related climate change adaptation measures such as mudflat nourishment (recharge), tidal creek enhancement, or direct fine sediment nourishment of salt marshes.

- Reduce marsh scarp erosion and reduce marsh edge retreat rates by
    - Reducing direct exposure of the scarp to erosive wave energy;
    - Modifying the vertical wave-reflective scarp profile to a sloping, wave-dissipating beachface;
- Enhance high tide cover of salt marsh by facilitating formation of perched high marsh berms composed of sand and organic detritus, which dynamically retreat landward in pace with the marsh edge;
- Develop construction methods for estuarine beach nourishment in sensitive wetland habitats with limited access for land-based equipment.

Goals and objectives proposed are broadly consistent with early consultations with local, state, and federal agencies with planning and permit authority over potential projects at the site. SFEI and the Town of Corte Madera held a series of calls with partner organizations in April-May 2020 to discuss adaptation on Corte Madera Marsh as part of the Corte Madera Climate Adaptation Plan process. All of the organizations were interested in participating in regional sea-level rise and marsh restoration planning. However, each organization has a different focus. Their early consultation comments are summarized below, but are not presumed as official endorsements or prejudicial approvals of goals, objectives, or designs.

- The California Department of Fish and Wildlife is responsible for management and protection of the marsh and public access to it. They do not have immediate plans for restoration or management changes, and are not likely to lead or contribute funding to any type of adaptation project, but are not opposed to being involved.

- The San Francisco Regional Water Quality Control Board takes a long view on determining ecological value and is supportive of regional estuarine shore planning efforts (SFEI and SPUR 2019).

- The Bay Conservation and Development Commission is similarly supportive of estuarine shore planning and adaptive management at CMER (BCDC and ESA 2013), and is also focused on public access.

- The County of Marin is interested in facilitating discussions between stakeholders; for example, at Heerdt Marsh, which involves overlapping jurisdictions of the towns of Corte Madera and Larkspur as well as the County.
- The Golden Gate Bridge, Highway, and Transportation District is in the process of constructing a four-acre marsh restoration, and plans to complete more mitigation projects in the area in the future to compensate for impacts of the Larkspur ferry service.
- The Marin Audubon Society recently completed the Madera Bay Park restoration and has some upland fill available for use in future projects.

All organizations and agencies consulted were willing to engage with the Town of Corte Madera as the Town writes their Climate Adaptation Plan, and as concepts for the marsh take shape. There was also general support for undertaking pilot adaptation projects in the near term, and developing a long-term planning process, which could include developing a regional shoreline master plan similar to the Hayward Shoreline Master Plan (J. Beagle and R. Leventhal, pers. comm. 2020).

3. Site and Setting

This conceptual design in this report is developed for the outer Muzzi Marsh shoreline within the California Department of Fish and Wildlife Corte Madera Ecological Reserve (CMER) in Corte Madera, southeastern Marin County, California. Muzzi Marsh is one of the first tidal marsh restoration projects in San Francisco Bay, and among the earliest using confined dredged sediment placement in a subsided diked bayland (reclaimed, drained salt marsh) as a method to establish a salt marsh platform for restoration. Tidal restoration was completed in 1976. The cumulative length of marsh scarp shoreline facing San Francisco Bay, including shallow embayments and shoreline irregularities, approaches 4000 linear feet.

Muzzi Marsh is bounded by two east-west trending levees at the north and south end of the site, and one internal east-west trending cross-levee near the center of the site. The levee crests are not actively maintained as flood control levees or roads for equipment and vehicles (other than vegetation mowing), and currently remain above extreme high tides. The outer bay levee is mostly eroded and reduced to a few discontinuous remnants. Interior dredged canals, pre-existing older salt marsh soils, and dredged sediment are exposed to wind-wave action where the bay levee has completely eroded (Carkin *et al*. 2020). Long-term rates of marsh edge retreat have been influenced by the erosion of the bay levee and exposure of interior channels and marsh.

Figure 1. Regional site location in San Francisco Bay, California. CMER is circled in red.

Figure 2. Muzzi Marsh, Google Earth image, April 2, 2020.

3.1. Marsh edge retreat rates and morphology

The Corte Madera marsh shorelines analyzed by the U.S. Geological Survey (USGS) retreated significantly during the 163-yr period from 1853 to 2016. Total shoreline retreat during this period ranges from about 70 to 150 m, which corresponds to a long-term rate of 0.4 to 0.9 m/yr, depending on the location along the highly irregular shoreline (Carkin *et al.* 2020). USGS detected a small decrease in long-term marsh shoreline retreat rates at CMER in recent decades, due in part to irregularities of the shoreline and earlier "jumps" of its position from levee edge to an exposed interior canal (borrow ditch) following complete erosion of bay levee segments. USGS estimated retreat rates of 0.62-0.72 m/yr +/- 0.25 m from 1992-2016, and 0.64-0.98 m/yr +/- 0.18 m 1965-1992 (Carkin *et al*. 2020).

By comparison, the marsh edge retreat rates of Heerdt Marsh (a prehistoric tidal marsh remnant north of Muzzi Marsh, also within CMER), are slightly less than Muzzi Marsh. The long-term marsh edge erosion rate of Heerdt Marsh was 0.52 m/yr from 1931 to 2016. From 1992 to 2016, the average rate was essentially identical, 0.48 m/yr (Carkin *et al*. 2020).

SFEI also conducted two unoccupied aerial system (UAS) surveys over a roughly 80-acre area to investigate change along the marsh edge over a one-year timespan (SFEI and Baye 2020). SFEI estimated marsh sediment loss from the scarp retreat from 2018-2019 to be about 30,000 metric tons (assuming a sediment bulk density value of 462 kg/m^3, derived from sediment core measurements taken at nearby Muzzi Marsh; Callaway *et al*. 2012). SFEI estimated average marsh scarp retreat rates over time periods (1993-2010, 2010-2018) similar to those of Carkin *et al*. 2020 (1992-2016). The differences among corresponding long-term scarp retreat rates by SFEI and USGS are less than 1 m/yr (0.43-0.99 m/yr; Table 1).

CMER location	New Life: avg 1993-2010 (m/yr)	New Life: avg 2010-2018 (m/yr)	New Life: 1993-2018 (avg of two left columns)	Carkin 1992-2016 (m/yr)	Difference (m/yr)
North Muzzi (north)	-0.97	-1.28	-1.13	-0.70	-0.43
North Muzzi (south)	-1.47	-1.49	-1.48	-0.72	-0.76
Outer Muzzi	-2.13	-1.08	-1.61	-0.62	-0.99
Heerdt	-0.79	-1.11	-0.95	-0.48	-0.47

Table 1. Comparison of estimated salt marsh scarp retreat rates (meters/yr) at Corte Madera Ecological Reserve, summarized from Carkin *et al*. 2020 and SFEI and Baye 2020 (New Life for Eroding Shores (Tasks 1 and 2) report on San Francisco Estuary marsh edge and beach change).

The outer salt marsh scarp defining the shoreline at Muzzi Marsh is mostly a near-vertical cliff in peaty marsh soil and dense, consolidated bay mud. The scarp height is variable along shore and over years, but is typically 2-3 ft high above the adjacent upper mudflat. Higher scarps occur where old bay levee remnants (built on older, outcropping salt marsh soil) occur. The scarp erodes by basal notching (undercutting), slumping (and slump-block scour and degeneration by waves), and cantilever failure (marsh sod overhang collapse). The scarp shoreline morphology is highly irregular and crenulate, consisting of protruding necks (marsh “headlands” of relatively more erosion-resistant soil) and shallow embayments), and indented notches and finger-like or funnel-shaped gullies (narrow wave surge channels that locally concentrate wave erosion and scarp retreat, often with heads with debris deposits). See Figure 3 below.

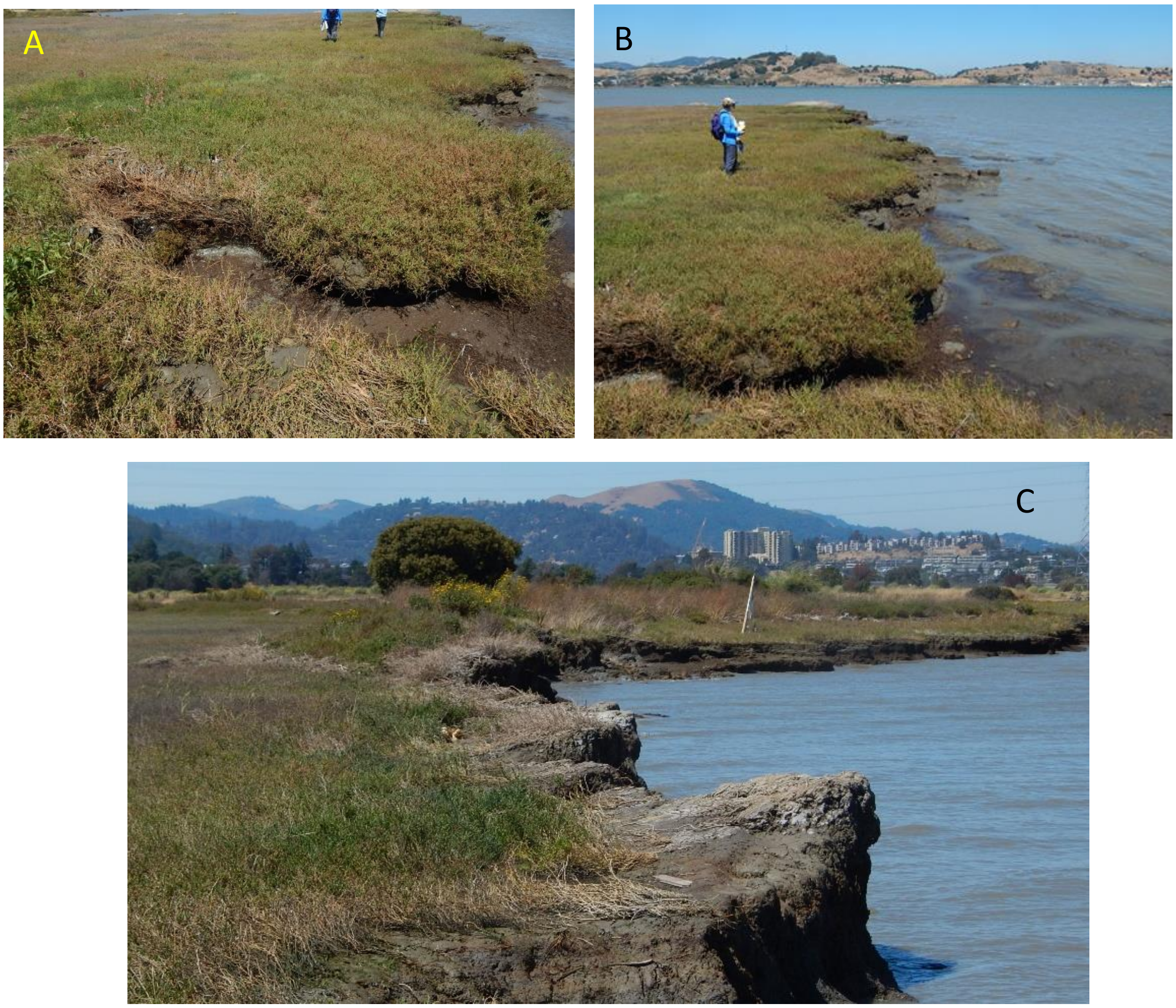

Figure 3. Salt marsh platform scarp at outer Muzzi Marsh. A) scarp with degenerating wave-scoured slump-blocks, and collapsing overhanging marsh sods (cantilevers), and irregular, crenulate configuration (protruding necks, headlands, and shallow embayments). A gully (surge channel) is in the foreground. B) Gully (wave surge channel) in the salt marsh scarp at Muzzi Marsh are finger-like to deltoid indentations with concentrated wave erosion and scarp retreat at locally increased rates, often associated with heads of deposited debris. These indentations are potentially receptive to coarse sediment deposition. C) A wave-cut scarp in eroded remnants of the former bay mud levee at Muzzi Marsh, exposing the formerly sheltered salt marsh platform to the erosional edge, August 2017. D) North Muzzi Marsh shoreline in plan view (Google Earth) exhibits a crenulate morphology: small protruding headlands or necks and intervals of shallow embayments and notches (gullies), as in (B) above.

3.2. Marsh edge erosion processes and drivers

Patterns of Muzzi Marsh salt marsh scarp retreat, and morphology of the scarp, provide indicators of erosion mechanisms. The scarp frequently exhibits an undercut, overhanging pickleweed sod (root mat) that fractures and topples (cantilever failure; Priestas *et al.* 2015; Bendoni *et al*. 2014; Schwimmer 2001). Mass wasting by slump block rotational failure is evident in various stages of scarp undercutting, cracks behind the scarp crest, active slumping, and degradation of blocks on mudflats, as reported in other cliffed tidal marshes (Allen 1989, Francalanci *et al*. 2013). Wave attack causing undercutting and notching of the scarp face occurs during tidal stages between Mean Sea Level (approximate mudflat level) and Mean High Water, well below the crest of the scarp; overmarsh tides dissipate over marsh platform vegetation, and tide levels below MSL are associated with strong wave dissipation over very shallow water over wide mudflats. The irregular edges of the scarp are consistent with variability in soil shear strength due to heterogeneous vegetation, and moderate wind-wave energy (Finotello *et al*. 2020, Priestas *et al.* 2015). Marsh scarp retreat rates are driven by direct wave attack, linearly related to wind-wave power (Leonardi *et al*. 2016, McLoughlin *et al.* 2015). Gullies, narrow funnel-shaped surge channels eroded in marsh soil, are also present (Figure 4). Salt marsh gullies in wave-cut scarps concentrate wave energy and exhibit local erosion rates often three to five times greater than that at the shoreline (Tonelli *et al*. 2010). In the absence of any intervention, the erosion of existing marsh can be expected to continue and accelerate as sea level rises.

The local sediment budget of the mudflat-salt marsh system at CMER is also an important potential indirect driver of marsh edge erosion. A significant portion of the bedload and suspended sediment load of Corte Madera Creek is trapped within the flood control channel, and removed from the system (Schoellhamer *et al*. 2018). Mudflat erosion bayward of the marsh scarp, and concave mudflat profiles, are likely to contribute to increased wave energy as sea level rises. Mudflat sediment nourishment has been proposed as a component of sea level rise adaptation (BCDC and ESA 2013), in conjunction with marsh erosion buffering.

4.0 Reference systems: basis of conceptual design for marsh scarp treatment at CMER

The primary basis for the conceptual design of marsh scarp erosion treatment at CMER is provided by salt marsh edge reference systems in the San Francisco Estuary. Reference sites selected intergrade between active peaty mud salt marsh scarps and marsh-fringing barrier beaches and washovers composed of sand, shell hash, or mixtures. Where estuarine beach profiles establish on wave-cut salt marsh scarps, they generally intercept wind-waves that dissipate energy in turbulent swash and backwash on the beachface, rather than the scarp face (SFEI and Baye 2020), reducing the duration and intensity of wave undercutting of the scarp.

Estuarine beach profiles fringing salt marsh scarps range between partial beachface profiles (swash slopes below the crest) to full estuarine beach ridge (berm or washover) profiles. Full beach profiles completely bury marsh scarps with a continuous beachface and berm across the bayward edge of the salt marsh platform (e.g., Roberts Landing, Whittell Marsh examples below). Intermediate, split barrier beach profiles consist of a beachface below the scarp crest, and detached swash bars, salt marsh berms, or washovers landward of the crest, perched on the marsh platform (e.g., Bair Island and West Pinole Creek marsh examples).

One of the most ecologically and geomorphically significant aspects of all these reference systems is the maintenance of well-drained wave-deposited high salt marsh berm providing topography and vegetation canopies elevated well above Mean Higher High Water (the approximate average elevation of equilibrium tidal marsh platforms deposited by tides alone). Wave deposition of coarse sediment (sand, shell hash, and organic debris) raises substrate elevations up to 1-2 ft above the marsh platform on washovers and berms at reference sites, depending on wave exposure and coarse sediment supply to breaking waves near the marsh edge. The well-drained, elevated washover and berm zone supports taller high marsh vegetation canopies and coarse debris perched on the elevated wave-built salt marsh topography, providing even higher elevation cover for wildlife during extreme high tides as the shoreline retreats.

The role of a nourished coarse high salt marsh berm/washover is important at CMER because of the inevitable loss of high tide cover (vegetation and topography) as the last remnants of the former bayfront levee erode away, and the scarp retreats through a planar marsh platform. Wave deposition is one of the only mechanisms of rapidly forming high salt marsh landforms above Mean Higher High Water. The topography and wide zone of increased vegetation roughness provided by the high salt marsh berm/washover zone also establishes a potentially self-maintaining wave attenuation feature. The self-constructing, self-maintaining high salt marsh berm/washover would, however, be dependent on artificial coarse sediment supply, since there is no modern natural source of coarse sediment delivery to the marsh edge here.

Regional examples of partial to full estuarine marsh fringing barriers, intergrading with exposed active salt marsh scarps alongshore, are presented below as partial models for analogous features designed for CMER marsh scarps.

4.1. Bair Island (south shore), Redwood City, South San Francisco Bay. Pure shell hash (flake fragments and whole shells) beaches are formed along the convex salt marsh scarp shoreline of South Bair Island by onshore transport of fossil Olympia oyster (*Ostrea lurida*) shell hash eroded from shell-rich intertidal and subtidal by wind-waves waves. Shell hash deposition occurs at the shore profile break of the marsh scarp. Net southerly longshore drift establishes a shell hash erosion-accretion gradient alongshore, with full cuspate spit and prograding beach ridge profiles down-drift, and partial or split (discontinuous) barrier profiles in more shell sediment-deficient profiles updrift. Split profiles updrift include a set-back high marsh berm perched above and behind (landward of) the scarp crest, detached from a shell hash beachface with a ramp-like profile below the scarp crest. Continuous shell barrier beach ridge profiles contain one or more relict steep beach ridges up to about 2 (maximum 3) ft high above the adjacent marsh platform, attached to the beachface, with no scarp crest exposure. Single shell hash beach ridges are less than about 20 (to 30) ft wide, but prograded multiple ridges are wider. Low-gradient washovers are infrequent in coarse, porous shell hash lacking sand. The highly wave-exposed Bair Island shell ridges, unlike more wave-sheltered relict, stable vegetated shell ridges near the mouth of Belmont Slough at Foster City, have been too mobile to support persistent high salt marsh vegetation in the last two decades.

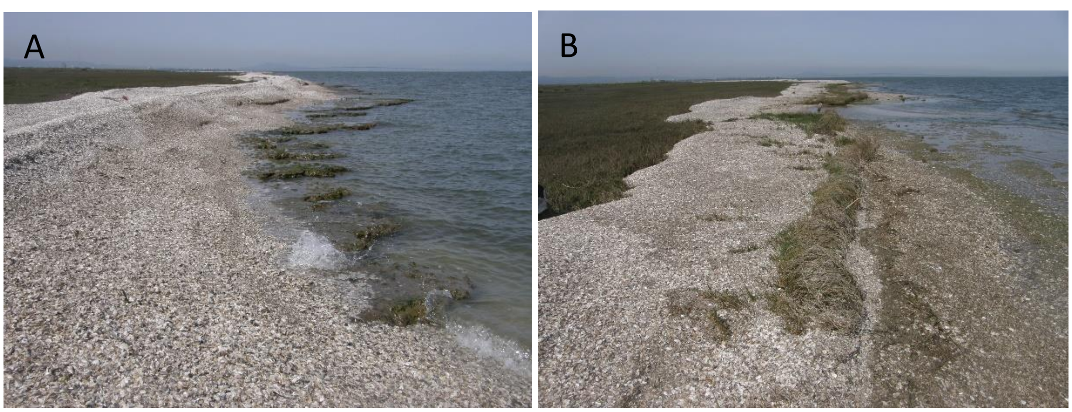

Figure 4. Shell hash beach ridge deposition is perched landward of the exposed marsh platform scarp crest at south Bair Island. The detached shell hash beachface (swash slope) is submerged below the scarp. The highly mobile, wave-exposed ridge is unstable and unvegetated. May 2010.

4.2. Giant Marsh (north shore), West Point Pinole, Richmond, San Francisco Bay. Sand eroded from low coastal bluffs at Point Pinole is transported south to the north end of erosional scarps at the bay edge of Giant Marsh. Beachface profiles attenuate down-drift. Beaches overtop the scarp crest at the north end, where they form dynamic sandy salt marsh berms that retreat by overwash during storm events. Salt marsh berm composition grades into fine woody or fibrous organic detritus (from marsh peat containing decomposed woody fluvial debris) southward. Marsh berm relief above the salt marsh platform is generally 1-1.5 ft at most, occupying a narrow washover zone about 20 ft most years.

Figure 5. Giant Marsh scarp and berms at Point Pinole, Richmond. A) Giant Marsh salt marsh scarp, with disintegrating toppled marsh sod (cantilevers) and slump blocks, south of the fringing estuarine beach. B) High salt marsh berm composed mostly of organic tidal litter deposited over mixed sand, driftwood, and detritus. C) Sandy high salt marsh berm (narrow overwash zone) covers a relict marsh scarp. February 2017.

4.3. Pinole Creek mouth (west shore pocket salt marsh), Richmond, San Pablo Bay. The delta of Pinole Creek is flanked by salt marshes that have been partially filled and developed. The outer edges of the western salt marsh receive relatively abundant deposits of fine to coarse organic fibrous and decomposed woody debris from Pinole Creek, as well as sand that drifts from the nearshore ebb tidal/fluvial delta. The mixed sand and organic debris dominate the pocket marsh beachface and salt marsh berm/washovers deposited above and below the salt marsh scarp. During depositional phases, the vegetated marsh berm crest relief is about 1.0-1.5 ft above the adjacent salt marsh/salt pan platform, usually extending less than 20 ft landward from the scarp crest. During active storm retreat, a relatively continuous wider sandy washover/low beach ridge is deposited immediately landward of the scarp crest.

Figure 6. Pinole Creek west marsh, Pinole, San Pablo Bay. A-B) high salt marsh berm above scarp, landward slope, with local sand and debris washovers. C-D) marsh berm crest and beachface below small exposure of scarp. A-D, August 2007. E) Aerial view of pocket marsh and mostly unvegetated active fringing sand beach and washover, March 2019 (Google Earth).

4.4. East Whittell Marsh, East Point Pinole Shore, Richmond, San Pablo Bay. The Whittell Marsh shoreline extends east from Pinole Point headland. It is a narrow marsh-fringing barrier beach complex migrating over a prehistoric salt marsh remnant. The low (1-3 ft) beach ridge grades into a high salt marsh berm with variable proportions of vegetation and bare sand. Eastern end of the beach system has local features relevant to planning for CMER: (1) upland headlands with blue gum eucalyptus topped into the mudflat and beachface, generating persistent (>15 yr) driftwood logs acting as weak groins or sand drift-sills; (2) beach accretion and overwash at small tidal channel mouths that become temporarily choked during neap tides or high wave conditions, naturally restricting tidal circulation of the salt marsh and channel.

Figure 7. East Point Pinole, Whittell Marsh, Richmond, San Pablo Bay. A-B, blue gum eucalyptus trees toppled into beach and tidal flats, persisting as drift-sill logs. C) Beach sand accretes at the outer salt marsh edge as a high salt marsh berm, and at the mouth of a tidal creek that becomes choked at low tide, flooded during high tide – a condition that would be undesirable at CMER.

4.5. Roberts Landing, San Leandro (Long Beach), San Francisco Bay. The proximal (north) end of the Roberts Landing sand spit ("Long Beach") in recent years has consisted of a sand beach and active sandy washover fan migrating over a tidal salt marsh platform. The downdrift (south) end of the beach has prograded bayward of the older marsh platform, and intergrades with the San Lorenzo Creek delta salt marsh and sand bar complex (ecotone between estuarine beach, salt marsh, and intertidal sand flat). Low foredunes and washovers support intermediate high salt marsh and estuarine beach vegetation on topography now mostly less than 2 ft above the adjacent salt marsh platform. In the 1970s-1980s, when sand supply was greater, a full barrier beach profile with moderate relief (3-5 ft) foredunes occurred here. This west-facing, long-fetch shoreline is one of the most highly wave-exposed beach-salt marsh reference systems in the region.

Figure 8. Roberts Landing Long Beach, north end, San Leandro, San Francisco Bay. High salt marsh sand berm with driftwood and tidal litter during active migration over over tidal salt marsh at Roberts Landing. Wave and wind deposition of medium sand occur together at this location near historical sand barrier beaches.

5. Conceptual Design for an artificially nourished barrier beach at Muzzi Marsh

The overall conceptual design is to use beach profile nourishment along the upper tidal flats below segments of the Muzzi Marsh scarp to provide wave action sufficient sand and fine gravel supply to rework the unconfined beach sediment to form natural (self-constructed) wave-deposited beachfaces (swash slopes) that intercept wave energy (Figure 9), similar to the design of some self-constructed Aramburu Island sand/shell beach profile stages in nearby Richardson Bay (Wetlands and Water Resources 2010). During storm waves and higher spring tides that submerge the salt marsh platform (overmarsh tides), wave action is expected to form swash bars (low sandy beach ridges or washover landforms mixed with marsh litter and woody debris). Swash bars and washovers are expected to subsequently evolve into low-relief vegetated high salt marsh berms during post-storm recovery phases.

The combination of high salt marsh berms/vegetated washovers (capped by tall high salt marsh vegetation) above the scarp, and beachfaces below the scarp, are expected to significantly reduce the frequency of storm wave events that cause undercutting, collapse, and significant net landward retreat of the salt marsh scarp shoreline, and enhance wave attenuation across the salt marsh platform. Salt marsh soil outcrops that act as transient, erosional headlands would be reinforced with embedded large woody debris to establish persistent local littoral cells (pocket beach series) with restricted longshore drift of sand.

The artificially nourished marsh-fringing barrier beach, in the absence of natural beach sediment supplies, would likely require re-nourishment over decades as sea level rises in order to maintain significant wave erosion-buffering capacity. Some sand would likely be transported seaward into mudflats and become buried or mixed into cohesive bay mud during high wave energy events. Sand deposited in mudflats may become relatively unavailable for calm-weather shoreward transport, resulting in deficits in sand availability to the beach and washovers. Replenishment of sand at the shoreline would be needed to offset this internal loss to the coarse sediment budget.

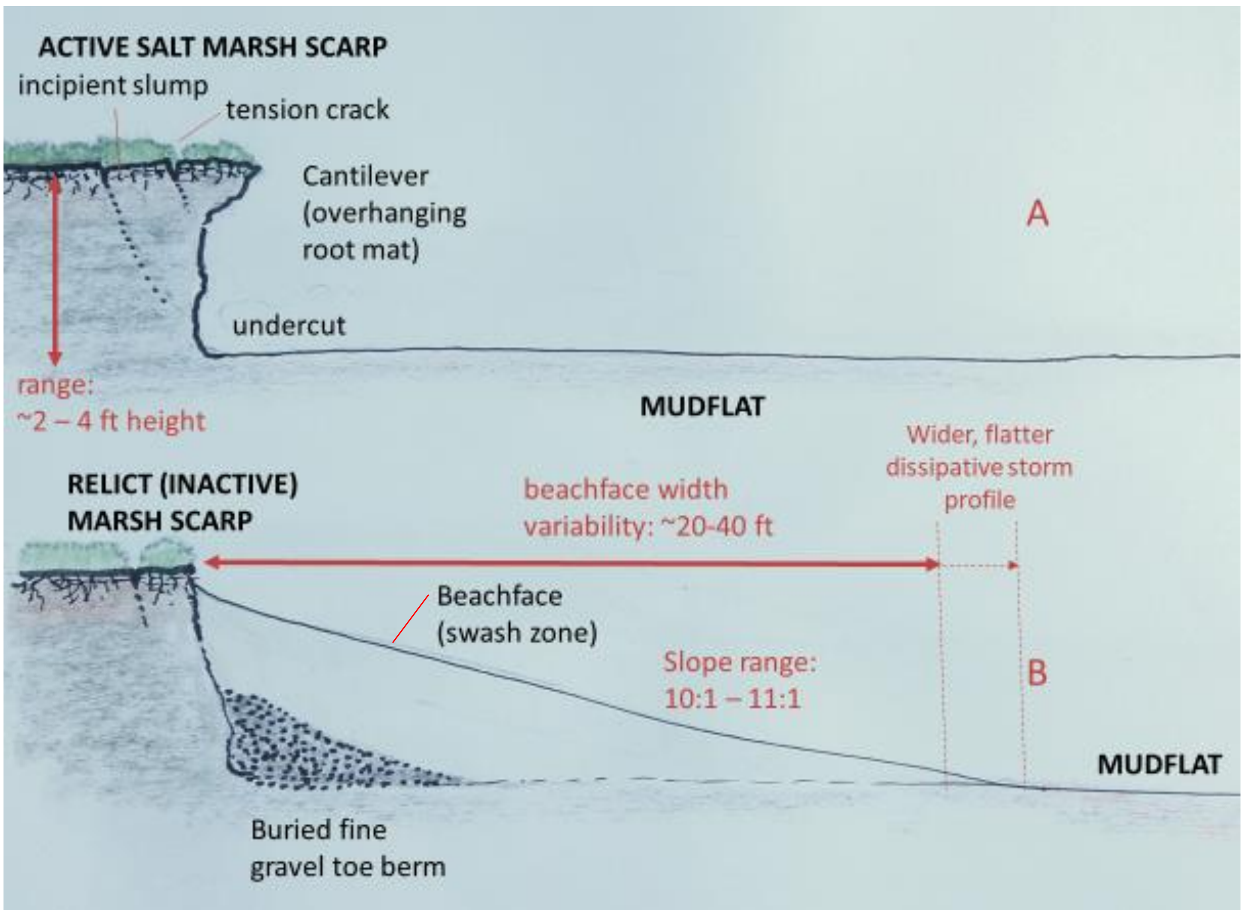

Figure 9. Conceptual design of Muzzi Marsh salt marsh scarp treatment with a self-constructed beachface. The beachface (sand slope, wave swash/backwash zone) is deposited by wave action that reworks unconfined artificial deposits of medium sand (with smaller volumes of fine gravel at the scarp toe).

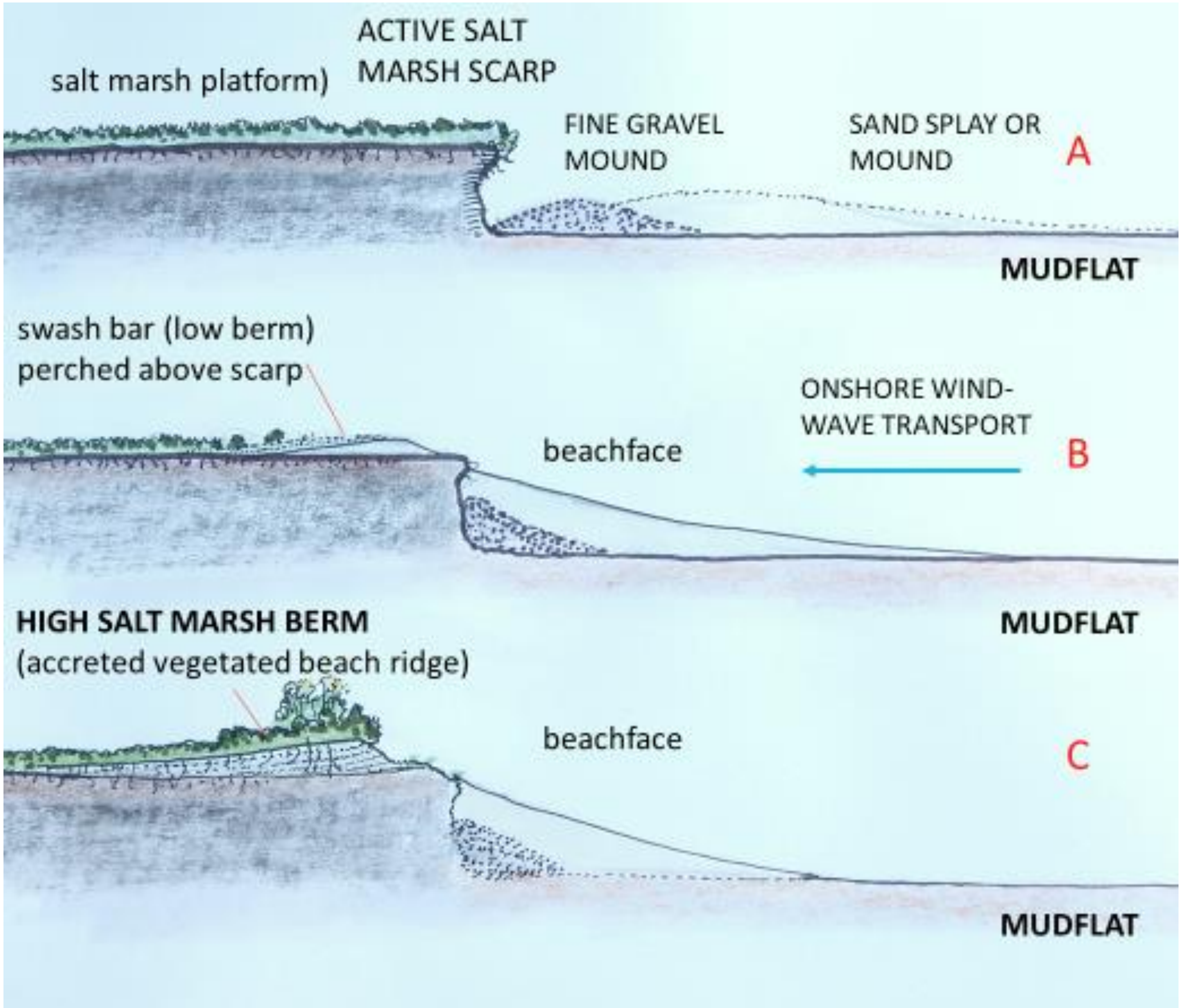

Figure 10. Conceptual evolution of marsh-fringing barrier beach/washover at salt marsh scarp. Sequence follows initial hydraulic slurry placement of sand and fine gravel, cross-section view. Hypothetical sequence is based on qualitative observations of natural and restored San Francisco Estuary reference sites.

A) Unconfined placement of fine gravel mounds and medium sand splays below erosional toe of scarp. Maximum mound thickness is less than approximately one half scarp height. Unconfined sand splay width is approximately 40-80 ft.
B) Wave action reworks fine gravel and medium sand (net landward transport of coarse sediment) to form a low gravel toe berm (exposed only when sand beach profile is flattened by storm waves) and sand beachface with variable slope about 1:10-1:11 V:H. Height of sand beachface in relation to scarp crest depends on local volume of sand and wave runup. A low-crested swash bar or washover terrace composed of sand and organic debris is deposited by high waves during overmarsh tides landward of the scarp crest.
C) Beachface and gravel toe berm buffer scarp undercutting and retreat. Scarp crest retreat occurs during storm lowering and flattening of beachface. A dynamic sandy swash bar/washover establishes cover of high salt marsh vegetation and accretes as a high salt marsh berm during constructive overtopping/overwash events. Extreme storm erosion erodes and flattens berm to a washover during gradual landward retreat. The dynamic washover/swash bar vegetates and accretes as a high salt marsh

berm. Extreme storm erosion events erode and flatten the berm to an active washover, driving pulses of gradual landward retreat. The high marsh berm accretes and regenerates during post-storm recovery phases.

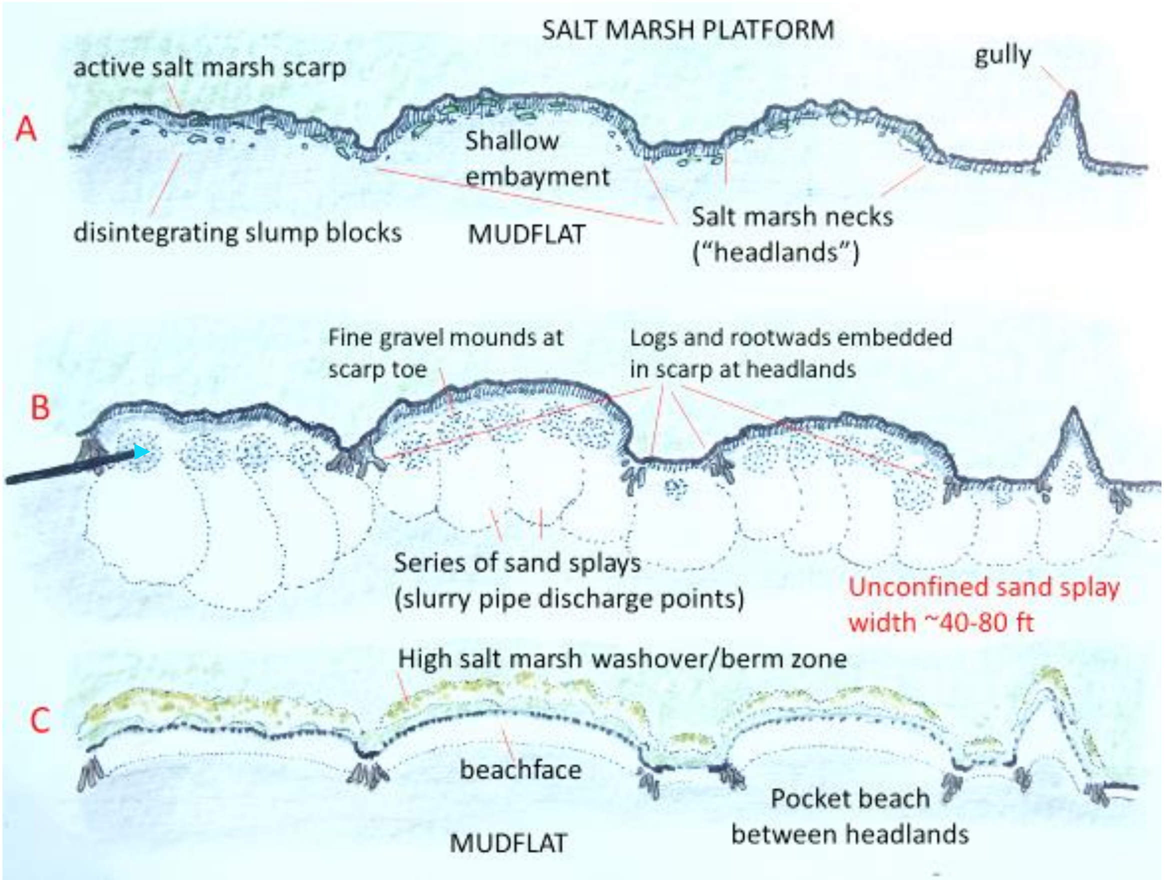

Figure 11. Conceptual evolution of artificially nourished marsh-fringing barrier beach/washover at salt marsh scarp in plan view. Sequence is based on qualitative observations of natural and restored San Francisco Estuary reference sites.

A) Irregular, crenulate salt marsh scarp configuration with shallow embayments, gullies (clefts) and necks like headlands.

B) Unconfined deposition of fine gravel mounds and medium sand splays along the scarp toe by discharging a slurry at sequential points along the foot of the scarp. Mounds and splays spread from point of discharge; pipe discharge point is moved when splay/mound volume, height, width thresholds are met. Maximum mound thickness is less than approximately one half scarp height. Unconfined sand splay width is approximately 40-80 ft. Large woody debris, brush and rootwads are inserted (jammed) into the soft bay mud at the foot of the scarp at headlands to form drift-sills (partial obstacles to sand drift).

C) Wave action reworks fine gravel and medium sand (net landward transport of coarse sediment) and forms a series of pocket beaches in shallow embayments between LWD-stabilized salt marsh headlands. Beachface narrows to ca. 40 ft after landward wave transport of sand. A low-crested swash bar or washover terrace composed of sand and organic debris is deposited behind the scarp during overmarsh tides during infrequent high wind-wave events. The dynamic washover/swash bar vegetates and accretes as a high salt marsh berm. Extreme storm erosion events erode and flatten the berm to an active washover, driving pulses of gradual landward retreat. The high marsh berm accretes and regenerates during post-storm recovery phases.

Specific design features, which are based on evolution of regional reference sites (Section 4 above), and coarse sediment placement experience in two San Francisco Estuary restoration projects (Sonoma Baylands tidal marsh restoration, Aramburu Island shoreline enhancement), are described below.

5.1. **Large woody debris drift-sills** (logjam headland stabilization). The naturally occurring irregularities of the salt marsh scarp – headland-like “necks” that bound shallow concave-bayward, arcuate marsh scarp embayments (Figures 3 and 11) – would be reinforced by embedding clusters (“logjams”) decay-resistant large woody debris (logs, limbs, and brush, similar to driftwood) in bay mud and marsh soil outcrops at marsh scarp “headlands”. Similar “micro-groins” constructed from eucalyptus logs and boulders were installed by land-based equipment at Aramburu Island. In the absence of access by land-based equipment, installation of large woody debris to partially stabilize marsh headlands would require either manual installation and delivery of wood by barge, or barge-supported amphibious excavators (pressing wood into mud) operating during high tides, braced in place next to headlands by spuds. Constructability of large woody debris drift-sills will require further feasibility assessment.

5.2. Beach sediment placement below the salt marsh scarp. Beach profile nourishment (Nordstrom 2000) is unconfined placement of beach sediment across the active beach profile to allow waves to rework the deposit into a natural beach profile. This method contrasts with a constructed “design profile” of an engineered beach berm. Since there is no existing land-based equipment access to the marsh edge (no load-bearing levee or levee road) along the marsh scarp, the proposed concept design scenario presumes that delivery of sediment would be based on deposition of splays (“mounds”) of sand transported as a slurry by pipelines carrying turbulent suspensions of sand and make-up bay water or brought to the site by marine based equipment and placed from barges. Based on the observed rapid reworking of unconfined upper intertidal sand and gravel deposited at the nearby Aramburu Island beach nourishment site (Tiburon), where a natural beach profile formed itself within a few months after placement (SFEI and Baye 2020), beach self-construction by natural wave transport is expected to occur rapidly at CMER as well.

Hydraulic placement of dredged sediments in the San Francisco Estuary is conventionally used for filling subsided diked baylands (reclaimed tidal marsh) for tidal marsh restoration. Imported hydraulic dredged sediments are usually bay mud, (e.g., Cullinan Ranch and Montezuma Wetlands Project), but also may utilize sandy dredged sediments (Hamilton Wetlands Restoration Project, Novato) or mixed mud and sand sediment (Sonoma Baylands, Petaluma). Each of these examples hydraulically place dredge sediment using a pumping system from barges brought from in-bay from dredge sites. The pipeline discharge location would need to be offset from the marsh scarp edge with sufficient distance (preliminary estimate: 20-30 ft, based on Sonoma Baylands discharge scour pit diameters at heads of sand splay fans; see Figure 12) to avoid short-term erosion impacts during filling. At Sonoma Baylands, despite large pipelines and high volumes of energetic, turbulent slurry discharge, scour pits were relatively small at the end of filling operations (Figure 12). Sandy sediment slurry discharge rates and pipelines sizes for smaller volumes of sediment delivery bayward of the CMER salt marsh scarp would presumably be lower than the larger-scale hydraulic slurry filling operations at Sonoma Baylands.

Hydraulic sediment slurry discharges would occur on mudflats during exposure of upper mudflats from mid to low tide (emergent tidal flat stage), to concentrate placement of splays along the scarp and minimize suspended sediment drift. Alternatively, mechanical placement of beach sediment using a long reach excavator mounted on a barge, would allow for greater control and precision in sediment placement. Long-reach excavators mounted on a barge would place sand from a temporarily fixed barge position and high or low tides, and the barge would be repositioned during high tides. Constructability analysis of the most cost-effective approaches to achieve project goals and objectives would be developed under the subsequent preliminary design phases of the project, with guidance from a scientific and technical advisory panel (Section 7, below).

Examples of hydraulic placement of sand-slurry sediment splays/mounds, deposited in a series by a moving pipeline discharge point, are shown in Figure 12 (Sonoma Baylands tidal marsh restoration project in 2002). Sonoma Baylands Main Unit dredge sediment fans were not intended to form sand mounds; the pipe discharge point was moved to prevent excessive mounding above target elevations for tidal marsh restoration (where they incidentally formed outstanding high marsh transition zones). The same technique may be applied deliberately to form a series of sand splays from pure sand slurry or mixed sand-fine gravel slurry. The Sonoma Baylands splays also contained fine gravel and shell; gravel was audible as bedload in the slurry pipe during placement. The size of the smallest splays ranged between 40-85 ft wide; larger fans, formed by long duration of a single slurry discharge point, ranged from 114-135 ft wide. The smaller splays would be appropriate for Muzzi Marsh beach nourishment, and are the basis for the concept design sketch (Figure 11 B).

The beach sediment placement at the scarp should include a small amount of fine gravel, such as the sand processing “screenings” (non-commercial shell and rounded fine gravel) from bay sand dredging wastes used for Pier 94 San Francisco and Aramburu Island shoreline enhancement (SFEI and Baye 2020). A small gravel toe berm (Figures 9-10) would provide additional protection against wave undercutting of the scarp when high energy waves flatten the sand beachface to a more dissipative profile. Fine gravel may be placed first in sequence of each splay deposit.

Gaps in sand placement would be planned for the erosional mouths of major tidal creeks. Major tidal creeks provide essential tidal circulation to the interior of Muzzi Marsh, so sand drift across creek mouths must be restricted to avoid choking or impounding them. Drift-sills (log structures) would be installed around creek mouths, even where no sand is directly placed for beach accretion. These “backstop” drift-sills would reduce the risk of drifting sand bypassing udrift drift-sills in beach nourishment zones, to protect tidal creek mouths against choking.

The location of feasible sand delivery and sand-slurry pumping and staging areas at Muzzi Marsh is uncertain. They may be onshore (on cross-levees at the south, center, or north side of Muzzi Marsh, if they can support equipment) or offshore (on barges). The wide, shallow nearshore mudflats and the unmaintained cross-levees within a salt marsh supporting two federally listed wildlife species would be expected to impose significant constraints on constructability of both onshore and offshore staging of hydraulic sand slurry placement options.

The volume of sand required for a sufficient beachface profile should allow for settlement, loss due to mudflat mixing (trapping in cohesive mud-sand mixtures, unavailable for wave transport onshore), and onshore transport loss to perched high marsh berms. Assuming a scarp crest elevation range of up to 3 feet above the scarp toe, an average beachface slope in the approximate range of 10:1-11:1 (reference beaches for Aramburu Island; Wetlands and Water Resources 2010), and sand beach crest elevation ranges up to about 6.0-7.0 ft NAVD (above scarp elevation), a rough volume (order of magnitude) of beach sediment for initial full profile nourishment would probably be close to 3.5 cubic yards per linear foot of treated shoreline (somewhat less if marsh headlands are excluded), or a total over 6000 cubic yards (under 10,000 cubic yards, even allowing for losses) of sand for the 1880 linear feet of exposed scarp estimated. This volume is less than the typical sand dredging volume (about 3 year maintenance cycle), for example, from St. Francis Yacht Harbor in San Francisco, Marina District, east of Crissy Field Beach, Presidio.

Environmental impacts of project construction methods are important feasibility considerations for permitting and implementation, and consistency with overall project goals and objectives. At a conceptual level, short-term and long-term environmental impacts of project construction that are likely to require focused assessment and mitigation are identified below:

- **Construction disturbance impacts to endangered wildlife** (salt marsh harvest mouse and California Ridgway's rail). Short-term construction impacts would include noise of equipment operation, field crews entering salt marsh habitats during the non-breeding season of rails when construction would potentially occur. Vegetation and wildlife impacts of hydraulic pipeline placement (land-based sediment delivery scenario) in salt marsh may be minimized by placement of pipelines along remnant cross-levees (E-W trend) and temporary bridges across channel gaps in cross-levees. Marine-based delivery of sediment by offshore barge pipeline, or long-reach excavators operating from barges, would avoid direct salt marsh disturbance.

- **Hydraulic slurry discharge erosion (scour) pits**. Points of hydraulic slurry discharge erode semi-circular pits in mudflat or marsh sediments. Pits of large-scale dredge sediment pipelines at Sonoma Baylands formed pits about 20-25 ft in diameter at the point of discharge during peak rates of discharge, and shrank during the terminal stages of filling (see Figure 12). Hydraulic slurry pipe discharge points would need to be located at sufficient distance (approximately 20-30 ft) from the marsh scarp to avoid excessive scour pit erosion of the marsh scarp. Backfilling of the scour pit by sand mounding, and subsequent beachface accretion (the objective of beach sediment placement) is expected to mitigate temporary local erosion impacts on the low tide terrace.

- **Short-term turbidity and water quality impacts**. The project location (wide mudflats) has naturally high background levels of suspended sediment during low to moderate wind-wave activity, as well as high wind-wave activity. Turbulent discharge of sandy slurry on mudflats at low tide is not likely to cause significant increases in background levels of suspended sediment concentration during rising tides over mudflats. High tide placement of sandy sediments during low wind-wave conditions may cause short-term local sediment plumes. Timing of temporary sediment plumes (high tide excavator operation scenario) should avoid seasonal salmonid migration times to avoid excessive potential turbidity impacts. Sandy sediments would be tested for suitability of placement in aquatic estuarine habitats.

Figure 12. Sonoma Baylands sand splays (mounds). (A) A series of hydraulically discharged sand slurry splays (yellow circled) within a tidal marsh restoration project based on dredged material placement as a slurry (mud suspension), 2002. Note remnant pipeline slurry discharge scour pits (dashed circles), offset from toe of levee, at heads of two larger splays at left. (B) Oblique ground view of newly deposited sand splays in 1996, showing scour pits. Sand splays are from Port of Oakland Merritt Sand mixed with bay mud, sorted differentially during hydraulic placement. San Pablo Bay, Petaluma) tidal marsh restoration project.

5.4. Expected evolution and maintenance of the nourished marsh-fringing barrier beach

The qualitative evolution of the nourished beach is subjectively estimated as a working hypothesis, base on long-term observations of storm/post-storm recovery cycles of reference beaches in the San Francisco Estuary. The expected geomorphic and ecological evolution of the nourished beach-salt marsh shoreline is summarized graphically and annotated in Figures 10-11. The sequence includes stages where introduction of California sea-blite, an element of the New Life for Eroding Shorelines project, can be integrated into the beach nourishment design.

Stage 1. Pre-construction. Relatively rapid marsh scarp retreat (about 2-3 ft/yr, varying with location and storm year, sediment supply). Outcrops of firm bay mud (basal strata of eroded marsh platforms, former levee footprints) are exposed near the surface of tidal flats below the scarp.

Stage 2. Large woody debris drift-sill placement. Logs, limbs, and brush are inserted into firm bay mud at salt marsh necks or headlands to provide obstacles for longshore drift of sand, and traps for floating woody debris.

Stage 3. Coarse sediment nourishment. Series of hydraulic sand splays are deposited along the base of the scarp, spreading bayward 40-80 ft. Sand splays are placed in fall before the winter storm season.

Stage 4. Coarse sediment reworking and beachface deposition. Winter storm wind-waves erode sand splays and cause net shoreward (landward) sand transport, forming a dissipative wide beachface, and sand washovers perched on the salt marsh platform above the scarp. Some longshore drift of sand occurs at the ends of sub-embayments, but is restricted by drift-sills, with little net drift among cells.

Stage 5. During non-storm wind-wave conditions in late winter/spring, post-storm beach profile recovery occurs; net onshore transport of sand, steepening of the beachface, and deposition of swash bars in the upper profile, below the winter storm overwash or swash bar deposits.

Stage 6. During the spring-summer growing season of the first year after profile nourishment, winter storm overwash and berm deposits are recolonized by high salt marsh vegetation by direct regrowth and emergence from below, and seedling colonization at the surface. Salt marsh vegetation grows through deposits less than 20 cm. New high salt marsh vegetation partially stabilizes the washover/berms, and develops a tall vegetation canopy.

Stage 7. Winter cycle: storm wave erosion of previous washovers and berms (bayward side), and net deposition and landward transgression of washovers and berms; net vertical accretion occurs where high salt marsh vegetation is dense and tall, trapping and stabilizing sand and debris. The beachface flattens during storm events. Some sand is transported bayward during storm events and mixes with bay mud, reducing availability for subsequent onshore transport by wind-waves (sediment sink, net loss of sand). Little significant erosion of the scarp below the beachface, except the outcrops of the scarp crest exposed at the top of the profile. Scarp undercutting is halted or significantly reduced.

Stage 8. Second (third?) year post-storm recovery. Vegetation recovery and net expansion of washovers and berms. Vegetated berm crest elevations increase to about 1.0-1.5 ft above MHHW, with perennial vegetation canopy (high tide cover) 2-3 ft above substrate elevation. Vegetation-stabilized washovers and high marsh berms are receptive sites for experimental introduction of (SFE-native) California sea-blite, *Suaeda californica*, to augment high tide refuge and wave attenuation on the high marsh berms/washovers.

Stage 9. Net loss of sand due to mudflat trapping, sea level rise (profile adjustment, Bruun Rule), and landward transgression of washovers, triggers excessive re-exposure of the marsh scarp during storms; marsh scarp retreat resumes at excessive high rates. Re-nourishment of sand over parts or all of the beach, at volumes up to about one half the original volume of sand, is expected within 20 years.

7. **Next Steps**

Next steps in the process of developing a project from conceptual designs would likely include:

- Establishment of a technical/scientific review and advisory group, representing physical and biological applied sciences, to guide development of alternatives and refinements of conceptual and preliminary designs, identification of potential fatal flaws (environmental, engineering constraints), and minimization and avoidance (mitigation) of potential environmental impacts.

- Development of concept designs into preliminary and final designs that produce scaled plans and cost estimates, and identify potential permitting and stakeholder concerns to resolve.

- Alternatives analysis, feasibility analysis, and constructability analysis would be performed to identify the environmentally superior alternative that meets agency permit requirements, meets project goals, and cost:benefit requirements.

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